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Soil Erosion Studies

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Meet the editors

Dr. Danilo Godone holds a PhD in "Agriculture, Forest and Food Sciences", doctorate's topic was cryosphere's phenomena monitoring by geomatic methodologies. Currently he is a PostDoc grant holder, at Turin University, studying geomatic contribution in land management and analysis. His main research interests are, however, landslide, glacier and, more generally, natural disasters monitoring. During his activities he has developed skills in GIS, also by developing customised tools by Visual Basic programming, and land surveying with GPS or Laser Scanners. He is a member of NATRISK - Research Centre on Natural Risks in Mountain and Hilly Environments, in the same University. He acts as a freelance consultant, in the same topics, for other research bodies, training agencies and professionals, too.

Dr. Silvia Stanchi holds a PhD in "Agriculture, Forest and Food Sciences", with a focus on fractal theory approaches for the study of soil aggregation and structure. Currently, she is a PostDoc at Turin University working on soil hazards and vulnerability in mountain areas. Silvia Stanchi is a member of NATRISK - Research Centre on Natural Risks in Mountain and Hilly Environments, in the same University. She is actively involved in outreach and soil awareness raising activities targeting kids and the large public, and in international training activities focusing on mountain development and management.

Contents

Preface

Soil erosion affects a large part of the Earth surface, and it represents one of the most relevant environmental problems worldwide. Intense land degradation processes that destroyed civilizations in the past are still going on at present.

Accelerated soil erosion is one of the main soil threats, as the natural balance between soil formation and loss may be seriously compromised, leading to desertification and permanent loss of fertility and protective function. Soil erosion is not only related to agricultural activities and farming practices, but also to land management in general.

In non-agricultural lands (e.g. forests, rangelands etc.) erosion plays a primary role in landscape evolution and landform development, affecting the availability of nutrients, the soil physical properties and therefore the vegetation cover. Moreover, erosion may lead to desertification phenomena interesting as waste areas.

The land management in areas affected by soil erosion is a relevant issue for landscape and ecosystems preservation. In literature, a wide discussion on erosion assessment methods, erosion effects and mitigation techniques is available, and the effects of erosion on both agricultural and non-agricultural land are widely treated. Among the major problems about soil erosion assessment and mitigation, there is the spatial and time scale at which erosion occurs.

In this book we collected a series of papers on erosion, not focusing on agronomic implications, but on a variety of other relevant aspects of the erosion phenomena.

The book is divided into three sections: i) various implications of land management in arid and semiarid ecosystems; ii) erosion modeling and experimental studies; iii) other applications (e.g. geoscience, engineering).

In the section on arid and semiarid ecosystems different environments are presented, from Mediterranean basin (Greece, Spain, Portugal) to Central and South America (Brazil, Mexico), and different aspects of soil erosion are treated.

Christopoulou examined the effects of deforestation in Greece, due to fire and land management, indicating some guidelines for forest management, fire prevention and soil conservation. Wildfires effects are widely discussed in the paper by Badía et al., focusing on restoration and recovery strategies in the post-fire soil and vegetation evolution. Nunes treated the relationship between erosion and land cover in marginal areas in Portugal, suggesting guidelines for land management and erosion prevention. Vásquez-Méndez et al. examined the role of native vegetation cover and pioneer species on erosion mitigation and soil protection, observing a favourable effect on runoff reduction due to the canopy effect. Marco da Silva et al., examined the natural susceptibility of Brazilian soil to erosion using the rainfall, soil and topography information of the USLE (Universal Soil Loss Equation), obtaining a GIS-based map for the assessment of the natural potential for erosion, i.e. the intrinsic susceptibility of a territory to soil loss by water erosion processes.

A wide section of the book focuses on experimental studies and models. Plot scale experiments are presented together with slope management sustainable techniques using hydro-seeding techniques and environmental friendly materials.

Le Gouée et al. present a model for the assessment of soil erosion hazard in relation to climate change scenarios.

A final section deals with other erosion-related issues involving engineering and building techniques (e.g. earth dams and earth structures), and sedimentary record analysis for land use change study.

The book covers a wide range of erosion-related themes from a variety of points of view (assessment, modeling, mitigation, best practices etc.), and represents an exhaustive review on the causes and effects of accelerated soil erosion that need to be taken into account in order to effectively monitor and assess erosion phenomena.

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Part 1

Arid and Semiarid Land Management

1

Natural Potential for Erosion for Brazilian Territory

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1. Introduction

Erosion and sedimentation refer to the motion of solid particles, called sediment (Julien, 2010). Erosion is a natural process and causes a breakdown of soil aggregates and accelerates the removal of organic and mineral materials (Gilley, 2005).

Soil erosion risk can be assessed by means of equations empirically derived from the superposition principle of this phenomenon. Using such models, during the last decade, several initiatives have assessed the risk of soil erosion at the national, continental, and global levels (Terranova et al., 2009).

The use of geographic information system (GIS) enables the determination of the spatial distribution of the parameters of some soil loss predicting models, as the Universal Soil Loss Equation - USLE (Dabral et al., 2008). Every factor within the USLE is calculated by GIS, which is obtained from meteorological stations, topographic maps, land use maps, soil maps and results of other relevant studies. The spatial distribution of the soil loss of a certain region is given by multiplying factor map layers in the GIS. The spatial resolution of the data is an option of researcher, and should be considered the resolution of the Digital Elevation Model (DEM), soil map, satellite images, among other sources of information (Yue-Qing et al., 2008).

Land use is the only factor affecting erosion that can be modified to reduce soil loss potential (Gilley, 2005). However, if we do not consider the land cover and soil management, i.e., if we consider the interaction of rainfall, topography and soil, assuming that the soil is totally uncovered along wholly study area, we may predict the total soil loss amount or the Natural Potential for Erosion (NPE) for a considered area (Castro & Valério Filho, 1997).

NPE might be used as a tool to show cartographically areas highly pre-disposed to erosion and the mathematic relation among PNE value and soil loss tolerance value. It might indicate the ideal CP factor to be used in determined region.

Brazil is largest South American country and the land use is far from to be conformable with land use capability. Hence, soil loss studies and researches are highly needed. On the other hand, a lot of studies have been developed in order to predict soil loss rates along Brazilian

territory. Some of them use GIS technology (Beskow et al., 2009), some use hydrosedimentologic database, or others approaches (Tornquist et al., 2009). But such studies involve only a part of territory (a river basin, for example).
Considering the scarcity of database of a map that presents the Natural Potential for Soil Erosion through a specific mathematical model, this study aims elaborate the NPE map for entire Brazilian Territory considering the USLE approach.

2. Soil degradation

Soil erosion is a process inherent in landscape evolution. The intensity of soil erosion is governed by numerous natural and anthropogenic factors. Natural factors include soil, climate, vegetation, relief and other ecoregional characteristics (Lal, 2001).
Soils are more exposed to erosion for different reasons: inappropriate agricultural practices, deforestation, overgrazing, forest fires, and construction activities (Terranova et al., 2009). Erosion process has both on-site and off-site consequences. On-site consequences results in the loss of productive topsoil and other physical and chemical consequences. Furthermore, off-site problems, such as downstream sediment deposition in fields, floodplains and water bodies, are also very serious, with significant costs to society (Verspecht et al., 2011).
Land degradation may be defined as long-term adverse changes in soil properties and processes, leading to a loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided (Bai et al., 2008; Palm et al., 2007). Through such changes in soil properties and processes, soil degradation undermines the sustainability of many of the ecosystem services (Palm et al., 2007).
Among the kinds of degradation, Bai et al. (2008) list water erosion, wind erosion, nutrient depletion, salinity, contamination, physical as the principal ones. Among them, water erosion is responsible by more than a half of the degraded land along world and also in South America.
South American continent is a region with particular and expressive areas presenting high or very high vulnerability for water erosion (Figure 1). It presents average soil loss rates of 16.7 t ha^{-1} y^{-1} that is significantly higher if compared to the world average of 11.5 t ha^{-1} y^{-1} (Nam et al., 2003).

3. Soil loss modelling

Assessment of risk of erosion has traditionally been carried out by application of one of the many available mathematical models (Boardman et al., 2009). Considering that any model is a simplification of reality (Morgan & Nearing, 2011) and, for some users, this creates an immediate theoretical issue, the approach here employed considers three elementary natural features involved in erosion process: climate, relief and soil.
This approach is the Natural Potential for Soil Erosion (NPE). NPE, or Potential Erosion Risk, is defined here as the inherent risk of erosion irrespective of current land use or vegetation cover (Grimm et al., 2002; Vrieling et al., 2002). The NPE map can be generated using a part of the USLE model. The USLE is:

$$A = R\ K\ L\ S\ C\ P \tag{1}$$

Where: A is the rate of soil loss (t ha^{-1} y^{-1}), R is a factor for annual rainfall erosivity (MJ mm ha^{-1} h^{-1} y^{-1}), K is a factor for soil erodibility (t h MJ^{-1} mm^{-1}), L is a factor for slope length (m), S is a factor for slope steepness (%). C is the cropping management factor and P is conservation practices factor (Wischmeier and Smith, 1978; Beskow et al., 2009). The two last factors are dimensionless and LS, when managed jointly, are also dimensionless.

Fig. 1. Water erosion vulnerability map. Source: USDA (2003).

The NPE map is generated using the factors related to physical environment (rainfall erosivity, soil erodibility, and topographic factor). Factors C and P, related to human influence (cover management and soil management), are not considered. So, the NPE model is:

$$NPE = R\ K\ LS \tag{2}$$

Where: NPE – Natural Potential for Erosion, in $t.ha^{-1}.y^{-1}$; R, K, LS – same of equation (1).

4. Brazilian environmental characteristics

Brazil extends from the equatorial to the subtropical belt. Environmental characteristics are highly changeable along Brazilian territory due to large territorial size. The country is characterized by a large diversity of soil types, resulting from the interaction of the different relieves, climates, parent material, vegetation and associated organisms. This diversity and the consequent potential uses are reflected in the regional differences. There are nineteen major soil orders occurring along territory (Figure 2). The complex formed by the FAO System Xanthic, Rhodic and Haplic Ferralsols (named, according to Brazilian classification system (EMBRAPA, 2006), as Latossolos, and as Oxisols, according to Soil Survey Staff, 1999) is the predominant category and takes place in 38.7% of the Brazilian territory. The complex formed by the FAO System Rhodic and Haplic Acrisols and some Lixisols (named, according to Brazilian classification system (EMBRAPA, 2006), as Argissolos, and as Ultisols, according to Soil Survey Staff, 1999), is the second predominant category, taking place in 20.0% of the Brazilian territory. So, such two soil major classes represents more than a half of the Brazilian soils (FAO, 2004).

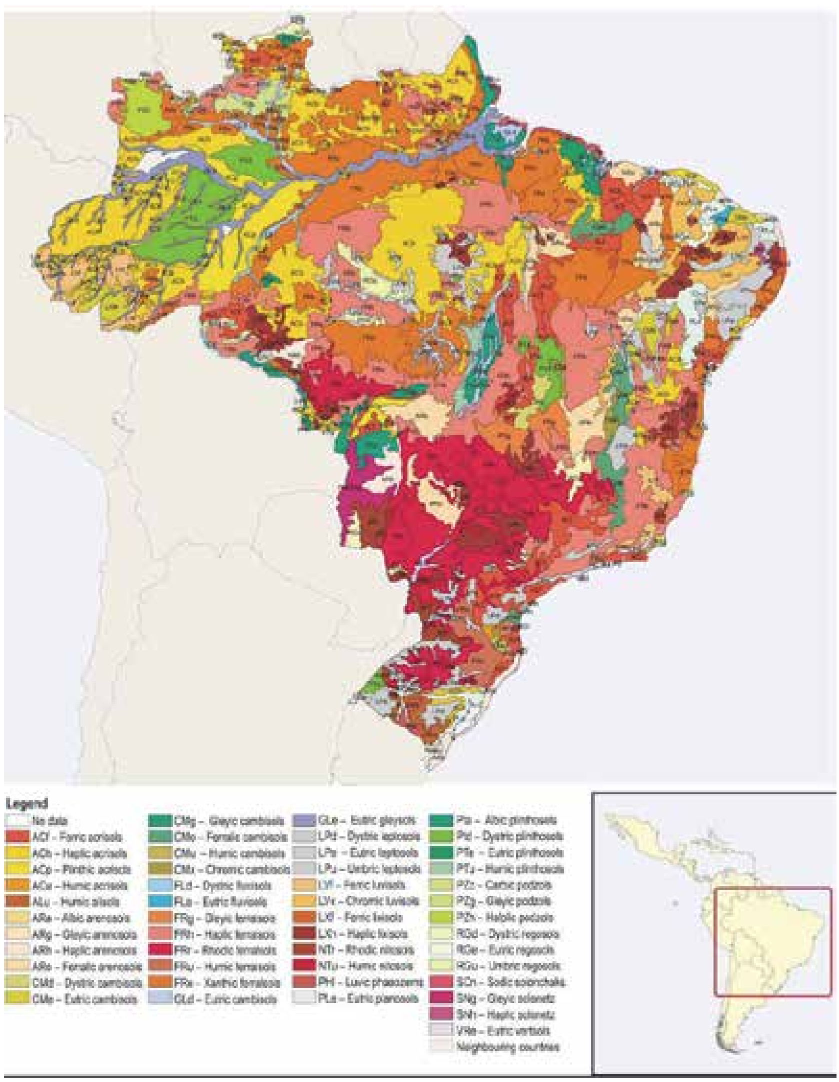

Fig. 2. Soil Classes occurring along Brazilian territory. Source: FAO (2004).

The largest part of its eastern front is characterized by a morphoclimatic domain called "sea of hills", with convex upslope and rectilinear lower slopes, sometimes with benches or shoulders, sometimes concave by the colluvial accumulation. In southeastern and partly in the south, hills are preceded by the scarps of the *Serra do Mar*, which limits the Atlantic plateau (Cruz, 2000).

Figure 3 depicts the relief compartments, showing predominance of plain regions along Amazon region and predominance of plateaus mainly along southeastern and southern regions (IBGE, n.d.).

Three main groups of natural processes take place on the slopes of these humid tropical areas: (i) weathering-pedogenesis, forming thick weathered mantles reworked by; (ii) overland and sub-surface flow, and river flow; and (iii) mass movements, especially on scarped slopes, such as those of *Serra do Mar* and *Serra da Mantiqueira*, in the southeast, and the *Serra Geral*, in the south. Such natural processes vary according to geographic position, declivity, range and length of the scarps, as well as their geological nature, the thickness of alteration beds and climatic conditions (Cruz, 2000).

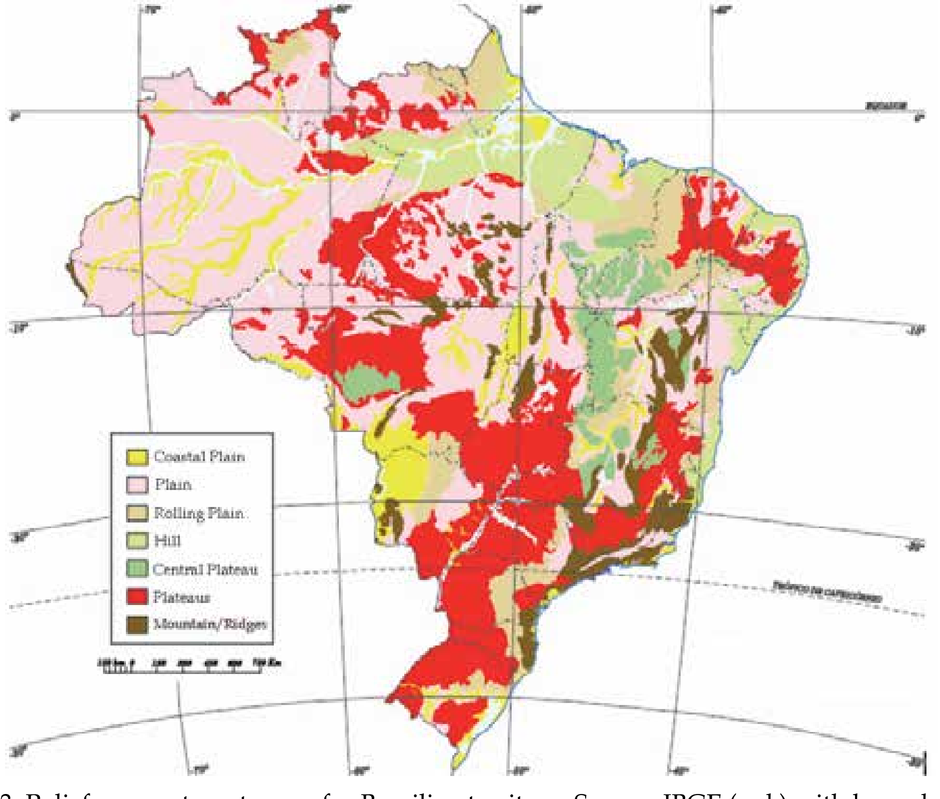

Fig. 3. Relief compartments map for Brazilian territory. Source: IBGE (n.d.) with legend translated according to map shown in Sayre et al (n.d.).

Climatologically, the minimal temperature (annual average values) ranges from 4 to 24^{o}C. Average temperature (annual average values) ranges from 8 to 30^{o}C. Maximum temperature (annual average values) ranges from 15 to 35^{o}C. In all cases, northern / northeastern regions present highest values, while southern region presents the lowest ones (INMET, n.d.).

Driest areas occur in northeastern region, where annual rainfall amount is approximately 600 mm. Northern region encompasses areas whose annual rainfall amount and erosivity are expressive (annual rainfall amount is usually over 2,500 mm), for example Amazon region (Silva, 2004). In most of Brazilian territory, annual rainfall depth ranges from 1,000 to 2,000 mm (Figure 4).

Fig. 4. Annual rainfall amount map of Brazilian territory (in $mm.y^{-1}$). Source: Silva (2004).

5. The natural potential for soil erosion map

For each one NPE factor a single, separated layer was elaborated (Figure 5) and for each factor, a specific database was elaborated, as described below.

5.1 R factor

For R factor layer, we used the digital map of rainfall erosivity (Silva, 2004). In this study, the author considered eight majors Brazilian regions covering the whole of the territory of Brazil, and for each region, one adapted equation was applied using pluviometric records obtained from 1,600 weather stations with continuous database of at least twenty consecutive years.

5.2 K factor

For K factor layer, a digital soil map (IBGE, 2001 and 2007) was considered. For determining the value of erodibility we used a soil profile database provided for whole Brazilian territory (Cooper et al., 2005). The erodibility was calculated indirectly through the method proposed by Boyoucos (1935), called clay-ratio method (Equation 3).

$$\text{Erodibility} = [(\text{sand} + \text{silt}) \;/\; (\text{clay})] \;/\; 100 \qquad (3)$$

Where: erodibility expressed in $t.h.MJ^{-1}.mm^{-1}$ and the textural attributes expressed in $g.kg^{-1}$.

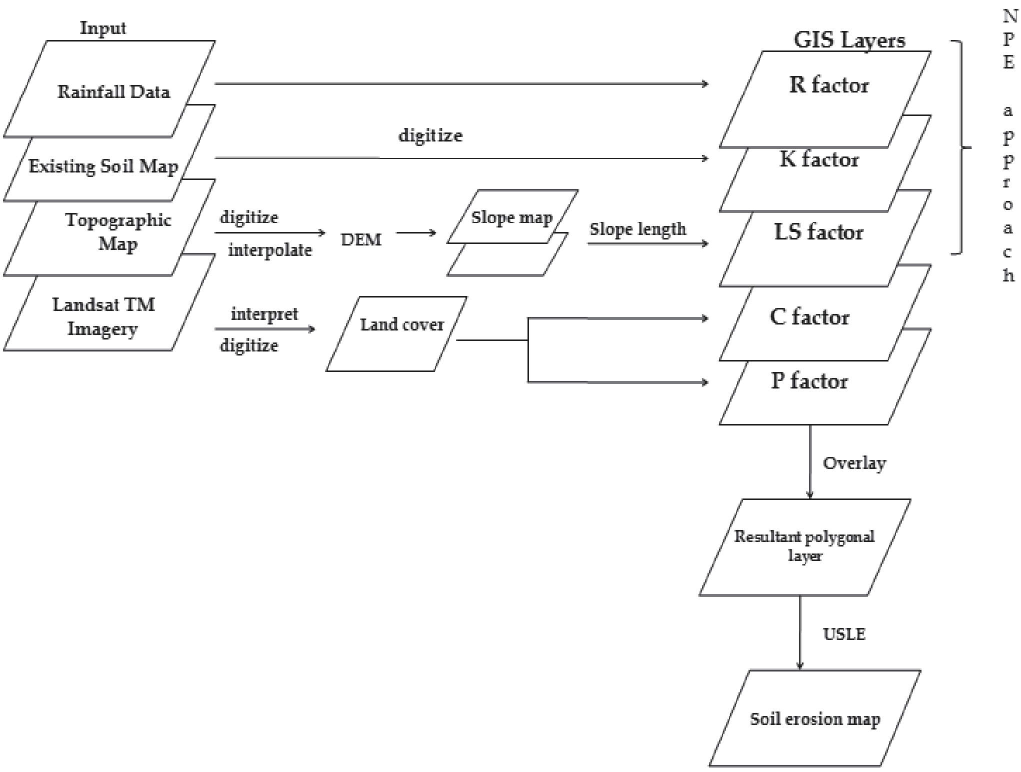

Fig. 5. Soil loss prediction through USLE approach and using GIS, modified from Mongkolsawat et al. (1994).

This equation is based only in textural characteristics of the soil. Due this simplicity and feasibility of obtaining, it is still largely used (Waswa et al, 2002, Lopes-Assad et al., 2009). We also used a complementary database regarding soil erodibility that occurs specifically along São Paulo State (Silva & Alvares, 2005). Soil erodibility values were classified into five classes, as shown in Table 1 (Giboshi, 1999).

Degrees of limitation	K Factor ($t.h.MJ^{-1}.mm^{-1}$)
null	$K \leq 0.010$
weak	$0.010 \leq K < 0.020$
moderate	$0.020 \leq K < 0.030$
strong	$0.030 \leq K < 0.040$
very strong	$K \geq 0.040$

Source: Giboshi (1999).

Table 1. Values and interpretation classes for soil erodibility.

Official Brazilian soil map (IBGE, 2001) was crossed with the soil erodibility map, and thus we obtained average values of the K factor as large groups of Brazilian soils. For this, we used the tool "Zonal statistics as table" in GIS ArcMAP 10 (Theobald, 2007).

Experimental semivariograms were determined until approximately 50% of the geometric camp, since after this value the semivariogram did not seem correct (Guerra, 1988), i.e., its accuracy was reduced due to a smaller number of possible pairs to calculate the semivariance at this distance. A geometric camp of 16 degrees (geographic coordinates) with partition groups (lags) of 1 degree was considered, as these lags are the estimators of the experimental semivariograms (Deutsch & Journel, 1998). Theoretical models considered, such as spherical, exponential, Gaussian and linear, were described by Guerra (1988) and Andriotti (2003).

Only this theoretical semivariogram group was considered because it usually covers the general dispersion situation of soil science spatial events (Burrough & McDonnell, 1998; Soares, 2006). Correlation coefficient of selected models were obtained through Cross Validation routine of the geostatistical software GS+, version 9. The spatial dependence index (SDI) was used according to Zimback (2001), which measures a sample's structural variance effect on total variance (sill). SDI comprises the following interpretation break: weak SDI ≤ 25%, moderate SDI between 25% and 75% and strong SDI ≥ 75%. This index is a complement of the traditional method recommended by Cambardella et al. (1994) in which the nugget weight effect (randomness) on total variance is evaluated. Through structural parameters obtained from experimental semivariograms, maps of some properties were created using GIS ArcMap v.10 (ESRI, 2010). A punctual ordinary kriging estimator was used for geostatistic interpolation.

5.3 Topographic factor

For LS layer (computed jointly), the Digital Elevation Model for Brazilian territory was obtained from SRTM project (Shuttle Radar Topography Mission) (Farr & Kobrik, 2000), that it is in the fourth version (Jarvis et al., 2008). The LS map was generated through the algorithm available in Wischmeier and Smith (1978):

$$LS = (\lambda/22.1)^m * (0.065 + 0.045\,\theta + 0.0065\,\theta^2) \tag{4}$$

Where λ = slope length (m); θ = slope gradient (%); and m = 0.5 if the percent of slope is 5 or more, 0.4 on slopes of 3.5 to 4.5 percent, 0.3 on slopes of 1 to 3 percent, and 0.2 on uniform gradients of less than 1 percent.

The values of λ and θ were derived from DEM (ESRI, 2010). For determination of λ value we used the method proposed by Moore & Burch (1986).

$$\lambda = (\text{Flow Accumulation} * \text{Cell Size}) \tag{5}$$

Where: Flow Accumulation is a grid theme of flow accumulation expressed as number of grid cells (readily derived from watershed delineation processing steps) and Cell Size is the length of a cell side (m). Flow Accumulation was derived from the DEM, after conducting Fill and Flow Direction processes in ArcGIS 10 (Theobald, 2007; ESRI, 2010).

5.4 NPE map

Using Equation 2 and approach shown at Figure 5, the NPE layer was created. The final map was reclassified into interpretative classes. We analyzed which feature(s) influence(s) more expressively the spatial variability of the values of NPE along the study area. Hence, we interpreted the map considering the possibilities of aggravation of erosive process by present land use patterns which can be changed.

6. Results and discussion

6.1 R factor

The annual rainfall erosivity ranges from 3,116 to 20,035 MJ mm ha^{-1} h^{-1} $year^{-1}$ (Silva, 2004). The region with the lowest values is represented by the northeastern region and an occurrence in southeastern region. Highest values are found in the northern region, mostly in the Amazon region (Figure 6). Predominant class was "> 12,000 MJ mm ha^{-1} h^{-1} y^{-1}" with 37.0% of occurrence (Table 2).

Spatial distribution of the rainfall amount and erosivity are irregular (Figures 4 and 6). In some regions the annual erosivity normally is incipient and others are extremely high (almost ten times more erosive than the areas with lowest erosivity). Maps elaborated by Rao et al. (1996) and showed in Figure 7 confirm this information. Such maps show that the trimester with major or minor contribution over seasonal distribution of amount of rain along Brazilian territory is also changeable.

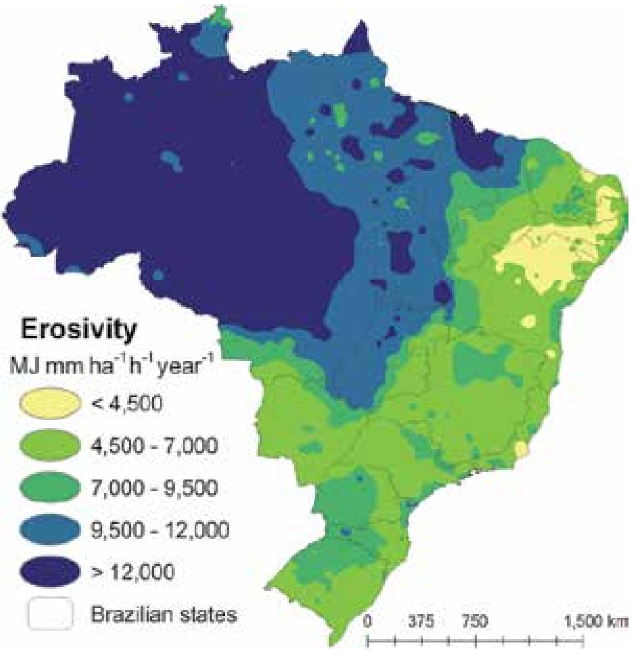

Fig. 6. Annual erosivity map (MJ mm ha^{-1} h^{-1} y^{-1}). Source: Silva (2004) – reclassified.

Erosivity (MJ mm ha^{-1} h^{-1} y^{-1})	%
< 4,500	3.0
4,500-7,000	25.0
7,000-9,500	13.0
9,500-12,000	22.0
> 12,000	37.0

Table 2. Percentage of occurrence of each class of the R factor along Brazilian territory.

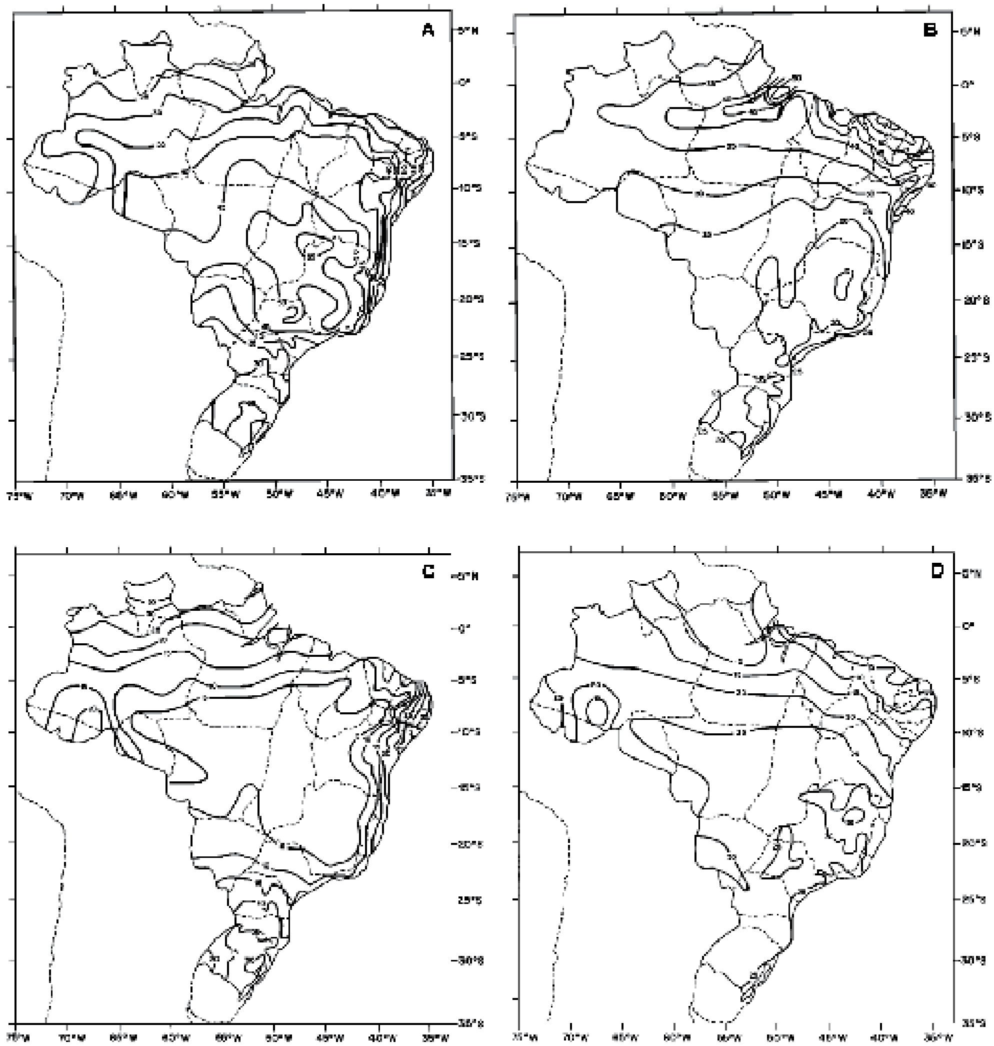

Fig. 7. Percentage contribution of trimester to the annual rainfall amount (A – December, January, February) (B - March, April, May) (C – June, July, August) (D – September, October, November). Source: Rao et al. (1996). For more details, see Rao et al. (1996).

6.2 K factor and semivariograms of soil texture

Most of the Brazilian soils are highly erodibles, independently of climate and relief. This is supported by data of Figure 8 and Table 3. Classes with high erodibility (strong and very strong) occupy 53% of Brazilian territory. Soils classified as "very strong" occur mainly along northeastern and center-western Brazilian regions. For two states of the southern region (Paraná, Santa Catarina), the predominant occurrence is soils with low erodibility (green stain located in lower portion of the map).

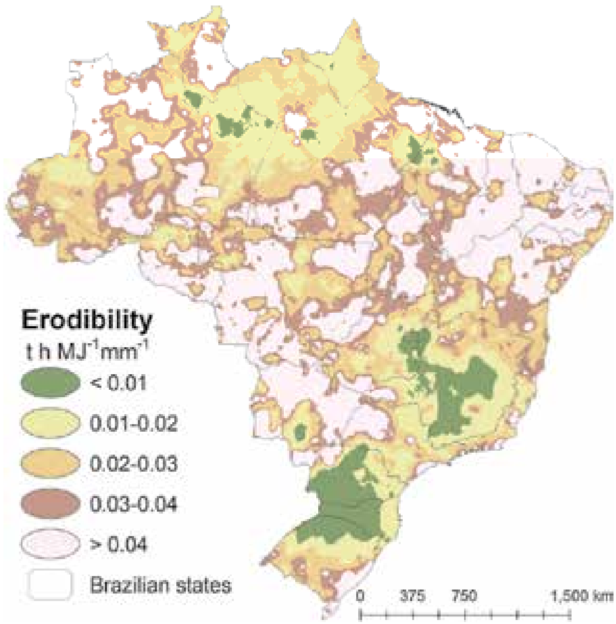

Fig. 8. Soil erodibility classes.

Erodibility classes	%
null	6.0
weak	18.0
moderate	23.0
strong	20.0
very strong	33.0

Table 3. Percentage of occurrence of each class of the K factor.

The soil data were well fitted to an exponential theoretical model (Figure 9). They showed moderate SDI and the quality of cross-validation were considered normal for soil attributes (Vieira, 2000; Vieira et al., 2002).

According to database provided by Cooper et al. (2005), Brazilian soils are predominantly loam. It seems that soils with higher erodibility are related with high sand percentage than low clay percentage. The soils with high percentages of clay are concentrated mainly in southeastern and southern Brazilian regions. The second biggest stain of clay soils occurs on "Brazilian highlands" (see Figure 10 – left). On the other hand, soils with high percentages of silt are concentrated mainly in northern Brazilian region. Sandy soils occur mainly on the central region (nor in the northern or the southern region).

The estimated average values of erodibility of major groups of Brazilian soils are presented in Table 4. The Nitisols, Ferralsols and Histosols had the lowest average erodibility across their areas of occurrence, considered low erodibility. On the other hand, Regosols, Podzols, Planosols, Arenosols, Luvisols, are the highest average soil erodibility. According to Table 1 they are interpreted as soils of high erodibility. These results are similar to those obtained by Silva & Alvares (2005), in State of Sao Paulo and Lino (2010), in State of Rio Grande do Sul.

Embrapa[1]	FAO[2]	Soil Survey Staff[3]	K (t h MJ^{-1} mm^{-1})
Argissolos	Acrisols	Ultisols	0.0374
Cambissolos	Cambisols	Inceptisols	0.0353
Chernossolos	Chernozems	Molisols	0.0287
Espodossolos	Podzols	Spodosols	0.0736
Gleissolos	Gleysols	Entisols	0.0344
Latossolos	Ferrasols	Oxisols	0.0246
Luvissolos	Luvisols	Aridisols	0.0478
Neossolos Flúvicos	Fluvisols	Fluvents	0.0450
Neossolos Litólicos	Leptosols	Lithic	0.0351
Neossolos Quartzarênicos	Arenosols	Quartzipsamments	0.0534
Neossolos Regolítcos	Regosols	Psamments	0.0791
Nitossolos	Nitisols	Oxisols Kandic	0.0132
Organossolos	Histosols	Histosols	0.0197
Planossolos	Planosols	Alfisols	0.0650
Plintossolos	Plinthosols	Plintic	0.0429
Vertissolos	Vertisols	Vertisols	0.0374

[1] Brazilian System of Soil Classification (EMBRAPA, 2006); [2] World reference base for soil resources (FAO, 1998); [3] Soil taxonomy (Soil Survey Staff, 1999).

Table 4. Computed K values for Brazilian soils in different classifications systems

6.3 DEM and topographic factor

More than a half of Brazilian territory presented LS factor values lower than 1 (Table 5). Class "< 1", that occurs in 53.6% (Figure 10), was especially separated because locals presenting LS < 1 mathematically represent diminution of the rates of soil loss and a possible opportunity for sediment deposition. For cells with LS values = 1 there is no influence of the topography over soil loss, at least mathematically. For locals where the LS > 1 topography accelerates the erosion process.

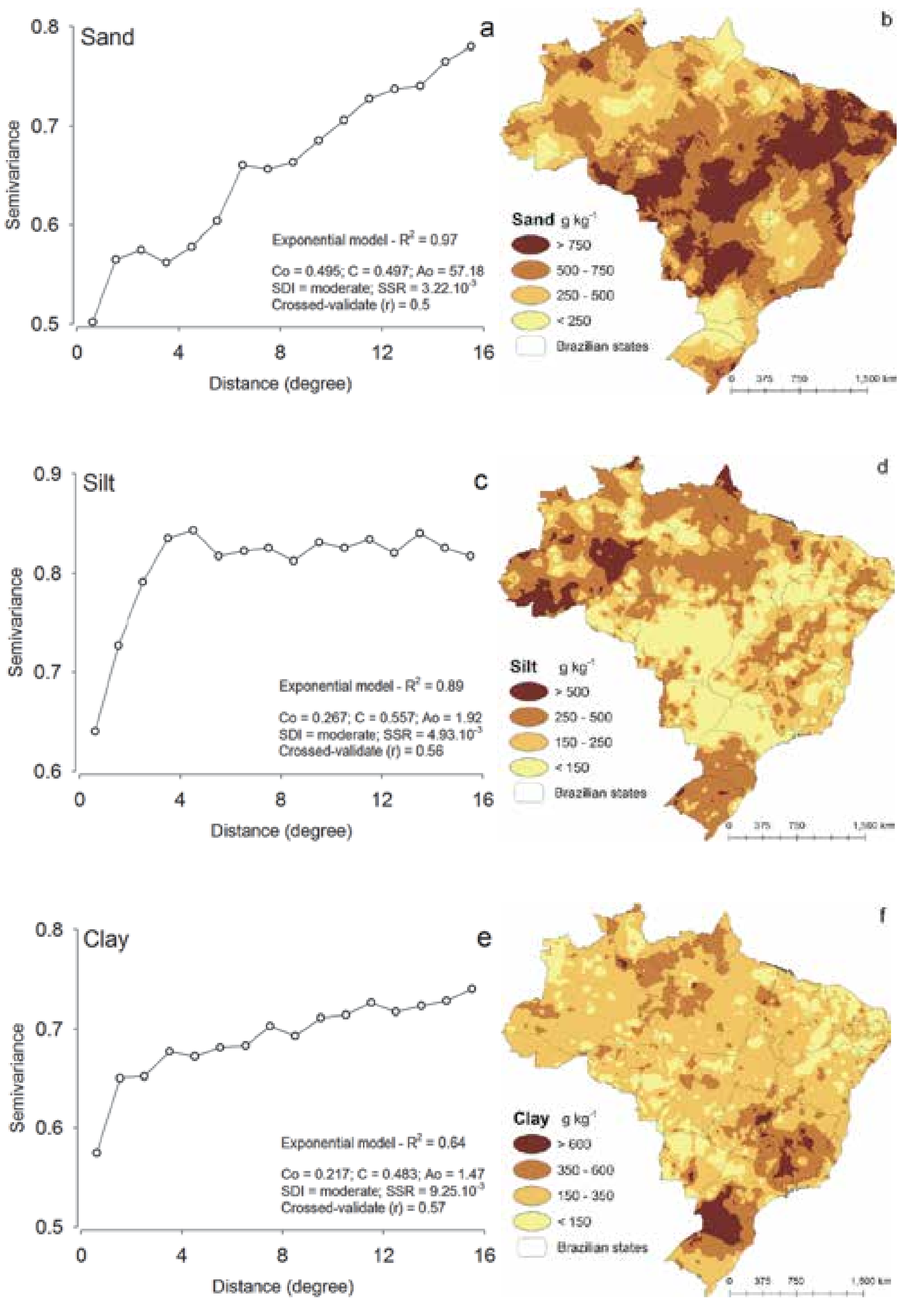

Fig. 9. Omnidirectional experimental semivariograms (sand, silt and clay) and maps of amount of sand (b), silt (d) and clay (f).

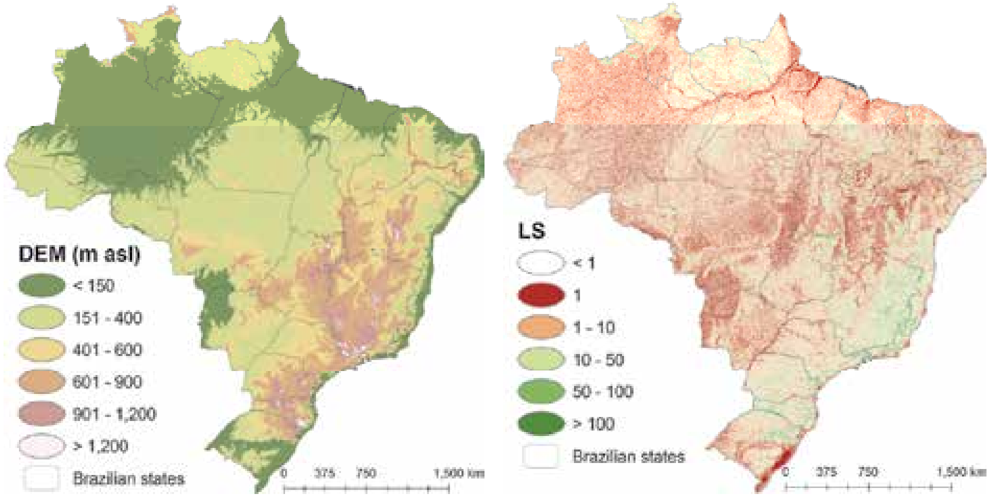

Fig. 10. Left: Digital elevation map for Brazilian territory (m). Right: map of LS factor values (dimensionless).

LS intervals	%
< 1	53.6
1	13.5
1-10	23.6
10-50	7.8
50-100	1.1
> 100	0.4

Table 5. Percentage of occurrence of each class of the LS factor.

DEM presented in Figure 10 suggests that higher LS values are associated with high altimetric values. Such high LS values are more concentrated along mountainous regions (see Figure 3 – relief). Along Brazilian territory occur predominantly regions with low altimetry, due: (a) antique lithology, (b) no occurrence of modern geological folding, and (c) due to be situated in the core area of a tectonic plate called South America Plate (IBGE, n.d.). Some of hilly or scarped regions are located near the shoreline and in regions with high population concentration, as cities of Santos and Rio de Janeiro. The three classes that represent most severe topographic condition occur in 9.3%.

6.4 NPE map

The integration of the three factors early described (R, K and LS) outcomes the NPE map, shown in Figure 11. Possibly due to relief influences, the predominant class was "< 200 $t.ha^{-1}.y^{-1}$", with 61%. Surprisingly, the second major class was "> 1600 $t.ha^{-1}.y^{-1}$", with 14% (Table 6). Besides of the occurrence of soils highly erodibles along Brazilian territory, the geographical distribution of high values of NPE has two notable distinct influences. The first one is an evident influence of very high erosivity values (R factor). The second one is major influence of relief (LS factors) in eastern portion. This information takes an important role on the establishment of land use politics in order to promote a sustainable land use, as rural or urban.

The pressure of population, among other factors, is leading to increased cultivation of tropical steeplands, generally defined as land with slope exceeding 20% (Presbitero et al., 2005). Brazil is a typical case of this problem, especially for southeastern Brazilian region, where the land use is more intensive.

In rural context, many crops have been cultivated in hilly areas and favoring the erosion process. Coffee, orchards (orange) and sugar-cane sometimes cultivated in steep lands in São Paulo State are examples. On the other hand, areas currently used for grain production, especially soy—located in western region of the *gaucho* countryside, Mato Grosso do Sul and Mato Grosso, and the Central Plateau from Goias to Tocantins, generally correspond to those areas with a high potential for sediment production (Castro & Queiroz Neto, 2010). However, Brazil has adopted over the last two decades the use no-tillage in agriculture, mainly soybeans and corn (Lino, 2010). In forestry, the sector employs mainly the technique of "minimum cultivation", which provides the least impact on soil (Gonçalves et al., 2000).

In urban context, in metropolitan regions like São Paulo, Rio de Janeiro, Belo Horizonte and Recife, there are a significant number of people living in sloped areas, characterizing risk areas. Catastrophic mass movements recorded in Brazil are concentrated in the southeastern (São Paulo, Rio de Janeiro, Minas Gerais, and Espirito Santo states) and southern (Rio Grande do Sul, Santa Catarina, and Paraná states) regions of the country. They are predominantly related to the occurrence of rainfall, that is of great intensity and short duration, and sometimes happen after rainy periods of long duration (Coelho-Netto et al., 2010).

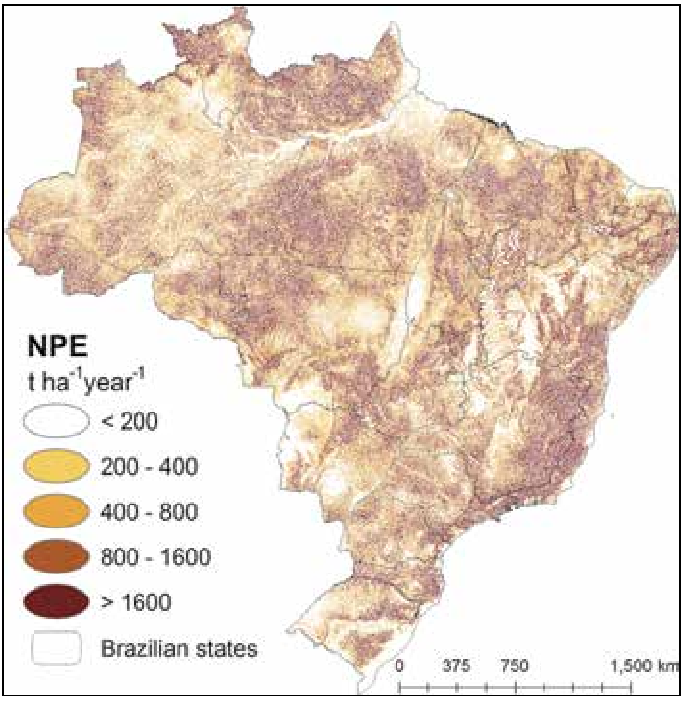

Fig. 11. NPE map for Brazilian territory.

NPE	%
< 200	61.0
200-400	8.0
400-800	9.0
800-1600	8.0
> 1600	14.0

Table 6. Percentage of occurrence of each class of the NPE.

Table 7 shows a summary of the main types of land degradation found in Brazil (Zuquete et al., 2004). Many of them are strictly related to erosion process, alter the hydrologic balance, and present some (hydro)geomorphologic consequences according to kind of human interference. Associating the human interferences (consequences according to activity), the NPE map, and the population density map (Figure 12), it is possible perceive that the zone of 300 km from shoreline to west is probably the most "problematic" region of Brazilian territory, because there is high concentration with high NPE values and simultaneously high population density, with many kinds of interferences.

Today, more than 20% of the total dissolved and suspended mass delivered to the oceans comes from the Himalaya and the Andes, carried by three rivers: the Brahmaputra, Ganges and Amazon (Goddéris, 2010). As early informed, some areas surrounding the Amazon basin has high potential for sediment production (Castro & Queiroz Neto, 2010), as well as the hilly areas located on southeastern Brazilian region (Figure 13).

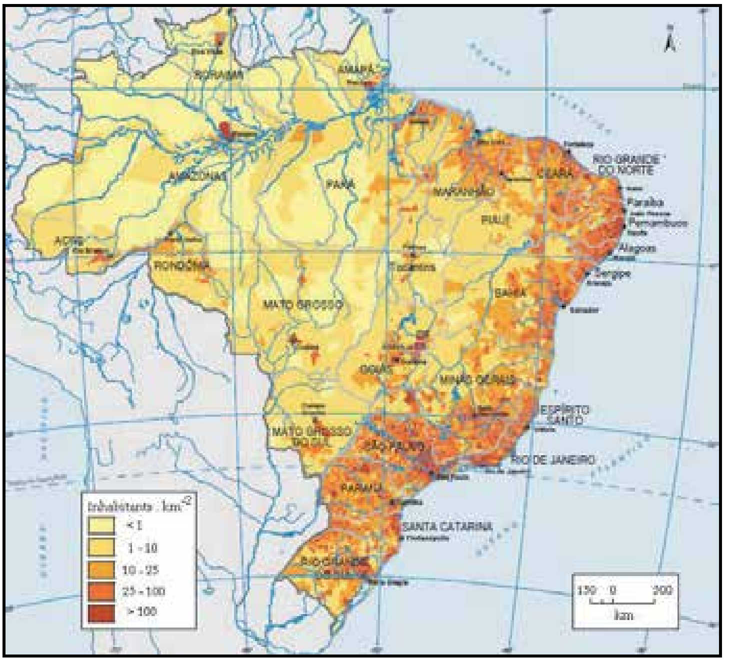

Fig. 12. Cartogram of Brazilian population density. Source: IBGE (n.d.).

Human interference				*Natural process*			
Agriculture	*Urban*	*Mining*	*Industrial*	*Soil / Rock*	*Geomorphology*	*Water*	*Vegetation*
Air, water and soil pollution	Air, soil and water pollution	Air, soil and water pollution	Air, soil and water pollution	Decline of biodiversity	Morphometric changes	Morphometric changes	Decline of biodiversity
Soil compactation	Soil compactation	Erosion rate	Acid rain	Cementation	Channel changes	Channel changes	Infestation
Erosion rate	Erosion rate	Runoff changes	Deforestation	Desertification	Channel density changes	Channel density changes	Biomass changes
Crusting	Runoff changes	Deforestation	Runoff changes			Morphometric changes	Forest fragmentation
Salinization	Flooding	Sediment load	Flooding				
Water balance	Deforestation	Channel density changes					
Leaching	Sediment load	Geomorphologic changes					
Decrease in biomass, carbon and biodiversity	Channel density changes	Mass movement					
Desertification	Morphometric changes	Relief changes					
Silting							
Deforestation							
Land cover change							
Climatic change							

Source: Zuquette et al. (2004) - modified.

Table 7. Main types of land degradation found in Brazil.

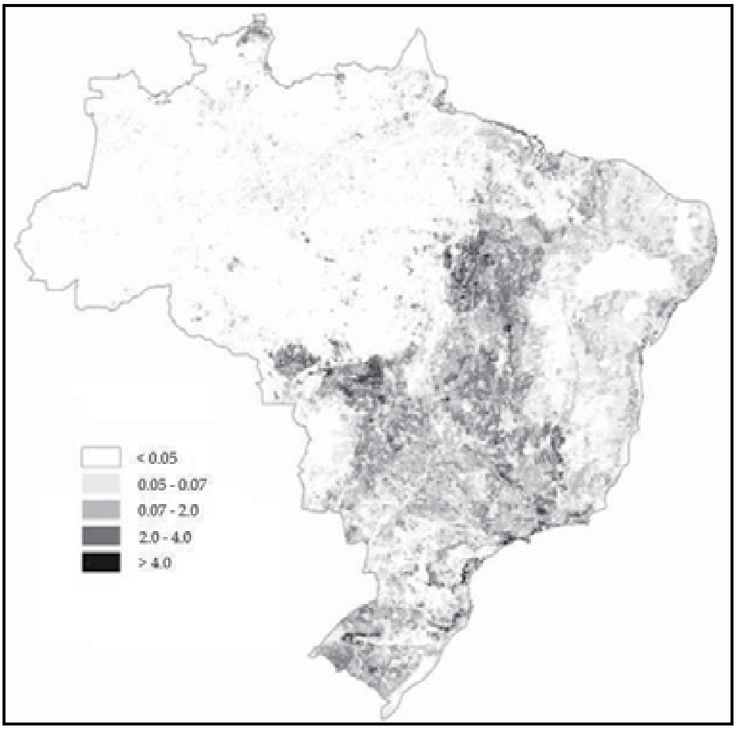

Fig. 13. Map of sediment yield in Brazil. Source: Castro & Queiroz Neto (2010). Legend modified from $t.km^{-2}.y^{-1}$ to $t.ha^{-1}.y^{-1}$.

If we adopt the soil density value 1,200 kg $m^{-3.}$ and average rate of soil formation -0.0002 m y^{-1} (Sparovek & Schnug, 2001), we infer the maximum tolerable soil loss is 2.4 $t.ha^{-1}.y^{-1}$. Using equation 6 (Valerio Filho, 1994) it is possible estimating the recommended CP value(s) that is in accordance with sustainable principles of soil conservation, i.e., the annual soil loss rate is smaller or equivalent to average rate of soil formation.

$$\text{Tolerable CP} = \text{tolerable soil loss} / \text{NPE value} \quad (6)$$

7. Final considerations

We reported here the NPE for Brazilian territory in a broad scale, especially for pedological cartographic database. As stated by Mendonça-Santos & Santos (2007), at present, approximately 35% of Brazil, 17 out of 26 states and the Federal District, is covered with soil maps at several intermediate scales (1:100,000– 1:600,000) and total coverage of the country is available at exploratory and schematic levels (scales 1:1,000,000 and 1:5,000,000).

In Brazil, soil surveys are still necessary, mainly at larger scales, to support evaluation of soil resources for planning, and management of agricultural and also for environmental projects. Detailed and semi detailed soil surveys are now available in small areas, to support local-specific agricultural and environmental projects (Mendonça-Santos & Santos, 2007). This confirms a necessity for further studies in intermediate scales or preferably, in detailed scales, both for NPE as for actual soil loss.

However, the study in such broad scale here presented permitted we found the major influences over the NPE values according to region of the Brazilian territory. Also, comparing the NPE map with population density, with specific sediment yield and with complementary bibliographic data, we identified major socio-environmental risk areas of NPE.

The great challenge is establish regional and local land use politics conformable with the average rate of soil formation. There are hundreds of cultivars that can be cultivated along the Brazilian territory according to local edaphoclimatic conditions. But they should be managed (both the cultivar and the soil) in order to reduce the soil loss to acceptable rates. The NPE is a tool that helps achieving this aim.

8. Acknowledgments

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2

Soil Erosion Processes in Semiarid Areas: The Importance of Native Vegetation

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1. Introduction

Arid and semiarid zones cover approximately 40% of the land surface, with a continuous increase in the area by desertification processes, induced mainly by anthropogenic activities and/or climatic change (IPCC, 2008). The process of desertification affects the world at ecological, economic and social levels (Salih, 1998).

Maestre et al. (2006) considers that desertification produces biophysics and socioeconomics consequences, with the later including household debt increasing, loss of traditional knowledge and local traditions, people migration, reduction of food production, costs of living increases, poor supplies in quality and quantity, increase in poverty, and political instability (Sivakumar, 2007). The UNCCD (2004), considers that over 250 000 million of people are directly affected by desertification, mostly in regions with significant poverty and marginalization in the world. In the case of Mexico, experts estimate that each year, between 700 000 and 900 000 people are forced to leave Mexico´s rural dry land areas in search of better livelihood in urban areas, including foreign countries.

On the other hand, biophysics consequences involve the loss of soil and vegetation cover, reduction in soil fertility and biodiversity, reduction in rainfall infiltration rates, and modification of local climate (Maestre et al., 2006). Soils of arid and semiarid zones are very susceptible of water erosion (Cornelis, 2006) mostly due to the scarce vegetation cover, low organic matter content and the small resistance to the erosion forces. The magnitude of water erosion also depends on their texture, water content, evaporation, percolation and lixiviation. These soil characteristics are not favorable to the resistance of the soil to water erosion (D´Odorico & Porporato, 2006). In terms of soil orders, typical arid and semiarid zone soils around the world include Aridosol, Alfisols, Entisols, Molisols, and Vertisols (Dregne, 1976).

In arid and semiarid areas, soils with little or no vegetation cover are exposed to torrential precipitation events, which are characterized by short durations and high intensities, and are prompt to the occurrence of physical and chemical processes that change the surface layer conditions, such as surface sealing and crusting. When the surface is dry, a hard layer is formed (crust). Crusting soils are typical of these dry areas, where soil degradation is induced soils by diminishing infiltration rates and increasing runoff and erosion rates (Ries & Hirt, 2008).

Arid and semiarid areas are considered fragile environments where vegetation cover is scarce and where soil erosion processes occur rapidly and severely after rainfall events fall in these areas. However, even under those conditions, the importance of native vegetation is very significant in the regulation of surface hydrological processes.

The objective of this chapter is to discuss through a study case from a semiarid area in Querétaro, Mexico, the importance of native vegetation on the regulation of soil erosion processes. An extensive work on the quantification of vegetation changes in space and time (Chen et al., 2006; Moro et al., 2007) has been done for arid and semiarid areas. However, only few efforts have been directed towards a better understanding of the hydrological functioning and the native vegetation-soil relationships (Huxman et al., 2004, Bautista et al., 2007; Vásquez-Méndez et al., 2010) compared with other environmental variables.

2. Precipitation

Precipitation is, without doubt, the most important component of the land-atmospheric system accountable for shaping the climatic state and variability of water in the soil and atmosphere (Wang et al., 2006). Precipitation is a major factor controlling the hydrological cycle of a region and, thereby, also the ecological and geomorphologic processes. This meteorological phenomenon has many characteristics, and the relative amount of rain and snow, their seasonal timing, and the volumes and intensities of rainfall events affect ecological developments and water management activities (Jong & Jetten, 2007).

Prediction of mean annual values is useful in areas where annual rainfall tends to follow a normal probability distribution (Figure 1). In arid and semiarid zones, annual rainfall distributions typically show a pronounced skew and correspond better to lognormal, extreme value or Pearson Type III probability density functions. In contrast to temperate regions, semiarid ecosystems are also more impacted by extreme events, such as severe storms, floods and droughts (Mannaerts & Gabriels, 2000).

In semiarid zones, the distribution of precipitation through the year is not uniform, and usually they are intermittent. In particular, in arid and hiperarid areas, it is possible that in some years precipitation does not occur at all (Salas, 2000). In general, the precipitation in these areas is characterized by torrential events, occurring in short time spans and at high rainfall intensities (Rango et al., 2006; Wei et al., 2007). It has been observed that the precipitation pulses promote biological activities in plants, soil and the ecosystems as a whole. Furthermore, these events are important drivers for soil physical processes (Huxman et al., 2004; Dekker et al., 2007). However, the influence of rainfall characteristics on the vegetation-soil relationship has been poor studied compared with other environmental variables (Huxman et al., 2004).

Rainfall precipitation is high variable in semiarid areas. Events in the semiarid area of Cadereyta, Querétaro, Mexico, for a 3 years period of registration showed that rainfall depth varied from 1 to 74 mm. The time span of occurrence varied from 5 minutes to 2 days. Also, 60% to rainfall events have a rainfall depth smaller than 5 mm (Figure 1). This percentage increased to 75% when considering events smaller than 10 mm. On average, only 10 rainfall events greater than 20 mm occurred per year, with a low probability of occurrence but with high potential consequences due to their erosivity (Figure 2).

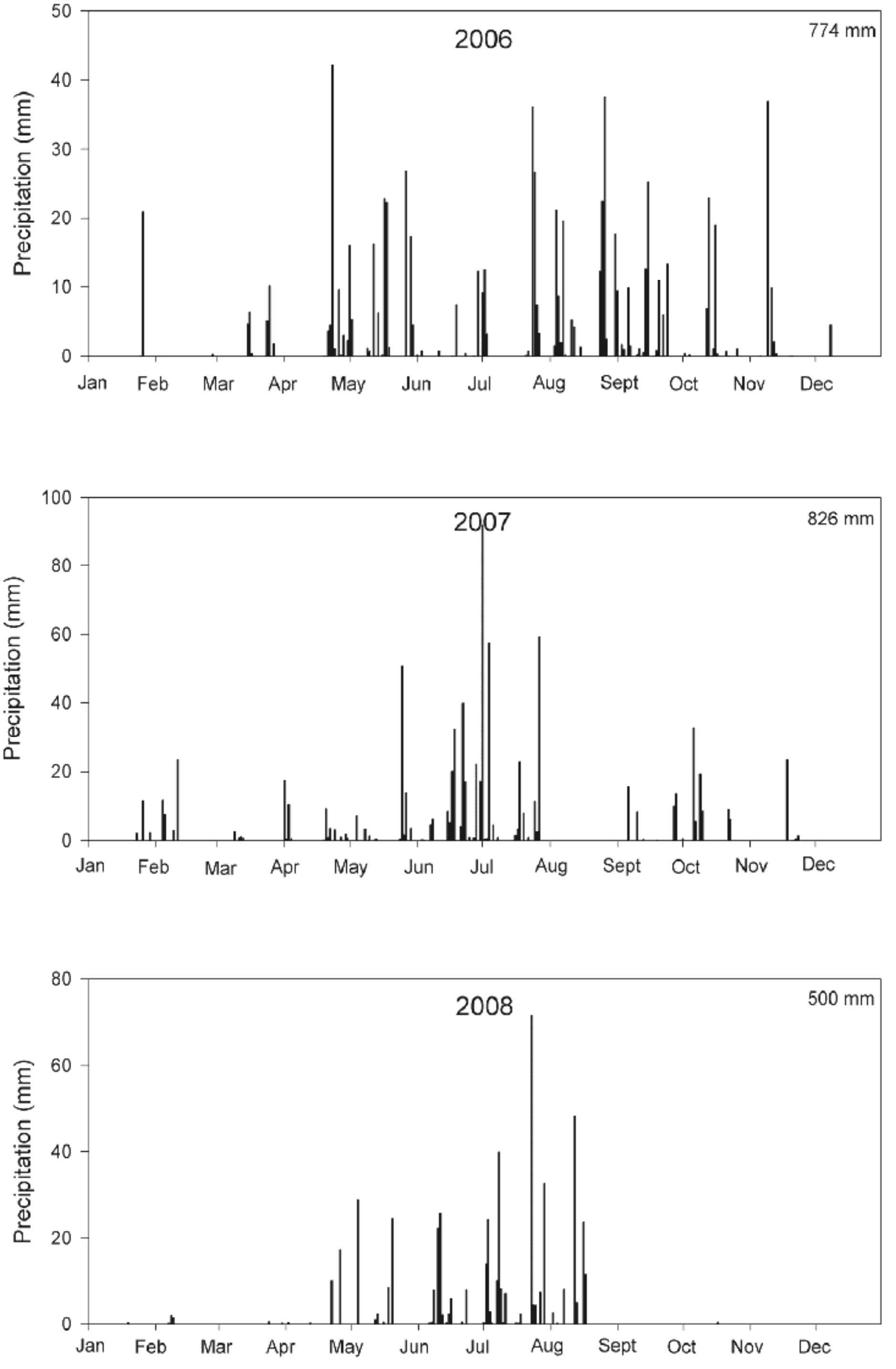


Fig. 1. Histogram distribution by year, with different characteristics in amount of year in Cadereyta de Montes, Queretaro, Mexico.

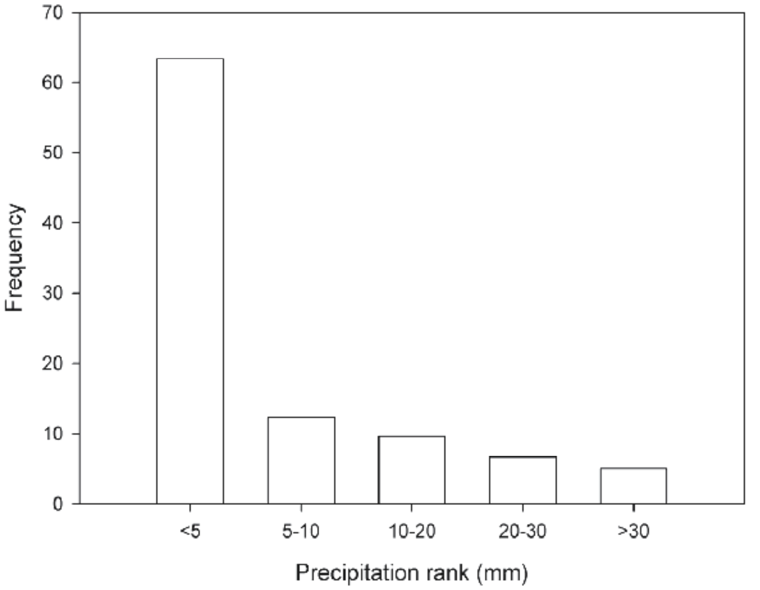


Fig. 2. Precipitation histogram for the years 2006, 2007 and 2008 at Cadereyta, Queretaro, Mexico.

One of the main factors related to the erosion potential of rain is the rainfall frequency and different magnitudes of events in combination with the soil geomorphic thresholds (Bisigato et al., 2009). High intensities of rainfall are the main factor driving the runoff processes (Renard et al., 1974).

Mean, maximum and maximum intensity in 30 minutes are shown in Figure 3 for the Cadereyta area. Overall, the values of intensities varied from 0.71 to 88.2 mm h^{-1}. Maximum

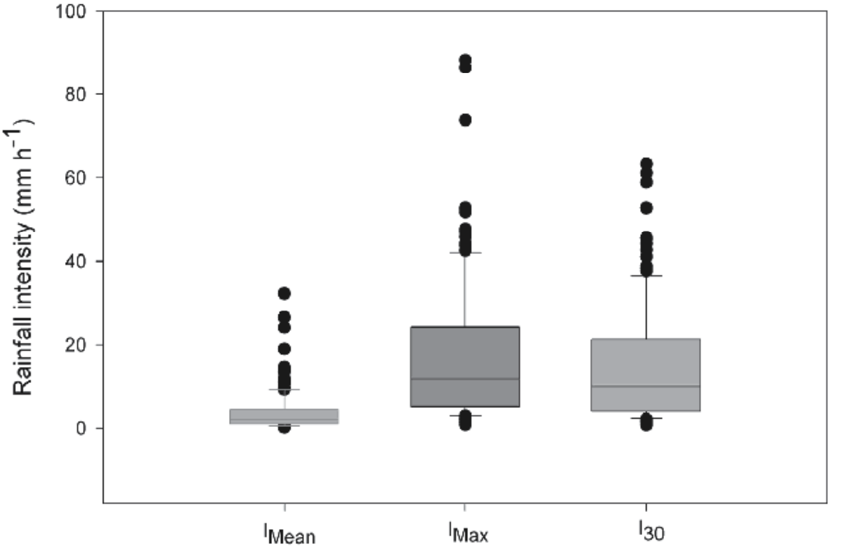


Fig. 3. Box plot of rainfall intensity by events measured in the semiarid of Mexico.

rainfall intensity in semiarid areas is comparable with the intensities from tropical climates (Hoyos et al., 2005). EI30 it is an important parameter for compute erosivity of a rainfall event. The mean value of I30 was 15 mm h^{-1}, while maxim values were from 40 to 60 mm h^{-1}, typical values registered in this arid and semiarid areas (Hussein et al., 1994; Wei et al., 2007; Stone et al., 2008).

3. Vegetation

Vegetation patterns in arid and semiarid ecosystems are characterized by the size and spatial distribution of the higher plant-cover patches. These patches have its main distribution in spots or bands distributed as a mosaic (Aguiar & Sala, 1999). The spots are generally isodiametric or with irregular circular shapes, and the bands range from 1 to less than 100 m (Aguiar & Sala, 1999). Investigators have documented the presence of "islands of fertility" or "resource islands" in arid and semiarid ecosystems at individual plant scale (Moro et al., 1997; Aguiar & Salas 1999; Facelli & Temby, 2002; Rango et al., 2006).

These areas can also be considered as hydrologic islands, and they are observed at the individual plant scale as well as in large area patterns of banded vegetation, where playettes and beaded drainage networks run-on and water infiltration stimulates vegetation growth (Rango et al., 2006).

Fig. 4. Typical distribution of native vegetation in a semiarid environment of Central Mexico.

Water availability it is a limiting factor in the productivity of arid and semiarid ecosystems. Plants use the necessary water for their metabolic processes. Studies such as those of Fowler (1986) and Nobel (1990) have demonstrated that the species of arid and semiarid regions are characterized by several different patterns of roots distribution. Perennials root zones are wider and deeper than those of annuals. As a matter of fact, phreatophytes are often very deeprooted.

Simpson & Solbring (1977) recognize three major methods of native plant strategies:

- Specialized photosynthesis (Crassulacean Acid Metabolism or CAM), which leads the plant to open their stomas during the night when temperatures are low and the loss of water by transpiration can be reduced.
- Xerofiphytic life forms, which allow plants to resist extremely, negative potentials. This group of plants is characterized by small leaves with thick epidermis, sunken stomata, and extensive root networks.
- Phreatophyte condition, present in plants from arid regions, induces them to take water from almost unattainable zones at very deep phreatic levels.

The association of annual plants with woody shrubs has been recognized as to have higher organic soil contents, to trap windblown seeds and to protect the seeds or seedlings from predation (Fowler, 1986).

The general vegetation distribution is controlled by precipitation, and at the same time, distribution and amount of precipitation affects the development and distribution of vegetation, which also modifies the atmospheric energy and the storage of water (Xue, 2006; Dekker et al., 2007). Under some circumstances herbaceous layer productivity is lower under tree canopies than in nearby open grasslands, whereas in other instances grassland productivity is higher under tree canopies (Belsky et al., 1989). Studies suggest that tree canopies may improve the water – status of understory species. Native species such as *Prosopis laevigata*, *Acacia farnesiana*, *Opuntia* sp., and even for O*puntia imbricate*, contribute to the development of surface vegetation. The combination of canopy cover and the greatest development of surface vegetation in the rainfall period, when soils are more susceptible to soil erosion, diminish the erosive effect of precipitation at the highest intensities. Therefore some trees of semiarid environments like adult Acacias are considered as nurse plants for understory native species (Yang et al., 2009).

Figure 5 shows the dynamics of vegetation leaf area index (LAI) for four species and their understory. It is clearly observed that once precipitation falls in those areas, ground cover increases significantly. However, canopy cover of O*puntia imbricate* and *Opuntia* sp. does not increased significant in comparison with *Acacia* and *Prosopis*, because the morphology of its rackets.

Some morphometric characteristic of the four main types of vegetation patches in semiarid Cadereyta, are listed in Table 1.

Currently, trees in semi-arid regions are viewed as having the potential to increase crop productivity (agroforestry), to increase the forage production, to improve soil fertility and to reverse or at least stop desertification (Beslky et al., 1989).

On the other hand, plants of *Prosopis* and *Acacia* possess nitrogen-fixing bacteria in their root systems that accumulate nitrogen under the canopy soils. These trees tend to propagate in overgrazing soils (Tapia-Pastrana et al., 1999) and become free of grass competition (Mooney et al., 1977). These trees can be optimal for reforestation and for sustainable use in arid and semiarid zones (El-Keblawy & Ksiksi, 2005; Deans et al., 2003; Álvarez-Yépiz et al., 2008).

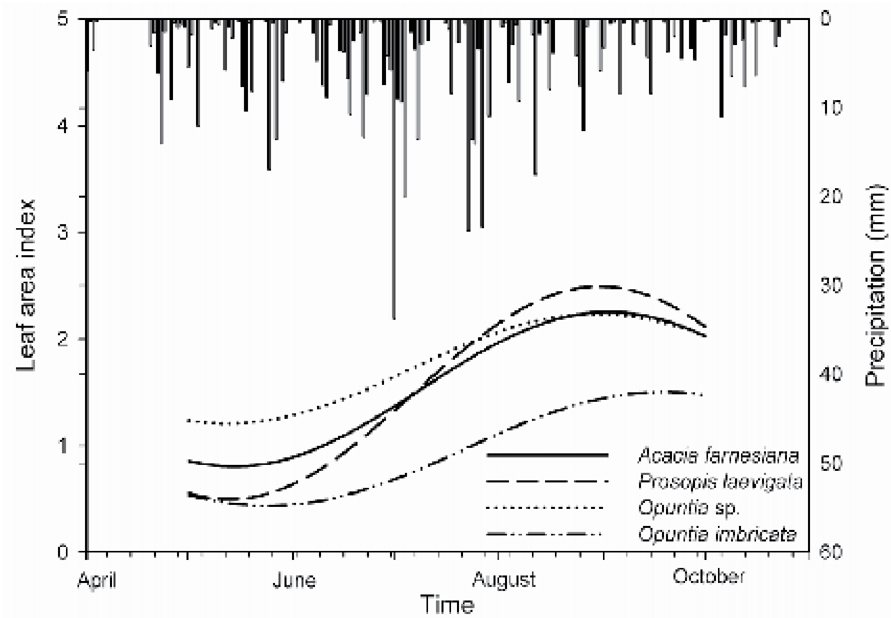


Fig. 5. Canopy and surface LAI dynamics in native plants at a semiarid environment during the rainfall season in Cadereyta, Queretaro, Mexico.

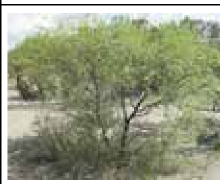
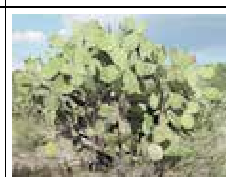
	Opuntia imbricata	*Prosopis laevigata*	*Acacia farnesiana*	*Opuntia* sp
				
Plot Area (m^2)	13.00	9.00	8.00	9.00
Total Height (m)	0.67	2.05	2.57	3.08
Trunk height (m)	0.20	0.69	0.86	0.45
Canopy cover (%)	23.60	60.00	53.50	86.70
Ground cover (%)	22.10	35.30	36.60	76.90

Table 1. Characteristics of the vegetation patches studied (Vásquez-Méndez et al., 2010).

4. Rainfall-runoff relationships

The relationships between rainfall and runoff processes that result in erosion at a given location are generally complex (Bedford & Small, 2008). Prediction of runoff and soil loss is important for assessing soil erosion hazard and for determining suitable land uses and soil conservation measures for a catchment (Bedford & Small, 2008). Soil erosion by water occurs as a result of the detachment of soil particles by raindrops and runoff (Kim & Gilley, 2008). The most known and widely used parameter to predict the erosive potential of raindrop impact and to reflect the amount and rate of runoff generated by erosive storms is the rainfall erosion index, also known as rainfall erosivity or R-Factor of the Universal Soil Loss Equation or USLE (Wischmeier & Smith, 1978).

The smaller amount of rainfall in semi-arid areas compared with that in humid climates does not mean a corresponding low level of soil erosion by water. Indeed rainfall erosion can be higher in semi-arid areas than in any other climatic zone. This is also because there is poor protective vegetative cover, especially at the beginning of the rainy season. Some of the soils common in semi-arid areas are particularly vulnerable, either because they have poor resistance to erosion or because of their chemical and physical properties (Schlesinger & Pilmanis, 1998).

Spatial patterns of soil properties are linked to patchy vegetation in arid and semi-arid landscapes. The patterns of soil properties are generally assumed to be associated to the ecohydrological functioning of patchy dryland vegetation ecosystems (Bedford & Small; 2008).

Researchers, such as Ares et al. (2003) and Bautista et al. (2007), have found an inverse relationship between water runoff and the scale of heterogeneity of a vegetation mosaic. They have suggested that the landscape scale characteristics, such as topography, constrain the plant spatial pattern at finer scales. More runoff is produced as the vegetation cover is more disperse or bare areas increase, since their soils are susceptible to develop physical and biological crusts (Rango et al., 2006).

Amount of runoff per event in four native species and a control (bare surface), as evaluated in USLE-type plots is presented in Figure 6. Runoff decreases considerable when a greater vegetation cover is present. Bare or nearly bared surfaces always produced greater amounts of runoff.

In a more specific analysis (Figure 7), an inverse relationship between runoff and leaf area index, both canopy and ground, was found for the studied species and their fertility island. The results demonstrate the positive effect of native vegetation by diminishing the runoff processes in a considerable way.

The contribution of different layers of vegetation (canopy, understory, and lower vegetation), is significant, by diminishing the kinetic energy of rainfall against soil and intercepting precipitation, promoting infiltration. Runoff decreased from 87 to 98% from the total rainfall amount due to canopy cover (Vásquez-Méndez et al., 2010).

Sealing soils occur when soil surface is unprotected against precipitation effects and wetting and drying occurs quickly. Rainfall impacts consolidation the surface, resulting in pressure and erosion by splash of soil particles (Ries & Hirt, 2008). The consequences of sealing and crusting soil are the reduction in hydraulic conductivity, increased in horizontal flow (runoff), the inability of soil gas exchange (Li et al., 2005; Ries & Hirt, 2008). When these conditions exist, depending on the vegetation cover area, runoff coefficients fluctuate from 8 to 60% (Al-Qurashi et al., 2008), and total runoff can increased up to 80 and 90% in sealed soils (Ries & Hirt, 2008, Vásquez-Méndez et al., 2010). Bare surfaces decrease infiltration, for sealing soils (Ruan et al., 2001; Chen et al., 2008).

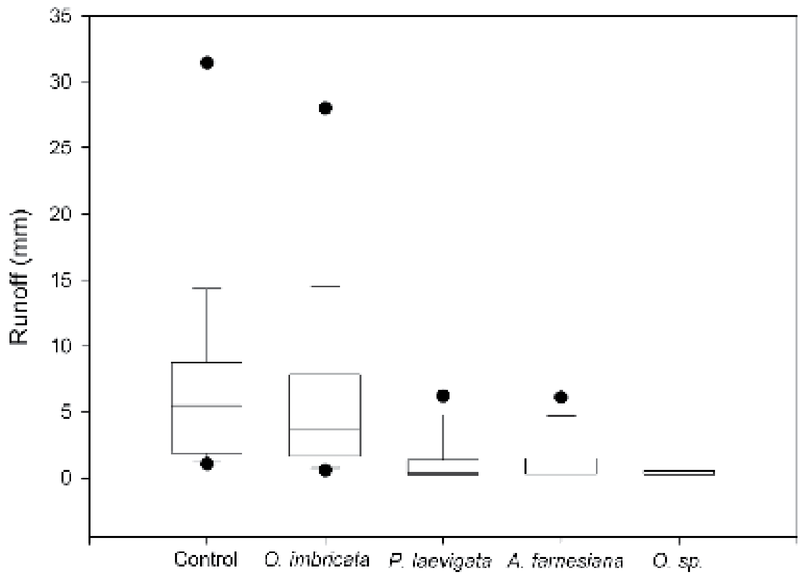


Fig. 6. Box plot of runoff by native vegetation in a semiarid environment of Central Mexico (Vásquez-Méndez et al., 2010).

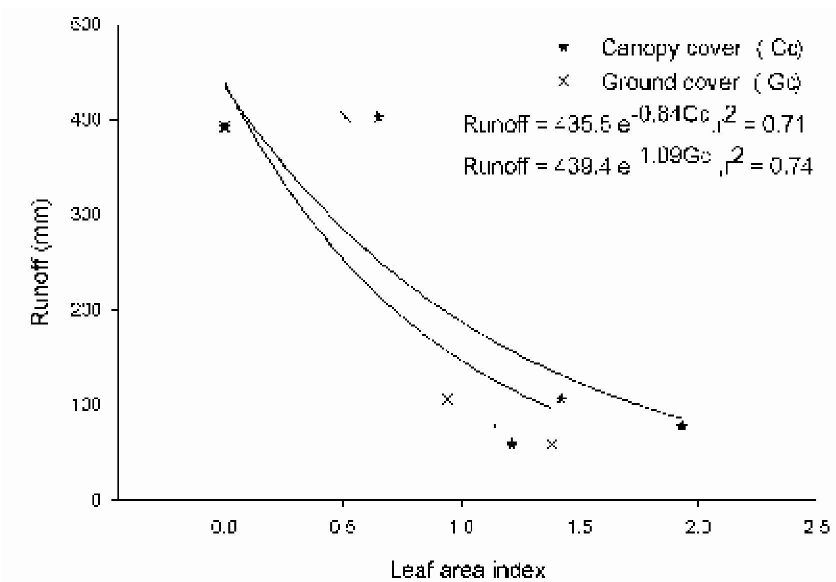


Fig. 7. Typical behavior between runoff and leaf area index of native vegetation in a semiarid environment of Central Mexico.

5. Soil erosion

Erosion, the detachment of particles of soil and surficial sediments and rocks, occurs by hydrological (fluvial) processes of sheet erosion, rill and gully erosion, and through mass wasting and the action of wind. Erosion, both fluvial and eolian (wind) is generally greatest in arid and semi-arid regions, where soil is poorly developed and vegetation provides relatively little protection. Where land use causes soil disturbance, erosion may increase greatly above natural rates.

Soil erosion, continues to be a primary cause of soil degradation throughout the world, and has become an issue of significant and severe societal and environmental concern (Wei et al., 2007). About 80% of the world´s agricultural land suffers moderate to severe erosion, and 10% suffers slight to moderate erosion (Pimentel et al., 1995). Erosion by water and wind adversely affects soil quality and productivity by reducing infiltration rates, water-holging capacity, nutrients, infiltration rates, water-holding capacity, organic matter, soil biota and soil depth.

The removal of vegetation is the main cause of soil degradation in semiarid areas (Castillo et al., 1997). Changes in soil properties induced by vegetation removal modified the runoff and soil erosion response in a semiarid area of Spain. Total runoff was significantly greater when vegetation was removed (48.8 mm) as compared to undisturbed conditions (34.9 mm). Runoff ratios between the disturbed and natural plots increased with time from 1.4:1 in 1990 to 2.5:1 in 1993. Vegetation removal increased the soil losses by 127% compared the undisturbed conditions. The annual soil loss ratio between the disturbed and natural plots increased from 1.6:1 in 1989 to 4.2:1 in 1993. The observed increase in surface runoff and soil loss was attributed to a progressive deterioration of soil physical properties. Bulk density increased by 8.4% (from 1.55 to 1.68 Mg m^{-3}), total organic carbon was reduced from 4.0 to 2.6% and the percentage of stable aggregates decreased from 81.6 to 56.3% in the disturbed area. There was no evidence of vegetation recovery, suggesting that reduced vegetal cover might lead to irreversible soil degradation in semiarid areas.

The relationship between erosion and vegetation cover have been shown from various researchers (Stocking & Elwell, 1976; Evans, 1980) that erosion declines exponentially as vegetation in cover increases. One particularly important interaction is how, during rainstorms, patches of vegetation serve as surface obstructions that slow and trap runoff, sediments, and nutrients from open interpatch areas (Schlesinger et al. 2000) due to their sufficient stem and biomass densities.

Soil loss from vegetation patches of *P. laevigata*, *A. farnesiana* and *O. sp*, was significantly smaller as compare to a bare surface area and an area with *O. imbricata*, with low vegetation cover.

The maximum values of soil loss were 1275, 1366, 120, 130 and 21 kg ha-1, while the soil loss cumulative correspond to values of 3520, 3913, 240, 177 and 38 kg ha-1 for bare surface, *Opuntia imbricate*, *Prosopis laevigata*, *Acacia farnesiana* and *Opuntia* sp., respectively (see Figure 8). Corresponding values of soil loss were 97%, 93% and 99% with respect to the bare surface of vegetal species of *Acacia farnesiana, Prosopis laevigata and Opuntia* sp.

6. Interception

Interception is defined in three different ways: i) Interception storage (L), is considered the amount of rainfall which is temporarily stored on the land and evaporated shortly after and during the rainfall event. ii) Interception flux is considered the amount of intercepted water, which is evaporated in a certain time (LT^{-1}). iii) Interception process (I) (LT^{-1}) is considered as the part of the rainfall flux which is intercepted on the wetted surface after which it is fed back to the atmosphere. The interception process is equals to the sum of the change of interception storage and the evaporation from this stock (Gerrits et al., 2007).

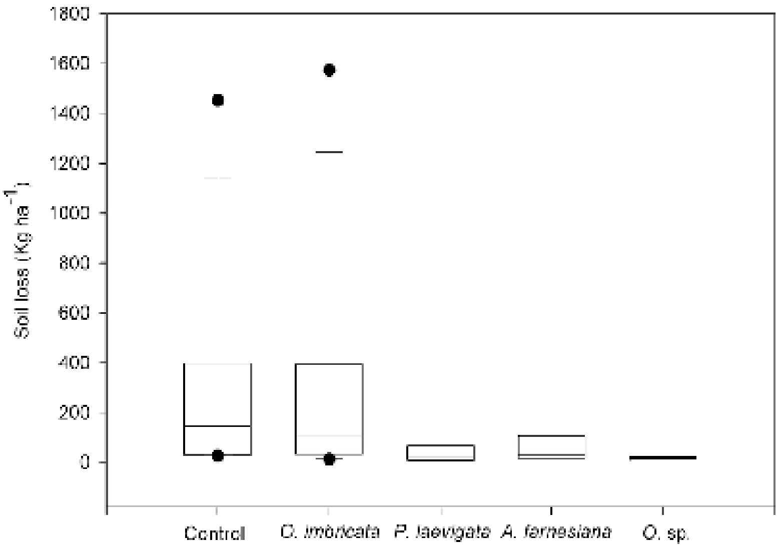


Fig. 8. Box plot of soil loss by native vegetation in semiarid environment (Vásquez-Méndez et al., 2010).

It appears that on average interception can amount to 10-50% of the precipitation (Calder, 1990; Gerrits et al., 2007; Wang et al., 2007). Therefore, knowledge about the process of interception is important (Gerrits et al., 2007). The canopy interception process, which is a basic process controlling interactions of precipitation with plant canopies, plays an important role in the water resources cycle of forest watersheds and isolated environments. This rainfall distribution affects the runoff generation and flow concentration.

Interception, a process affecting the availability of water in the hydrological cycle, is often considered as the trapping, storage and disposition of materials on the vegetative surface of plants, or as the process of aerial redistribution of precipitation by vegetation. Rainfall interception includes the processes that result from the temporary storage of precipitation by the tree canopy. Water can either evaporate directly to the atmosphere, absorbed by the canopy surfaces, or ultimately transmitted to the ground surface (Xiao et al., 2000). Thus, interception can be described as the difference between gross rainfall (PG) and throughfall (T).

There are two principal ways in which the physical and physiological characteristics of plants can influence the hydrological cycle. These effects can be separated broadly into the effects vegetation has on water delivered as precipitation on the quantity and distribution of that water to the soil, and on the amount and distribution of water that is removed from soil and subsoils (Wang et al., 2005). The first influence is to a large extent a physical one, whereas physiological characteristics determine the way plants remove water from the soil. The interception processes determine water losses from vegetation canopies wetted by rain (Wang et al., 2005).

Rainfall interception processes is considerable in the tree or shrub canopies at semiarid and arid environments. Plant communities have a positive response to intercept rainfall water through their leaves, branches and trunks. Mastachi-Loza et al. (2010) and Návar & Bryan (1994) registered that canopy of native vegetation (Prosopis and Acacia trees) can intercept up to 20 to 30% of the rainfall.

Infiltration rates in arid and semiarid depend on factors like vegetation cover, rainfall amount, intensity, and duration, soil type and moisture, slope degree, and land use (Salas, 2000; Wilcox et al., 2003). Soil water infiltration rates are greater under canopies as a result of the soil protection from raindrop impact and compaction by the addition of organic matter from plants, improving soil crumb structure (Salas, 2000; Rango et al., 2006). Trees are a principal factor to increase organic material levels, to moderate soil temperature and to improve soil moisture, resulting in a higher infiltration rate beneath the canopy cover (Gutiérrez, 2001; Zehe, 2008).

7. Vegetation-soil interaction

The typical soils of arid and semiarid environment are poor in fertility. However, when native vegetation is still present, the properties of soils are positively enhanced. Table 2 shows the behavior of fertility of soils in three different native plant species and at bare surfaces. Organic matter in surface with vegetation cover is improved by 100% beneath canopy of Prosopis and Acacia.

	Bulk Density	Sand	Silt	Clay	Organic Matter	N	K	Ca	Mg	Na	Fe
	g cm^{-3}	%				ppm					
Without Vegetation	1.38	65.12	12.88	22.00	0.88	4.53	586	2404	308	22.8	6.35
Cilindropuntia imbricate	1.39	76.56	7.44	16.00	0.67	3.78	516	2144	289	1.17	6.53
Prosopis laevigata	1.31	75.56	8.44	16.00	1.98	5.29	769	2996	308	1.17	9.66
Acacia farnesiana	1.32	80.56	7.44	12.00	1.57	9.06	500	1501	213	1.17	33.3

Table 2. Soil characteristics comparing three different plant species of native vegetation.

Soils under trees canopies in semi-arid environments are often more fertile than soils from the surrounding grasslands. Quantities of mineralizable nitrogen, phosphorous, potassium, calcium, organic matter, and the microbial biomass, are significantly higher in soils beneath the canopy than in the open area (Belsky et al., 1989).
Soil characteristics shows are better beneath species vegetation in comparison with bare surface, found up to twice of organic matter, minor values of bulk density, greater values of hydraulic conductivity that foster the increase in infiltration rates (Vásquez-Méndez et al., 2010).

8. Final remarks

Precipitation is one of the most important climatic variables to characterized arid and semiarid environments, especially in these environments precipitation varied from year to year. In Cadereyta, Querétaro, México it was found that maximum rainfall occurs in July and August months, besides that erosivity was major to in comparison with the rest of the year.
Vegetation cover is a very important factor to diminish runoff quantity, and native vegetation of semiarid areas contributes to protect the soil against rainfall erosivity and surface sealing phenomena.

For some insects and epiphytes, trees are the minimum habitat unit and can be considered islands, because, like islands, there are discrete ecological units with fixed borders surrounded by different environment (Flores-Palacios & García-Franco, 2006). In pastureland trees are often isolated and distant from other trees.

Some phreatophytes, especially in drier regions, have extensive, subsurface lateral roots to take advantage of any light rainfall that might occur. Such subsurface root systems help to stabilize the soil. The aerial system too has a role in reducing wind erosion and ameliorating the microclimate although information on changes in humidity and temperature is generally lacking (Wickens, 1995).

The indirect contribution of native species to soil fertility is two-fold. First, there is a contribution through nitrogen is probably minimal since the foliage on the ground probably undergoes two periods of rapid degeneration (Wickens, 1995). Along with the improvement in soil fertility, soil physical and micro-climate conditions, the trees play an important role in soil binding processes and the reduction in the eroding action of both water and wind (Pimentel et al., 1995).

The amount and seasonality of rainfall is also reflected in the amount of vegetation cover within the increase of vegetation (surface and canopy). The annual distribution of vegetation has a tendency to increase shortly after the first rains, as in all arid and semiarid environments. However, there was a greater contribution of shrubs or beneath the surface patches of vegetation with a greater coverage area of vegetation.

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3

Deforestation / Reforestation in Mediterranean Europe: The Case of Greece

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1. Introduction

Forests perform multiple and interrelated social, economic and environmental functions and can be comprised among the ecosystems with the greatest biodiversity. The contribution of forests is multiple and renewable and, therefore, they constitute a most valuable natural resource.

The benefits / values of forests can be divided into those of direct and indirect use. The first category includes the value of timber, which is used, on one hand, in shipbuilding and, on the other hand, in supporting a great chain of industries such as construction, furniture manufacture, printing and packaging. The forestry sector provides about 8% of the total manufacture added value. Forest feedstock, goods and services can also provide important background for the economic reinforcement and green development in the countryside. The primary wood industry offers sawn wood, fibreboard, particleboard, pulpwood, fuelwood as well as wood chips and bark for bioenergy, in fact it employs more than 2 million people and it often involves small or medium enterprises in rural areas (Confederation of European Forest Owners).

Apart from wood, which constitutes the main forest product, forest ecosystems provide a range of products of economic value such as bark, resin, honey, small berries, aromatic leaves (laurel), mushrooms, medicinal herbs, game, forage material etc. The value of forest biodiversity can not be ignored. Forests serve not only as shelter of flora and fauna, but also as a valuable natural gene pool. The value of information deriving from forest biodiversity for pharmaceutical use is subject to ongoing scientific research.

Recreational, aesthetic and health effects of forests can also be placed among their economic and socio-cultural values of immediate use. Forests, with their great surface, are the only part of every country that is free from pollution sources, while forest light, with its low intensity and high content in green radiation, has a soothing effect on the nervous system. For these reasons, forest-tourism, a specific form of tourism, is being developed which can be combined with walking tourism and ecotourism, and is a constantly developing category of mild and environmentally friendly tourism. Forests that are being managed for recreational purposes raise the value of neighbouring properties (Pearce 2001) and encourage tourism. Moreover, employment, particularly for populations who live near the forests and the exploitation of forest energy sources to produce soft forms of energy (biomass) can be added to the long list of benefits from forests.

The hydrologic function of forests, including protection against soil erosion, prevention of flooding while protecting settlements and infrastructure, a significant reduction in flood peaks, enrichment of underground aquifers and a contribution to the quality of water from an chemical and microbiological point of view, can be placed among the benefits and indirect use values of environmental character of forests.
The forest also has many environmental functions: it provides wind protection, protection from noise, and has an impact on climatic factors (light intensity and quality, mitigation of extreme summer and winter temperatures, air humidity).
Special attention should be paid to the key contribution of forests to the oxygen cycle, to absorption carbon dioxide and to air de-pollution (with physio-mechanical and biochemical means), also taking into account the context of climate change. According to the Global Organisation of Food and Agriculture, the world's forests store more than 650 billion tons of carbon (44% in their biomass, 11% in dead wood and litter and 45% in forest soil). Whereas, according to data from Eurostat (2009), at least 9.580 million tons of carbon have been stored in biomass in the forests of the EU of 27, without taking into account the amount absorbed by the dead biomass or forest soils.
Forests along with the oceans comprise the main mechanisms that regulate the balance the equilibrium of the CO_2 cycle. A hectare of forest of average productivity processes, each year, 10-12 million cubic meters of air to retain at least four tons of CO_2. Thus, it contributes significantly to maintaining / improving atmosphere quality both as a CO_2 consumer, as much as an O_2 producer. Concern for increased CO_2 and its implications on climate change is plausible, however, a truly significant problem, arises from the fact that the largest feedback mechanisms for regulating CO_2, such as forests and oceans, are losing their regulatory capacity due to deforestation (2/3 of forests worldwide have already been destroyed) and marine pollution.
The above mentioned complex values of forests demonstrate the imperative need to protect and preserve them.

2. Condition of forests globally and in Europe

At a global level, forests cover 30.3% of the total surface of the earth, meaning that 0.62 Ha of forest correspond to each inhabitant of the earth. More than half of the forested areas belong to the Federal Government of Russia (Russian Federation), Brazil, USA, Canada and China (FAO, 2005).
Regarding the European Union, forests cover an area of 177 million hectares or 42% of its total area. The countries with the largest forest coverage are Finland (77%) and Sweden (75%), followed by Spain (57%), Italy (37%), Germany (32%) and France (31%). The countries with the smallest forest coverage are Malta (1%), Ireland (10%), Holland (11%) and the United Kingdom (12%). In the territory of the united Europe about 4% of the world's forests are located, but, average forest land corresponding to each European resident is small (0.36 Ha), due to increased population density. However, forest land per capita varies from 4.4 Ha (Finland) to 0.07 Ha (Belgium) (Eurostat, 2010).
Between the years 2000 and 2005, forest coverage in the EU increased by 1.6%, a fact that can be attributed not to a cease of pressure on forests, but mainly to the abandonment and consequential afforestation of agricultural land and to the abandonment of mountain summer pastures.
While, at global level, deforestation has decreased, however, the conversion of tropical forests to agricultural land, in some countries, continues and at an alarming pace too.

Overall, 13 million Ha of forest land per year were being attributed to other uses or destroyed by natural causes during the decade 2000-2010, while during the decade 1990-2000, the corresponding forest land was 16 million Ha / year. On the other hand, the creation of new forests, protection programs of the landscape and natural expansion of forests reduce this loss. For instance, the net modification in forest land for the years 2000-05 was -7.3 billion Ha / year. (FAO, 2005)

In the Caribbean, Europe, North America and Oceania, most countries do not present significant changes in their forest lands, whereas, in Africa and South America, the majority of countries are presenting significant losses in forest land.

During the decade 2000-2010, the six countries that presented the highest rates of forest land loss were Nigeria, Zimbabwe, Myanmar, Indonesia, Brazil and Venezuela. Correspondingly, the six countries that produced the largest growth rates of their forest land were Viet-nam, China, Turkey, Italy, Norway, Spain and India. The increase of forest land in these countries can be attributed mainly to the afforestation programs (China has proceeded to a large-scale afforestation) and to the natural expansion of forests. Agriculture is considered to be the main cause of afforestation. In the logic of "slush and burn" agriculture, farmers cut down and burn trees in order to produce farm lands or stockbreeding lands (FAO, 2005). Forest insects and diseases are a major threat to the forests of the world, particularly in temperate and northern forests (e.g. beetle Dendroctonus *ponderoseae*, wiped out more than 11 million hectares in Canada and the western United States of America since late 1990), however, they affect less than 2% of forests at a global level (FAO, 2010). Finally, fires affect not only forest cover and the subsequent reduction of carbon accumulation, the protection from soil erosion and, generally, the reduction of all functions and services of the forest, but they also release into the atmosphere large quantities of greenhouse gases. Naturally, certain types of forest ecosystems are adapted to natural fire (eg in Mediterranean ecosystems), but, very often, a fire can get out of control, or torrential rains may follow immediately after the fire leading to soil erosion and simultaneous loss of seeds (eg of the Mediterranean Pinus *halepensis*). Globally, forests affected by fire contribute for 1% of the total annually, taking into consideration that several countries, particularly in Africa, do not record forest lands hit by fires.

Therefore, overall, global carbon capture is decreasing as a result to a forest land loss tendency.

3. Current state of forests in Greece

The first systematic effort to record Greek forests was made by the Forest Service via the "First National Forest Inventory" that started in 1963 and ended in 1992. The inventory data cover important quantitative aspects of forests, allocated geographically by county, catchment basin and forestry. However, qualitative data, on one hand concerning the trees and on the other hand the entire forest ecosystem, are not adequately covered.

Therefore, according to this first national inventory of Greek forests, land uses in Greece, were as shown in Table 1.

Land uses	**% of the total expanse of the country**
Forests	19.0
Forestlands – Pastures	43.3
Agricultural crops	30.0
Settlements, arid areas, rocks	5.6
Lakes, rivers, marshes	2.1

Table 1. Land uses according to the first inventory of Greek forests

However, the inventory of 1981 produced different results presented in Table 2.

Land uses	% of the total expanse of the country
Forests	22.4
Forestlands – Rangelands	39.8
Agricultural crops	29.90
Settlements, arid areas, rocks	5.60
Lakes, rivers, marshes	2.30

Table 2. Land uses according to the inventory of 1981

From the above tables, it becomes evident that the land of Greek forests has increased by 3.4%, whereas today, the land occupied by forests (industrial forest) contributes for 25.4% of the total country land, thus, overall, Greek forests have increased by 6.4% since the first forest inventory.
The composition of Greek forest according to species can be observed in Table 3 below (Ministry of Environment, Energy and Climate Change / General Directorate for Development and Protection of Forests and Natural Environment, 2010).

Tree species	Land (Hα)	Percentage %
A. Coniferous		
Abies-Picea *abies*	3,297.62	13.1
Pinus *halepensis-brutia*	4,757.77	18.9
Pinus *nigra*	1,370.47	5.5
other Coniferus	237.87	0.9
Total Coniferus	**9,663.73**	**38.4**
B. Broadleaved		
Quercus	7,475.49	29.8
Fagus	2,190.70	8.7
other Broadleaved	1,017.65	4.1
maquis	4,776.61	19
Total Broadleaved	**15,460.45**	**61.6**
Total	**25,124.18**	**100**

Table 3. Forest cover according to tree species

Mediterranean evergreen sclerophyllous vegetation (maquis) is dominant, as demonstrated on the table, while the oak is a common species in Greek forests as well.
Regarding the ownership regime of Greek forests, the vast majority of them, as shown in Table 4 (Ministry of Environment, Energy and Climate Change / General Directorate for Development and Protection of Forests and Natural Environment, 2010) below, are public. The management of all Greek forests of different ownership regimes is subject to State control and management of all forests takes place based on the principle of sustainability of yields. However, there are cases of non-compliance with the principle, where extraction of higher woody mass than the one that ensures the productivity of the specific ecosystem takes place with the consequence of its gradual quantitative and qualitative degradation, which adversely affects the biodiversity of forest ecosystems, the future production of wood, the quality and quantity of water, the protection against soil erosion, the capture of carbon

dioxide and, generally, all beneficial to humans functions of forests that have been mentioned above.

Ownership type	Land (Hα)	Percentage %
State forests	1,644,005	65.5
Municipal	301,527	12.0
Monasterial	109,946	4.4
Charitable Institutions	11,225	0.4
Forests in public ownership	245,845	9.7
Private	199,870	8.0
Total Forests	**2,512,418**	**100.0**

Table 4. Type of Greek forests ownership

Greek forests according to their utility and functions can be divided into: a) Productive Forests which are important for the production of forest products or other goods of primary production, b) Protective forests, which might have special protective effects on soils and underground water, might also protect subjacent settlements, cultural monuments and structural works and facilities and c) Forests of special scientific, aesthetic, ecological or geomorphological interest, such as National Parks (10), Aesthetic Forests (19), conserved natural heritage sites or Recreation Forests that can be used for leisure or act as agents of tourism development.

Depending on their capacity to produce wood, they can be divided into Industrial Forests (covering 25.4% of the country's land) which are capable of *"producing 1 m^3 of wood / Ha / year, as well as trees with trunks of cellulose wood (with a diameter) of at least 1, 2 m"* and Non-industrial Forests (covering 23.9% of the land of the country) constituting of multibranched dwarf trees and shrubs which do not currently produce marketable timber products and are available for grazing, firewood and protection of catchment basins (Ministry of Agriculture, 1992).

Depending on their management form, they can be divided into: high forests (34.7%), whose regeneration, naturally or artificially, made with seeds or seedlings from seeds, coppice forests (48%), whose revival originates from coppice sprouts for species that possess the ability to multiply in this way (oak, beech, chestnut, maquis) and are plainly anthropogenic and finally medium forests (17.3%) (Kotoulas et al., 1989).

Finally, depending on the extent of human influence and the degree of deterioration caused by human intervention, forests are divided into Virgin or Natural, when anthropogenic disturbances have not influenced the natural development of the forest ecosystem (in Greece there is such a forest in Mount Rhodope) Semi-natural, where human intervention has affected the natural progression, however without making impossible its function and natural development, and Artificial or Plantations where forests result from human management actions that control their creation process and evolution.

Regarding the sanitary condition of Greek forests, it is strongly influenced by biotic (insects, fungi), as well as abiotic (drought, late frosts) factors. Up until today, there have been no signs of damage (defoliation / needle-fall), attributable to air pollution and acid rain in particular, although episodes of acid rain have been recorded (Oikonomou *et al.*, 2004).

4. Deforestation / forest degradation

According to the Working Document of the Commission of the European Communities, entitled "Addressing the challenges of deforestation and forest degradation to tackle climate change and biodiversity loss. Impact Assessment" (COM(2008) 645), deforestation is defined as *"the conversion of forest land to another land use (or reduction under 10% crown cover without change in land use)"*. Additionally, the term degradation is defined by the IPCC (Intergovernmental Panel on Climate Change) *as "a direct human-induced loss of forest values (particularly carbon), likely to be characterised by a reduction of tree cover. Routine management from which crown cover will recover within the normal cycle of forest management operations is not included"*.

In the same text, the main direct causes of deforestation include: the change in land use due to the expansion of agriculture, mining and quarrying activities, infrastructure development (roads, electricity and water-supply systems etc.). (Chomitz and Gray 1996), and illegal or non sustainable logging. As indirect causes, we can report institutional issues such as governance issues (e.g. non-definited property rights), issues of spatial planning, policies that indirectly provide incentives for deforestation by subsidies in agriculture, urban expansion, infrastructure increase, etc.

Other causes that may lead to deforestation and / or degradation of forests may be related to the environment (e.g. soil quality, topography) (Kaimowitz and Angelsen, 1998), to biophysical factors (e.g. drought, fire) or social events (wars, revolutions, social upheavals, sudden movements, sudden political changes, economic shocks etc). The above, may be enhanced by the following factors: demographic factors (population density, natural population growth, migration, etc.), economic factors (e.g. market growth and commercialization, urbanization and industrialization), technological factors (e.g. in agriculture or in wood utilization), and cultural factors (such as attitudes, values, beliefs of societies and individual behavior in relation to forests).

Geist and Lambin (2001), mentioned three major causes of deforestation: the return of forest land to agriculture, timber extraction and the expansion of infrastructure. These interact with five primary indirect factors: the demographic, the economic, the technological, politics and cultural changes. Their study concludes that deforestation is best explained by a combination of direct and indirect causes: the construction of roads creates new access to forest land, forest protection and regulation of export activities is inadequate, forestlands can be converted for the needs of agriculture or, there may be a large inflow of immigrants due to demographic and poverty-related factors in the regions from which the immigrant waves originate from.

Inadequate logging practices that leave behind large amounts of combustible wastes make forests vulnerable to fires caused in order to clear land for agriculture, further degrading the forest.

According to Lambin *et al.*, 2001, the most important phenomena of land use conversion concern forests and are related to forest fragmentation and transformation of forest land. The processes that incite this type of change are particularly complex and are due to a plethora of interactions between natural ecosystems and human demand for land use for many different purposes (Minetos and Polyzos, 2010) and relate to economic as well as social and environmental factors (Verburg *et al.*, 2006). It should be noted that these factors or a combination of factors may be different for different countries and different time periods.

4.1 Deforestation in Greece

According to the Greek Parliament (2003) in the explanatory report regarding the new Law on Forests, recent land use changes on forests and forest land in Greece are the result of complex economic and social processes that result in creating spatial patterns in which a decline in the forest component can be observed. This negative image is due to high growth rates, coupled with an inefficient and fragmented land planning and urban design legal framework (Rizos, 2004). In several areas, forests and forest lands take the greatest heat for the expansion of urbanization and of agricultural or livestock operations (Beriatos, 2002, Christopoulou et al., 2007). Particularly in southern Greece, the islands and much of continental lowland and upland areas, forests are gravely destabilized due to fires, overgrazing, widespread building out of the city plan, and the creation of traffic infrastructures (Minetos, 2009).

According, again, to Minetos (2009), who studied the changes in land use in the time period 1990-2000, the 'diffusion' of urban land uses outside city plans and settlements in Greece, has negatively affected forest lands. The phenomenon extends to areas that are relatively remote. On the contrary, no trends of extending rural uses to the detriment of forests, in counties designated by a dynamic agricultural sector, were found. Finally, tourism development in recent years, due to the institution of Environmental Impact Assessments, had limited effects on forest lands, except for some cases of intense tourism growth in out of city plan areas.

4.1.1 Overgrazing

Overgrazing occurs when the number of animals using a pasture is greater than the grazing capacity, assuming that the excess number of animals could range from a few to very many. Consequently, the number of animals kept in a pasture or grazing intensity is an important indicator of pasture degradation (Papanastasis, 1998; 2000). Grazing results in the deterioration of pastures leading to erosion and desertification of soils as well as in inadequate nutrition of livestock animals since they can not receive an adequate ration in a degraded pasture.

Since ancient times, grazing, mainly involving goats and sheep, can be viewed as one of the key factors of degradation in mountainous and upland (semi-mountainous) Mediterranean ecosystems. This is due to the large number of animals, the constant, throughout the year, grazing and the combination of stockbreeding with deforesting logging and fires for improving fit for pasture material (Greek Committee for Combating Desertification, 2000).

Mediterranean rangelands include pastures, as well as "forest" rangelands, namely low bushy land (e.g. phrygana, garrigues), shrubs (e.g. maquis) and sparse forests (tree cover less than 40 %). According to Le Houerou (1981), these pastures are being grazed with a density of 2.2 sheep / Ha. Bearing in mind that the grazing capacity of Mediterranean rangelands cannot surpass 1 sheep / Ha, we conclude that Mediterranean pastures are being overgrazed.

In Greece, grazed forestlands (forest rangelands) cover 40% of the country. In these, the largest area is occupied by forests (48%), followed by grasslands (32.5%), shrublands (15.1%) and finally phrygana (4.4%). Grazed forests are estimated to stretch for about two million Ha. The proprietary rights of these areas belong, in the largest proportion (75%), to the state and their use (occupancy) belongs to the municipalities and communities. The continuous and ongoing for many years overgrazing has led to deterioration of both the forage and soil (Ministry of Environment, Energy and Climate Change, 2010).

This, naturally, is aided by the mild Mediterranean climate that contributes to grazing throughout the year, the xerothermic conditions in the summer, the peculiar ownership regime in combination with the lack of cadastre and the subsidies to animal breeders through CAP (until Agenda 2000 enters into force) depending on the number of animals.

A common practice for farmers in order to control unwanted vegetation, in different parts of Mediterranean Europe (e.g. Corsica, Sardinia, Crete, and Western Greece), is the use of fire. Although Mediterranean vegetation has adapted to these circumstances and usually re-germinates, however, this may lead to desertification, if the fire is combined with overgrazing. Several studies have demonstrated that the combination of fires and overgrazing are the main cause of degradation and desertification of rangelands in Mediterranean Europe (Margaris and Koutsidou, 1998; Papanastasis et al., 1990).

Papanastasis (2008) reports that in a study on the impact of overgrazing on Mount Pseloretis in Crete, aerial photographs of the area, for the years 1961-1989, were analyzed and the major types of land uses were identified and recorded. The results demonstrated an increase in sparse and medium density brushlands (mainly ecosystems of phrygana), at the expense of high-density areas, as well as forests. This course indicates land degradation as fewer shrubs account for less forest plant coverage for soil protection and the support of its productivity. The consequences of overgrazing were greatest when it was combined with deliberate rangeland fires.

4.1.2 Fires

Forest fires are part of the ecology of Mediterranean ecosystems and could not be eliminated even through the development and implementation of the perfect fire management planning (Xanthopoulos, 1998). They are to some extent an inevitable ecological phenomenon that can also be caused by physical factors (eg, thunderbolt, spontaneous combustion). For this reason, Mediterranean ecosystems have developed adaptations to natural fires that allow them to be renewed after a fire. Such adjustments are the resprouting capacity of maquis, when their surface part is burned, as well as the opening of the Mediterranean conifer cones to release seeds (e.g. Pinus *halepensis*).

But when the frequency of fires in this zone increases due to anthropogenic agents (arsons), then the natural process and balance becomes diverted, resulting in degradation of forest ecosystems. When repeated fires are combined with overgrazing, the consequences are irreversible and lead to desertification. In the last decades, despite an increase in personnel and engineering resources, fires are getting increasingly destructive, (Tambakis and Karanikola, 2002).

The causes of forest fires in Greece are complex and interrelated.

a. Natural Causes

Thunderbolt is a well known and very old natural cause of fires. It should be noted that in Alberta, Canada it has been established that 81.1% of the burned surface in large (over 200 Ha) fires originated from lightning strikes. In Greece, thunderbolt is culpable for 2.2% of forest fires. Additionally, spontaneous combustion of flammable ecosystems (forests with a thick layer of dry pineneedles) has been recorded as a possible cause of fire (Kailidis and Karanikola, 2004).

Therefore, the view supporting that fires are an eco-factor is valid for only 2% of forest fires (Zagas *et al.*, 1998).

b. Anthropogenic Causes

$B_{1.}$ Unknown

Unknown causes account for 35% of all causes of forest fires according to the Ministry of Agriculture (2005) or for 25.7% according to Kailidis and Karanikola (2004). Sparks originating from cars, trains, chain saws, farm machinery or even live wire from the Public Enterprise of Electricity may constitute random / unknown anthropogenic causes of fire outbreaks, as reported by foresters (Kailidis and Karanikola, 2004). Broken and discarded glass bottles exposed to high temperatures (summer afternoons) or mineral bottles of aerosols can start a fire in litter or in forests.

B_2 Negligence

Human negligence also constitutes 35% of the causes of forest fires for the time period 1990-2004 (Ministry of Agriculture, 2005), whereas Kailidis and Karanikolas (2004), attribute 42.8% of all fires to negligence. Negligence is considered to be the extension of fires from burning stubble, burning dry branches and grass in fields and gardens, disposing lit cigarettes or matches (10.7% of events) and garbage burning (6%). The burning of crop residues is prohibited by the EU and compliance with environmental conditions is a prerequisite for the granting of subsidies to farmers. Regarding the latter cause, it is expected to decline significantly, since shutting down all uncontrolled waste disposal sites (landfills) and replacing them with sanitary landfills has been imposed by the government. Easy access to forests by all people, due to the opening of several kilometers of forest roads, and recreational activities in forests (e.g. use of fire for picnics) can become the cause of fire by negligence.

$B_{3.}$ Intent

Intentions account for 25% of forest fire causes (Ministry of Agriculture, 2005) or for 29.3% according to Kailidis and Karanikola (2004). This figure may, of course, be much higher if one considers that a significant proportion of unknown causes may be attributed to arson that has not been confirmed.

Regarding the causes of arson (intentional fires), these stem from many factors and are also assisted by many others.

a. Shepherds still consider fires as a means of foraging material amelioration, although the legislation of all Mediterranean countries prohibits the use of fire near forestlands.
b. Flammable forest material has increased 2-4 times when compared to that of 1974 (regime change) (Kailidis and Karanikola 2004). This is due to the fact that in many regions the countryside has been abandoned by young people in particular, also, the use of forest biomass waste for heating purposes has been replaced, in many areas, by burning petroleum (stoves and ovens that burn wood are rare in the Greek countryside) and the collection of resin is virtually abandoned, thus, resin forests have gradually lost their old means of protection.

The tendency of abandonment of mountain regions by people living near forests who were concerned about forests as, among other things, they were a source of income, worsens the situation.

c. Political reasons or terrorist acts. Kailidis and Karanikola (2004) argue that fire outbreaks observed were associated with political events in the country (e.g. the catastrophe of Minor Asia, land occupation during wars, civil war and, during the last years, elections).
d. Land use conflicts on forest lands. The expansion of human intervention is particularly intense due to a high demand for urban uses, holiday residences and tourist

development. Trespassing, the illegal creation of building sites and land use changes are not directly made, but after degradation actions of forests and forestlands take place, such as fires. The regions suffering the greatest pressures are suburban or areas of holiday or tourist interest (e.g. island regions). This kind of pressures is based on legislative and administrative deficiencies concerning both forest protection and spatial planning. This has created extensive zones of mixing forest lands with settlements, resulting in an extremely high risk of fires, the destruction of forests, properties, as well as the loss of human lives. According to surveys, about ¾ of fire-ignition points lie in these zones and their majority is located in the type of zone characterized by high accumulation of vegetation and high density housing. So, in case of fire, it is self-evident that priority is given to protecting human life and property (Vélez, 2009). The issue of arbitrary construction in forested areas is particularly acute. Only in the County of Attica (around the capital) there are estimates for the existence of about 250,000 illegal constructions. Kailidis has mentioned that while in lowland and island areas a decline in forestlands favoring other land uses is observed, in mountain areas, due to their abandonment, forests are expanding since forest vegetation is introduced in abandoned fields.

e. Complex proprietary regime. The lack of forest maps and forest cadastre (the first three forest maps in the country were formed in the spring of 2011 and concern Attica, while the Ministry of Environment, Energy and Climate Change has initiated the issue of forest maps for the whole country) is causing continuous controversy about the status of the land (forest or non-forest), conflicts between the Forest Service and the public, time-consuming administrative procedures regarding the designation of lands, and, finally, their non effective protection. In Greece, the rebuttable presumption that the owner of the land is the state applies to forests and forestlands. That is, lands with forest vegetation belong to the public, unless their claimers can prove their ownership with an administrative recognition or a definitive decision by accord. The above explain the conflicts between the public and the forest service and the huge delays in resolving property disputes.

The above mentioned forest fire causes are also determined by several factors such as meteorological conditions (air temperature, wind intensity and speed, moisture content of forest flammable matter), type and quantity of the flammable matter, topography (altitude, exposure and slope), accessibility of the area, means available to extinguish the fire, the start time of the fire, season (most fires occur during the summer months and in the time period from 12 to 15 o'clock) and the response time to start extinguishing it. It is worth noting that wind speed is considered by Smith (2002), as the main factor for fire initiation. Dry and warm conditions characterizing summer months in Mediterranean regions, promote the outburst, and the easy spread of forest fires.

Other factors contributing to the phenomenon of forest fires in Greece is the fact that greater emphasis is given on fire suppression and not fire prevention, inappropriate vegetation control (management), insufficient involvement of the public and volunteers and also insufficient public information / education (WWF, 2010).

4.1.2.1 Protection against fire

Various bodies with, to an extent, interrelated responsibilities get involved in the protection of Greek forests and forest land. These bodies include (WWF, 2010): the Forest Service, the Fire Service, the General Secretariat for Civil Protection, Organizations of Local

Government, Management Bodies of Protected Areas, General Directorate of Forestry, Greek Police Force, the Ministry of Foreign Affairs, Volunteers and Nonprofit Organizations. Examples included: the Forest Service is responsible for the fire prevention (e.g., maintenance of forest road networks, thinning vegetation, cleaning fire lane, preparation for fire suppression (e.g. patrols) and ecosystem restoration (burnt area mapping, issuing reforestation acts where protection and restoration of burned forests is necessary). The Fire Department is responsible for the suppression preparations (e.g. organization of fire lookout stations, recruitment and distribution of seasonal staff, training staff and volunteers) and the suppression (fire extinction, watch over for fire reactivation). The Managing Bodies of Protected Areas are responsible for the preparation of management plans for the areas and the design and implementation of measures of protection and restoration of burnt protected areas, the General Secretariat for Civil Protection is aiming, amongst others, to draw a map of fire risk and the declaration of areas in a state of emergency. The daily risk prediction bulletin is an important tool in preventing forest fires in which the development of an indicator system has been adopted methodologically, with its prevailing approach being the one followed by the American fire risk assessment systems (United States - NFDRS and Canada - NFFDRS) adapted to the specificities of our country.

The main goal of fire risk determination systems is the ability of presenting forecasts in the form of thematic maps presenting the risk as it has been assessed in the different geographic departments of the country. The fire risk map is usually composed in digital form and can be upgraded at regular intervals (daily during fire season) and depicts five risk levels as estimated in the various departments of the country. This measure leads to the immediate adoption of additional measures of prevention, alertness of the bodies involved in fighting forest fires and to avoid unnecessary alerts. The preparation of the map gets finished at 12:30 on the previous day of its application. Immediately after its compilation, the map becomes available, in minimum time, by the website of the General Secretariat for Civil Protection (www.civilprotection.gr), where all relevant bodies, volunteer fire squads, as well as all interested citizens can be informed (General Secretariat for Civil Protection).

4.1.2.2 Statistics

According to Dimitrakopoulos (2001), who analyzed fires in forests and woodlands during the period 1955-1999, the average annual burnt areas were rising exponentially every decade, thus, in the 80s they increased five times compared to the 50s, whereas in the 90s, there was a relative decline when compared to the 80s. Overall, while the number of fires has nearly doubled in the '80s and the '90s when compared to the '60s and '70s, the burned areas almost tripled.

The phenomenon of forest fires as evolving from the beginning of the last decade is demonstrated in Table 5 (Ministry of Environment, Energy and Climate Change / General Directorate for Development and Protection of Forests and Natural Environment, 2010).

As observed in table 5, the percentage of unknown causes is very high as it fluctuates between 41% and 91.5 % (for the years 2005-2008 we have no definitive data regarding the causes). There is a great chance that human causes are a part of these unknown causes. Outbreaks occur not on the number of fires, but the size of the area burned. According to Kailidi and Karanikolas (2004) and Dimitrakopoulos (2001), in general, concerning the period 1980-2000, outbreaks concern the years 1985 (elections), 1988 (drought, political excerbation), 1998 (the year in which extinguishing forest fires came under the provision of the Fire Service rather than the Forest Service that was responsible until then by an act of law) and 2000. According to table 5, the year 2007 was particularly devastating for Greece with regard to fires. Extensive fires in many parts of the country (mainly in August), burned more than 200,000 Ha of land. At least 63 people died, 1,500 houses got burned leaving 6,000 homeless. Also, 4.5 million trees, 60,000 sheep and thousands of swarms of bees got burned. Seven " Natura 2000" areas, burned down by 16.3% to 50.4%. The areas affected were in the Peloponnese, the island of Euboea and Central Greece (Attica and Fthiotida counties). The cost of the disaster reached 5 billion euros.

YEAR	TOTAL NUMBER OF FIRES	TOTAL BURNT LAND (Ha)	TOTAL BURNT FORESTS (Ha)	BURNT WOODED LAND (Ha)	HUMAN CAUSES	NATURAL CAUSES	UNKNOWN CAUSES
1990	1,322	38,593	21,088	17,505	48.60	3,32	48.08
1991	941	23,574	8,000	15,574	57.27	1.91	40.81
1992	2,042	66,347	23,194	43,153	42.51	2.98	54.50
1993	2,406	54,049	24,200	29,849	42.50	2.53	54.96
1994	1,954	52,603	23,392	29,211	39.15	4.91	55.93
1995	1,493	19,177	9,035	10,142	36.10	3.95	59.94
1996	1,527	22,990	8,111	14,879	29.60	3.27	67.12
1997	2,273	34,781	16,119	18,662	35.41	2.37	62.22
1998	1,842	92,901	46,077	46,824	11.45	2.50	86.05
1999	1,486	8,289	4,773	3,516	8.54	8.71	91.46
Mean	**1,728.6**	**41,330.4**	**18,398**	**22,931.5**	33.60	3.21	63.19
2000	2,581	145,034	69,579	75,455	13.01	4.99	81.99
2001	2,658	18,342	8,423	9,929	15.24	6.66	78.10
2002	1,400	4,337	887	3,450	10.00	11.0	79.00
2003	1,425	3,263	960	2,303	11.01	16.21	72.77
2004	1,755	10,722.1	2,586	8,136.1			
2005	1,544	6,437.4	2,180	4,257.2			
2006	1,417	12,661.4	6,513	6,148.3			
2007	1,992	222,894	85,970.6	136,923.4			
2008	1,486	29,172	13,397	15,775			
Mean	**1,806.4**	**50,318.1**	**21,166.2**	**29,153**	**14.36**	**9.70**	**75.93**

Table 5. Number of fires and burned area in Ha during the period 1990-2008

After the fire, recording of burnt areas of forest character of the Greek Territory takes place using high resolution satellite images with the cooperation of ESA (European Space Company) and the National Observatory of Athens. The mapping provides information about the overall expanse and magnitude of the damages of burnt areas and supports procedures for the recovery of the burned areas.

5. Reforestation / afforestation in Greece

As mentioned previously, after the fire, the Forest Department (or the Management Authority in the case of Protected Areas) is responsible for further protecting and restoring the area burned.

Rehabilitation / protection actions begin immediately and generally (differ according to case) may include: a) Anti-erosion works: avoiding tillage, prohibition of any kind of grazing in order to facilitate the development and regeneration of vegetation burned, anti-erosive construction projects in streams and gorges to slow down the flow of flood waters, placing branch-meshes, trunk-meshes, construction of small dams on streams, b) Projects for slope formation and protection, c) Reforestations: When the burnt area includes maquis forests or Mediterranean conifer forests (e.g. Pinus *halepensis* and Pinus *pinea*), they can be recreated in a few years. The Forest Service takes into account the type of vegetation that has been burned, the success potential of natural regeneration of trees and the general conditions (e.g. slope), and, accordingly, shall proceed, or not, to artificial reforestation of burnt areas using native species.

Reforestations, being a duty of the Forest Service of Greece, are not limited to the post-fire period.

The purpose of reforestation is the creation of new forests, the renewal of mature forests and the recovery of degraded forest ecosystems while ensuring natural regeneration or artificial intervention (seeding or planting) for production purposes and the protection of soils. There are also hydrologic purposes, as well as environmental and aesthetic purposes.

On average, over the past 5 years, approximately 1.000 Ha of land have been reforested. Last year (2010), a very ambitious program has started that predicts only for the Attica Prefecture (the county in which the country's capital is located), reforestations of 10,000 Ha by 2014. This program concerns areas that have been burnt 2 or 3 times and, therefore, can not be naturally regenerated. Especially in the Attica region, according to data from the Ministry of Environment, Energy and Climate Change (2010) (see Table 7), the cost of reforestation in the last 8 years was enormous. However, it should be noted that the costs of Reforestation projects in Attica, also included, maintaining and improving existing roads and the creation and maintenance of fencing.

Year	**Reforestations (Ha)**	**Planted saplings (thousands)**	**Incurred Expenditure (€)**
1941 - 1950	24,706.1	40,978	36,616
1951 - 1960	54,353.1	104,055	340,461
1961 - 1970	36,613.2	103,265	865,010
1971 - 1980	41,682.0	90,098	3,273,843
1981 - 1990	72,796.0	71,403	34,583,941
1991 - 2000	31,408.6	47,226	68,658,711
2001 - 2007	9,234.4	9,509	18,218,804

Table 6. Realized reforestation projects and incurred expenditure from the start of the action until 2007

Year	Reforested land (Ha)	Planted saplings (No)	Seed Plantations (No)	Road openings (km)	Expenditure current prices
1976 - 1982	5,481.1	3,154,480	159,102	234.67	130
1983 - 1990	2,546.9	1,746,650	88,470	82.43	7,622
1991 - 2000	3,533.5	1,991,745	93,100	46.68	14,702
Total 1976-2000	**11,561.5**	**6,892,875**	**340,672**	**363.77**	**22,453**
2001 - 2008	1,361	912,704	0	2.93	4,654,000

Table 7. Reforestation projects in Attica

Apart from reforestations, under the Common Agricultural Policy (CAP), the measure of afforestation of agricultural land is being implemented since 1992 (Reg. 2080/1992 and Reg. 1257/99). According to this measure, owners of marginal productivity agricultural land are encouraged to transform it into forest land by planting forest tree species. This way, the afforested area in the EU (and Greece) increases with favorable consequences on global warming and on increasing biodiversity, slopes become effectively protected and non-productive lands get withdrawn from production. Beneficiaries of this measure, receive subsidizes to cover planting and maintenance costs for up to 5 years after planting tree species, support for the construction of windbreaks, fire lanes and an annual support payment per hectare afforested (up to 20 years) to cover income losses resulting from land use change (Christopoulou, 2001).

In Greece, the implementation of Regulation EEC/2080/92 from 1993 to 2001 resulted in the establishment of 35,840 Ha of forest plantations mainly of *Robinia pseudoacacia* L (black locust*), Populus sp* (poplar) and *Juglans regia* (walnut) (Arabatzis *et al*., 2006, Chalikias and Christopoulou., 2010).

6. Conclusions – proposals

From the preceded analysis, it can be concluded that regarding Greece an increase of forest area in mountainous regions has been observed and an expansion of forest vegetation due to the cessation of farming activities, whereas in areas around urban centers (mainly around the capital), in islands or areas of a tourist interest, a significant decline in forest vegetation can be observed. The great frequency of forest fires, overgrazing, the scattered and out of city plan building and creation of traffic infrastructures are the main causes of deforestation in Greece. The lack of forest maps and cadastre is an important factor contributing to deforestation, as it favors tresspassing and illegal housing development of woodlands and the creation of arbitrary structures within them. This phenomenon is naturally based on legislative and administrative deficiencies relating to both forest protection and spatial planning. Thus, extensive areas of mixing forests with residential areas have been created, where the most frequent and most destructive fires occur. In the spring of 2011 the first 3 maps were posted and are now in the process of submitting complaints concerning the status of lands (forest or not) aiming to create forest maps and a forest cadastre for the entire country (already maps are being prepared for 107 regions corresponding to 190,000 Ha), in order to resolve the complex ownership regime regarding forestlands in Greece and lead us to efficient spatial planning and effective environmental and forest policy.

Regarding policies to increase forest area, they focus on reforestations materiazed by the Forest Service, and the implementation of the EU Regulation on afforestation of marginal agricultural land.

Finally, for the protection of forest ecosystems in general as well as, specifically, in order to protect them from their main enemies (grazing, fire and subsequent change of use), the implementation of the following is necessary:

- Rapid composition of forest maps for the entire country
- Application of contemporary standards regarding the compilation of management plans on forests, which should take into account, the productive functions of forests (sustainability of yields) the protective, ecological and social functions (multifunctional forest management, sustainable management of forest ecosystems), as well as new data on climate change. The state should strengthen the forest sector, both materially and with the necessary personnel, given that, according to science experts, public forests managed for a long time with high quality management plans, are currently being managed with logging plans due to lack of funds and personnel.
- Creation of management plans by the Management Bodies of Protected Areas.
- Conversion of all managed coppice forests in the country, especially oak forests, not only to achieve higher timber stock, but also for ecological / environmental reasons (more effective soil protection, increase of biodiversity, landscape aesthetics, the hydrological role of forests etc.).
- Greater emphasis on the prevention of forest fires, through managing tree clusters and dead biomass.
- Emphasis on public information – awareness regarding the multidimensional functions of forests, as well as the impacts of fires in nature, climate and public health. Awareness of local authorities and organizing locals into voluntary groups aiming for fire prevention, suppression and reforestation, coordinated by the Forest Service.
- Integrated management of burned areas.
- Rigidity regarding compliance with the ban on grazing in burnt forest areas, in accordance with legislation, while ensuring alternative sources of food for animals, the composition and implementation of management plans for pasturelands and compliance with the carrying capacity of rangelands.
- Rigidity regarding the observance of the legislation concerning the protection of burnt areas and specifically the issue of land use change.
- Strict compliance with the use of native species, well adapted to the particularities of each region, during reforestation.
- Logging and wood transport should take place in a manner that causes no damage to the ecosystem and its regeneration.
- Taking into account that Forest Service officials have scientific knowledge on the physiology of forests and wild areas and are well aware of the area for which they are responsible, it would be advisable that the responsibility of suppressing forest fires should be assigned to the Forest Service.

Particular attention, sparingness and skepticism regarding the opening up of a dense road network in forests.

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4

Soil Erosion Under Different Land Use and Cover Types in a Marginal Area of Portugal

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1. Introduction

According to the CORINE programme, Spain and Portugal are the Mediterranean countries in the European Union facing the greatest risk of erosion (Desir & Marín, 2007). In Portugal, areas at high risk of erosion cover almost one third of the country (Grimm et al., 2002). The main causes of soil erosion are inappropriate agricultural practices, land abandonment, deforestation, overgrazing, forest fires and construction activities (Grimm et al., 2002; Yassoglou et al., 1998). Several studies in the Mediterranean region have addressed the present-day hydrological response and erosion rates for arable and marginal land affected by land abandonment (Casermeiro et al., 2004; García-Ruiz et al., 1995, 1996; Nunes et al., 2010, 2011; Nunes, 2007; Pardini et al., 2002, 2003; Romero-Díaz, 2003; Ruiz-Flaño et al., 1992), forest fires (Cammeraat & Imeson, 1999; Coelho et al., 2002, 2004; Doerr et al., 2000; Ferreira et al., 2005; Ferreira, 1990; Ferreira, 1996; Imeson et al., 1992; Shakesby et al., 1993, 1996) and afforestation (Ferreira, 1996; Ternan et al., 1997; Thomas et al., 2000; Shakesby et al., 2002). The results show wide variations in runoff generation and sediment yield, mainly depending on environmental conditions, vegetation cover, changes in previous land use, the period of soil abandonment, etc.

In Portugal, as well as in many other Mediterranean countries, the main type of land use was rainfed cereal crops until the middle of the twentieth century. After the introduction of modern agriculture, the opening up of the international markets and the lowering of crop prices, market-oriented cultivation of cereals became unprofitable in most marginal areas in Portugal. In addition, socio-economic and political changes in Portugal in the 1970s led to higher agricultural wages and migration from the countryside (Pinto-Correia & Mascarenhas, 1999). Thus, abandoned farmlands became evident, very often in marginal, mountainous or semi-mountainous areas and areas that were difficult to access, in which traditional or semi-traditional agriculture was practised until recent decades, involving low input and intensive human labour. Abandonment implied the extensive decline of arable land and resulted in very important transformations to the landscape, characterised by the spread of natural vegetation, including both shrub land and forest.

Additionally, the EU's Common Agricultural Policy recognises the natural handicaps of such areas and their association with depopulation and land abandonment through its structural support for 'Less-Favoured Areas' (Regulation 950/97). Around eighty per cent of the Portuguese Utilised Agricultural Area (UAA) falls within the definition of Less Favoured Areas (LFAs), and a substantial amount of this is classified as mountain area. Much of this mountain zone is designated Objective 1.

In 1992, measures accompanying the reform of the Common Agricultural Policy (CAP) were adopted to benefit the environment, early retirement and forestry. These measures aimed to support the envisaged processes of change, and to mitigate some of the effects deemed to be disadvantageous to farmers (Van-Camp et al., 2004). European Economic Commission (EEC) Regulation 1765/92 (EEC, 1992) led to a substantial increase in set-aside land in the European cereal-growing regions (Crabb et al., 1998; Van Rompaey et al., 2001). Agricultural land afforestation (Regulation 2080/92), which established an aid programme for the afforestation of former agricultural lands, also aimed to enhance long-term forest resources and combat soil erosion and desertification by promoting forestry as an alternative form of land use. However, the overall effectiveness of afforestation in reducing soil erosion remains uncertain, due to the poor development of the forest cover in some areas leading to significant areas with sparse tree cover, and the erosional impact of forest harvesting, which usually involves clearcutting (Porto et al., 2009). In fact, little data is available. The extent to which these measures are applied in areas under medium/high risk of soil erosion needs to be assessed (Van-Camp et al., 2004).

According to Caraveli (2000), the implementation of CAP measures in Mediterranean countries has reinforced *intensification* processes in productive practices in the more fertile areas of the lowlands and *extensification* (i.e. abandonment or marginalisation and the collapse of traditional farming systems) in the LFAs, which has been going on for decades. Land use changes characteristic of extensification include fewer cultivated fields, more shrub patches, larger areas of natural pastures, and abandonment of some patches, followed by the development of stratified bush communities. The CAP agreement requires Member States to maintain a permanent pasture area, which should prevent the wide-scale ploughing up of land for arable cultivation and potential problems with soil degradation often associated with arable farming in some areas (Van-Camp et al., 2004). Nevertheless, the influence of grazing on vegetation development and soil erosion processes is rarely quantified in literature on the subject (Ries, 2010).

The specific objectives of the current research were: (i) to evaluate and compare the hydrological and erosional response of soils under different land uses and vegetation types in central inland Portugal, (ii) to identify and describe the main factors that control their hydrogeomorphic response and (iii) to assess the efficiency of alternative land uses proposed by the CAP for soil erosion control. The six land uses and vegetation types studied (cereal crop, fallow land or short-term abandonment, shrub land or long-term abandonment, recovering autochthonous vegetation or very long-term abandonment, arable land afforested with *Pinus pinaster* and arable land transformed into pastureland) are representative of situations frequently found throughout central and northern Portugal, and also in other Mediterranean systems. The main aim was to obtain consistent conclusions for ecosystem management in marginal areas of Portugal. This information on the hydrogeomorphic response could be useful in the future as a guide for regional soil conservation planning.

2. Study area

The study was carried out in the high Côa river catchment, in a peripheral area of Portugal close to the Spanish border (Fig. 1). The substratum comprises mainly granites with poor, shallow soils, classified as distric cambisols (FAO-UNESCO, 1974), and an undulating relief with elevation ranges from 700 to 900 m a.s.l. The area has a sub-humid Mediterranean climate, characterised by wet, cool winters (5.8 ºC average temperature) and hot, dry summers (25.8 ºC average temperature). The mean annual precipitation of 800 mm has a high inter- annual variable distribution and seasonal concentration. The wettest periods of the year are concentrated in the autumn and winter months, between October and February, and the driest in summer, between June and September.

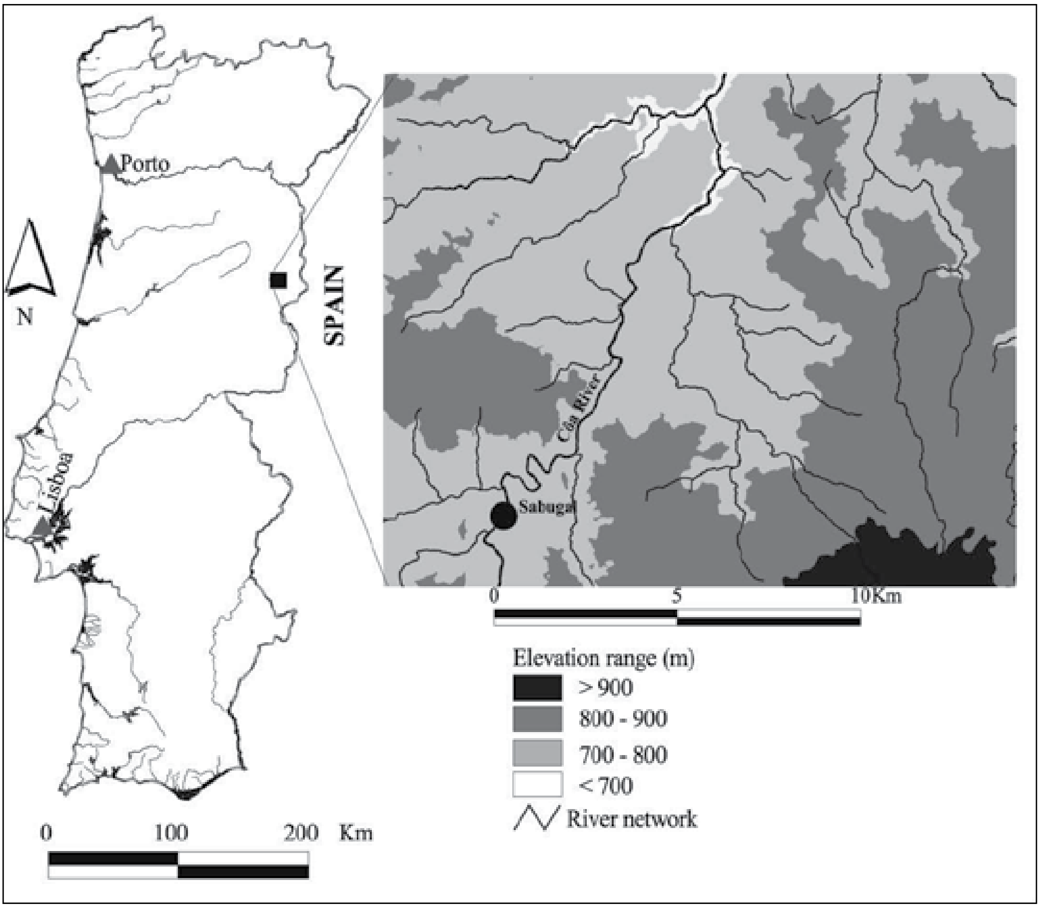

Fig. 1. Location of the study area

Agricultural activities dominated land use in marginal areas of Portugal for many decades. In the 1960s, approximately over half the utilized agricultural area was divided between non-irrigated cereals (the dry system) and unseeded fallow rotations. Cereal crops were sown from October to mid November to make use of autumn precipitation for germination. Spring was the main growing season and mature cereals were harvested in June to early July before the onset of the hot, dry months. Cereal fields were rotated with unseeded fallow in order to regenerate soil moisture and nitrogen levels for the following year's cereal rotation.

Agricultural activities have become less important since the mid-20th century, coincided with the widespread migration of the population to certain European countries (France, Germany, Luxembourg, etc.) and to urban centres (Nunes, 2007). This exodus and subsequent abandonment of cultivated land was associated with the low rate of return from traditional crops, a result of the low productivity of dry farming systems (a Mediterranean climate, undulating relief, and poor, shallow soils), uncompetitive farm structures (with small, scattered plots), the peripheral location of the area, the lack of alternative employment sectors and the extensive presence of elderly farm owners. Furthermore, the socio-economic and political changes in Portugal in the 1970s that led to higher agricultural wages and migration from the countryside, made it difficult to maintain traditional management and manual shrub clearing, which was essentially based on low labour costs. During the period 1960-2001, the study area lost about 60% of its total population and more than 90% of its farmers.

According to SROA (Service of Agrarian Recognition and Management, 1951-56) statistics, in the middle of the last century cereal cultivation occupied about 55% of the total area of the Guarda district. Five decades later, the same crop only represented 10% of the total surface (CORINE Land Cover, 2000), meaning that approximately 80% of the cereal crop area had been abandoned.

Complete farm abandonment has resulted in enhanced natural secondary succession and the spread of shrub and woodland (Lasanta et al., 2009). In the first stage of land abandonment, after 4-5 years the dominant vegetation belongs mainly to the *Gramineae* family and forms a sparse herbaceous cover (Fig. 2). Perennial shrub communities, mainly dominated by nanophanerophytes such *Cytisus multiflorus* and *Lavandula sampaioana*, follow after two decades of farmland abandonment. As a result of the abandonment of cultivated land and the decline in forest land, shrub plant communities have become one of the most important vegetation types in the Iberian Peninsula (Casermeiro et al., 2004). Negligible areas are covered by recovering *Quercus pyrenaica*, indicating a lengthy period of abandonment of approximately 30-40 years. The *Quercus pyrenaica Willd*. wood is the characteristic autochthonous vegetation in the study area. The unmanaged accumulation of large quantities of fuel has led to a dramatic increase in forest fires and burnt areas (Carvalho et al. 2002), and therefore to difficulties with *Quercus* regeneration.

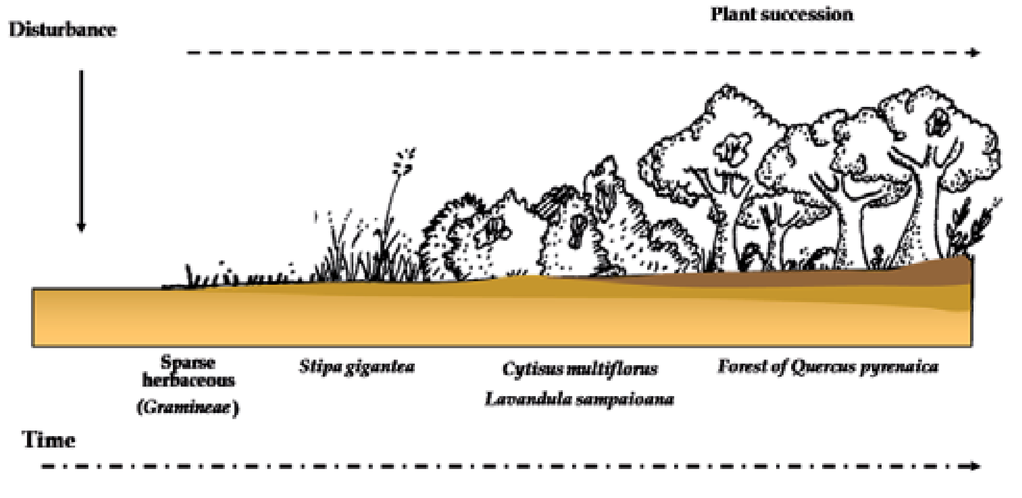

Fig. 2. Dynamic evolution of vegetation in the study area following land abandonment (adapted from Capelo, in Costa et al., 1998)

The 1992 MacSharry reforms to the European Union Common Agricultural Policy have reinforced the falling rates of cereal production. The reforms included a set-aside program requiring farmers to take certain percentages of their arable land out of production. With the opening up of international markets and the lowering of crop prices, the market-oriented cultivation of cereals became unprofitable in most of Portugal. Farmers receive more in the form of direct payments per hectare under the set-aside regime in comparison with arable crop production. Consequently, they put greater percentages of their farms into set-aside. As an example, in the Guarda district early retirement has affected about 10 000 farmers and an area between 60 000 ha and 90 000 ha, since 1996. This represents about 40% of the total number of farmers and 30%-45% of the utilised agricultural area.

In contrast, pastureland has increased by over 25%, in the last two decades (INE, 2000). In fact, recent EU agri-environmental measures support the maintenance of natural pastures or the extensive cultivation of fodder crops (without deep ploughing and the use of fertilisers) and the livestock unit subsidy supports maintenance of livestock (Borges et al., 1997). The current CAP measures for Portugal also promote forest development measures (EU Regulation 2080) by supporting new plantations and shrub clearance.

3. Methodology

Six types of land use associated with traditional land use, land abandonment and subsequent plant recovery, and alternative land uses proposed by the CAP for marginal areas (extensification of land use and conversion of arable land to forest) were selected for the study.

1. Cereal crops (traditional land use)

In dry cereal systems with Mediterranean marginal soils, during March/April the 20-30 cm of top soil is turned over and remains without vegetation until sowing. This process is called laying fallow. The cereals are planted from October to mid November to make use of autumn precipitation for germination. Spring is the main growing season and mature cereals are harvested from June to early July before the onset of the hot, dry months.

2. Fallow land (traditional land use or short-term abandonment)

In a rainfed cereal system, fallow land is a traditional part of the cereal rotation system. During fallow cycles, land remains unseeded for 2, 3 or more years to enhance soil fertility and soil moisture availability for subsequent crops. No chemical fertilizers or manures are used, and the plant residue is kept in the fields. Fallow lands are usually used as grazing land in traditional land use agropastoral herding practices in the territory.

3. Shrub land (long-term abandonment)

When arable land is abandoned, a process of plant colonisation begins. This is a very complex process in which ecological conditions (both physical and biotic factors), human activity (the agricultural history of the fields' as well subsequent management, namely grazing, fire, clearing, etc.) and time interact. Before shrubby species, mainly *Cytisus spp.,* proliferate, abandoned fields in central inland Portugal are invaded by herbaceous plants during the first years of abandonment. It can take more than 15-20 years for shrub land with a high percentage of ground cover to develop. Due to the accumulation of biomass in abandoned fields after recolonisation, there has been an increase in forest fires.

4. Recovering oak (very long-term abandonment)

The Pyrenean oak (*Quercus pyrenaica* willd.) is the autochthonous species in this area. Human activities over the centuries have led to considerable deterioration of the native arboreal vegetation characteristic of the region. The restoration of native vegetation is a very long process, disturbed by the regular occurrence of forest fires.

5. Afforested land (conversion of arable land to forest)

The main aim of Afforestation Regulation 2080/92 (Community Aid Scheme for Forestry Measures in Agriculture) was to reduce agricultural surpluses, but the EU also hoped that it would 'enhance forest resources'; 'provide greater ecological balance in countryside management'; and 'combat the greenhouse effect". The CAP measures for afforestation of marginal fields promote the use of a wide range of native species; however the main species selected in the area studied was *Pinus pinaster*. In Portugal, soil preparation before planting, often carried out by public works companies, involves the use of heavy machinery and deep ploughing techniques.

6. Pastureland (conversion of arable land into pasture - extensification of land use)

Recent EU agri-environmental measures support the maintenance of natural pastures or extensive cultivation of fodder crops (without deep ploughing and the use of fertilisers) and the livestock unit subsidy supports the maintenance of livestock. The study area was used for grazing cattle and the unit head per hectare was lower than 1. This value has been classified as light to moderate grazing (Rauzi & Smith, 1973; Van Haveren, 1983).

A total of 26 x 50m^2 plots were created. In each plot, the percentage of plant cover (lichens + mosses, herbaceous + shrub canopy, litter cover and bare soil) were estimated at the end of the dry and wet seasons. The height of the vegetation was also determined (in cm). Two soil samples (0-10 cm) were collected and certain characteristics (grain size distribution, bulk density, soil organic matter, etc.) were determined. A Coulter LS Particle Size Analyzer was used for grain size analysis for fractions of < 2 mm. Dry bulk density and porosity were measured using the cylinder method. Soil resistance was assessed through the use of a pocket penetrometer. Soil moisture was determined by the gravimetric method. Organic matter content was determined by the Tinsley method (1950). Soil water repellency was measured using the Ethanol Method (MED), at the suggestion of Doerr et al. (1998). The ethanol concentrations used in this study area were 0, 1, 3, 5, 8.5, 13, 18, 24 and 36%, representing liquid surface tension intervals of approximately 5 dynes/cm (Coelho et al., 2005). A zero value corresponds to hydrophilic (or wettable) soil and 36% to extremely water repellent soils. These tests were carried out before the rainfall simulations.

A rainfall simulator similar to the one described and tested by Cerdà et al. (1997) was used to evaluate the main hydrological and erosional characteristics of the soil[1]. It consists of a springlink device placed 2 m above the soil. A small 0.24 m^2 round plot is inserted carefully into the soil (Fig. 3). Rainfall simulations have a duration of 60 minutes and intensities of around 53-55 mm h^{-1}. Tests were carried out over two years (2005 and 2006) under different plant cover and soil moisture conditions. Tests were carried out in August of 2005 and 2006, when there was a severe drought due to very low precipitation in the preceding three months (10 mm and 45 mm, respectively) and in April and November of 2006 after a very intense period of natural rainfall (160 mm and 300 mm, respectively, during the preceding months). The average monthly temperatures also differed, ranging

[1] It is important to note that although rainfall simulation tests on small surfaces are used worldwide, their results should only be considered for comparative purposes, especially in the case of sediment concentration (Lasanta et al., 2000; Pardini et al., 2002). In fact, measurements on experimental plots are acceptable only for comparative purposes, that is, to assess the amount of overland flow and erosion in different environments and land use types. They cannot be accepted as absolute coefficients or rates.

from 10ºC and 13ºC during the wet season experiments to 21ºC and 22.5ºC in the dry season. The slope gradient varied from 0 to 20%. The number of simulations for each land use type varied from 4 to 10. Time to runoff (number of minutes between the beginning of simulated rainfall and runoff), runoff coefficient (rates for the relationship between rainfall intensity and runoff, in %) and total soil loss (in g m^{-2}) were the evaluated parameters. Water and sediment samples were taken continuously (every 2 minutes) from the beginning of runoff.

Fig. 3. Example of the plot used in the rainfall simulations (shrub and pastureland)

To understand the factors influencing runoff generation, the detachment of sediments from the plot and their removal to the outlet, explorative data analysis, correlation analysis and Principal Component Analyses (PCA) were performed using the SPSS 17.0 statistical package. One-way analysis of variance (ANOVA) and the Waller-Duncan multiple comparison procedure were performed on each soil property layer and for runoff and soil erosion to test whether the changes in land use and cover were statistically significant (p-value <0.05). The *Spearman-Rho* correlation coefficient (Rs) was selected to estimate the correlation between the quantitative attributes of the soil surface and runoff and sediment production. This rank-correlation method is considered robust against outliers and non-normal distribution of data.

Principal components analysis is an ordination method, used to simplify data by reducing the number of variables. The PCA procedure generates indices called principal components, which are linear combinations of the original variables. The most efficient data description and reduction are obtained when the variables are highly correlated.

4. Results

4.1 Soil cover

Results for plant cover for the different types of land use and vegetal covers are summarised in Table 1. The percentage of plant cover is clearly related to seasonal changes in vegetation. The lowest soil cover percentages were recorded in late summer. Conversely, the highest values were registered for the soils with the highest moisture content, peaking in the autumn and spring. These differences were mainly due to the variations registered for the density of grass cover, lichens and mosses, which dry up in the summer season and grow in the winter and spring. The existence of a marked seasonal dynamic due to the predominance of annual vegetation generated significant cycles and temporal differences, both for the protection of the soil against erosion and evapotranspiration, and for the incorporation of organic matter and, obviously, primary production.

Land use types/covers	Lichens & mosses	Herbs & shrubs	Litter cover	Total vegetation cover
Dry, hot season				
Ploughed land	2.0	3.0	0.0	5.0
Cereal crop	a	a	a	a
Fallow land	3.0	20.0	10.0	33.0
Shrub land	4.0	60.0	20.0	84.0
Recovering oak	1.5	2.5	90.0	94.0
Afforested land	0	3.0	2.0	5.0
Pastureland	2.5	2.5	65.0	70.0
Mean	2.7	15.2	31.2	41.6
Wet, cold season				
Ploughed land	9.5	2.0	0.0	11.5
Cereal crop	15.0	56.0	0.0	71.0
Fallow land	32.5	30.0	5.0	67.5
Shrub land	14.0	68.0	10.5	92.5
Recovering oak	3.5	3.0	92.0	98.5
Afforested land	13.5	1.5	0.0	15.0
Pastureland	22.5	69.0	5.0	96.5
Mean	15.8	32.8	16.1	64.6

a. Not available in this season of the year.

Table 1. Plant cover (%) per season for the different land use types/cover monitored

The results demonstrate that the highest surface cover was recorded in wood plots, with figures exceeding 90%. Old abandoned fields with recovering oaks showed a very homogeneous yearly soil cover related, in particular, to the predominance of litter cover. In the shrubland, the soil cover of grass, lichens and mosses explained the differences observed between the dry and wet seasons, with values between 84 and more than 92%. In fact, during the different stages of vegetation succession, the development of soil cover, mainly the herbaceous, shrub and litter cover, depends on the length of time the land has been abandoned and the activities developed after cropland abandonment.

The soil cover of recently abandoned fields increased around 30%between the dry and wet periods, mainly due to the development of lichens, mosses and grass. The pastureland shows a similar behaviour, with an increase by more than 20% between dry, hot and wet, cold season.

In contrast, the ploughed and afforested land revealed average annual values of less than 15%. As the cereal (mainly rye) is planted in the end of September or beginning of October, the crop is covering the ground before winter and continues to grow in the spring. Therefore the percentage of soil cover during the monitored wet season was high.

4.2 Soil characteristics

Table 2 summarizes the physico-chemical properties of soils for the different types of land use and vegetal covers. There were no significant differences in particle size distribution for the top 10 cm layer among the land cover types. A sandy loam texture was found in all the soils studied, in line with the same parent material on which they lie. In this layer, the soils revealed a very high percentage of sand fractions, over 70% of the total, and a low silt and clay fraction. In general, a sandy, coarse-textured soil drains easily and quickly after rain but has a lower moisture-retention capacity and a lower nutrient-retention capacity. Unlike texture, there was a significant difference in bulk density (g cm^{-3}) among land covers (p-value <0.001). The lowest values were recorded for the cereal crop and arable land afforested with *Pinus pinaster*, as a consequence of ploughing up the top layer for cereal cultivation, tree planting and the removal of ground cover to avoid forest fires.

Conversely, the highest values for bulk density, which correspond to the lowest porosity percentages, were registered in grazing plots and fallow land or short-term abandoned land. Soil bulk density is a more direct measure of soil compaction (Roberson, 1996) and perhaps the greatest impact of grazing consists of changes to the soil structure due to compaction (Roberson, 1996; Wood, 2001). In fact, the intense and continual pressure from moving livestock easily compacts soils, particularly when they are wet and more susceptible to compaction (Brady, 1984; Warren et al., 1986). Firestone (1995), for example, observed a 13% increase in the bulk density of grazed soils under oaks in California. Orr (1960) measured an increase of up to 20% in bulk density in the top 4 inches of grazed South Dakota steam bottom soil when compared with exclosures. Compaction is a strong direct effect of force which leads to the indirect effect of reduced infiltration and the resulting force of increased overland flow, which in turn leads to increased erosion (Trimble & Mendel, 1995). Extension of the abandonment stage and the expansion of shrub and wood communities tend to reduce soil bulk density.

All the soils were very low in organic matter. In the soils with cereal crops and in fallow land the organic matter content was around 0.50%. Despite the higher organic matter obtained for afforested and grazed land, there were still no significant differences between these four land uses. Soil erodibility in all land use types was expected to be high because of the sandy soil texture and low organic matter content. Vegetation restoration after abandonment, involving the development of shrub and tree cover, seems to enhance the organic matter within the upper layer of the soil. These changes in soil surface conditions are related to the greater contribution to organic matter provided by the leaves and roots of both the annual and perennial species of these vegetal communities.

	Cereal crop	Fallow land	Shrub land	Recovering oak	Afforested land	Pasture land	ANOVA
Texture, % (0-20 cm)							
Sand	74.18±4.17	76.70±1.95	71.96±5.32	69.67±4.18	71.11±3.34	72.04±3.34	ns
Silt	20.99±3.14	19.01±1.47	22.50±4.88	25.35±4.22	24.02±33.15	22.77±4.39	ns
Clay	4.92±1.09	4.30±0.65	5.48±1.56	6.48±1.45	4.88±0.49	5.19±1.43	ns
Soil bulk density, g cm^{-3} (0-10 cm)	0.85±0.13[a]	1.23±0.11[c]	1.04±0.16[b]	0.91±0.16[ab]	0.81±0.06[a]	1.22±0.07[c]	**
Soil resistance to penetration, g cm^{-2}	0.77±0.30[a]	2.86±1.11[b]	2.22±1.24[b]	1.88±0.99[b]	0.60±0.22[a]	3.98±0.59[c]	**
Organic matter, % (0-10 cm)	0.55±0.27[a]	0.53 ±0.31[a]	1.38±0.71[b]	1.46±0.23[b]	0.84±0.22[a]	0.73±0.26[a]	**
Soil moisture content, % (0-10cm)							
Dry season	2.18±1.32[ab]	1.20±0.98[a]	0.80±0.22[a]	3.63±1.10[bc]	3.70±1.20[bc]	4.00±1.83[c]	**
Wet season	11.1±1.81[a]	14.53±3.79[ab]	13.84±3.08[ab]	18.13±5.48[b]	13.64±1.25[ab]	18.00±3.91[b]	*
Water repellency, %	0.65±0.27[a]	2.65±1.98[a]	13.25±3.45[c]	19.75±2.36[d]	1.04±1.18[a]	6.24±0.91[b]	**

Significance level notations are: ** p<0.01, * p<0.05 level (1-tailed), ns: not significant; Means within a column followed by different letters differ at the 0.05 probability level according to Waller-Duncan test; a: not available in this season.

Degree of hydrophobocity (% of ethanol): 0- hydrofilic; ≤5- slightly hydrophobic; ≤13- strongly hydrophobic; ≤ 24- severely hydrophobic

Table 2. Physical and chemical properties of soils (mean and ± standard deviation) in different land use types/covers

The amount of water in the soil changed significantly from one season to another. On average, the soil water content in the upper 10 cm rose from 0.8% during the dry period to 18.1 % during the wet period. The highest values were detected in the top layer of the recovering oak and pasture land plots. Under very wet conditions, all the soils were hydrophilic, which agrees with the finding of Coelho et al. (2005). Under dry conditions, the shrubland and *Quercus pyrenaica* woods showed water repellency, which was more pronounced in the tree formation. This may be due to the higher levels of litter cover and organic matter in the soil that were recorded. The results for soil water repellency show a spatial discontinuity in shrubland, linked to the spatial variability of the land cover. The substances responsible for the soil's ability to repel water are related to the organic compounds derived from living or decomposing plants (Doerr et al., 2000). In fact, the relationship between these two variables and water repellency are very high (Rs= 0.782 for the percentage of soil cover with litter and Rs= 0. 674 for the percentage of organic matter content). These results are similar to those referred to in literature on the subject, which considers that there is a strong correlation between soil water repellency and organic matter and litter cover (Coelho et al., 2005; Doerr and Moody, 2004).

4.3 Hydrogeomorphic response

Table 3 summarizes the statistical analysis for the hydrological and sedimentological parameters in the different types of land use during the dry and wet periods. The results from the preceding ANOVA demonstrate significant statistical differences (P <0.000) for land use and soil covers, which means that variables have an important effect on runoff and soil loss amounts regardless of the season.

With high intensity rainfall, the afforested and laying fallow land produce the highest runoff and sediment yield coefficient, with an annual average of 64% and 45% of the rainfall and 75 g m^{-2} h^{-1} and 43 g m^{-2} h^{-1}, respectively. These results show that the soil in these plots, which has very poor plant cover and low infiltration, encourages overland flow and soil erosion. Ploughing soils for cereal crop or soil operations for forestation procedures (that involve the use of heavy machinery and deep ploughing techniques) have a direct and influential effect on soil losses, essentially increasing them. Even in the first years of tree development, especially when it is necessary to control vegetation cover to prevent forest fires and competition from other species, the soil surface remains unprotected for extended periods of the year, thus accelerating water and sediment flows. In fact, ploughing completely destroys the vegetation and litter cover, breaks up the soil structure and reduces the number of obstacles to overland flow, leading to a more efficient transport of sediments. This hydrological response is also affected by the lack of macroporosities, meaning that only a little water infiltrates into the soil matrix. The soils also offered weak resistance to penetration (Nunes et al., 2010).

The growth of cereals results in increased soil cover, which explains the higher runoff time and lower overland flow and sediment yields. Crops protect the soil surface from splash and surface sealing. In the initial growth stage, the area covered with plants is small but as the crop matures at the end of winter and early spring it plays an increasing role in protecting the soil surface (Nunes & Coelho, 2007). The average recorded values during the wet period were twice lower than the values recorded for ploughed land without cereal crops. In fact, the effectiveness of any crop, management system or protective cover depends in particular on how much protection may be available at different times of the year.

Recently abandoned fields or fallow land present the highest variation in overland flow response, with values ranging from 74% to 12% of the total rainfall. The soil erosion rate varies between 68 g m^{-2} h^{-1} and 3 g m^{-2} h^{-1}. A detailed analysis shows that rainfall simulations performed during the dry period present overland flow and sediment yields that are significantly higher than those which occur during the wet season. The reason for the high overland flow and therefore the effect on erosion yields may be ascribed to the low plant cover density after a long, hot, dry season, and the presence of a microcrust (2-3 mm deep) in most of the plots (Nunes, 2007). This crust considerably reduces the infiltration capacity of the topsoil and its hydraulic conductivity also tends to decrease over time (Seeger & Ries, 2001), even in sandy soils (Kidron & Yair, 2001). The increased vegetation cover and destruction of the microcrust layer in wet periods reduces the runoff percentage and enhances infiltration capacity. At the same time, it also reduces splash and sediment detachment, and therefore the erosion rates. A similar intra-annual behaviour was observed under grazing plots, however a delay in runoff, an increase in soil infiltration capacity and a reduction in soil erodibility were recorded. Soil loss from the pasture plots was lower, approximately 4 times less than that of the fallow land or recently abandoned fields.

	Time to runoff		Runoff (%)			Erosion (g m^{-2} h^{-1})		
Land use/ plant cover		(min.)*	Dry season	Wet season	Average	Dry season	Wet season	Average
Ploughed land n=5+4 (100%)	Max. Med. Min. S.D	34.00 9.30 5.15 9.36	49.00 30.30 8.00 14.25	67.70 59.83 54.00 5.30	45.07	56.36 28.55 3.40 18.20	84.86 57.66 43.68 16.32	43.10
Cereal crop n=4 (100%)	Max. Med. Min. S.D	24.30 16.37 9.20 6.57	a. a. a.	41.00 20.33 8.00 12.35	20.33	a. a. a.	34.70 18.13 4.20 12.01	18.13
Fallow land n=6+4 (100%)	Max. Med. Min. S.D	23.05 9.55 1.00 8.23	74.00 43.83 14.00 22.54	24,00 16.90 12.10 4.53	30.34	67.56 21.48 2.96 22.46	9.13 5.92 2.90 2.28	13.70
Shrub land n=4+4 (62.5%)	Max. Med. Min. S.D	20.00 11.23 4.30 6.00	14.00 7.83 0.00 5.02	3.70 1.80 0.00 1.78	4.80	0.90 0.38 0.00 0.33	0.24 0.06 0.00 0.10	0.22
Recovering oak n=4+4 (12.5%)	Max. Med. Min. S.D	38.00 . . .	2.00 0.50 0.00 0.87	0.00 0.00 0.00 0.00	0.25	0.10 0.03 0.00 0.04	0.00 0.00 0.00 0.00	0.01
Afforested land n=5+4 (100%)	Max. Med. Min. S.D	5.00 3.58 2.10 1.31	71.00 61.00 47.60 8.57	70.00 66.20 63.20 3.49	63.60	145.50 97.40 65.80 33.10	87.00 52.20 36.80 21.82	74.80
Pastureland n=4+4 (87.5%)	Max. Med. Min. S.D	23.00 11.00 3.50 7.00	41.80 32.50 21.80 8.96	25.90 14.50 0.00 12.15	23.50	8.10 4.10 1.30 2.82	4.80 2.40 0.00 1.98	3.25
Med. S. D. ANOVA *(p-value)*		11.40 9.10 0.000	29.33 24.15 0.000	25.65 41.44 0.000	26.84 23.50 0.000	25.32 26.08 0.000	19.48 27.11 0.000	21.89 33.77 0.000

n: number of rainfalls simulations performed under dry and wet season. *(100%)*: Percentage of rainfall simulations with runoff. *: Calculated values based on rainfall simulations with runoff. a: Not available in this season of the year.

Table 3. Overland flow and erosion yields measured during rainfall experiments

Measurements performed on recovering *Quercus pyrenaica* revealed very low or no overland flow in both dry and wet seasons. In these plots, the infiltration capacity exceeds the intensity and quantity of rainfall simulations; both soil erosion and surface runoff are very well controlled, ensuring soil conservation and even improving some of the soil characteristics (organic matter content, porosity, exchange capacity and nitrogen content). These results also suggest that water repellency does not play an important role in overland flow generation, mainly due to the high litter cover, but additionally as a result of the patchy and discontinuous nature of soil water repellency at plot level, as suggested by Ferreira et al. (2005). In fact, since water repellency is a patchy soil surface phenomenon, the existence of hydrophilic patches and macropores that allow water to infiltrate the soil will considerably reduce superficial water transport. Moreover, macroporosities created by roots and soil animals allow for infiltration into the deeper layer, despite the existence of strong water repellency in the top layer of the soils. Deep and interconnected macropores may cause rapid flow to the soil without significant water recharge into the matrix (Seeger & Ries, 2001).

Shrubland presents significantly higher overland flow and erosion rates during the dry summer period than in the wet season. These results can be related to an increase in soil water repellency after a long period without rainfall. In fact, a dual trend can be described (Fig. 4): first, runoff increases slightly from the beginning and a runoff discharge peak was detected between 15-20 minutes of the experiment. This behaviour could be due to the hydrophobic character of the soil surface. After that, infiltration increases, due to a decrease in soil water repellency after wetting. The hydrophobic substances act as a cement that binds the soil mineral particles together (Coelho et al., 2005) but has a tendency to attenuate in contact with water. Similar results, with a progressive decrease in runoff, have been observed, for example by Contreras López and Solé-Benet (2003), in semi-arid Mediterranean soil (SE Spain). Jordán et al. (2008) also detected a runoff rate peak after 20 minutes in dry conditions in a Mediterranean climate. Subsequently, the overland flow declined slightly. Another reason which explains why the highest runoff and erosion amounts occur during the dry season is associated with the disappearance of the herbaceous cover, which implies a higher percentage of bare soil and an increase in soil compaction.

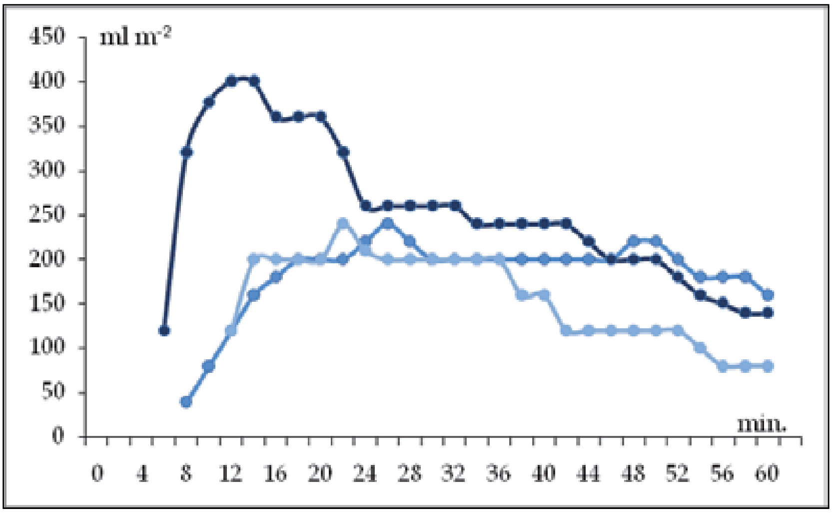

Fig. 4. Shrubland runoff curves in the dry period.

4.4 Relationship between variables (statistical analysis)

To determine which variables have more influence on runoff and sediment loss, Spearman correlations and principal components analysis were carried out. Analysing the relationship between all the data (Table 4), significant correlation coefficients between the characteristics of the plot and runoff and sediment production were found, in both the wet and dry period. The results obtained show that, annually, total plant cover is the main factor which explains runoff generation (Rs= -0.824) and the movement of sediments (Rs= -0.913). This concords with other studies (Grove & Rackham, 2001; Kosmas et al., 2000; Lattanzi & Meyer, 1974; Trimble, 1990) which found a (negative) linear relationship between the total volume of overland flow and the mass per unit of plant cover. In fact, plant cover decreases the kinetic energy of the rain that is released and dissipated to the soil surface, reducing the amount of detachment and, hence, the erosion that can occur (Greene & Hairsine, 2004). As a result, the increase in soil cover corresponds to an increase in the range of conditions under which the soil surface is stable and therefore less exposed to crust or seal. Consequently, an increase in plant cover during a wet season decreases splash and sediment detachment and improves the negative correlation coefficients (Rs: -0.836 for overland flow and Rs= -0.940 for erosion rates).

Vegetation type is also important, with litter cover offering more protection against overland flow and water erosion, especially under dry conditions. Several studies have analysed the influence of various forms of cover on the formation of crust and seal (Greene & Hairsine, 2004). This cover can be a canopy cover of vegetation or contact covers, such as litter cover, mulch or cryptogams (mosses, lichens, etc.), which form in close association with the soil surface. Vegetal litter cover absorbs some of the energy of raindrops and leads to an exponential decrease in splash erosion (Casermeiro et al., 2004).

	Year (dry + wet period) n= 56		Dry period n= 28		Wet period n= 28	
	Runoff (%)	Erosion (g m^{-2} h^{-1})	Runoff (%)	Erosion (g m^{-2} h^{-1})	Runoff (%)	Erosion (g m^{-2} h^{-1})
Slope (%)	ns	-0.280*	ns	ns	ns	ns
Total plant cover (%)	-0.824**	-0.913**	-0.726**	-0.882**	-0.836**	-0.940**
Lichens + Mosses (%)	ns	ns	ns	ns	ns	ns
Herbs+ shrubs (%)	ns	ns	ns	ns	ns	-0.375*
Litter cover (%)	-0.675**	-0.782**	-0.681**	-0.795**	-0.711**	-0.795**
Height of vegetation (cm)	-0.369**	-0.395**	ns	-0.386*	-0.588**	-0.541**
Antecedent soil moisture (%)	-0.360**	-0.307*	ns	ns	ns	ns
Resistance to penetration(g m^{-2})	ns	-0.369**	ns	-0.393*	-0.444*	-0.580**
Total of porosity (%)	0.230*	0.357**	ns	ns	0.557**	0.599**
Water repellency (%)	ns	-0.391**	-0.619**	-0.817**	a	a
Soil organic matter (%)	-0.694**	-0.708**	-0.731**	-0.676**	-0.450*	-0.502**
Runoff (%)	.	0.917**	.	0.869**	.	0.948**

Significance level notations are: ** p<0.01, * p<0.05 level (1-tailed), ns: not significant, a: not available in this season.

Table 4. Spearman-rho correlations between runoff and erosion and some characteristics of the soils.

The role of organic matter in stabilizing aggregates against breakdown by water seems to be evident. In all the experiments, the organic matter content was negatively related to runoff and soil erosion (Rs: -0.694 and Rs: -0.708, respectively) (Table 4). Nevertheless, a more detailed analysis shows that after a hot, dry summer the organic matter in the top layer was more closely related to runoff (Rs: -0.731). In the wettest season, this variable seems to be less important in soil runoff and erosion rates, as the relationship has a lower significance (Rs: -0.450 for runoff and Rs: -0.502 for soil erosion). During this period, others variables show a highly significant correlation with runoff and sediment yield, such as total porosity (Rs: 0.557; Rs: 0.599) and resistance to penetration (Rs= -0.444; Rs= -0.580).

The high negative correlation between water repellency and runoff (Rs= -0.619) and soil erosion (Rs: -0.817) during the driest season inversely corresponds to what has been found in other studies, particularly at plot level, where a clear relationship between hydrophobicity and overland flow was detected (Doerr & Moody, 2004; Doerr et al., 2003; Ferreira et al., 2000). As Doerr & Moody (2004) state, apart from the spatial variability of repellent soil itself, additional spatially variable factors may influence the hydrological effects of water repellency: the variability of macropores (root channels, animal burrows) will affect infiltration and water movement in repellent terrain.

Although slope gradient has been identified as a very important factor affecting runoff generation and soil erosion intensity (Fox & Rorke, 2000; Morgan, 1986), our analysis shows that its influence on runoff and erosion during the two contrasting seasons is insignificant in terms of soil erodibility.

A positive correlation was found between eroded sediments and runoff generation in all the experiments (in dry and wet periods), despite the closer relationship obtained for the wet season (Rs: 0.948) as opposed to dry season experiments (Rs: 0.869).

The results of principal components analysis (Tables 5 and 6), which covered 77.6% of the variance in the first four axes, are determined for the first two as 53.4% of the total variability. The results therefore imply that at plot level quantitative data on surface characteristics helps to explain the processes. Axis 1 shows the contrast between the organic supply to the soil (soil cover, litter cover, soil organic matter) and erosion (surface runoff and the movement of sediment). Component 2 describes the positive plant cover relationship between herbaceous shrub cover and vegetation height. The data indicate that, regardless of the type of vegetation, the factors that offer most protection against erosion are total plant cover and soil litter. This concords with the data proposed by Elwell & Stocking (1976) and Casermeiro et al. (2004). The supply of organic carbon to the soil is also related to the role of vegetation. Soils with a higher organic carbon content appear to offer good protection against erosion. Slopes appear to be less important than plant cover in the generation of surface runoff and, therefore, in sediment transport.

Component number	Eigenvalue	Percent of variance	Cumulative percentage
1	4.361	36.342	36.342
2	2.044	17.033	53.375
3	1.487	12.390	65.766
4	1.417	11.808	77.574

Extraction Method: Principal Component Analysis.

Table 5. Total Variance Explained

Axis 3 shows both the expected opposition between soil porosity and resistance to soil penetration, and its positive relationship to the existence of lichens and mosses, which means less disturbance of the soil surface. Obviously, antecedent soil moisture does not favour water repellency, hence the opposition shown in Axis 4. These two components explain about 24 % of the total variance observed.

Soil parameters	Component 1	Component 2	Component 3	Component 4
Slope (%)	0.254	0.512	8.65E-02	-5.93E-02
Soil cover (%)	0.795	0.315	-0.411	-2.86E-02
Litter cover (%)	0.874	-0.265	-0.616	-0.198
Herbs+ shrubs (%)	-0.134	0.854	-0.321	-9.88E-02
Height of vegetation (cm)	7.16E-02	0.892	7.35E-03	-3.440E-02
Antecedent soil moisture (%)	0.399	8.16E-02	-0.113	-0.838
Resistance to penetration (g m^{-2})	6.65E-02	-1.00E-01	-0.873	4.72E-02
Total of porosity (%)	-8.79E-02	-0.118	0.816	7.13E-02
Water repellency (%)	0.405	3.60E-02	-7.87E-02	-0.833
Soil organic matter (%)	0.859	5.99E-02	9.41E-02	-9.09E-02
Runoff (%)	-0.757	-0.331	0.297	4.78E-02
Soil erosion (g m^{-2} h^{-1})	-0.556	-0.288	0.595	-1.73E-02

Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization.

Table 6. Results of Rotated Component Matrix

5. Discussion

As pointed out by several authors (García-Ruiz, 2010; Kosmas et al., 1997; Mitchell, 1990), land use and soil cover are considered the most important factors affecting the intensity and frequency of overland flow and surface wash erosion. The results obtained agree with those observed by different authors in varied environments, who consider that runoff and sediment yield decrease with an increase in soil cover with vegetation (Bochet et al., 1998; De Ploey, 1989; Durán Zuazo et al., 2006; Elwell & Stocking, 1976; Francis & Thornes 1990; Roxo 1994). As can be seen in Figure 5, increasing vegetation cover leads to an exponential decrease in runoff, but only when this exceeds a threshold value of over 40%. Correspondingly, similar behaviour can be observed with regard to the relationship between sediment loss and vegetation cover.

However, wide variations in the percentage of plant cover were presented as critical between studies. Studies carried out in natural Mediterranean environments have shown that when vegetation cover drops below 30% soil erosion and runoff increase dramatically (Francis & Thornes, 1990; Gimeno-García et al., 2007). Thornes (1988) suggests that a value of 40% vegetation cover is considered critical, below which accelerated erosion dominates on sloping land. If the vegetation cover covers an area of more than 40%, it will act as a resilience or protective factor for the land. Molinillo et al. (1997) observed an increase in runoff and soil erosion in up to 60% shrub-cover and only above this value a reduction in runoff and erosion processes. Sauer & Ries (2008) consider that only plant cover exceeding 60% can significantly reduce soil erosion in semi-arid environments.

Land use and the type of management applied to each site explain, to a large extent, the variability in annual plant cover and, therefore, the occurrence of overland flow and soil erosion processes (De Luna et al., 2000; Francia Martínez et al., 2006; Gómez et al., 2004). Annually, as it involves mobilisation of the top layer (laying fallow and afforested land), ploughed soil erodes more easily and causes great soil loss. Cereal growth, mainly when it offers a good vegetal protection for the surface of the soil, enhances infiltration and reduces erosion rates. However, the results for soil erosion were greater in comparison with recent abandonment and were one hundred times greater if compared to land cover after very-long abandonment (Table 7). These results also enable us to conclude that traditional cereal cultivation, in particular ploughing in preparation for cereal crops, is a very negative land management practice due to the high runoff and water erosion response. Organic matter content, probably the most important component of soil quality, is also strongly influenced and registered very low figures of less than 1% for arable land. A limit of 1.7 per cent of soil organic matter content is considered an indicator of the pre-desertification stage (Pardini et al., 2002). The gradual depletion of nutrients, which reduces soil fertility and creates a high level of soil degradation, are further reasons for abandoning agricultural plots in the changing cultivation process (Paniagua et al., 1999). Planting trees, according the CAP measures for afforestation of marginal fields, with deep ploughing and bare soil has resulted in very high erosion rates during both rainfall seasons, as observed in other agro-ecosystems in Mediterranean Europe (Shakesby et al., 2002; Ternan et al., 1997; Van-Camp et al., 2004).

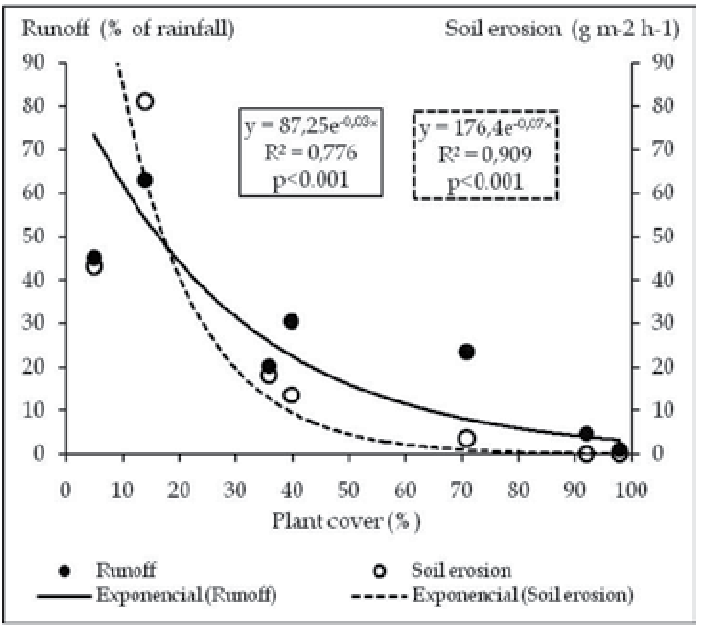

Fig. 5. Relationship between runoff and soil erosion and average percentage of plant cover

However, in large parts of marginal areas of the country farmland abandonment has enhanced plant colonisation, replacing historically highly erosive cereal fields with dense shrub and woodland communities. Herbaceous cover, the first successional stage in vegetation recuperation after land abandonment, seems not to enhance soil fertility after a crop cycle, but positively influences runoff and sediment yield, in addition to the higher values presented after a hot, dry period. These results stress the importance of non-ploughing as a soil protection measure.

When a permanently vegetated cover is dominant, as a result of a long plant succession, with shrub communities and oak-trees, even in recuperation, both soil erosion and surface runoff are very well controlled. Trees and shrub cover also ensure soil conservation and improve some of the soil characteristics, mainly the organic matter content, which registered a significant increase (Table 7). This hydrological and erosional behaviour, together with the soil properties, is closely interrelated and well understood in terms of the dynamics of plant and litter cycling. Vegetation and litter reduces direct raindrop impact on the soil, prevents the formation of mechanical crusts, enhances infiltration capacity and reduces soil erodibility (Nunes et al., 2010). In these soils, long-term spatially structured vegetation patterns play an important role in addition to cover, by increasing the stability and resilience of the system (Boer & Puigdefabregas, 2005; Cammeraat & Imeson, 1999). In general, our data agrees with other results obtained for the Mediterranean basin, in which land abandonment followed by natural vegetation regeneration is improving soil properties such as organic matter content, soil structure and infiltration rates, resulting in more effective protection against soil erosion (Cammeraat & Imeson, 1999; Francis & Thornes, 1990; Grove & Rackham, 2001; Kosmas et al., 2000; Morgan, 1986; Trimble, 1990).

Benefits compared to ploughing land			
Vegetation cover/stages of abandonment	Organic matter content (%)	Runoff (mm h^{-1})	Sediment loss (g m^{-2} h^{-1})
Fallow land or short-term abandonment	Not detected	-32.7%	-68.2%
Shrub land or long-term abandonment	+247.3%	-89.0%	-99.5%
Recovering oak or very long-term abandonment	+265.5%	-99.5%	-99.9%
Afforested land	+52.3%	+41.0%	+73.5%
Pastureland	+32.7%	-47.9%	-92.5%
Benefits compared to cereal crop			
Fallow land or short-term abandonment	Not detected	+49.2%	-24.4%
Shrub land or long-term abandonment	+247.3%	-76.4%	-98.8%
Recovering oak or very long-term abandonment	+265.5%	-98.8%	-99.9%
Afforested land	+52.3%	+212.8%	+312.6%
Pastureland	+32.7%	+15.6%	-82.1%

Table 7. Benefits detected in the comparison of cultivated land and the different vegetation cover/stages of abandonment.

Although abandoned land in humid and sub-humid regions self-regulates the development of natural vegetation (grass, weed, bushes, and later woodland) and normally does not need support except in the first years of abandonment, the cessation of traditional management practices, the creation of large homogeneous patches of vegetation and the accumulation of fuel due to fire exclusion policies are cited as some of the major causes of changes to the forest fire regime in Mediterranean Europe (Moreno, 1996). In fact, Portugal's burnt area has increased chiefly during the last three decades. This rising trend, although including some periods of lower burnt area, distinguishes Portugal from the other southern Member States with the highest burnt areas, particularly in the central and northern regions. It is commonly accepted that fire increases runoff and soil erosion (Benavides-Solorio & MacDonald, 2005; Cerdà & Doerr, 2005; Cerdà & Lasanta, 2005; Coelho et al., 2004; Ferreira et al., 2005, 2008; Shakesby et al., 1993, 1996, 2002). Increased erosion after forest fire stems primarily from the destruction of vegetation and changes in the soil physical and hydrologic properties that reduce infiltration rates and increase availability of loose sediment (Ferreira et al., 2005, 2008). The loss of vegetation and other ground cover due to wildfire reduces rainfall interception and attenuation, rainfall storage, and flow resistance (Martin & Moody, 2001). Rainfall-generated runoff therefore accelerates more quickly and less is retained as pounded water, resulting in reduced residence times and reduced total infiltration (Ferreira et al., 2008). In the Mediterranean basin, potential for post-fire soil erosion is very high as heavy autumn rainfalls commonly occur after summer wildfires.

Converting arable land into pasture can be positive, negative, or without impact depending on management practices. Several studies have evaluated how different grazing intensities affect both plant cover and water infiltration into the soil. These studies are consistent in showing that as grazing intensity is increased and soil cover is depleted, water infiltration declines and soil erosion increases (Rauzi & Smith, 1973). In fact, the direct impact of cattle hooves reshapes the land. Compaction is, perhaps, the strongest direct impact of force which leads to indirect consequences in terms of overland flow and soil erosion. Direct measurements of overland flow and soil loss rates from the pasture plots were more pronounced after the dry, hot season. During wet season, runoff and sediment yield decrease significantly.

Despite these negative effects, the conversion of arable land into extensive grassland had a strong, positive effect on surface runoff and erosion in the area monitored. A permanent plant cover of over 50%, in the form of vegetation or ground litter, provides a cushion between raindrops and the soil, preventing the "splash effect" or dislodging of soil particles by rain drops (Molinar et al., 2001). Research findings indicate a threshold at which removing the plant cover and volume have little effect on infiltration rates and soil protection. This threshold is generally about 50% of the current year's growth, which corresponds to the old adage of "take half and leave half" for sustainability (Wood, 2001).

The existence of marked seasonal dynamics related to the dominance of annual vegetation creates cycles and temporal differences in protecting the soil against geomorphic processes. At the end of the summer, with exception of ploughed land, the largest amount of runoff and sediment export from soils occurred, chiefly due to the greater erodibility of the soil surface after a warm, dry season and poor soil cover (Romero Díaz et al., 1999). The development of microcrusts in some plots encouraged runoff and, therefore, sediment transport. The water repellency observed in such soils (with shrub and tree species) after a long period without precipitation did not have a significant impact on overland flow generation and erosion rates. Soils with a higher organic matter content appear to offer good protection against runoff and soil erosion. This is provided by litter, from recovering *Quercus pyrenaica* and *Cytisus multiflorus*, for example.

As pointed out by Imeson (1990), the main characteristics affecting the vulnerability of the Mediterranean area to erosion are intense rainfall after a very dry summer. In fact, autumn is the most water erosive season as a consequence of the heaviest concentration of rainfall and rainfall erosivity (Nunes et al., 2011). Recent research into climate change in Portugal (the SIAM Project, Miranda et al., 2006) for the 21st century (including 3 greenhouse gas emission scenarios used by many global and two regional climate models), are homogeneous predicting a reduction in annual rainfall in mainland Portugal (within the range of 20 to 40% of the current value), as a result of a decline in the duration of the wet season. Predictions for temperature changes agree on an overall increase in the annual mean, with a much more pronounced maximum summer temperature particularly affecting inland areas of Portugal. This climatic trend will extend the long, dry, hot summers in the Mediterranean region and lead to more frequent and intense extreme weather events, which could increase the rates of erosion and the risk of desertification that is threatening substantial areas of Portugal (Nunes & Seixas, 2003; Nearing et al., 2005).

6. Conclusion

In Portugal, as well as in the Mediterranean countries, important land use and cover changes have occurred since the second half of the last century. The abandoning of traditional subsistence systems based on cereal cultivation, probably the most important change, has taken place mainly in the more disadvantaged areas where farming systems in general and livestock farms in particular are often operating close to the margins of sustainability. This was originally a consequence of the difficulties associated with adopting modern farming systems. Later, it was the result of the demographic exodus from these rural areas, and more recently it has been reinforced by the implementation of CAP measures. In several areas, cereal crop soils were neglected and a natural vegetation succession occurred, increasing plant recovery and establishing shrub and woodland areas. In other areas, the adoption of measures aimed at reducing intensive agricultural methods involved afforestation schemes and conversion to grazing land.

There are important differences in the hydrological and erosional functioning of the different land uses/cover types monitored. Shrub and woodland are considered better for soil and water conservation, producing less surface runoff and therefore less soil erosion. The results obtained also show a positive trend in organic matter content, highlighting the importance of vegetation in these very shallow soils with a low clay content in increasing structural stability and avoiding soil loss. The major threat to these ecosystems is associated with controlling the frequency of wildfires.

Conversely, cereal cultivation and tree planting accelerate runoff and soil erosion, which is attributed to soil tillage which loosens the soil and reduces anti-erodibility. Erosion and land degradation became a problem in Portugal when arable farming expanded into marginal areas over the decades. The poor water and soil protection provided by young pine is attributed to the poor ground coverage under the trees.

In fact, the amount of bare soil on a site is generally a good indicator of the soil's vulnerability to erosion and degradation. Good soil coverage is an essential element in soil conservation programmes. Vegetation protects the soil from eroding in various ways. Rainfall interception by the plant has two main consequences, the most important being that it reduces the erosive power of impacting raindrops. It also reduces the volume of water reaching the soil surface. Subsequently, soil erosion can be controlled by changing land use and increasing ground coverage, which was shown to be one of the basic approaches to controlling soil erosion in all land use types.

On the basis of the experiment results, pastureland should be encouraged, particularly for the degraded soils that are used to produce cereals in order to minimize the amount of soil loss by erosion, thus avoiding slumping and promoting stability. Accommodating pasture management with a weighted number of grazing animals per area unit and extending pasture rotation times could reduce soil erosion processes effectively and ongoing land degradation could be prevented according to the 'Directive of the European Parliament and of the Council Establishing a Framework for the Protection of Soil' (Commission of the European Communities, 2006). Additionally, is important to emphasise that extensive grazing is the main focus of landscape management in marginal areas of the Mediterranean region with very low population densities, only small resident communities, little mechanised agriculture and poor communications.

In addition to better pasture management, another possible consideration may be management of native shrub land and recovering oak. Land afforestation should be supported by a set of measures to minimise the impact of site preparation techniques, forest management and fire prevention on soils. Plough use as a tool in preparation of soils for sowing seeds in dry farming systems should be replaced in favour of other less pernicious tillage techniques.

However, in the study area, as well as in the majority of Portuguese rural areas, key problems remain and are complex to solve. They include: a) How to stop the demographic exodus that took place in the middle of the last century and continues nowadays? b) How to supply an appropriate income to attract young farmers to depopulated areas where the great majority of the population are elderly? c) How to improve farm structures that consist of small scattered plots? d) How to manage systems that favour soil conservation and combat land degradation but maintain economic viability? e) How to adjust Mediterranean agriculture to climate change scenarios for the 21st century?.

7. Acknowledgment

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5

Soil Erosion and Conservation Measures in Semiarid Ecosystems Affected by Wildfires

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1. Introduction

Fire is a factor of the first order in the interpretation of current ecosystem composition and landscape shape. Wildfires are a common phenomena dating back to the Earth's origins when they were caused by volcanic events or lightning. However, nowadays fires are more often caused by human interventions, accidental or deliberate, than by natural ones. In the European Mediterranean regions wildfires increases from 1960s aided by a general warming and drying trend, but driven primarily by socio-economic changes, including rural depopulation, land abandonment and afforestation with flammable species (Shakesby, 2011). Within that global Mediterranean region, semiarid areas have plant communities of sclerophyllous evergreen shrubs, rich in essences and with low plant water content, especially in dry seasons. These conditions facilitates the burning of these ecosystems.

Wildfires can be considered as a disturbance with a relatively severe temporary impact (Cerdà & Doerr, 2005). Their severity will depend on key factors such as the intensity and frequency of fire, but also on the the ecosystem components (vegetation, soil, rainfall, etc). The burning of plant cover and litter leaves the soil unprotected against rain impact. Also, immediately following a wildfire, a layer of ash and charred material typically covers the ground. It can increase or decrease the post-fire runoff and erosion response, depending upon the soil and ash properties and the ash thickness (Bodí et al., 2011). Soil loss after wildfire increases as long as there is no a minimal recovery of both plant cover and soil properties (Mataix et al., 2007). Although some strategies, such as plant resprouting, allow them to recover quickly, high fire frequency or soils with low quality can requier restoration strategies (Cerda & Robichaud, 2009); these aspects that will be discused in this chapter.

2. Erosion on contrasting soil types affected by fire

Soil loss after fire in different soil types and plant community structures were analyzed in the semi-arid central Ebro Basin (NE-Spain) after fire.

2.1 Methods

Soil loss after fire is affected by soil properties, plant community structure (i.e. seeders versus sprouters ratio) as well as fire and rainfall intensity. In this subchapter, we analyze these effects by means of two field methods: (i) sediment traps or Gerlach boxes and (ii) a rainfall simulator. Sediment traps give us a continuous measurement of soil erosion in microplots. A total of six Gerlach collectors (50 x 16 x 16cm) were installed under different vegetation covers and limited in area of influence with foil of a meter in length. Rainfall simulators give us a measurement of sheet erosion in burned microplots against a rain of given intensity (80 mm h^{-1}) in comparison to paired unburned areas (n=9). Experiments were carried out after fire for different soil units, such as Calcaric Regosol developed on Oligocene marls (calcareous soils) and Rendzic Phaeozem developed on colluvium (colluvial soils) as well as gypsiferous soils, classified as Haplic Gypsisol.

2.2 Results and discussion

Runoff and soil loss increased significantly after fire with exposure to strong rainfall (80 mm h^{-1}) in a Calcaric Regosol below a *Pinus halepensis* forest (Fig.1).

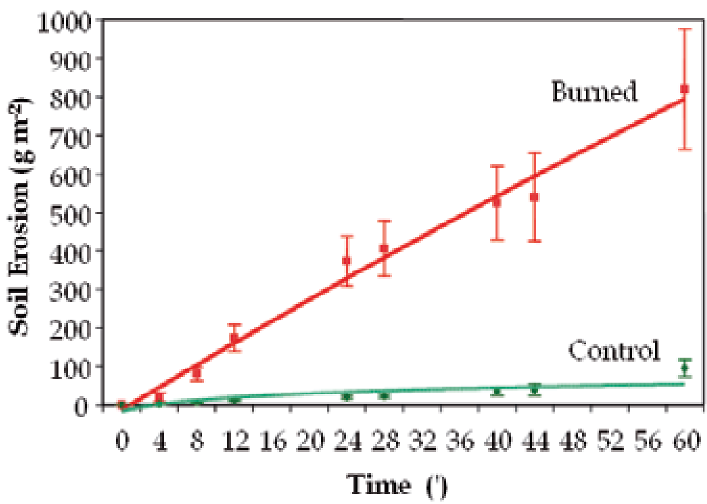

Fig. 1. Fire effects on soil erosión (g m^{-2}) in a Calcaric Regosol (rainfall simulations=9).

The increase in soil erosion and runoff after fire is related to the decrease of soil surface cover, as well as in the soil aggregate stability on the surface by heat effect (Badía & Martí, 2003). Also, the different soil characteristics generate different responses closely related to their parent material, thus the erosion of soils developed on marls is greater than those developed in gypsum and colluvium (Fig. 2).

This relates to the low infiltration of marly soils, as well as temporary surface alteration due to fire (Cerdà & Doerr, 2005; Giovannini et al., 1990). Gypsiferous soils, with a lower fuel availability to alter the soil surface, and calcareous colluvial soils with more organic matter, stony and well-structured, did not reveal many problems of sheet erosion. The influence of the parent material of burned soils is shown in Figure 2 where we see a different curve for each soil type tested and confirm that the differences in soil characteristics generate different responses. The variability of these and other results is due to the diversity of variables under field conditions and confirms that the differences in soil characteristics generate different responses (Badía & Martí, 2003a). A compilation of tests performed with rainfall simulators in similar semi-arid Mediterranean environments can be found in Table 1.

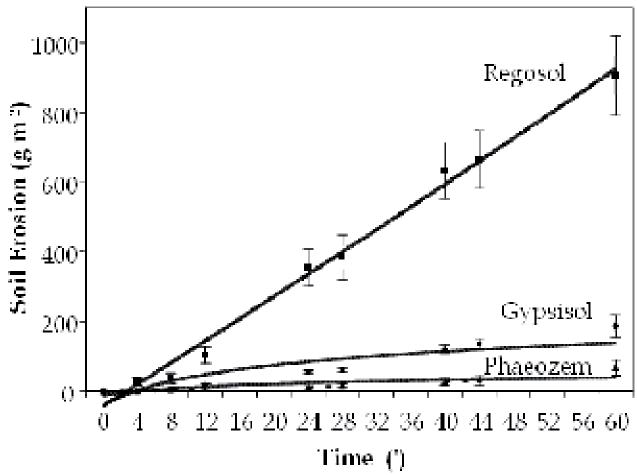

Fig. 2. Erosion (g m-2) of the three types of burned soils (n=9). Rainfall simulator method.

In burned soils with a bare surface and therefore with the soil surface altered, the runoff coefficient (~90% of applied water) and erosion (~850 g m^{-2} h^{-1}) are very high. In different localites, the soil loss was lower in unburned plots (~0,2 Mg ha^{-1} $year^{-1}$) than in burned plots, which accounted for between 2 and 20 Mg ha^{-1} $year^{-1}$ over the first years. The following relationship between erosion and plant cover was established after the fire.

$$\text{Sheet erosion (g m}^{-2}\text{)} = 282 - 140{,}1 \text{ (Plant cover, \%); } r = 0{,}97,\ n = 10 \qquad (1)$$

The relevance of plant composition on plant cover evolution after fire and the effects on soil erosion has been demonstrated (Fig. 3). So, soil loss was significanty lower in a dense *Quercus coccifera L.* shrubland than in an open *Pinus halepensis L.* forest in Castejón de Valdejasa. The figure 3 shows as plant community structure, as well as the sprouters:seeder ratio, explains differences in bare soil surface (Y2) and their relationship with soil loss (Y1) during the first months (X, time) after a wildfire.

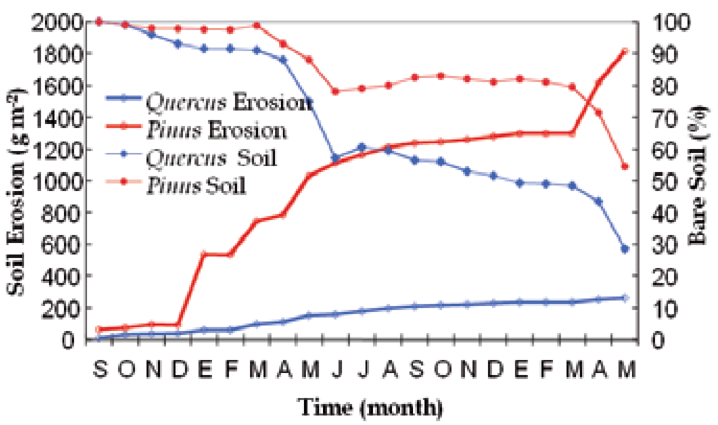

Fig. 3. Accumulated soil erosion (g m-2) and bare soil (%) evolution in burned Castejón de Valdejasa hills (NE-Spain).

Author	Location and Mean Annual Precipitation	Slope (%)	Soil	Vegetation	Plot size (m^2)	Rainfall duration - intensity
Cerdà et al., 1995	Valencia 688 mm	24-31	Calcareous, sandy loam	Pine & shrubs	0,24	60' 55 mm h^{-1}
Kutiel et al., 1995	Carmel Mont 690 mm	15-22	Chromic Luvisol	Aleppo pine and oak forest	1	120' 30 mm h^{-1}
Cerdà & Lavee, 1995	Judea's Desert 260 mm	35-40	Limestones	Shrubland	0,24	60' 37 mm h^{-1}
Cerdà et al., 1998	Cáceres 511 mm	35-40	Dystric Cambisol, silty	Dehesa	0,24	60' 50 mm h^{-1}
Imeson et al., 1998	Benidorm 387 mm	36-40	Lithic Leptosol Limest. colluvium	Aleppo pine forest	0,24	60' 50 mm h^{-1}
Imeson et al., 1998	Finestrat 400 mm	36-40	Lithic Leptosol Limest. colluvium	Shrubland	0,24	60' 50 mm h^{-1}
Lasanta et al., 2000	Zaragoza 324 mm	<10	Calcisols, Gypsisols	Barley, weeds	13,85	30' 60 mm h^{-1}
Johansen et al., 2001	Los Alamos, USA 300 mm	4-8	Loam	Ponderosa pine forest	32,4	120' 60 mm h^{-1}
Cerdà, 2001	Valencia 688 mm	21-31	Leptosols & Luvisols	Shrubland	0,24	60' 55 mm h^{-1}
Ortiz & Alcañiz, 2001	Taradell 563 mm	20-25	Luvisols, sandy surface	Pines & oaks burned	0,24	40' 95 mm h^{-1}
Cerdà, 2002	Alacant 358 mm	36-58	Badlands	Negligible vegetation	0,24	60' 55 mm h^{-1}
Cerdà & Doerr, 2005	Valencia 688 mm	16-25	Lithic Leptosols & Luvisols	Aleppo pine forest	0,24	60' 55 mm h^{-1}
Desir, 2002	Zaragoza 350 mm	25-45	Gypsisol, silty	Shrubland	0,24	60' 45 mm h^{-1}
Calvo et al., 2003	Callosa 474 mm	40-50	Calcaric Regosol	Pine forest & shrubland	0,24	60' 55 mm h^{-1}
Calvo et al., 2003	Benidorm 387 mm	40-50	Lithic Leptosol	Pine forest & shrubland	0,24	60' 55 mm h^{-1}
De Luis et al., 2003	Alicante 466 mm	50	Kastanozem, loamy	Gorse shrubland	4	105' 156 mm h^{-1}
Arnáez et al., 2004	La Rioja 800 mm	10-60	Kastanozem eroded	Bare soil to shrubs	0,24	30' 75 mm h^{-1}
Badía & Martí, 2008	Fraga 318 mm	28-32	Calcaric Regosols	Aleppo pine forest	0,24	60' 85 mm h^{-1}
León et al, 2011	Zuera 560 mm	30-40	Rendzic Phaeozem	Shrubland	0,21	60' 60 mm h^{-1}
León et al, 2011	Zuera 560 mm	30-40	Haplic Gypsisol	Shrubland	0,21	60' 60 mm h^{-1}

Table 1. Runoff and erosion data with rainfall simulator method in semi-arid Mediterranean ecosystems (arranged by publication date).

Author	Treatment or variable	Soil loss (Kg ha^{-1} mm^{-1})	Runoff (%)	Other parameters
Cerdà et al., 1995	Fire, time and N-S aspect	0-68,2	0-73	I=15-55 mm h^{-1} ; Tr=138-872 s
Kutiel et al., 1995	Fire, time and N-S aspect	0-11,6	0-56	I=16-40 mm h^{-1}
Cerdà & Lavee, 1995	Plant cover	1,4-62,2	50-91	Sc=0-2-9,4 g L^{-1}
Cerdà et al., 1998	Plant cover	-	24-50	I=24-37 mm h^{-1} , Wf=5-7 cm Tr=266-510 s
Imeson et al., 1998	Plant cover	0,8-9,4	34-58	EC=0,13-0,16 dS m^{-1} Sc=0,88-2,85 g L^{-1} ; Tr=186-360s
Imeson et al., 1998	Plant cover	24,8-39,8	27-35	EC=0,28-0,29 dS m^{-1} Sc=9,4-11,3 g L^{-1} ; Tr=260-360 s
Lasanta et al., 2000	Abandonment, festilisers, crops	3,9-14,7	40-75	Wf=5-23 cm , Sc= 1,2-6,1 g L^{-1} EC=0,95-1,65 dS m^{-1}
Johansen et al., 2001	Sever wildfire effect	3-76	23-45	-
Cerdà, 2001	Rock fragments cover	0,36-14,1	12-38	I=27-44 mm h^{-1}
Ortiz & Alcañiz, 2001	Seeding and treatments	5-105	5-95	Tr=53-253 s
Cerdà, 2002	Parent material and season	24-374	36-85	EC=0,03-1,10 dS m^{-1} Tr=70-430 s
Cerdà & Doerr, 2005	Vegetation type, season and time from burning	0,03-9,4	5-45	I=25 to 52 mm h^{-1} Sc=0,03-0,84g L^{-1}
Desir, 2002	N-S Aspect	2,6-21,7	14-53	I=3,6-35,5 mm h^{-1} Wf=5-31 cm EC=1,0-2,5 dS m^{-1}
Calvo et al., 2003	N-S Aspect and soil moisture effect	0,2-8,6	2-55	I=17-49 mm h^{-1} Sc=0,46-1,06 g L^{-1} , Tr=67-665 s
Calvo et al., 2003	N-S Aspect and soil moisture effect	0,2-8,6	0,1-29	I=33-42 mm h^{-1} Sc=0,43-0,97g L^{-1} , Tr=116-406 s
De Luis et al., 2003	Fire intensity effect	0,07-30,8	-	-
Arnáez et al., 2004	Slope gradient	1,4-23,0	34-58	Wf=5,2-8,5 cm
Badía & Martí, 2008	Fire effects and raindrop size	0,73-39,9	41-81	I=14-49 mm h^{-1} Sc=0,22-4,81 g L^{-1} EC=0,45-1,01 dS m^{-1} Tr=74-97 s ; Wf=10,4-25,2 cm
León et al., 2011	Fire effects (control vs burned)	8,5-18,8	24-25	I=44-45 mm h^{-1}, Tr=197-379 s EC=0,62-0,91 dS m^{-1}
León et al., 2011	Fire effects (control vs burned)	25-152	22-60	I=24-47 mm h^{-1}, Tr=199-232 s EC=1,54-1,71 dS m^{-1}

Abbreviatures: I, Infiltration (mm h^{-1}); Tr, Time to runoff (s); Sc, Sediment concentration (g L^{-1}); Wf, Wetting front (cm); EC, Electrical conductivity of runoff (dS m^{-1}) of overland flow.

Table 1bis. Runoff and erosion data with rainfall simulator method in semi-arid Mediterranean ecosystems (arranged by publication date).

In Figure 3, there are also some turning points in the vegetation cover and erosion evolution related to environmental conditions. Thus, in spring vegetation the cover rate is accelerated then decreases during the summer period mainly dominated by therophytes plants; the pulses in the soil erosion are related to the greatest intensity of rainfall.
It must be taken into account that in burned kermes evergreen oak shrubland, the average erosion is 7 times higher than in unburned plots; in Aleppo pinewood soil loss can be as much as 36 times higher in the early years (Rodríguez et al., 2000). This is due to the differential evolution of vegetation to cover the soil surface after the fire.

3. Rainfall energy effects on soil erosion and runoff generation in semi-arid forested lands

The effects of fire and torrential rainfall, two important factors in Mediterranean semiarid environments, on the soil erosion and hydrology, are analyzed in this section.

3.1 Methods

Experiments were carried out using a portable sprinkler-based rainfall simulator with different nozzles and pressures. Two levels of rainfall energy (12,6 J m^{-2} mm^{-1} and 24,7 J m^{-2} mm^{-1}) and similar intensity (85±8 mm h^{-1}) reproduce torrential rainfall characteristics. Rainfall simulations were conducted immediately after Aleppo pine (*Pinus halepensis L.*) litter covering soil surface was burned. The experiments were conducted on calcareous, loamy clay soils classified as Calcaric Regosol, frequent in the semi-arid Central Ebro Valley (NE-Spain). Paired burned areas were established in nine micro-plots and compared with paired not burned control areas (2-soil status x 2 rainfall energy x 9 plots or replicates). In each rainfall simulation the soil loss, soil infiltration (calculated by Horton model), wetting front, runoff coefficient and runoff quality (EC and pH) were measured (Badía & Martí, 2008).

3.2 Results and discussion

The results indicate that when litter cover was burned rainfall significantly increases the sediment yield. Burned plots generated 18.5 times more sediment than unburned plots (control) for fine rainfall energy (Raindrop D_{50} = 1,0 mm) and 33.6 times more for coarse rainfall energy (Raindrop D_{50} = 1,4 mm) (Fig. 4).
The return period for a single storm with I_{30} (rainfall intensity for 30 min) ranged from 5 to 200 years from the East Mediterranean areas to semiarid Central Ebro Valley, respectively (Fomento, 2001). These rainfalls of high intensity are especially frequent in autumn, just after summer, the season of maximum risk of wildfires. Sediment loss was given as solutes dissolved in overland flow, mainly in unburned plots, and as particles in suspension, mainly in burned plots. However, soil erosion rates were without significant differences between both rainfalls. Fire increased runoff quantity (about 1,6 times) and decreased its quality temporarily by increasing significantly both pH and specially EC in relation to unburned plots (Fig. 5).
The results indicate that when vegetation and litter cover of soils were burned, the first rainfalls duplicate runoff, soil infiltration decreases significantly and soil erosion increases 20 – 30 times in relation to unburned plots, especially with the highest rainfall energy. Because of the dynamic climate of the area that we discussed, a restoration strategy for a short-term response would be an interesting response, especially in conditions where plant succession is very slow, e.g., high slopes and soils of low permeability materials, thus highly erodible.

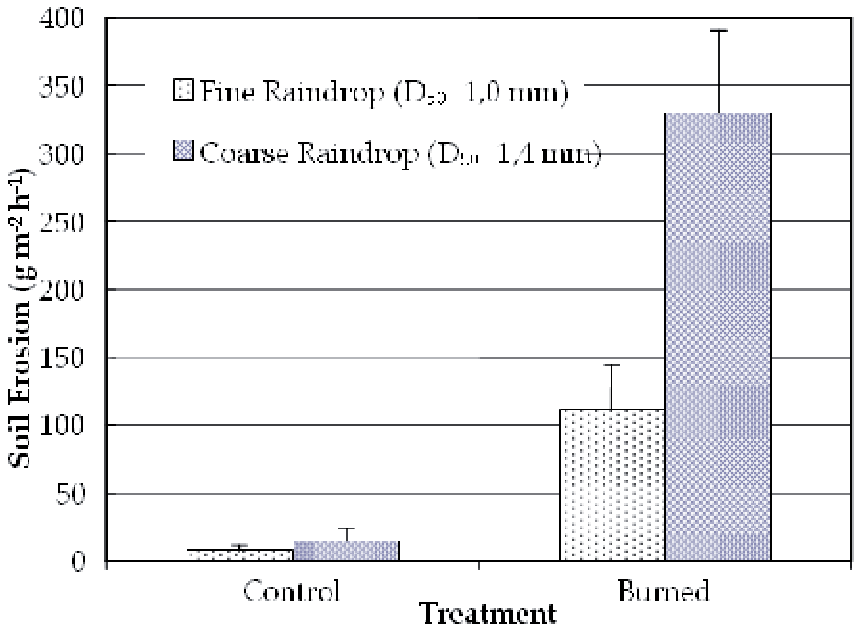

Fig. 4. Fire and drop size effects in the soil erosion (g m^{-2} h^{-1}) with rainfall simulator method.

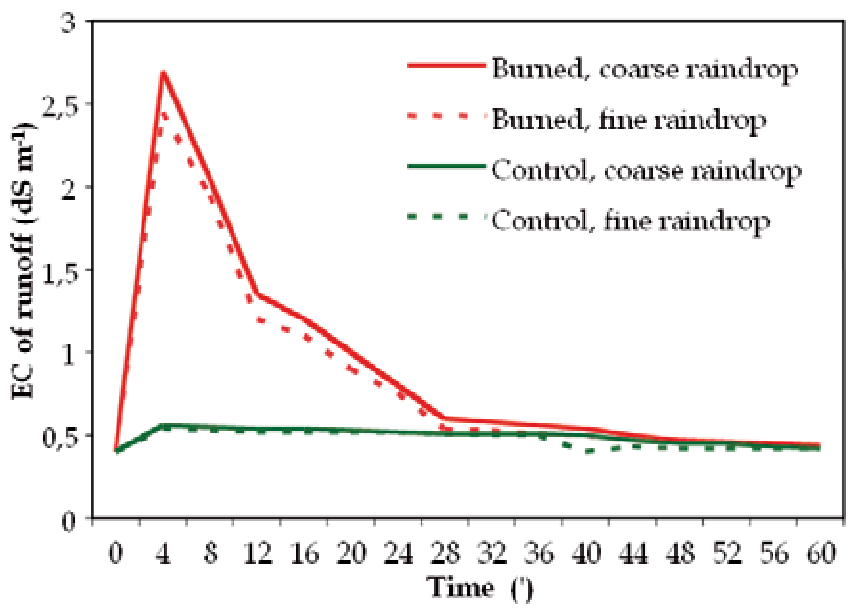

Fig. 5. Evolution of electrical conductivity of runoff (EC, dS m^{-1}) in burned and control plots with rainfall simulator method (in a Calcaric Regosol).

4. Fire effects on soil properties under laboratory–controlled heatings

Wildfire passage is accompanied by a heat wave and a deposition of ash as a result of biomass combustion (Fig. 6). Fire effects are directly related to the soil type affected as well as fire severity, i.e. the heat reached and the quantity and quality of ashes deposited on soil surface. To test these variables we treated two contrasting soils under laboratory conditions, the most frequently found soils in the semi-arid Central Ebro Valley (NE-Spain), a Calcaric Regosol developed on marls and a Haplic Gipsisol, developed on gypsiferous marls.

4.1 Methods

Samples of both soils (calcareous and gypsiferous soil) were collected randomly and analyzed separately with 4 replicates for each soil type. Soil samples were heated for 30 minutes in a muffle furnace at temperatures of 25°, 150°, 250° and 500°C. These temperatures cover the range that is habitually reached in surface soils affected by fires (Chandler et al., 1983; Giovannini & Lucchesi, 1997; Walker et al., 1986). Soil sample treated at 250ºC was selected for adding black ashes, in a quantity related to plant biomass growing on each soil (Martí, 1998). The amount of ashes added to calcareous soil was twice (10 g kg^{-1}) that added to gypsiferous soil (5 g kg^{-1}).

Fig. 6. Appearance of a recently burned soil surface in Mountains of Zuera and Castejón de Valdejasa (Zaragoza).

4.2 Results and discussion

Similar changes in chemical properties were found for both soils at highest temperatures but differences between soils were observed at intermediate temperatures (Table 2).

	Gypsiferous Soil, G					Calcareous Soil, C				
Treatment	**G25**	**G150**	**G250**	**G250A**	**G500**	**C25**	**C150**	**C250**	**C250A**	**C500**
SAS (%)	75b	72b	48d	45d	0.8e	86a	83a	65c	63c	0.9e
Particle density (Mg m^{-3})	2.45c	2.44c	2.48c	2.49c	2.68a	2.55b	2.57b	2.58b	2.57b	2.65a
Water available (%)	22.6b	23.9b	24.4b	24.8b	27.8a	12.6d	12.6d	13.1d	12.7d	18.4c
$CaCO_3$ (mg kg^{-1})	96b	95b	103b	122b	136b	308a	319a	320a	326a	328a
pH 1:2,5 (H_2O)	7,8d	7,7de	7,3f	7,5e	8,8b	8,2c	8,1c	7,6e	7,8d	9,4a
OM (g kg^{-1})	27d	28d	22e	25d	3f	42a	42a	32c	35b	4f
Total N (g kg^{-1})	1,5b	1,6b	1,5b	1,5b	0,5c	2,7a	2,6a	2,5a	2,3a	0,7c
C/N ratio	10,4a	10,1a	8,5a	9,7a	3,5d	9,0ab	9,4a	7,4c	8,8b	3,3d
CEC ($cmol_c$ kg^{-1})	12,7c	13,9c	12,4c	12,1c	9,9d	27,2a	28,8a	22,0b	21,7b	14,4c
P-Olsen (mg kg^{-1})	0,4g	0,4g	1,2f	1,3f	1,7e	2,3d	2,7d	9,1c	9,8b	11,5a
K^+-exc (mg kg^{-1})	46,0f	36,5f	48,0f	102,0e	186,0d	176,0d	154,0d	204,0c	286,0b	528,0a
ECe (dS m^{-1})	2,6e	5,6b	8,5a	8,7a	3,3d	0,9f	1,2f	3,4d	3,7c	2,4e
Basal respiration	100.1e	89.2f	86.9f	98.3e	29.2g	153.7d	198.6c	254.8b	277.0a	33.4g
Biomass C (mg C kg^{-1})	635c	532d	387e	426e	217f	737b	742b	812a	821a	353e

Table 2. Changes induced by simulated fire at different temperatures and ash addition (A) in the physical, chemical and biological properties of gypsiferous (G) and calcareous (C) soils in the semi-arid Central Ebro Basin. In each row, treatment data with the same letters are not significantly different (LSD test, P>0.05). Basal respiration (mg CO_2 soil kg^{-1} day^{-1})

Among the results it should be noted that heating soil to 250°C caused a decrease in pH and an increase in electrolytic conductivity (ECe) and soluble Ca. Heating soil to 500°C caused an increase in pH and a decrease in ECe and soluble Ca. Increasing heat intensity increased organic matter loss by combustion, which was accompanied by an increase of available nutrients content. Total N content decreased at temperatures greater than 250°C, with about one-third being volatilized. Cation exchange capacity (CEC) was reduced for gypsiferous soil heated to 500°C and to 250°C for calcareous soil. As for physical soil properties, heating increased the quantity of sand-sized particles by fusion of clay with the greatest increase occurring in soil heated to 500°C. Soil aggregate stability (SAS) of both soils was reduced by heating to 250°C with greater reductions at 500°C, likely due to a reduction in organic matter and clay size particle content. Bulk density and particle density increased in both soils when heated to 500°C. Water availability (difference between field capacity and permanent wilting point) increased when soils were heated to the highest temperature, likely due to texture and structural modifications. The addition of ashes increased organic matter content, C/N ratio, and pH in both soils and increased nutrient availability, especially in the calcareous soil where soil addition was higher than in gypsiferous one.

Soil respiration were quickly enhanced in calcareous soil but depleted in gypsiferous soil for intermediate heating treatments (150°C and 250°C). At the highest temperature (500°C), these biological properties were significantly reduced in both soil types and on a long term basis. Black ash addition increased basal respiration in both soils but did not affect other biological properties. These results demonstrate the existence of both labile and permanent effects of soil burning and a differential response to C dynamics as a function of soil properties (Badía & Martí, 2003b).

The unburned or control soils (25ºC) have originally contrasting properties (C versus G soil) that are not strongly altered at intermediate temperatures (150ºC, 250ºC). But the highest heat treatment (500ºC) conducted on both soils (C500 vs G500) showed a lot of similarities as result of the degradation of their initial properties (Fig. 7).

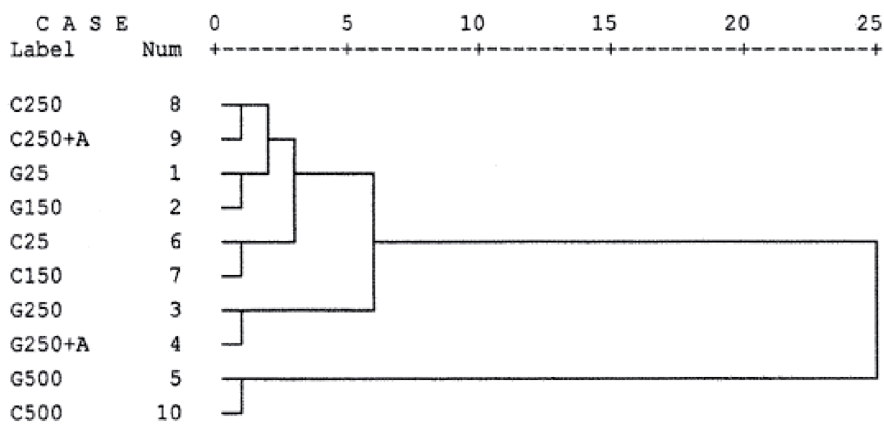

Fig. 7. Dendrogram of experimental calcareous (C) and gypsiferous (G) soils at different temperatures (25ºC, 150ºC, 250ºC, 500ºC) and ash addition (A). Numbers 0 to 25 shows the rescaled distance cluster combine, and 1 to 10 are the case numbers.

5. Fire effects on soil water repellency: A laboratory approach with contrasted soils

5.1 Methods

Water repellency is a soil property that affects its hydrological response and its erodibility (Cerdà & Doerr, 2008; Jordán et al., 2010). In this chapter, the effect of an experimental fire is studied on the soil water repellency of three different ecosystems. Three experimental soils have been selected in the NE of Spain with different properties (Table 3).

Soil Unit (FAO)	Rendzic Phaeozem	Hypercalcic Calcisol	Haplic, Eutric Cambisol
Plant community	Aleppo pinewood with moss	Evergreen oakwood	Meadow
Soil moisture regime	Xeric-aridic	Xeric	Udic
Soil temperature regime	Thermic	Mesic	Mesic
Soil parent material	Marls & limestones (Miocene)	Calcareous coluvium (Pleistocene)	Coluvium (Pleistocene)
Organic matter in A (%)	9.8 %	4.1 %	7.0 %
Textural class in A (%)	Clay Loam	Loam	Loam
Location: municipality	Zuera	Arascués	Linás de Broto
UTM 30T (X-Y)	671-464	708-467	733-472
Altitude (m)	630	581	1218

Table 3. Some characteristics of the studied soils and their ecosystems.

Non-altered blocks of soil have been obtained in the field in every area. All treatments have been carried out three times. Once in the laboratory, all the soil blocks have been air-dried and they have been burnt with a blowlamp (Llovet et al., 2008) up to reaching a maximum of 250ºC at 1 cm depth (Fig. 8).

Fig. 8. Soil blocks were burned with a blowlamp reaching 250ºC at 1 cm soil depth.

In order to evaluate the soil water repellency, the water drop penetration time (WDPT) test has been used, applying three drops per soil block. In addition, the water repellency variation is assessed in three different levels of depth (at the surface, at 2 cm and 5 cm-depth). The water repellency classification criterion is the one used by Doerr et al., 2009).

5.2 Results and discussion

Fire affect soil water repellency in a different way according to soil type and soil depth (Table 4). Fire decreased significantly the presence of water repellency on the surface of all experimental soils: Phaeozems, Calcisols and Cambisols. The fire reduced water repellency even in depth in Phaeozems (to 5 cm depth) and Calcisols (to 2 cm depth). Unlike, fire increased water repellency in Cambisols at 5 cm depth, from hydrophilic (unburned soil samples) to strongly hydrophobic (burned soil samples).

Soil Group	Soil depth (cm)	Unburned Soil	Burned Soil	*P*
Phaeozem	0	833.6±656.0	0.69±0.14	0.003
	2	1100.6±479.3	12.80±22.0	<0.001
	5	835.3±438.6	13.0±11.3	<0.001
Calcisol	0	666.0±333.2	8.0±20.2	0.001
	2	382.2±412.9	16.6±39.9	0.029
	5	79.0±87.4	40.0±67.4	0.305
Cambisol	0	14.2±6.9	0.81±0.1	<0.001
	2	1.4±0.9	107.9±207.3	0.162
	5	3.7±1.3	273.9±293.7	0.025

Table 4. Effect of fire on water repellency (WDPT, s) of Phaeozems, Calcisols and Cambisols at different soil depths (mean values and standard deviation; n=9).

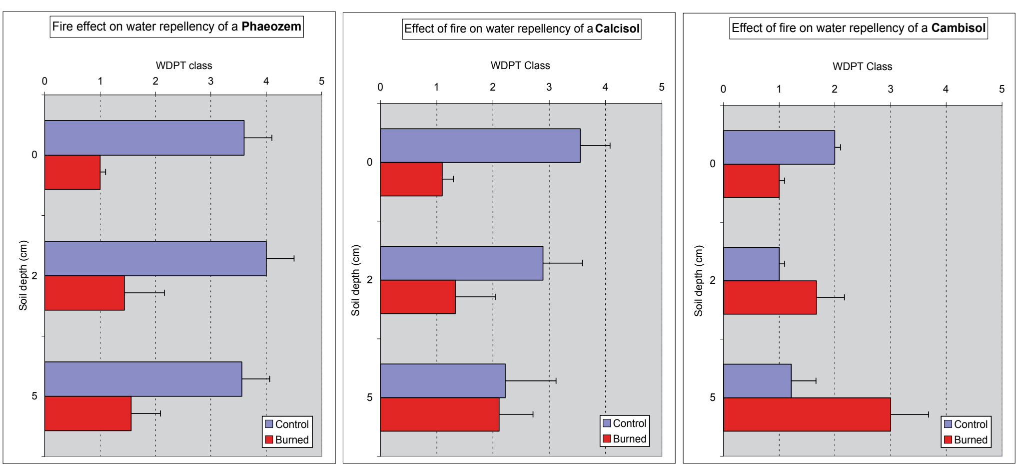

Fig. 9. Fire effect on water repellency (WDPT classes) in the studied soils.

Waxes and similar lipid materials could be mostly responsible for the original soil water repellency, which can be enhanced or reduced according to soil properties (Fig. 9). The increase in water-repellent conditions at 5 cm depth in Cambisol could be attributed to the translocation into the soil depth of lipid fractions released from burning organic matter or biomass (González et al., 2004).

6. Rehabilitation practices in areas affected by wildfires

Some rehabilitation practices have been implemented as urgent measures to control soil erosion in areas affected by wildfire in thesemiarid Central Ebro Valley (Figure 10): rehabilitation practices include herb seeding, re-mycorrhization and mulching with barley straw and pine woodchip. The effectiveness of these treatments are discussed in this section.

Fig. 10. Rural depopulation, land abandonment and afforestation with flammable species increased wildifres in Mediterranean semiarid ecosystems: Burned Aleppo pine afforestation in Fraga mountains (left) and abandoned terraces in Sarsa Castle (right).

6.1 Methods

In a paired plots design, treatments of seeding, seeding and mycorrhized, seeding and mulching, and control (untreated) erosion plots were established in four different slopes and on calcareous one (*Calcaric Regosols*) and gypsiferous (*Haplic Gipsisols*) soils (Fig. 11).

Fig. 11. Left: detail of seeding and mulching plots under slow and poor conditions of post-fire cover regeneration. Right: planting oak species on hillslopes which have been removed because of high fire frequency.

All sites were north-facing with a slope of around 20º. The seeding treatment consisted of the addiction of legumes and grass seed mixture, either native or established through cultivation in the region: *Medicago sativa* L., *Medicago truncatula* Gaertn., *Onobrychis viciifolia* Scop., *Vicia villosa* Roth, *Agropyron cristatum* (L.) Gaertn., *Dactylis glomerata* L., *Lolium rigidum* Gaud. and *Phalaris canariensis* (L.). Planting was done manually in rows, perpendicularly to the maximal slope (parallel contour seeding). The sowing rate for the whole mixture was 30 g m^{-2}, with an equivalent weight for each species. Mulching consisted of barley (*Hordeum vulgare* L.) straw covering the soil surface at a 100 g m^{-2} rate (Badía & Martí, 2000). And mycorrhization has consisted of contribution of vesicular-arbuscular mycorrhizae (*Glomus mossae*) to increase the nutrient and water potential of sown plants (Mataix et al., 2007; Vallejo, 1996).

6.2 Results and discussion

Plant cover (native and sown plants) in both soils (calcareaous and gypsiferous) after four months of seeding treatments are shown (Fig. 12).

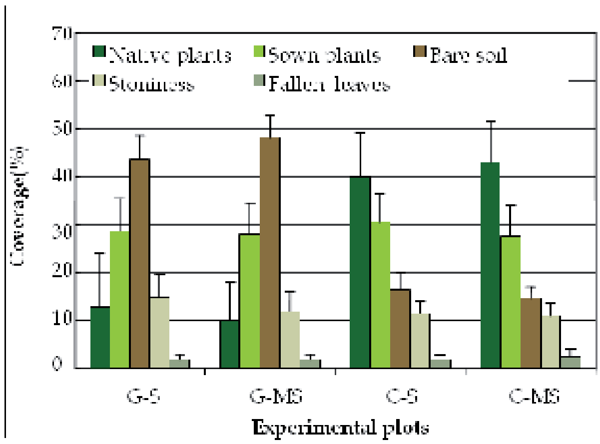

Fig. 12. Soil cover (%) in seeded plots (S) and seeded+mycorrhized plots (MS) on calcareous (C) and gypsiferous (G) soils after four months of treatments application.

Native plant coverage in calcareous soils (40%) is greater than in gypsiferous soils (10%) where physical, chemical and biological properties are relatively worse. Moreover, in calcareous soils the resprouters are higher than in gypsiferous one. In gypsiferous plots the principal native species was *Helianthemum syriacum* while *Brachypodium retusum* was dominant in calcareous plots, in some cases reaching 50% of total plant cover.

It is important to remark that plant cover of seeded plants is similar in both soils (~30%). Among the introduced species *Lolium rigidum* covered about 12% of soil surface. The other seeded species had a similar importance, 5% of the total for *Onobrychis vicifolia* and about 2-4% for each of the other six species.

Regarding the effectiveness of applied measures on soil erosion, we found differences between soils because bare soil after treatments was about 45% in gypsiferous soils and only 15% in calcareous one (Fig. 9). The soil loss in gypsiferous soils twice that one in calcareous soils (Table 4). The cumulative annual erosion rate measured in Gerlach boxes was about 4 Mg ha^{-1} year^{-1} for gypsiferous soils, 3 times more than treated soil. And in calcareous soils, soil losses was about 2 Mg ha^{-1} year in control plots were about 2 times higher than treated plots (Table 5).

	Gypsiferous Soil				Calcareous Soil			
Treatments	**C**	**S**	**SM**	**SMS**	**C**	**S**	**SM**	**SMS**
Mg ha^{-1} year^{-1}	3,63a	1,24c	1,21c	1,11cd	1,78b	0,97cd	0,98cd	0,67d
Control / treatment	-	2,9	3,0	3,3	-	1,8	1,8	2,7

Table 5. Average erosion rate (n=4) in Gerlach collectors under different soil treatments: burned control plots (C), seeded plots (S), seeded and mycorrhized plots (SM), and seeded and mulched with straw (SMS). The plots were monitorized during two years after wildfire in Fraga hillslopes (NE-Spain). Different letters between treatments and soils indicates significant differences (LSD test, $P<0,05$).

The parallel contour seeeding treatment increases soil cover and acts as a sucessive micro-barriers to the maximal slope to reduce flow velocity and runnoff coefficient while increasing infiltration and trapping sediments. This was verified in experiments with rainfall simulator (Badía et al., 2008). The runoff coefficient was significantly lower for seeding plots (13 to 38%) than for control soils (45 and 58% for calcareous and gypsiferous soils respectively). The lower calcareous soils runoff is associated with better physical and chemical properties than gypsiferous soils, differences in soil characteristics which are also reflected in the vegetation cover (Fig. 9). Because of the heterogeneity of rainfall in the region, the erosion is generated in the most rainy months of the study on both the gypsiferous and calcareous soils, and then is when there are significant differences between seeding and control plots. The Figure 13 note these differences on gypsiferous burned soils, and is representative also for calcareous soils.

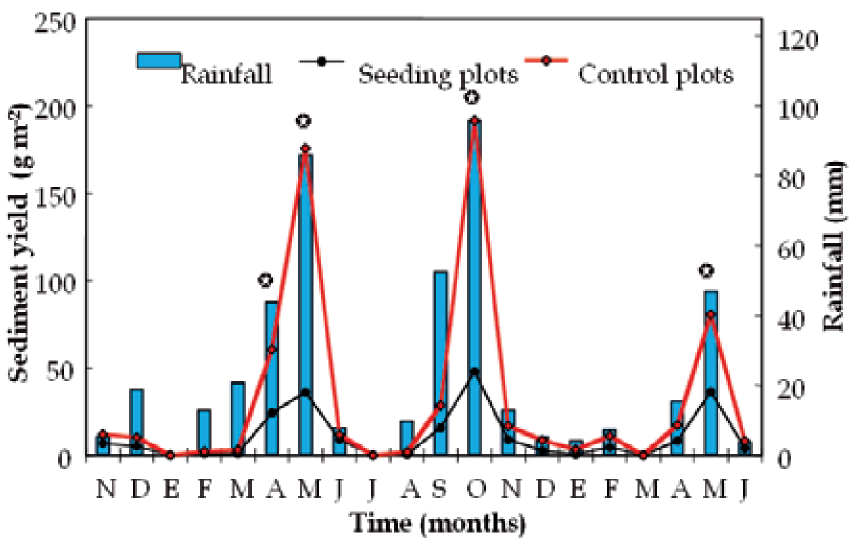

Fig. 13. Sediment yield (g m^{-2}) under different treatments (control and seeding) on gypsiferous burned soils (n=4) and monthly rainfall (mm) along the period of study. Asterisks indicate the significant differences between seeding and control plots in the reporting month. From Badía & Martí, 2000.

Cumulative soil loss was higher in gypsiferous soils than in calcareous soils for control plots (untreated). Although the application of any of the treatments reduced these rates and the benefits are clearly apparent, the erosion levels of post-fire degradation with no treatment cannot be classified as severe. These facts are consistent with other studies where wildfires are considered as a perturbation with a relatively severe temporary impact (Cerdá & Doerr, 2005). Analyzing the vegetal cover from the point of view of the pastoral value (Badía et al., 1994), fresh and dry plant matter increased with sowing as well as non-nitrogenous products. Straw mulching is the most effective treatment against soil erosion, inducing some improvement both in quantity and quality of plant matter in both types of soils. Remycorrhization did not affect these parameters. Endomycorrhizae recovery after the fire has been rapid (Table 4), hence the low response of a mycorrhizal inoculum allochthonous (Badía & Martí, 1994a and 1994b).

Although at intermediate temperatures soil microbial activity is quickly enhanced, for specific organisms, such as endomycorrhizal fungi, linked to the recovery of vegetation, this recovery is slower (Table 6).

	Gypsiferous Soil (G)		Calcareous Soil (C)	
	Control	**Burned**	**Control**	**Burned**
Nº spores /g dry soil	50.0±16.9	33.60±14.3	48.2±22.1	37.8±11.8
Diversity index	1.266±0.19	0.980±0.12	1.586±0.2	1.025±0.35

Table 6. Characterization of endomycorrhizal state ($x \pm sd$) in burned soils (n=4) one year after wildfire in NE-Spain (Barceló et al., 1994).

6.3 Other treatment: planting of shrubs and trees

In this case the treatment was applied only on young soils developed on calcareous marls (*Xeric Torriorthent*) in Fraga (Fig. 14). Five plant species were transplanted in man-made holes: two woody species (*Pinus halepensis, Quercus ilex*) and three shrub species (*Juniperus phoenicea, Pistacia lentiscus, Retama sphaerocarpa*); all of them ectomycorrhizae and with only one sap. After a year of monitoring, the portentaje of survival is almost null for *Quercus ilex* while for the other species is between 94 and 100%. Height growth rate is significantly different between the five species (average of the different slopes in which were transplanted): *Pinus halepensis* (16,4±5,8 mm/year), *Pistacia lentiscus* (10,3±3,9 mm/year), *Retama sphaerocarpa* (5,0±1,6 mm/year), *Juniperus phoenicea* (2,5±1,1 mm/year) and *Quercus ilex* (0,5±0,4 mm/year). In a similar way, diameter growth rate maintains the following order: *Pinus halepensis* (2,3±0,08 mm/year), *Retama sphaerocarpa* (1,4±0,09 mm/year), *Pistacia lentiscus* (1,1±0,06 mm/year), *Juniperus phoenicea,* (0,04±0,03 mm/year) and *Quercus ilex* (0,03±0,02 mm/year). These latter species show a relative diameter growth rate not statistically differentiated (0,4-0,6 mm mm^{-1} $year^{-1}$), whereas the relative height growth rate follows the order: *Pinus halepensis* and *Pistacia lentiscus* (0,5 mm mm^{-1} $year^{-1}$), *Retama sphaerocarpa* (0,4 mm mm^{-1} $year^{-1}$), *Juniperus phoenicea* (0,25 mm mm^{-1} $year^{-1}$). All the species studied show a clear sensitivity to soil water content, showing growth increments in spring and autumn, as well as greater increments in north slopes than in the southern slopes (Viñuales & Badía, 1995).

Table 7 summarizes the growth parameters (survival, height growth rate and diameter growth rate) of the species mentioned, used for reforestation in areas degraded by fire and other disturbances, and studied for different authors.

Species	Survival and/or growth	Location /Rainfall	Years	Author
P. halepensis	S: 94,5% (90,7-97,5). HGR=35,8cm/year (30,7-42,3). DGR=9,7mm/year(8,7-11,6)	Alloza, Teruel 391 mm	10	Badía et al., 2007
P. halepensis	S < 50%	Almería, 200 mm	6	Oliet et al., 2000
P. halepensis	S (1-2-3 years): 56-43-36% HGR: 15-52 cm/year	Paracuellos del Jarama, 430 mm	1-3	Peñuelas et al., 1997
P. halepensis	S: 13-56 %	Sierra Estancias 400 mm	1	Carrera et al., 1997
P. halepensis	S: 60 %	Montes de Málaga, 400 mm	1	Navarro et al., 1997
P. halepensis	S: 73-95% HGR: 11, 8 to 18,5 cm/year	Aspe, 306 mm; Agost, 301 mm	4	Baeza et al., 1991a and 1991b
P. halepensis	S: 20-48 %. HGR: 6,1-9,4 cm/year. DGR: 1,6-2,4 mm/year	Alicante, 277 mm	6	Cortina et al., 2004
P. halepensis	S:88%(S)100%(N).HGR:14,7cm/year(S)-23,2(N).DGR: 1,9(S) to 3.3mm/year(N)	Murallot de Fraga, 345 mm	1	Viñuales and Badía, 1995
P. halepensis	HGR: 0,85 -2,73 cm/year	Castillonroy, 414 mm	40	Olarieta et al., 2000
P. halepensis	HGR=4,1-6,5 cm/year DGR=3,8-4,8 mm/year	Sant Simó, Fraga 350 mm	0,4	Martí and Badía, 1995
P. halepensis	S: 80%	Alicante 277 mm	1	Maestre and Cortina, 2004
P. halepensis	S: 68-71%	Valencia 400 mm	1	Alloza and Vallejo, 1999
P. halepensis	HGR: 8,9-11.2 cm/year DGR: 0,29-0,37 cm/year	Garraf 500 mm	1	www.creaf.uab.es /iefc
P. halepensis	HGR: 17,7-26,1 cm/year DGR: 1,52-2,59 cm/year	Almatret 420 mm	28-46	www.creaf.uab.es /iefc
P. halepensis	S: 8-59%	Montseny 1000 mm	1	Espelta et al., 1993
Q. ilex	S: 40,7%(27,5-64,2%).HGR=7,5 cm/year (4,8-11,3%). DGR=2,0 mm/year(1,0-2,1)	Alloza, Teruel 391 mm	10	Badía et al., 2007
Q. ilex	S: < 40 %	Montes de Málaga, 400 mm	1	Navarro et al., 1997
Q. ilex	S: 2-51 %	Sierra Estancias 400 mm	1	Carrera et al., 1997
Q. ilex	S: 35-49%. HGR:2,4 cm/year - 1,3 cm/year	Aspe, 306 mm; Agost, 301 mm	4	Baeza et al., 1991a and 1991b
Q. ilex	DGR: 1.05 mm/year	Puechbon (Francia), 807 mm	1	Ducry and Toth, 1992

Species	Survival and/or growth	Location /Rainfall	Years	Author
Q. ilex	DGR: 0.87 mm/year	Montseny 1000 mm	1	Mayor and Rodà, 1992
Q. ilex	S: 92-70-38%	Montseny 1000 mm	1	Espelta et al., 1993
Q. ilex	S: 5-95%. HGR: 6,3-12,6 cm/year. DGR: 1,4-2,7 mm/year	Alcalá de Henares, 416 mm	3	Rey et al., 2005,
Q. ilex	S: 58% (1992 year), 54% (1993) and 11% (1994)	Spain 300-400 mm	1	Alloza and Vallejo, 1999
Q. ilex	DGR: 0,87-0,94 mm/year	Almatret 420 mm	40	www.creaf.uab.es/iefc
Q. coccifera	S: 34,1 % (17,9-54,2). HGR=1,5-6,6 cm/year. DGR=1,0-1,5 mm/year	Alloza, Teruel 391 mm	10	Badía et al., 2007
Q. coccifera	S: 40% (1993) and 0% (1994)	España 300 mm	1	Alloza and Vallejo, 1999
Q. coccifera	S: 10-20%	Campello 300 mm	3	Maestro et al., 2003
Q. coccifera	S: <40 %. HGR: 1,6-4,7 cm/year. DGR: 0,055-1,05 mm/year	Alicante 277 mm	6	Cortina et al., 2004
Q. coccifera	S: 2.5-80%. HGR: 3,5-12,4 cm/year. DGR: 1,3-2,2 mm/year	Alcalá de Henares, 416 mm	3	Rey et al., 2005,
P. lentiscus	80,9 % (70,4-86,7). HGR=6,1 cm/year (2,9-8,2). DGR= 2,1 mm/year (1,5-3,0)	Alloza 391 mm	10	Badía et al., 2007
P. lentiscus	S: <40 % HGR: 5,3 cm/year. DGR: 1,4 mm/year	Alicante 277 mm	6	Cortina et al., 2004
P. lentiscus	S: 100%; HGR: 5,02 cm/year. DGR: 1,1 mm/year	Fraga 345 mm	1	Viñuales and Badía, 1995.
P. lentiscus	DGR: 1,9 mm/year	Garraf 700 mm	1	Abril and Gracia, 1989
P. lentiscus	S: 0-10%	Campello 300 mm	3	Maestro et al., 2003
J. phoenicea	S: 61,7%(45,8-71,4).HGR=11,1 cm/year. (8,3-14,0). DGR=2,1 mm/year (1,7-2,6)	Alloza, Teruel 391 mm	10	Badía et al., 2007
J. phoenicea	S: 94%. HGR: 2,51 cm/year. DGR: 0,1 mm/year	Fraga 345 mm	1	Viñuales and Badía, 1995
J. phoenicea	S: 47%	Peñaflor 305 mm	1	Blanco, 1991

Table 7. Survival and growth of woody species used in restoration of areas affected by fires and other disturbances. Abbreviatures: S. Survival; HGR. Height growth rate; DGR. Diameter growth rate.

In a parallel experience the two woody species, *Pinus halepensis* and *Quercus ilex*, were planted in man-made holes too, in gypsiferous and calcareous soils affected by wildfire. After almost three years, *P. halepensis* survival is high, 81,2% on gypsiferous soils and 41,7% on calcareous soils. The *Q. rotundifolia* just had a 17,1% in gypsiferous and 8,3%on calcareous soils (Martí & Badía, 1995). The low survival in calcareous soils (more fertile than gypsiferous soils), is due to competition with other species, especially with *Brachypodium ramosum* with which it has been important. In fact, the mortality of *Pinus halepensis* is inversely related to vegetal recovery, which highlights the competition for soil water reserves:

$$\text{Mortality, \%} = 2{,}054\ (\text{Vegetation cover, \%}) - 23{,}513 \quad r^2 = 0{,}578;\ P<0{,}01 \tag{2}$$

More evidence of the role of soil water as a limiting factor in the study area, is that when reforestation practices are accompanied by a support irrigation in the plantation phase of the species, the survival rate and growth rises significantly. This was observed in a study of reforestation of opencast surfaces in the Val of Ariño coalfield (Teruel, NE-Spain) (Badía et al., 2007). In this study, the effect of a slope gradient on the growth and survival of different species 10 years after the reconstruction of mining banks was evaluated. Their survival shows significant differences: 95% *Pinus halepensis*, 81% *Pistacia lentiscus*, 62% *Juniperus phoenicea*, 41% *Quercus ilex* and 34%*Quercus coccifera*. Aleppo pine has been the fastest growing both height (36 cm year^{-1}) and basal diameter (10 mm year^{-1}), because of its greater adaptation in semiarid environments. For the other species, height values are less than 12 cm year^{-1} and 2,1 mm year^{-1} for basal diameter values. Growth and survival obtained here were higher than those of the same species in other afforestations in semiarid conditions. This outcome demonstrates the adequacy of species and applied techniques of restoration, in particular irrigation of summer season support, that allow a long-term reliability of reclaimed mine slopes.

7. Conclusions

In the semi-arid environments of NE-Spain, there are different types of soil conditioned by the lithology of the substrate derived, and whose erosion reponse is significantly divergent. Thus the calcareous burned soils with low stoniness and loamy clay texture, as well as eroded gypsiferous soils, show runoff and erosion levels higher than gypsiferous soils, and especially that colluvial soils. The coverage provided by vegetation is a key element to stop sheet erosion on these soils. The combined effect of heat and ash incorporation involves a number of changes in physical, chemical and biological characteristics of soils affected by wildfire. These effects vary according to intensity of the fire, the amount of ash incorporated and soil characteristics starting. The protective measures such seeding and mulching treatments involve a significant reduction of sediment yield in the first years after fire, higher in eroded gypsiferous soils than in fertile calcareous ones. The remycorrhization is not effective when the soil mycorrhizal status has already been recovered from the effects of fire.

In the forest domain of the area there is a diversity of species whose response after the fire is clearly different. Those with resprouting shrub species tend to recover its previous status faster, the vegetal recovery is higher and temporarily stable. In mature Aleppo's pine forest, the germination of pine is high; the pine density is 3-times higher before than after fire, although it will be prgressively reduced. The shrub and woody species introduced show a differential response according to the soil in which they are implanted and restoration techniques, especially related to soil water conditions.

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Part 2

Experimental Studies and Modeling Applications

6

Investigation of Effective Factors on Runoff Generation and Sediment Yield of Loess Deposits Using Rainfall Simulator

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1. Introduction

Erosion is a process in which soil materials are transported by water, wind and gravity. This phenomenon is one of the environmental issues which has undesirable effects on all natural ecosystems and is considered as a serious risk for well- being of human. The amount of erosion in Iran in 1951, 1961, 1971, 1981 and 1991 has been estimated to be 0.5, 0.75, 1, 1.5 and 2.2 billion Ton/Year, respectively (Ahmadi, 2006). This trend emphasizes that knowledge about erosion process for presenting suitable measures for decrease of erosion in Iran is very important.

Many studies have been performed for proper recognition and quantification of the effective factors and processes of erosion and by combining these factors, equations for prediction of soil erosion are developed, but many effective factors and processes of erosion are still unknown.

Important Quaternary deposits on northeastern parts of Iran, in Kopeh- Dagh Geological Zone, are Loess deposits which are widespread and significant from the view point of agriculture and animal husbandry. Iranian loesses are part of Eurasian loesses belt which spread from north Europe to Central Asia to China and belong to Pleistocene. A major part of Iranian loesses are present between Atrak and Gorganrood Rivers in Golestan Province with thickness of about 70 meters which cover Tertiary and Mesozoic Geological Units (Frechen et al., 2009). Primary loesses have originated from periglacial regions of higher latitudes, then northerly winds have transported these materials which after passing Turkmanestan Kavir and forming widespread sand dunes on these areas, lots of silt particles have been transported to the south as suspended materials. These wind storms have lost their power. After encountering Kopeh- Dagh Mountain Ranges in northeast part and Alborz Ranges in north part, these wind storms have lost their power and materials have been deposited in area of Golestan Province (Ahmadi and Feiznia, 2006).

Due to the structural nature and abundance of terrigenous particles (silt- size grains) and chemical salts, usually loesses are erodible and cause in- site and off- site damages(Pashaee, 1998).

Therefore, investigation of effective factors on sediment production of loesses and identification of most important factors on each erosion feature for proposing more effective measures for erosion control in region where dry- farming and range lands are widespread and play an important role in the economy of Golestan Province are very helpful. Due to the fact that loess deposits are widespread in Golestan Province, especially in Gorganrood Catchment which are exploited improperly (dry- farming in sloped lands and overgrazing of rangelands), the amount of yearly erosion in some subcatchments of Gorganrood Catchment reaches about 20 t/h/y of which a major part is from surface and gully erosions (Golestan Province Watershed Management, 2003).

Although scattered studies about erosion and sediment production of loesses in Iran have been performed, but comprehensive studies from the view point of effective factors in sediment production, prioritization of each factor and determination of the amount of their effects, have not been performed yet. The objective of this research is determining the effective factors on erosion of loesses on surface and rill erosion features. For this purpose, portable rainfall simulator with 1 m^2 plot was used. Rainfall Simulator has two advantages. First, the speed of performance of research projects increases notably, because waiting for the occurrence of rainfall is not needed. Second, by controlling some of the most important rainfall parameters, the results of study are usually more accurate and reliable. By using rainfall simulator, analogy, reasoning and statistical relationships of the results obtained from natural rainfall close to considered conditions are not necessary and similar rainfalls can be simulated in order to obtain repeatable results (Refahi, 2001).

The results from the study about the effective factors on erodibility of non- loessic areas cannot be generalized for loessic regions including northern part of Iran. Therefore, it is necessary that research and investigations would be performed in this region with respect to particular status and conditions of the area, in order to be able to identify the main effective factors on erosion and sediment production of loesses in predominant erosion features of the region and subsequently, with applying suitable measures, the erosion of these deposits would be controlled.

The research has been performed with the objective of determination of effective factors on erosion and sediment production of loesses and proposing regression models between sediment production of loesses and some of their physical and chemical characteristics, using field rainfall simulator in semi- arid climatic condition of Sarab Drainage Basin on surface and rill erosion features. With regard to the prevailing conditions of the area, it is tried to determine the most important effective factors on erosion and the amount of their effectiveness.

2. Loess deposits

For the first time in the world in 1823, a scientist, Leonhard from Heidelberg University, found a sample of yellow silty loam in an area called Harlas near Heidelberg and due to prevalence of local name, called it Loess and introduced it to the world. People of the area used the term "Loesch" for a soft soil which is probably cognate with English word "Loose", meaning soft. In 1911, Oberochov studied these sediments in more detail. This Russian geologist is actually pioneer in recognition of loess and loess- like sediments (Rozoycki, 1991).

Despite of many studies which have been performed on loesses, a comprehensive and acceptable, international definition of loesses does not exist yet which can be due to complex formation, physical characteristics and diversity of loesses on the surface of the earth. Therefore, many researchers express loess according to their own objective and subjective. Loess and loess- like deposits cover about %10 of the earth surface. The main areas covered by loesses are: China, Central Asia, east and central Europe, parts of North America, Argentina and New Zealand (Rozoycki, 1991).

One of the effective sedimentary processes in Quaternary of Iran is combined glacial-aeolian processes which formed loess deposits. Loess deposits of Golestan Province have the area of more than 320000 ha, of which 220000 ha are located in Gorganrood Catchment (Khaje, 2003). By researching paleosoles of Iran, Kehl et al. (2005) proposed that the formation of paleosoles formed in interglacial and more arid periods after interglacial phases of Quaternary period.

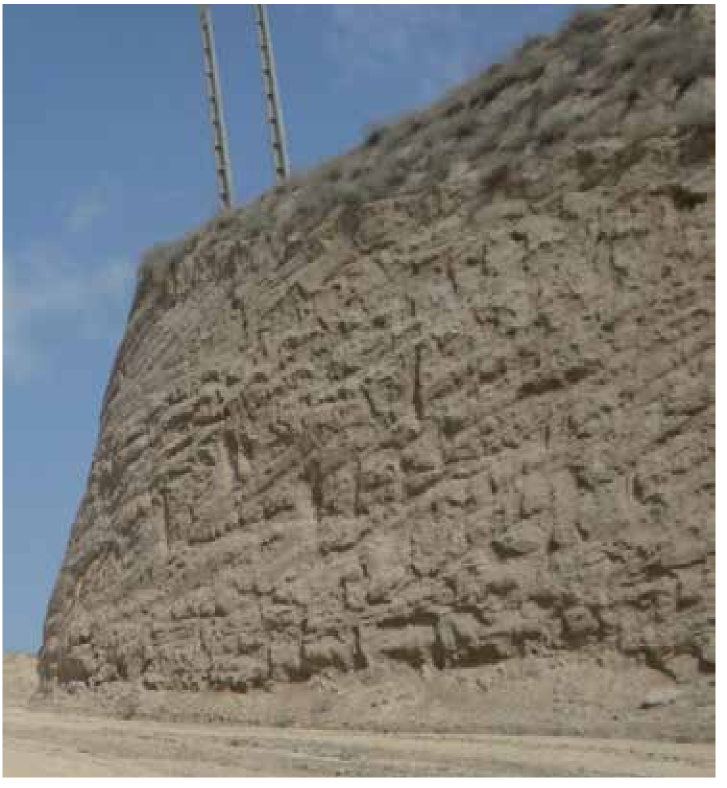
According to the definition, typical loess or real loess is a porous, non-layering, yellow and homogenous sediment which has undergone a little diagenesis and its particles are mostly coarse-grain silt. Different perspectives have caused naming loess different terms such as rock, sediment, formation or soil.

Loesses which have been transported and deposited in a new place by different processes, mainly water, have been called "Reworked Loess". Some of the most typical differences of these loesses with true loesses are that reworked loesses are heterogeneous and layered. Usually these deposits have undergone erosion and sedimentation phases and fine to coarse gravels may also be found in them. Paleosoles which are present as interlayes in some loesses are red horizons which have been formed due to climatic changes in Quaternary and formation of warm and humid climatic conditions.

Mineralogical composition of most of loesses includes: Quartz, Feldspar, Calcite, Dolomite, Mica and Clay minerals. Due to chemical weathering of ferroginous minerals and formation of iron oxide and hydroxide, the color of loesses is usually yellow and rarely brown (Okhravi and Amini, 2001). They usually form highly sloped even vertical walls. Due to the fact that particles of loesses are angular, their porosity is high, but due to the abundance of silt particles, low permeability and absence of cement between the particles, they are usually erodible and produce high amount of runoff. Loessic deposits of the studied area are usually relatively resistant in arid conditions but in contact with water, they are highly unstable and erodible. These deposits usually have considerable thicknesses that can be observed in road-cuts (Picture 1).

3. Application and importance of loesses of the area

In general, loesses deposits have economical, industrial and scientific applications. Economic application of loesses is mainly from the view point of soil fertility and high productivity of agricultural products. Loessic area are mainly dry-farming lands and are allocated to cultivation of products such as wheat, barley, sun flower, grain, etc. From the view point of industry, loesses are used in manufacture of brick and pottery. There are a number of factories in the studied area which are producing bricks. Scientifically, the loesses are considered as the most important continental materials which are proxy indicators of Quaternary climatic changes. The study of loesses is also important in Archeology. The evidence obtained from central Asia is also indicator of this fact that most archeological findings from loesses are related to mild climatic conditions (Liu, 1988).



Picture 1. View of loess thickness in the studied area (route to Gharnagh village)

4. Literature review

In recent years, a lot of attention has been oriented toward investigations of amount of erosion and sediment production, using rainfall simulator in the field. Despite of difficulties and high cost of working in the field, if erosion could be measured and monitored there, more actual data are obtained. Generally runoff and soil loss can be measured in different scales such as drainage basin, large plots (bigger than 10 m^2) and small plots (smaller than 10 m^2) (Barthes and Roose, 2002).

Standard runoff plots (SPR) and rainfall simulators (RS) are two field research methods for measuring sediment and runoff productions. In SRP, runoff and erosion are measured in natural rainfall which is costly and timely. The RS method is not as accurate as SRP method but repeatability, time and cost savings are its privilages (Victora et al., 1998).

In continue, some studies performed on this subject with emphasize on ones preformed on loesses will be reviewed.

- Due to the fact that loesses are widespread in China and they are important in agriculture of this country, numerous researches are studying different aspects of Chinese loesses.
- Rozoycki (1991) by publishing book of "Loess and Loess-like deposits", investigated central Asian loesses, explained the formation of these deposits and in: "Inventory map of Eurasian Loesses" indicated Gorgan Plain as one of the important regions of Iranian loesses.

- Bissonnais et al. (1995) in studying relationship between sediment, runoff and erosion characteristics in loess lands using rainfall simulator, found that the amount of produced sediment has direct relationship with the amount of clay, organic matter and texture of the deposits.
- Keli et al. (2002) determined erodibility of loess deposits, China, in experimental plots and by use of K-factor of USLE and found that changes in erodibility is related to grain size and the amount of organic matter of the deposits and slope of plot.
- Qiangguo (2002) investigated the relationship between erosion and human activities in loess plateau of China and found that some human activities such as plowing before rainfall season are important in loss of structure in loesses and increase of erosion.
- Khaje (2003) investigated sedimentology, sedimentary environment and sediment production of Quaternary Deposits in Gorganrood Catchment and found that the loesses can be subdivided into critical, intermediate and stabilized once, according to sediment production.
- Sheklabadi and Charkhabi (2003) investigated the amount of runoff and sediment production in soils with different parent materials using field rainfall simulator and found that the highest amount of correlation exists between the amount of erosion and amounts of cations, sodium absorption ratio and clay.
- Zhang et al. (2004) studied erodibility of agricultural lands of loessic areas in China using K factor of USLE and found that meaningful relationship exists between erodibility and percentage of clay. They presented this relationship as a regression equation
- Schiettecatte et al. (2005) in investigation of the effect of simulated rainfalls on physical properties of soils in agriculture landuse in Henan Province of China using field plots, found that there is meaningful difference between porosity and erodibility before and after simulated rainfall and there is not considerable changes in the rest of properties of soils such as retainment of water in soil and resistance to infiltration.
- Feiznia et al. (2005), by investigating the effect of some environmental factors on sediment production of loesses and comparing the rate of sediment production in different areas of loesses, indicated that sediment production is highly related to Domarten Aridity Index and percentage of organic matter and the rate of sediment production in loesses of arid regions is considerably higher than loesses of humid areas.
- Fernandeze and Avega (2006), by investigating the effective variables on runoff and sediment using rainfall simulator in 1 m^2 in Spain, indicated that there is a direct relationship between soil humidity and the amount of erosion and indirect relationship between runoff and amount of erosion.
- Zhenge (2006), by using lengthily data of runoff on experimental plot in Loess Plateau of China, indicated that accelerated erosion caused by vegetation degradation is due to intensification effects of rainfall and slope so that after degradation of forest erosion is more than 100t/h/y.
- Yu et al. (2006), while investigating the relationship of different factors with sediment in loessic regions, proposed regression equations for estimation of erosion and sediment and indicated that in the studied area, rainfall intensity was more important in sediment production then vegetation.
- Zheng et al. (2007)studied the effect of vegetation on runoff and sediment production in plot, slope and small and large drainage basins and found that the increase of vegetation in plot scale is more effective in lowering sediment production than lowering runoff, but in larger scales of slope and drainage, these relationships change.

- Zhou and Shangguan (2007) investigated the effect of Rye roots and stems (in different growth stages) on loess erosion using rainfall simulator and concluded that with the growth of plant, the amount of runoff and erosion decreases considerably and erosion rate and average permeability linear correlation with root density in the soil.
- Wei et al. (2007) studied the effects of landuse and rainfall regime on runoff and erosion of loessic hills in semi-arid regions, using 14 years field measurements and investigation of 131 rainstorms and found that bushes in comparison to forest and grasslands, played a considerable role in lowering erosion.
- Rhoton and Duiker (2008) compared erodibility of loessic soils in upper and lower parts of slope using laboratory rainfall simulator with a plot of 0.36 m^2 area and found that the lower parts of slope are more erodible and the amount of iron oxide is the most important factor in erodibility.
- Vitharana et al. (2008), in investigating loessic regions of Europe, concluded that slope, the percentages of clay, silt, humus and calcium carbonate are suitable criteria for the selection of suitable measure for lowering erosion in agricultural lands.
- Zhang et al. (2009) studied the effect of climatic change on soil erosion in Loess Plateau of China in two time intervals of 10 to 20 years and indicated the kind of agricultural measures such as protective ploughing, decreases the effects of climatic change on soil erosion.
- Hasanzade Nafuti et al. (2009), by using rainfall simulator on marly formation, indicated that SAR, EC, and K^+ ion are the most important factors in sediment productions of marly units.
- Zhou et al., 2010 studied the effect of grazing on physical characteristics and soil erodibility, in the area and found that intense grazing and trampling decrease permeability, retainment of water in the soil and stability of aggregates and therefore, increase runoff and sediment production.
- Ribolzi et al. (2010) investigated the effect of slope on the amount of changes in landscape of the soil surface and sediment production using field rainfall simulator with 1 m^2 plot and Laser scanning technology and concluded that the changes in landscape are more considerable in steeper slopes. Also in steeper slopes with other conditions being constant, runoff and sediment productions are higher.

By investigating the literature, it is distinguished that physical and chemical properties of the soil and morphometric characteristics of the area, play important role in erosion but the importance of these factors vary in different regions. In some studies, models for prediction of erosion and sediment production have been proposed using integration of factors. But, despite of these efforts, many effective factors on erosion and sediment production and the way they relate to each other, are still unknown.

5. Material and methods

5.1 The studied area

Iranian loesses are located in northeast of Iran, comprising of North Khorasan and Golestan Provinces. The studied area is Sarab subcatchment of Gorganrood Catchment in 55° 17' 54' to 56° 04' 32" east longitude and 37° 22' 43" to 37° 47' 31" north latitude, having an area of 223000 hectares, with semi-arid climatic conditions. This subcatchment is covered with loess sediments and sometime soil over loess sediments. Figure 1 shows the location of the studied semi-arid loesses in Sarab Drainage Basin and the location of Sarab Drainage Basin in Gorganrood Catchment.

6. Physiographic characteristics

By using 1:50,000 topographic maps of Army Geographic Institute, the boundary of the drainage basin was determined. Then different information layers and data including contour line with elevation difference of 100 meters, drainage network, road, villages and residential areas distributions, were digitized and entered into GIS environment. Coordinate systems were change from longitude and latitude into UTM using sphericity of WGS 84. The studied area is located in UTM zone #40. The map of elevation (Figure2) indicates that the maximum elevation of the basin is 2169 meters which is located on southeast dividing line and minimum elevation is 59 meters which is located on outlet of the drainage. The maximum elevation of the areas of loessic deposits is 1250 meters in western part of the area and the minimum elevation is 120 meters in southwest part of the area.

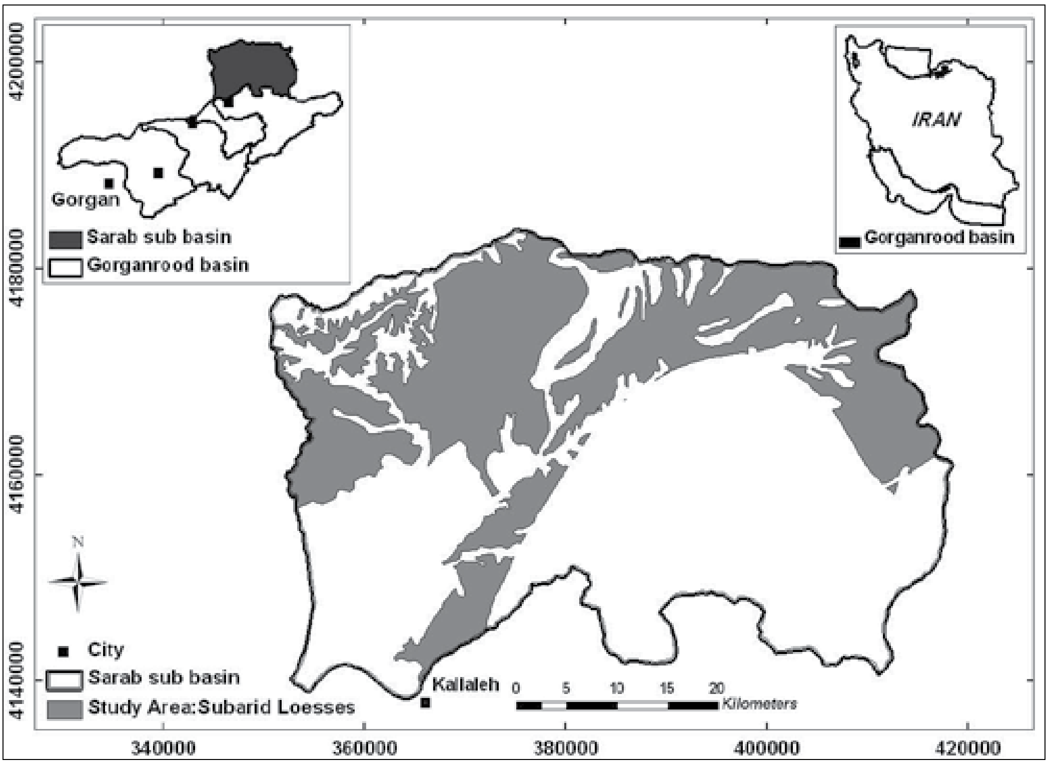


Fig. 1. The location of the studied semi-arid loesses in Sarab Drainage Basin and the location of Sarab Drainage Basin in Gorganrood Catchment

7. Climate

Sarab Drainage Basin is located in the extreme northeast part of Gorganrood Catchment. For investigating climatic conditions of the studied area, statistical data of stations within and around the basin were used. After controlling and completion of the data, statistical period was chosen from 1971 to 2002 in which most of the stations had data. The highest mean monthly precipitation of basin is from March which is 65 millimeters and the lowest from July which is 14 millimeters. Winter season is with the highest amount and summer season with the lowest amount of precipitation. Also evapotranspiration potentials of the basin vary from 880 to 990 millimeters in year.

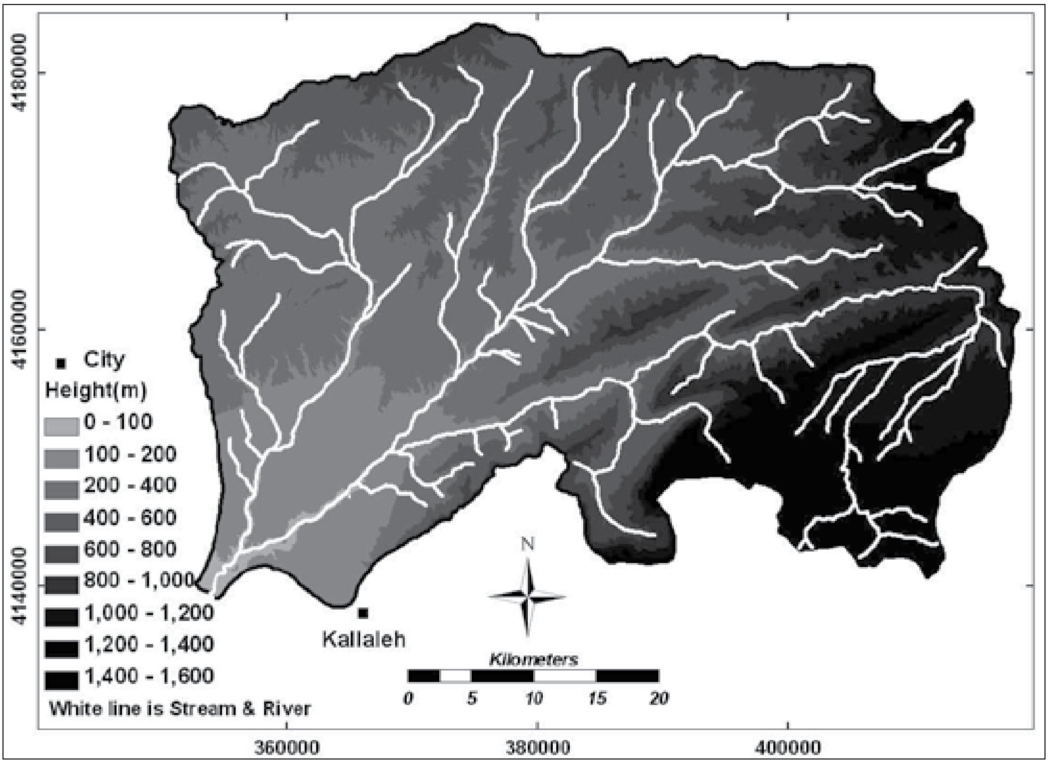


Fig. 2. Map of elevation of Sarab Drainage Basin

Considering the existing data, two methods of Domarten and Amberge climatic classifications were used. Figure 3 shows climatic classification of Sarab Drainage Basin which is prepared using climatic classification of Gorganrood Catchment (Jamab Consulting Engineering Co., 1996) and was corrected later on (Golestan Province Watershed Management, 2007). Vegetation and geomorphological conditions of the area confirm this classification.

For studying the intensity and the amount of precipitation in different time periods, statistical data of climatic station of Tamer Village which belongs to Ministry of Energy, is located in the studied area and has suitable statistical data(suitable quality and duration of data) was used. Figure 4 shows Intensity-Duration-Frequency curves of this station.

8. Geology

Diverse geological formations are not present in Sarab Drainage Basin and more than half of the area of basin is covered with loess deposits (Figure 5). Due to the fact that a part of basin is located in Kopeh-Dagh and a part of basin in Alborz Geological Zones, stratigraphic characteristics of geological units of the basin in these zones are gathered and indicated in Table1.

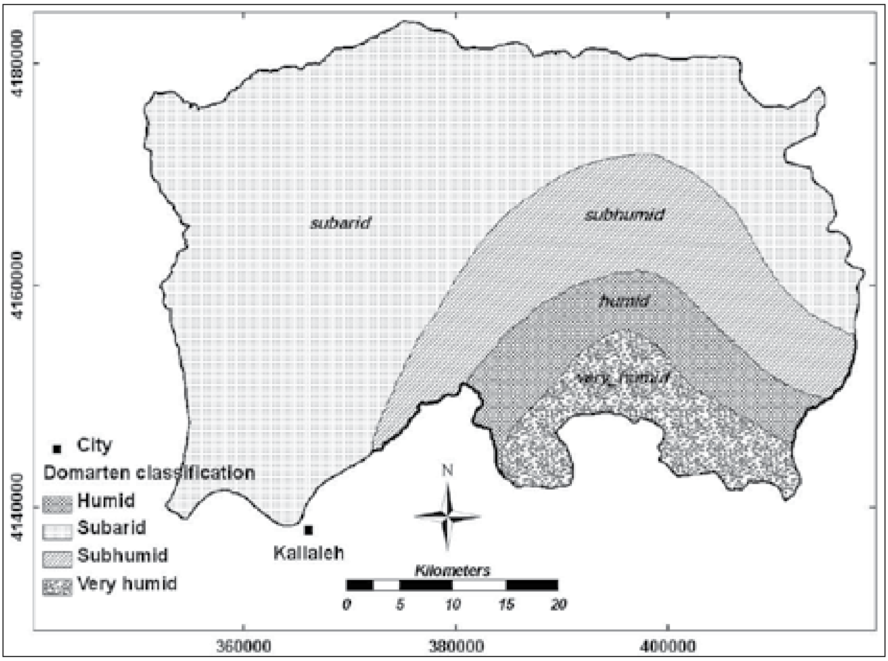


Fig. 3. Climatic classification map of Sarab Drainage Basin using Domarten Index (Jamab Consultant Engineering Co., 1996)

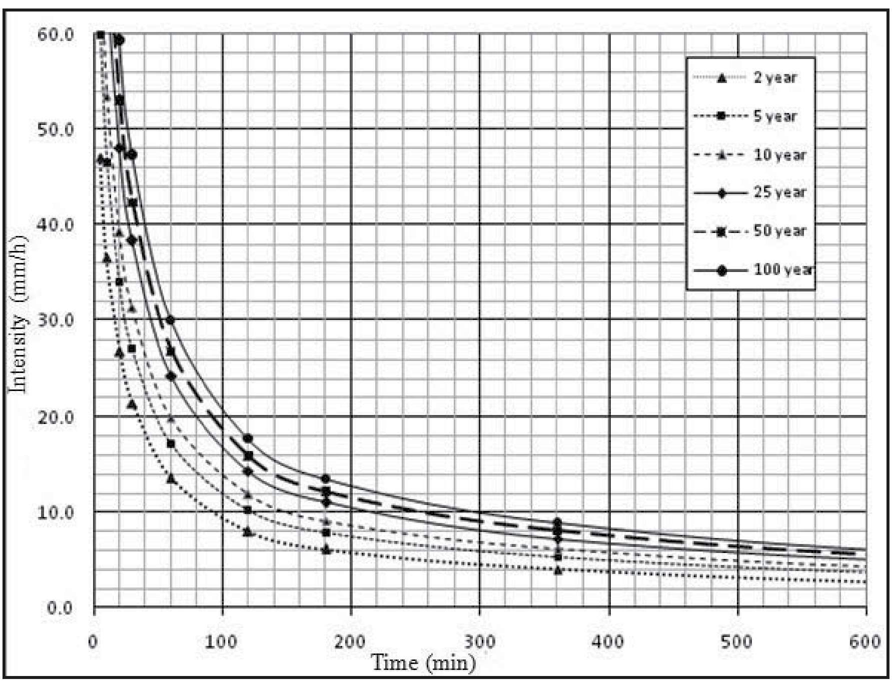


Fig. 4. Intensity-Duration-Frequency curves of Tamer Station (Golestan Province Watershed Management, 2007)

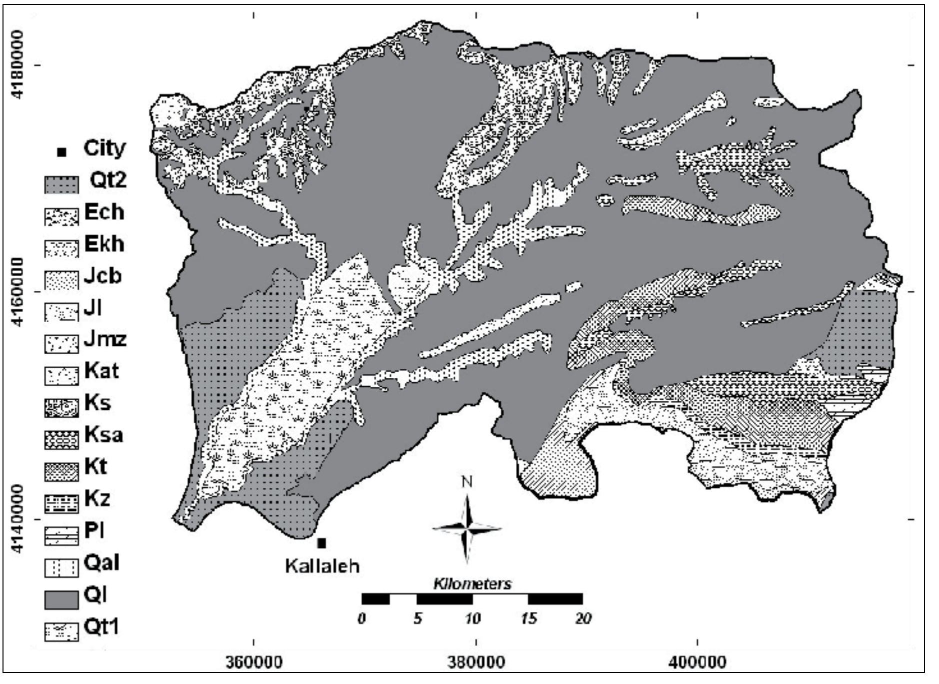


Fig. 5. Geological map of Sarab Drainage Basin

9. Research methods

Different phases of the research and the methods which were followed are listed below:

- Collecting necessary basic data including air photos, landsat images, geology and topographic maps and climatic data of the area.
- Preparing inventory map of loesses in semi-arid climate of Sarab Drainage Basin using geologic map and climatic classification using Domarten method.
- Preparing landuse map using landsat images, air photos and field visits and controls.
- For identification and separation of different erosion features on loesses and preparation of erosion features map, processing of Landsat ETM (2002), interpretation of air photos and numerous field controls and checking were used.
- Preparing slope map in four predominant classes consisting of 0-%10, 10-%20, 20-%30 and more than %30 classes using GIS facilities. Slope steeper than %40 are rarely found in the area. Also in slopes steeper than %35, agricultural activities are not present.
- Calibration of rainfall simulator equipment for rainfall with 32 millimeters per hour intensity(rainfall intensity of 30 minute with return period of 10 years for the studied area with regard to statistical data of Tamer Climatological Station). Researches have shown that due to higher frequency of occurrence and threshold for runoff production is important in erosion and sediment studies (Saghafian, 2003).
- After extraction of the regions of semi-arid loesses in Sarab Drainage Basin using geological map and climatologic classification map of the area, land unit map was prepared by combining landuse, slope and erosion features (except gully and bank erosions) maps in the regions of semi-arid loesses of Sarab Drainage Basin in GIS environment. The total of 23 land units with more than 300 polygons were obtained.

These units are similar in view points of geology, climate, slope, the kind of morphological processes and prominent erosional features (Ahmadi, 2006). Among polygons of each unit, the polygon that is accessible, has higher area and is good indicator of other similar polygons were selected for rainfall simulator tests. In each land unit, rainfall simulator analyses were performed in three repetitions (total 69 cases) and the produced runoff and sediments were collected and measured (Picture 2). After the analyses, the depths which were wetted by penetration of rainfall, were measured in 3 points of the rainfall simulator plot. Rainfall simulator unit produced rainfalls with constant intensity of 32 millimeters/hour with 30 minutes duration using urban water of Kalaleh in each plot. The time of field tests was late summer after harvesting of dry-farming wheat and before ploughing of cultivated lands for next cultivation. In these times residue of agricultural lands are used by livestock. In rangelands, the growth period was terminated and exploitation of rangeland was started. In most parts of the dry-lands, wheat has been cultivated and the tests of agricultural lands were performed in these areas.

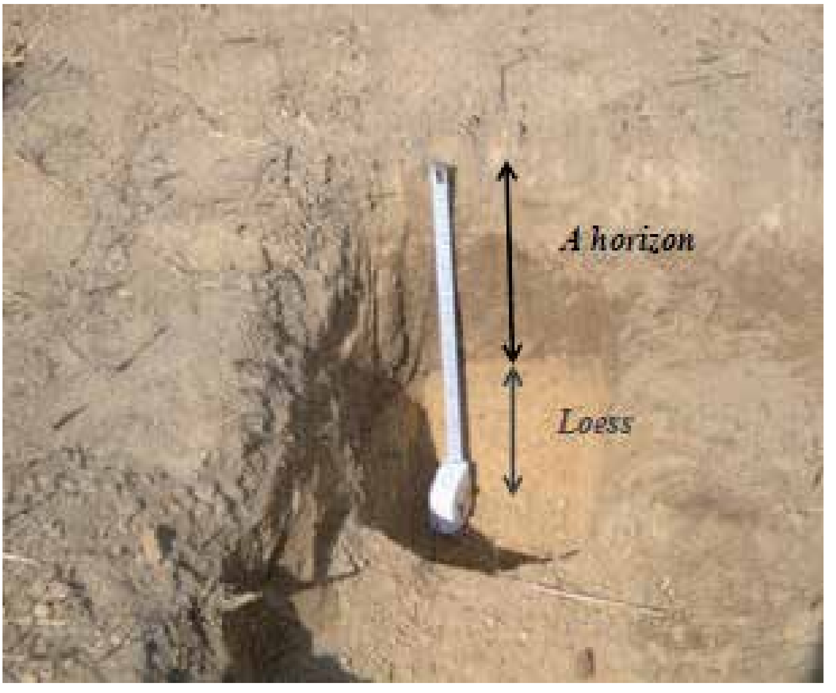
Zone	**Age**	**Symbols**	**Lithology**	**Formation**	**Area**	
					(ha)	**(%)**
Alborz and Koppeh Dagh	Quaternary	Q^{al}	Recent alluvium (River beds)	--	12996	5.94
		Q_{t2}	Younger Terraces	--	17042	7.78
		Q_{t1}	Older Terraces	--	14184	6.33
		Q^{l}	Loess deposits	--	126110	56.30
		P_{l}	Conglomerate and Sandstone	--	1094	0.49
Koppeh Dagh	Paleogene	E^{kh}	Shales	Khangiran Formation	1700	0.76
		E^{ch}	Limestone	Chehl Kaman F.	618	0.28
	Cretaceos	K^{at}	Shales	Atamir F.	1207	0.54
		K^{s}	Shales	Sanganeh F.	14736	6.58
		K^{sa}	Marl	Sarcheshmeh F.	8314	3.71
		K^{t}	Limestone	Tirgan F.	11013	4.92
		K^{z}	Sandestone	Zard F.	1552	0.69
	Jurassic	J^{mz}	Limestone	Mozduran F.	1581	0.71
		J^{cb}	Limestone and Marl	Chamanbid F.	4013	1.79
Alborz	Jurassic	J_{l}	Limestone and Oolitic Lst.	Lar F.	7158	3.20

Table 1. Stratigraphic characteristics and area of geological units of Sarab Drainage Basin

Picture 2. Collecting runoff at the outlet of plot

- Estimation of the percentage of vegetation including live and litter and determination of the tests. For measuring the percentage of vegetation cover in the area where rainfall simulator was used, a square quadrate of 1m×1m was used which gives reasonable results in these areas (Moghaddam,2007). It should be mentioned that due to structural and physical conditions of loesses, there is no rock and rock debris on the surface.
- Due to the fact that maximum wetted depth was 12 centimeters, for determining physical and chemical properties of the samples in the laboratory, samples (total of 69 samples) were taken from the top 20 centimeters materials adjacent to each plot .Also adjacent to each plot, loess was sampled for determination of apparent specific weight (bulk density) with steel cylinder having the volume of 360 cubic centimeters. In each land unit, a profile was dug to determine the depth of A-horizon (Picture 3).
- Runoff and sediment of each plot were collected in special bottles and transferred to the laboratory. After separation of sediments and drying of samples in Ovon for 24 hours and 105 degree centigrade temperature (Feiznia, 2008), the amount of produced sediments at the end of rainfall was measured.
- In area where rainfall simulator was used, descriptive table was completed (Table2),in which information about geographic coordinate, slope percentage, elevation, depth of A-horizon, wetted depth, the time of runoff appearance and other necessary information of each sample, were entered. Despite of the fact that slope of the land unit was known, percentage of the slope in the area where rainfall simulator was used, was accurately measured.

After transferring samples to the laboratory, the samples were sieved using a sieve with 2 mm apertures, and the weight percentage of gravel in each sample was measured which was low(due to the nature of loesses). Then, the following physical and chemical analyses were performed on each sample: Apparent specific weight(bulk density), percentage of moisture during performance of the test, sediment concentration of runoff



Picture 3. Measurement of the depth of A-horizon in each land unit

samples, percentages of clay, silt and sand in surface materials by hydrometric method, acidity using pH meter in saturated mud, electrical conductivity using Electro conductivity meter in saturated extract, percentage of organic matter by oxidation method, percentage of gypsum, percentage of equivalent calcium carbonate by Calcimetry, cations by flame photometry and titration with EDTA (Ethylene Diamine Tetra Acetic acid), anions by Titrometry, cation exchange capacity by Bour Method and determination of kind and percentage of clay minerals by X-Ray Diffraction Analysis.

- Controlling data and repetition of tests when required.
- The results were analyzed using SPSS and Excel softwares by the following methods:

1. Fore investigating the fact that whether the runoff and sediment production have normal distribution or not (this investigation is necessary for searching the regression models), Kolmogrove-Smirnov Test was used (Kalantari, 2006).
2. For investigating the effect of two predominant landuses of rangeland and dry-farming cultivation on the amount of sediment, Independent T-Test was used (Bihamta and Zare Chahouki, 2008).
3. For investigating the changes of runoff and sediment production of loesses in different slope classes, One Way Variance Analysis (ANOVA) was used. For determining the fact that which slope classes are different from each other, the method of Clustering of Means used. For this, Duncan Method was used in order to be able to compare all slopes classes dually (Bihamta and Zare Chahouki, 2008).

   For determining logical relationships among different variables, correlation and regression analyses were used. Correlation investigates the relationship between variables with sediment and runoff productions and regression investigates the relationship of effective factors with the amount of sediment produced. Due to the fact

<table>
<tr><th colspan="2">Parameters</th><th>Quantity or Quality</th><th>Explanation</th></tr>
<tr><td colspan="2">Time</td><td></td><td></td></tr>
<tr><td colspan="2">Region</td><td></td><td></td></tr>
<tr><td colspan="2">Work unit</td><td></td><td></td></tr>
<tr><td colspan="2">Treatment</td><td></td><td></td></tr>
<tr><td colspan="2">longitude</td><td></td><td>UTM</td></tr>
<tr><td colspan="2">latitude</td><td></td><td>UTM</td></tr>
<tr><td colspan="2">(m) Elevation</td><td></td><td></td></tr>
<tr><td colspan="2">Weather condition</td><td></td><td></td></tr>
<tr><td colspan="2">Slope direction</td><td></td><td></td></tr>
<tr><td colspan="2">Erosion type</td><td></td><td></td></tr>
<tr><td colspan="2">Landuse type</td><td></td><td></td></tr>
<tr><td colspan="2">Dominant species</td><td></td><td></td></tr>
<tr><td colspan="2">Locality slope (%)</td><td></td><td></td></tr>
<tr><td rowspan="4">Land cover (%)</td><td>Vegetation cover</td><td></td><td></td></tr>
<tr><td>cover Litter</td><td></td><td></td></tr>
<tr><td>Rock and Pavement cover</td><td></td><td></td></tr>
<tr><td>Bare Soil cover</td><td></td><td></td></tr>
<tr><td colspan="2">Experiment duration(cm)</td><td></td><td></td></tr>
<tr><td colspan="2">Simulated rain intensity(mm/h)</td><td></td><td></td></tr>
<tr><td colspan="2">Runoff production time(min)</td><td></td><td></td></tr>
<tr><td colspan="2">Total runoff volume(cm^3)</td><td></td><td></td></tr>
<tr><td colspan="2">Depth of A-horizon in the soil(cm)</td><td></td><td></td></tr>
<tr><td colspan="2">Depth of wetted zone(cm)</td><td></td><td></td></tr>
<tr><td colspan="2">Photo No.</td><td></td><td></td></tr>
<tr><td colspan="2">Team members</td><td></td><td></td></tr>
<tr><td colspan="2">Other explanations</td><td colspan="2"></td></tr>
</table>

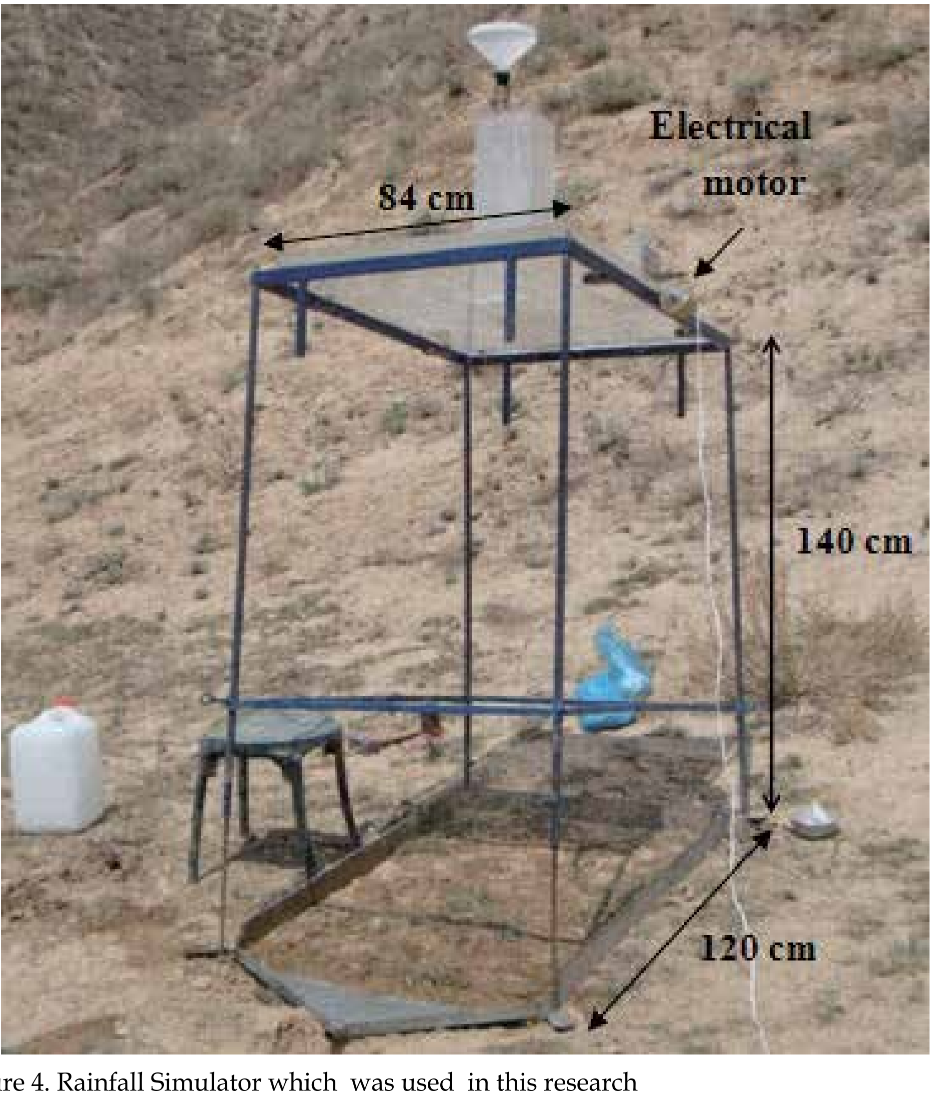
Table 2. Descriptive information of the areas in which rainfall simulator tests were performed

that the data have interval scale nature, for determination of correlation between variables with sediment and runoff productions, Pearson Correlation Coefficient was used. This coefficient usually changes between +1 and -1, in which the number indicts the slope and the sine shows the direction of linear relationship (Bihamta and Zare Chahouki, 2008).

4. For predicting the variations of the amount of produced sediments from physical and chemical characteristics and determination of the share of each on explanation of sediment production, multiple regression method was used. For doing this, first the factors that have significant correlation with the amount of produced runoff and sediment were selected as independent variables and the amount of produced runoff and sediment of each plot as dependent variable in Stepwise method regression analysis. In this method, the most important variable are entered into regression equation one by one and this function is continued until the error of significant test reaches %5(Kalantary,2006). For observation of co-linearity between the present variables in the extracted models, Variance Inflation Factor (VIF) was considered (Montgomery et al., 2001).

10. Specification of rainfall simulator

In general, these equipments are classified into two main types. In some of them, the initial falling velocity of raindrops is zero. In other type, rain drops fall from nozzles which are under pressure and have initial velocity. The equipment which was used in this research is type one from Soil Conservation and Watershed Management Research Center which has been designed and fabricated according to climatic conditions of Iran and can simulate intensities of 5 to 80 mm per hour (Picture 4). It has a plot with dimensions of 84 cm× 120 cm in which all of the resulted runoff and sediments are directed to the outlet where they can be collected(Picture 5). The equipment can be regulated and installed in different slopes. The specifications of the rainfall simulator are shown in Table 3. This equipment produces rain drops which fall without initial velocity under gravity force.



Picture 4. Rainfall Simulator which was used in this research

Picture 5. Plot of rain fall simulator

Dimension	84cm×120cm×160cm
Elevation of falling drops above slope	1.45m
Average aperture diameter	0.66 mm
Area of plot	1.008 m^2
Initial velocity of drops	0
Number of capillary tubes	204
Length of tubes	8 mm
Voltage of electrical motor of equipment	12 volts
Capacity of reservoir of equipment	80 liters

Table 3. Specification of rainfall simulator

11. Different parts of the equipment are as follows

a. The reservoir and the splashing part of the rainfall simulator are made of Plexiglas with thickness of 8 mm. The capacity of these two parts is 80 liters.
b. 12 volts electrical motor is located on special small balls for easier movement of the reservoir. This prevents falling of drops in one point.
c. The metal stand of the equipment slides and is adjustable from 140 to 180 centimeters in order for the reservoir and falling plate to be adjusted on the slope for being completely horizontal and the equipment to be used on slopes.
d. Metal frame of plot: This frame is hammered on the ground, just under the part which produces rainfall. All resulted runoff and sediment from rainfall are collected and directed to the outlet which are collectable.

12. Clay minerals in loesses

Clay minerals are the main factors in attachment of silt particles in loesses, therefore, play important role in erodibility and physical-chemical properties of loesses (Khormali and Kehl, 2010). About 23 samples from the top 20 centimeters of materials (one sample from each land unit) were analyzed for determination of clay minerals by X-ray diffraction (XRD) method. In general, clay minerals are about %10 in different samples. The rest are other minerals, majority of them are Quartz, then Feldspar and Carbonate calcium. For purization of clay and removing chemical substances which act as cement, sodium acetate normal in 80 degrees centigrade, for oxidation of organic matter, oxygen peroxide %30 and for removing Iron oxide, sodium dithionate were used. Then pure clay of each sample was separated using sedimentation method.

For the peaks of XRD to be obvious, facilitating identification of clay mineral types, five analyses with different treatments were performed as follows (Moore and Reynolds,1989):

1. XRD of normal tile(raw sample)
2. XRD of tile saturated with KCl(which later on indicated as K)
3. XRD of tile saturated with KCl and heated to 550 degrees Centigrade for four hours(KT)
4. XRD of tile saturated with $MgCl_2$(MG)
5. XRD of tile saturated with $MgCl_2$ – Ethylene Glycol(MGG)

Figure 6 shows a XRD difractogram from land unit A-SRE-1.

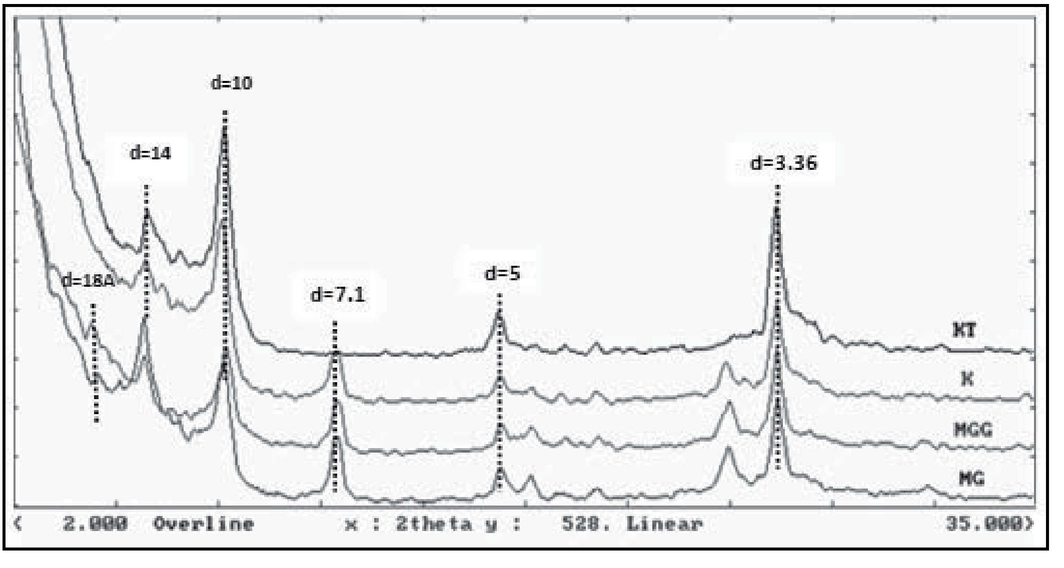


Fig. 6. XRD difractogram of loess of land unit A-SRE-1. letters MG, MGG, K and KT written on peaks show $MgCl_2$, $MgCl_2$ - Ethylene Glycol, KCl and KCl-heated treatments of clay tiles.

13. Results

13.1 Erosion features of loesses

In the studied area, different erosional features with different intensities are present. Water erosion is the main erosion processes of the area and terraces of wind erosion were not observed. Erosional features of the area are described below (Figure 7):

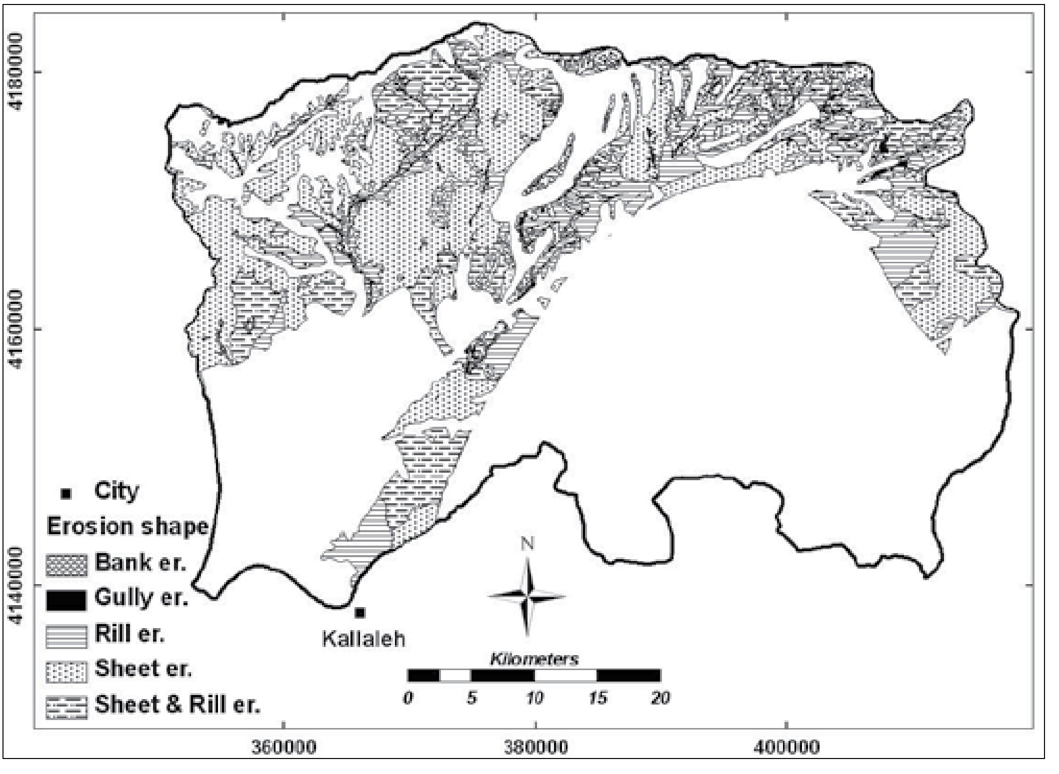


Fig. 7. Map of erosional features of studied area

a. Surface Erosion

Due to abundance of silt-size particles and lack of cement between particles, loesses are usually friable and shortage of vegetation causes particle susceptibility to rain drop impact and surface runoff which appear as surface erosion throughout the studied area, This feature is one of the most prominent erosional features in the area, is seen both in rangelands and dry- farming lands and play important role in sediment production of the area. During rainfalls, sediment-laden water flows are observed at the foot of slopes. With regard to the amount of surface flow, slope, vegetation cover of soil, intensity of surface erosion are different in different parts of the area. Surface erosion in rangeland is seen as the appearance of roots (Picture 6) and in cultivated land as light sports or shortage of crops in growing seasons in some parts of agricultural lands (Picture 7). This kind of erosion acts slowly but finally most of the fertilized surface layer of soil is lost and the underlying loess sediment is appeared. Transported materials, from surface erosion are usually fine clay and organic matter.

Picture 6. Surface erosion in rangelands (route to Islamabad Village)

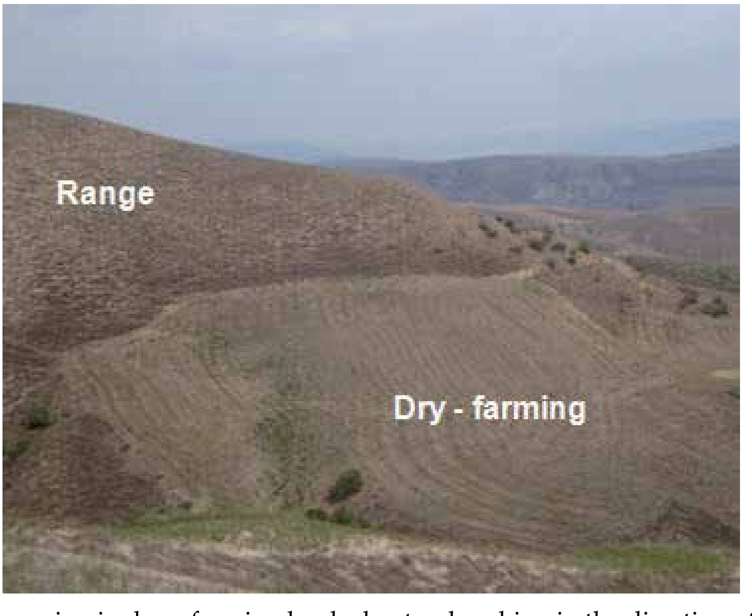
Picture 7. Surface erosion in dry-farming land (south of Dahane Village)

Due to the presence of excess livestock, overgrazing and entrance of livestock to rangeland in inappropriate times, tracks appear as notable and visible lines (microterrace) on slopes (Picture 8). Due to the pressure of over population of livestock, soil is compacted and losses its infiltration capacity and vegetation growth, therefore, runoff and consequently erosion are increased.

Picture 8. Microterrace on rangelands (Route to Oghchi Village)

b. Rill erosion

Rill erosion is not usually seen on loesses of the area and is mostly limited to sloped cultivated lands (Picture 9), because water is concentrated in rills resulting from ploughing and flows down the slope with higher velocity. The depths of rills may be 20-40 centimeters, but with later ploughing, there is usually no sign of rills on the slopes.



Picture 9. Rill erosion in dry – farming lands due to ploughing in the direction of slope (Route to Roshan Dareh Village)

c. Gully erosion

Contrast to rill erosion, gully erosion is the prominent erosion feature in the studied area, which in addition to soil loss, causes major damages to agricultural lands, roads, houses and other establishments. Gully erosion starts as headcuts in most parts of the area and it happens suddenly. In some parts, stepped gullies are observed which in time change to single gully. In addition to the nature of loesses and their erodibility, degradation of ranges and agricultural lands, increase runoff volume which causes formation of big gullies(Picture 10). The walls of gullies are falling, collapsing and retreating which cause increase of the area and volume of gullies and intensification of damages. In some parts of gullies, vegetation growth has stabilized the substrate. In regard to the gathered information from residences and local experts, the rate of gully advancement in the area is different and may reaches 10 m/y.

Picture 10. Gully erosion (Gharnagh Village). Advancing headcut toward the village is shown in the picture with arrow.

d. Bank Erosion

In the studied area, especially in low-slope regions, meandering processes (Picture 11), mainly along the main drainages, have caused bank erosion (Picture 12) which vanishes agricultural lands adjacent to drainages each year. The exterior part of the curve of river is undercut due to impact of water flow and nature of loesses and falls down in blocks.

Picture 11. Meander (near Tamer Village). Flow direction is shown with arrow in the picture

Picture 12. Bank erosion (adjacent to Haji Beik Village)

e. Mass Movements and Landsliding

Due to semi-arid climatic conditions and low rainfall, mass movements are not frequent in the area and are formed after bank erosion along drainages (Picture 13). After undercutting and degradation of walls, loess slope slides as rotational slides to river-bed, due to high slope and lack of cement between loess particles.

Picture 13. Landslide in the studied area (Rout to Oghchi Village)

f. Tunnel Erosion

One of the erosional features seen in the area is tunneling or piping (Picture 14) which after spread of the dimension of tunnels and collapse of their roofs, gullies are formed. Porosity and chemical characteristics of the loesses and also hydraulic slope for flow of water in loesses are the major factors in development of tunnel erosion. This erosion is intensified with the animal activities such as mice. Due to animal activities, holes are formed at the surface. The holes are connected in the subsurface to form channels in which water flows and transports soil and sediment and their dimensions are increased. Finally their roof collapse and gullies are developed.

Picture 14. Tunnel erosion or piping in loesses (Route to Oghchi Village)

14. Slope

Figure 8 shows slope map of the area. Class slope of 10 to %20 is most widespread one in the studied area. In slopes higher than %30, agricultural lands are less present due to difficulty in access and agricultural activities. The weighted mean of the slope of the studied area is %16.5 .

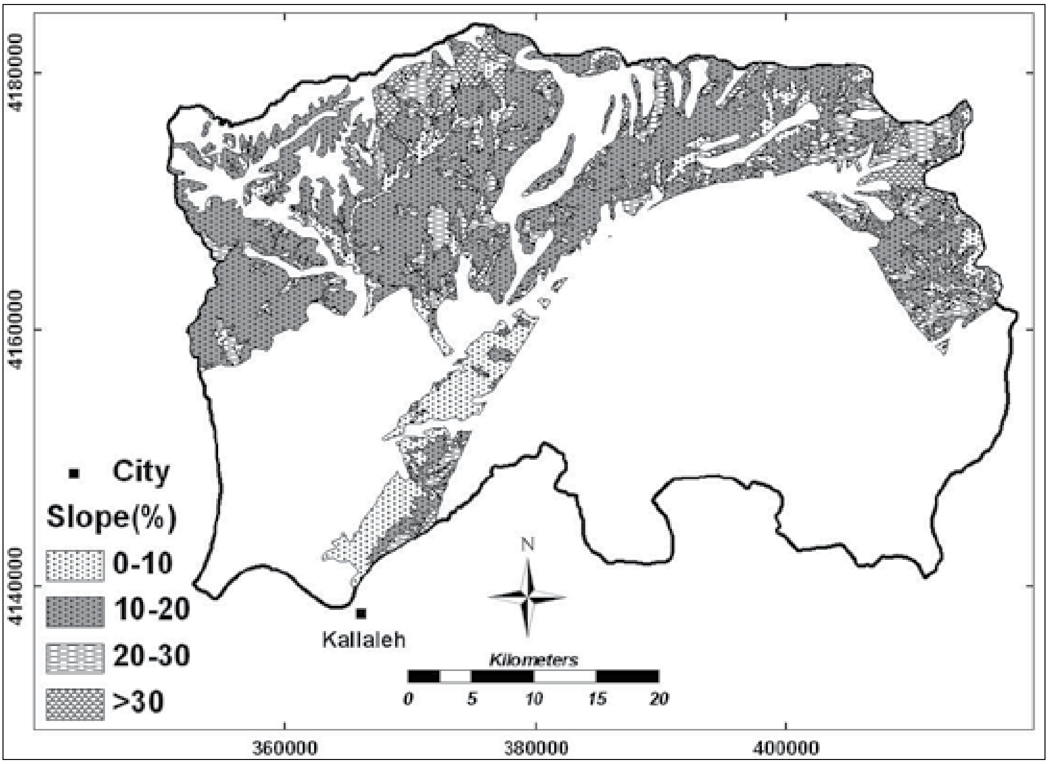


Fig. 8. Slope map of the studied area

15. Landuse

Landuse of the Sarab Drainage Basin are: Cultivation, range, forest and residential areas (villages) (Figure 9). Forest makes a small part in southeastern part of the basin and consists of *Quercus*, *Ulmus* and *Acear* species. There is also hand-planted forest consisting of *Pinus* species. In semi-arid zones, there is no forest and dry-farming lands mainly consisting of wheat, barley, sunflower and watermelon are present which due to not performing fallow, lack of vegetation after harvesting, ploughing in the direction of slope and nature of loesses, they are highly erodible. Rangeland mainly consist of *Artimisia+Dactylis glomerata*, *Artimisia +Poa bulbusa*, *Carpinus+Artimisia* and *Poa bulbusa+Medicago sativa* which due to not paying attention to the season for exploitation, they are overgrazed by tribal and villagers livestock and are erodible.

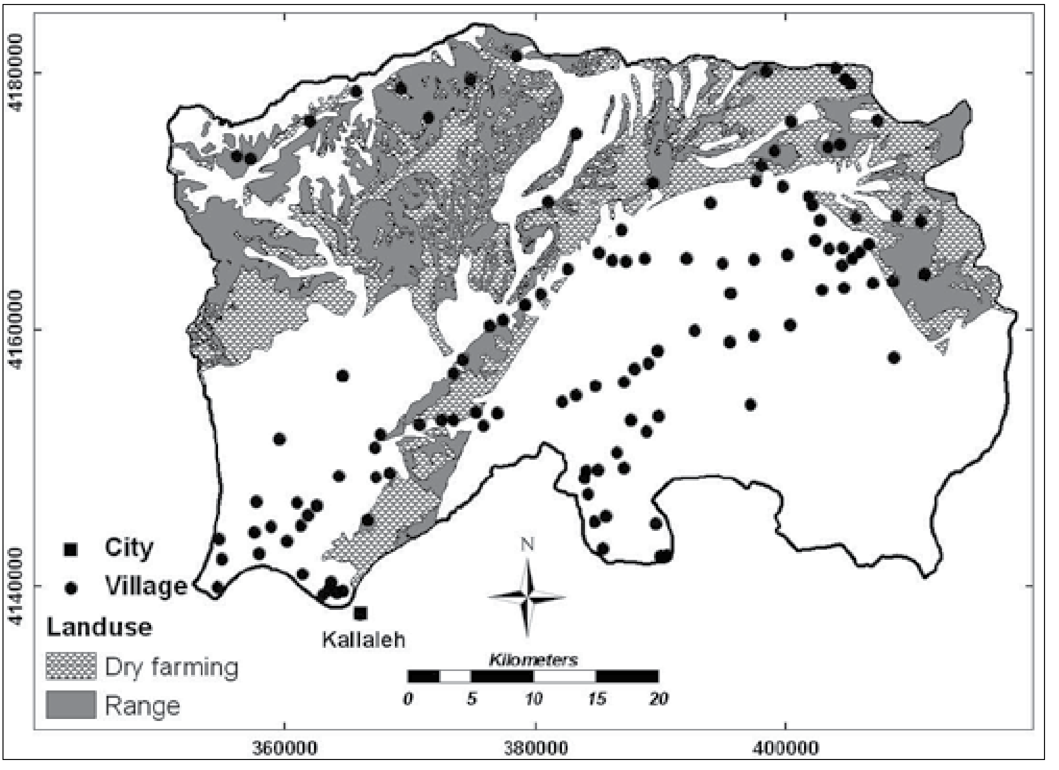


Fig. 9. Landuse map of the studied area

16. Land units

Figure 10 shows the land units of the area which are 23 units and more than 300 polygons. Each land unit is assigned letters and numbers. The first letter of the name of land unit is land use (A for dry-farming cultivation and R for rangelands). The second letter is for erosional features (SE surface erosion, RE rill erosion and SRE for surface and rill erosion) and latest number is for slope class (1 for class 0-%10, 2 for 10-%20, 3 for 20-%30 and 4 for more than 30 percent). Among the polygons, the ones which are accessible, having the largest area and are good indicators of similar polygons, were chosen (Figure 11), Rainfall simulator analyses were performed on each one with three repetitions and the resulted runoff and sediment were collected and measured.

17. Results of field and laboratory analyses

Table 4 shows the mean and variation coefficient of all measured variables including physical and chemical properties of the samples and variables measured in the field. The amount of electrical conductivity is usually bellow 3 ms/cm, the abundance of silt-size particles is more than %55 is completely evident and in some samples reaches %70. In contrast, abundance of clay particles is not more than %30 and the mean amount of sand in all samples is less than %20. Gypsum is not present in many samples or is little. Carbonate anion is not present.

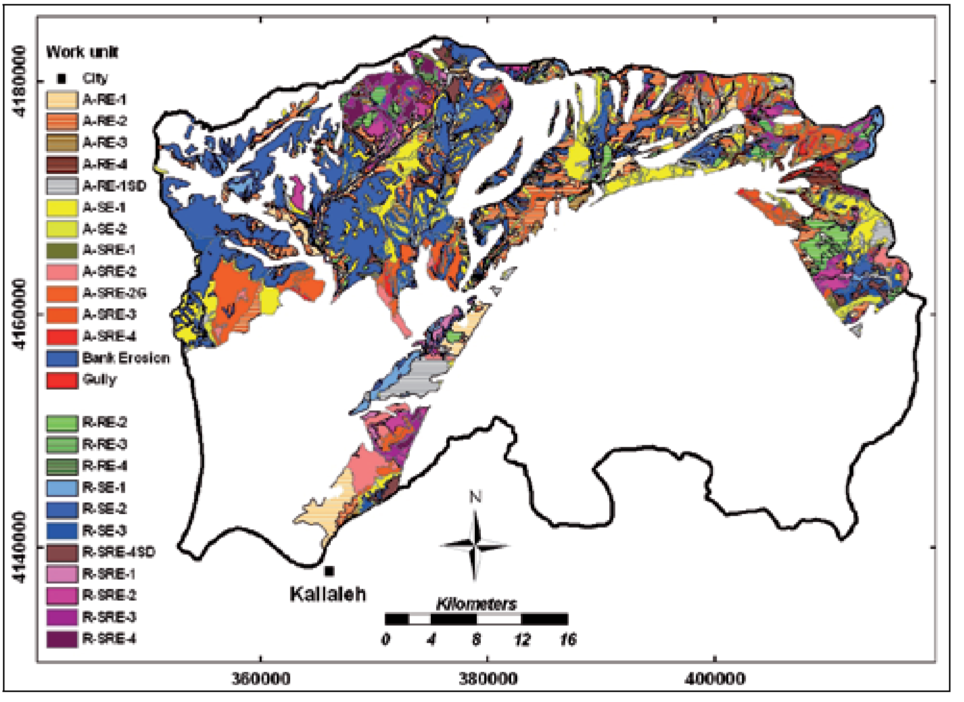


Fig. 10. Land units map of the studied area

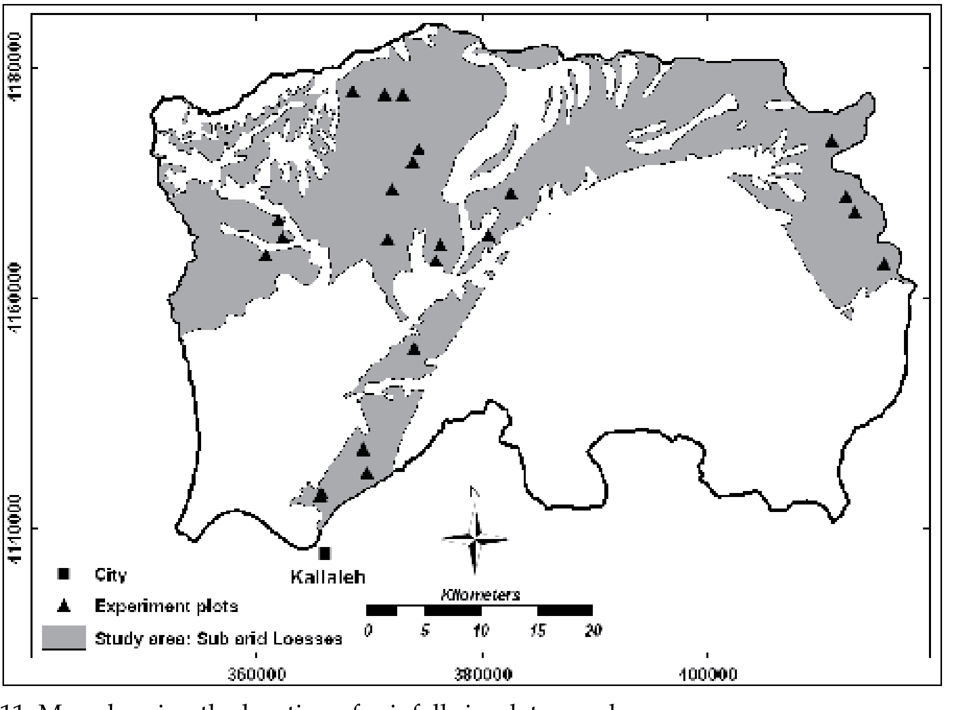


Fig. 11. Map showing the location of rainfall simulator analyses

Variable	Unit	N	Mean	Coefficient of variation (%)
Total runoff volume	cc	69	1653.61	39.92
Turbidity	gr/lit	69	17.51	61.73
Plot sediment	gr/m^2	69	32.36	85.83
Slope	%	69	19.46	49.27
Land cover	%	69	23.19	26.40
A-horizon depth	cm	69	19.83	46.07
Humidity	%	69	6.48	23.27
Bulk density	gr/cm^3	69	1.34	4.41
EC	ms/cm	69	2.20	17.99
pH		69	7.93	1.68
Organic mater	%	69	1.54	19.62
$CaSO_4$	meq/100s	69	0.78	121.05
Sand	%	69	19.36	22.55
Clay	%	69	28.88	13.55
Silt	%	69	51.75	8.91
CEC	cmol/kg	69	17.16	12.16
equivalent calcium carbonate	%	69	14.48	17.68
Ca^{++}	meq/lit	69	15.28	18.37
Mg^{++}	meq/lit	69	12.80	31.36
K^+	meq/lit	69	0.36	52.07
Na^+	meq/lit	69	26.11	46.97
Sum of cations	meq/lit	69	54.55	25.38
CO^{3--}	meq/lit	69	0.00	-
HCO^{3-}	meq/lit	69	3.42	19.20
SO^{4--}	meq/lit	69	35.66	39.29
Cl^-	meq/lit	69	15.39	46.08
Anion sum	meq/lit	69	54.48	28.71
SAR		69	7.00	46.13
ESP		69	8.14	48.60
Illite	%	69	31.30	13.60
Chlorite	%	69	25.43	16.43
Kaolinite	%	69	19.35	19.27
Smectite	%	69	22.17	17.50
Mixed layer Clay Minerals	%	69	2.61	159.62

Table 4. Descriptive statistics of all measured variables

work unit	Geo-logy	Erosion type	Slope	treatment	Sample no.	Runoff	Turbi-dity	Plot sediment
			%			cm³	gr/lit	gr/m2
A-RE-1	Loess	Rill erosion	0-10	1	1	570	10.44	5.95
				2	2	800	9.52	7.62
				3	3	710	12.12	8.61
A-RE-1SD	Loess	Rill erosion	0-10	1	4	590	12.95	7.64
				2	5	410	7.88	3.23
				3	6	510	10.25	5.23
A-RE-2	Loess	Rill erosion	10-20	1	7	1,060	21.07	22.33
				2	8	1,320	15.96	21.07
				3	9	1,620	17.33	28.07
A-RE-3	Loess	Rill erosion	20-30	1	10	1,790	37.23	66.64
				2	11	1,970	28.41	55.97
				3	12	2,330	23.78	55.41
A-RE-4	Loess	Rill erosion	30-40	1	13	2,470	38.83	95.91
				2	14	2,850	35.63	101.55
				3	15	2,700	28.39	76.65
A-SE-1	Loess	Sheet erosion	0-10	1	16	1,040	12.18	12.67
				2	17	1,160	11.23	13.03
				3	18	970	9.75	9.46
A-SE-2	Loess	Sheet erosion	10-20	1	19	1,380	19.12	26.39
				2	20	1,500	13.96	20.94
				3	21	1,190	15.15	18.03
A-SRE-1	Loess	Sheet & rill	0-10	1	22	820	11.31	9.27
				2	23	570	9.87	5.63
				3	24	750	13.56	10.17
A-SRE-2	Loess	Sheet & rill	10-20	1	25	940	23.96	22.52
				2	26	1,400	25.44	35.62
				3	27	1,500	19.22	28.83
A-SRE-2G	Loess	Sheet & rill	10-20	1	28	1,550	26.82	41.57
				2	29	1,710	20.47	35.00
				3	30	1,410	21.24	29.95
A-SRE-3	Loess	Sheet & rill	20-30	1	31	1,910	36.74	70.17
				2	32	1,410	34.10	48.08
				3	33	2,100	27.72	58.21
A-SRE-	Loess	Sheet & rill	30-40	1	34	2,200	50.85	111.87
				2	35	2,370	47.50	112.58
				3	36	2,400	45.56	109.34

Table 5. Data from work unit in Agriculture landuse

Clay minerals of loesses are smectite (18 A° peak in MGG), illite (10 A° peak), kaolinite (considerable decrease of 7.1 A° peak in KT relative to other treatments) and chlorite (14 A° peak in all treatments). Clay minerals in the order of decreasing amount are as follows: Illite, Chlorite, Smectite, Kaolinite and low amount of Mixed-layered clay minerals. In areas reaching arid climate, Smectite increases. Tables 5 and 6 show runoff volume, sediment concentration and sediment production of each plot in 3 repetitions in each land unit. Table 7 shows the average runoff and sediment in dry-farming and range Landuse.

work unit	Geology	Erosion type	Slope	treatment	Sample no.	Runoff	Turbi-dity	Plot sediment
			%			cm^3	gr/lit	gr/m2
R-RE-2	Loess	Rill erosion	10-20	1	37	1,160	8.65	10.03
				2	38	1,420	7.23	10.27
				3	39	1,310	10.24	13.41
R-RE-3	Loess	Rill erosion	20-30	1	40	1,670	16.63	27.77
				2	41	1,750	12.80	22.40
				3	42	1,550	15.62	24.21
R-RE-4	Loess	Rill erosion	30-40	1	43	2,140	21.02	44.98
				2	44	2,280	22.63	51.60
				3	45	2,420	16.57	40.10
R-SE-1	Loess	Sheet erosion	0-10	1	46	1,469	2.45	3.60
				2	47	1,120	3.16	3.54
				3	48	1,000	2.25	2.25
R-SE-2	Loess	Sheet erosion	10-20	1	49	2,220	6.44	14.30
				2	50	1,820	5.61	10.21
				3	51	1,600	8.39	13.42
R-SE-3	Loess	Sheet erosion	20-30	1	52	2,530	12.80	32.38
				2	53	1,750	11.53	20.18
				3	54	2,180	10.41	22.69
R-SRE-1	Loess	Sheet & rill	0-10	1	55	970	3.15	3.06
				2	56	740	5.20	3.85
				3	57	1,050	3.90	4.10
R-SRE-2	Loess	Sheet & rill	10-20	1	58	1,930	10.56	20.38
				2	59	2,340	14.75	34.52
				3	60	1,870	8.81	16.47
R-SRE-3	Loess	Sheet & rill	20-30	1	61	2,010	16.03	32.22
				2	62	2,340	18.10	42.35
				3	63	2,090	17.18	35.91
R-SRE-4	Loess	Sheet & rill	30-40	1	64	2,740	16.34	44.77
				2	65	2,420	19.70	47.67
				3	66	2,980	14.55	43.36
R-SRE-4SD	Loess	Sheet & rill	30-40	1	67	2,550	16.82	42.89
				2	68	2,280	21.25	48.45
				3	69	2,420	22.52	54.50

Table 6. Data from work unit in rangeland landuse

Variable	Unit	Landuse	N	Mean
Runoff observation time	min	Dry-farming	36	8.42
		Range	33	6.36
Moisture depth	cm	Dry-farming	36	5.50
		Range	33	3.33
Total runoff	cm^3	Dry-farming	36	1443.8
		Range	33	1882.3
Runoff	mm	Dry-farming	36	1.44
		Range	33	1.88
Runoff coefficient	(%)	Dry-farming	36	9.02
		Range	33	11.76
Turbidity	gr/lit	Dry-farming	36	22.37
		Range	33	12.22
Plot sediment	gr/m^2	Dry-farming	36	38.64
		Range	33	25.51

Table 7. Average runoff and sediment in dry-farming and range landuses

18. Discussion

Investigation of the results indicates that the elevation of resulted runoff from produced rainfall on the plots varies from 0.41 to 2.98 mm and runoff coefficient from 2.6 to %18.6 . Sediment concentration which is due to runoff and sediment production together is between 2.25 to 50.8 gr/lit and sediment production from 3.06 to 112.5 gr/m^3. If unit change for a plot having the highest amount of sediments, the amount of sediment production for this type of rainfall is 1.125 ton/hectare which is considerable.

Kolmogrove-Smirnov Test shows that runoff and sediment production data have normal distribution. In independent t-test, with regard to the amount of significant for Levene Test which is lower than 0.05, the variance is not equal in two landuses, therefore with regard to significant of this part which is 0.028, there are differences between sediment production in two cultivations and rangeland landuses so that in dry-farming cultivation, the amount of sediment production is %50 more than rangeland which is due to decrease of soil structure stability due to yearly cultivation activities and overgrazing(Zhou et al., 2010). Of course deep ploughing decreases runoff volume but increases erosion and sediment production. Figure 12 shows sediment variations in two prominent landuses in the area.

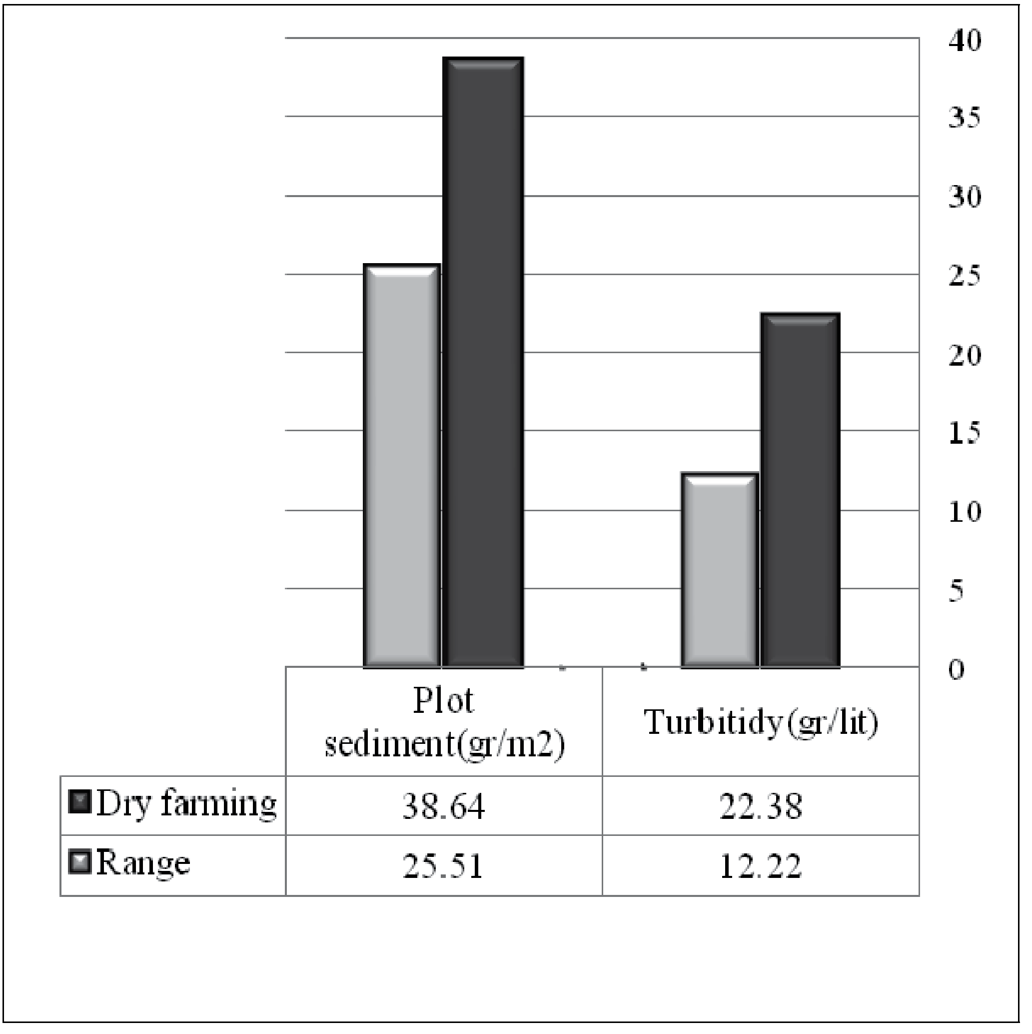


Fig. 12. Mean sediment concentration and sediment production in rangeland and dry-farming cultivation

In ANOVA Test, due to the fact that the level of significant is lower than 0.01, there are significant differences in runoff and sediment production between different slope classes. For determining which slope classes are different from each other, Clustering of Mean Method was used. The results of Duncan Method indicates the notable effect of slope on the amount of runoff and sediment production, so that each slope class is clustered in a separate group and is indicative of meaningful difference between slope classes. Figure 13 and 14 show mean amount of runoff and sediment in different slope classes, respectively.

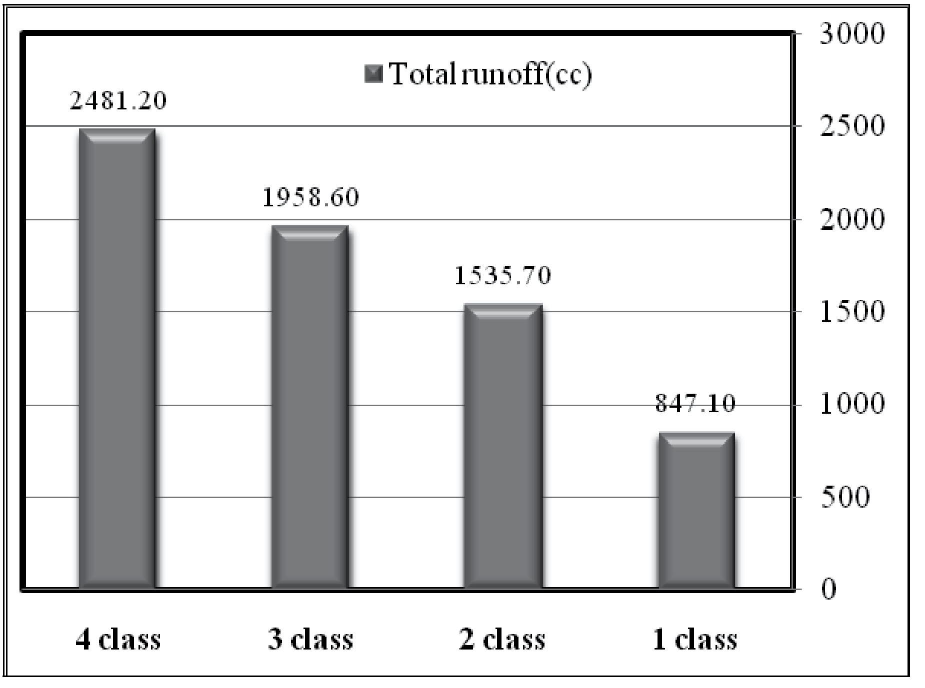


Fig. 13. Mean runoff production in each slope classes

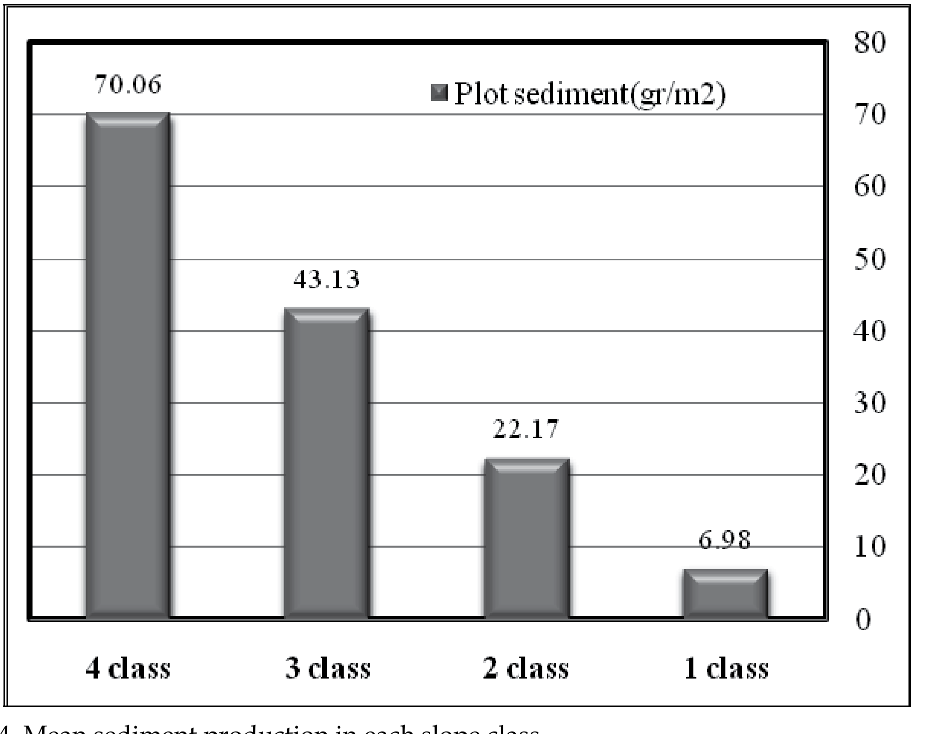


Fig. 14. Mean sediment production in each slope class

Depended variables / In depended variables	Unit	Total runoff	Turbidity	Plot sediment
		cm^3	gr/lit	gr/m^2
slope	%	.880(**)	.665(**)	.80 (**)
Land cover	%	-.298(*)	-.273(*)	-.36 (**)
A-horizon depth	cm	-.428(**)	-.107	-.25 (*)
humidity	%	.27 (*)	.24 (*)	.21
Bulk density	gr/cm^3	-.11	.04	-.04
EC	ms/cm	.24 (*)	.04	.10
pH		.30 (*)	.21	.31 (**)
Organic mater	%	-.31 (**)	-.16	-.28 (*)
$CaSO_4$	meq/100s	-.15	-.19	-.17
Sand	%	-.25 (*)	-.17	-.26 (*)
Clay	%	-.35 (**)	-.27 (*)	-.33 (**)
Silt	%	.54 (**)	.39 (**)	.53 (**)
CEC	cmol/kg	-.16	.46 (**)	.27 (*)
equivalent calcium carbonate	%	.28 (*)	.02	.06
Ca^{++}	meq/lit	.09	-.42 (**)	-.29 (*)
Mg^{++}	meq/lit	-.23 (*)	-.22	-.23
K^+	meq/lit	.29 (*)	.10	.16
Na^+	meq/lit	.46 (**)	.18	.30 (*)
Sum of Cations	meq/lit	.36 (**)	.01	.14
CO_3^{--}	meq/lit	.(a)	.(a)	.(a)
HCO_3^-	meq/lit	.20	-.01	.05
SO_4^{--}	meq/lit	.32 (**)	.02	.11
Cl^-	meq/lit	.23	.20	.25 (*)
Anion sum	meq/lit	.40 (**)	.11	.22
SAR		.48 (**)	.27 (*)	.38 (**)
ESP		.48 (**)	.28 (*)	.38 (**)
Illite	%	.12	.10	.13
Chlorite	%	.26 (*)	.13	.20
Kaolinite	%	-.53 (**)	-.20	-.33 (**)
Smectite	%	.17	.26 (*)	.29 (*)
Mixed layer Clay Minerals	%	-.04	-.15	-.12

(**) Correlation is significant at the 0.01 level (2-tailed). (*) Correlation is significant at the 0.05 level (2-tailed).

Table 8. Pearson Correlation coefficient between different measured variables with runoff volume, sediment production and sediment concentration

Table 8 shows Pearson Correlation Coefficient between different measured variables with runoff volume, sediment production and sediment concentration. With statistical investigation, it was found that slope with %80 and %88 correlation coefficients, has the highest direct relationship with the amount of produced sediment and runoff, respectively, these results are similar to a part of Ribolzi et al. (2010) results. After that is the amount of silt with %53 correlation coefficient with sediment production and %54 correlation coefficient with runoff production. Materials having higher amount of silt are easily dispread and transported and are more erodible (Meyer and Harmon, 1984). The amount of clay has negative relationship with sediment and runoff production. With increase in the amount of sand, permeability is increased and lower amount of runoff is produced, in addition, despite having low adhesion and easy to be separated due to their coarser sizes, sand grains resist to transportation by runoff and produce lower amount of sediment. This result is similar to Vanesland et al. (1987) result. Vegetation cover has a negative correlation coefficient of %36 and the highest adverse relationship with sediment production and meaningful negative relationship with runoff. The reason is decrease of rainfall drop energy and velocity of surface runoff by vegetation (Yu et al. 2006). Percentage of Kaolinite has the highest negative correlation coefficient with runoff volume (%53). Other variables have weaker relationship with sediment and runoff productions. Chemical characteristics also affect runoff and sediment production so that the amount of organic matter has reverse relationship with sediment and runoff productions. In the studied area, the effect of Mg^{++} ion on decreasing sediment production is lower than Ca^{++} ion, so that it does not have meaningful correlation. Two factors of SAR and ESP, although they are not in regression models, have positive relationships with runoff and sediment production. These two are affected by other characteristics such as cations which are important in soil aggregate stability, soil infiltration and formation of surface crusts. The investigation of correlation matrix shows that none of the parameters can solely describe all observed variations in the amount of sediment.

Model no.	**Dependent variable**	**Adjusted R^2**	**Sig.**	**Regression Model**	**Standardized regression model**
1	Runoff(cm^3)	0.812	.000	$Y_{Run.}$= 54.254Sl–31.937Ka+18.704Co+ 739.80	$Y_{Run.}$= 0.788Sl–0.180Ka + 0.118Co
2	Sediment concentration (gr/lit)	0.771	.000	$Y_{Turb.}$= 0.798Sl+ 2.153CEC–1.084Ca-18.393	$Y_{Turb.}$= 0.707Sl+ 0.416CEC– 0.282Ca
3	Total sediment(gr/m^2)	0.809	.000	$Y_{Sed.}$= 2.144Sl+ 3.792CEC–2.071Ca+ 0.968Si – 92.90	$Y_{Sed.}$= 0.740Sl+ 0.285CEC– 0.209Ca+ 0.161Si

$Y_{Run.}$ = Total runoff volume (cm^3), Sl = slope (%), Ka = kaolinite mineral (%),
Co = Chlorite mineral (%), $Y_{Turb.}$= turbidity(gr/lit), CEC= cation exchange capacity(c mol/kg),
Ca= Calcium cation(meq/lit), $Y_{Sed.}$= Total sediment (gr/m^2), Si= silt (%)

Table 9. Regression analyses and obtained models for runoff and sediment

For anticipating variation of sediment production based on physical and chemical properties and determination of share of each variable on explanation of the amount of sediment production, Multiple regression analysis was used. For observing the phenomena of Co-linearity between variables in the extracted models, Variance Inflation Factor (VIF) was noted. In the obtained model VIF for all variables is less than the critical threshold (10) which indicates the absence of co-linearity between independent variables and that presence of all of them in the model is also meaningful. In Table 9, the summary of obtained models for produced runoff volume, sediment concentration and sediment production are shown.

19. Conclusion

Although it seems that a lot of factors are effective on runoff and sediment production of loesses, but investigation of the results show that a few number of key parameters are more important in the studied area and that other parameters have indirect effect on this matter. Slope is the most important factor in sediment and runoff production. Presence of Kaolinite decreases and the increase in the amount of silt increases sediment and runoff productions. Meyer and Harmon (1984) and Vanesland et al. (1987) also found similar results. Among chemical properties which were analyzed in this research, CEC and SAR have direct relationship and calcium cation, the amount organic matter have reverse relationships with sediment production. These are similar to a part of Hasanzade Nafuti et al. (2009), Vitharana et al. (2008) and Mahmoodabadi et al. (2009) results. Among clay mineral, smectite having week bounds between layers and being highly expandable, has direct relationship and Kaolinite being a stable clay mineral, has negative relationship with runoff and sediment production. Zhang et al. (2004) in studying loesses of China found similar relationships between erosion of loesses and the kind and amount of clay minerals. The results of regression analyses show that between the amount of runoff and sediment productions as dependent variables and independent variables with significant correlation, there is a significant relationship at %1 level. Among independent variables, only four factors: Percentage of slope, CEC, soluble Calcium cation and amount of silt, have important role in sediment production and slope and kaolinite and chlorite percentages have important role in runoff production so that these factors control %80 of sediment variations and %81 of runoff volume variations and other %20 relates to factors which are not studied in this research. Among the variables which were entered in the model, slope factor is more important so that one unit change in standard diversion of this factor produces 0.74 unit change in standard diversion of sediment production and 0.79 unit change in standard deviation of runoff volume which is because of its effect on increase of velocity, surface runoff and rain drop impact (Toy et al., 2002). Silt from the view point of size and cohesion is susceptible to erosion. CEC is effective on size and stability of soil aggregation. Calcium cation causes chemical bounds between aggregates and flocculates the grains, therefore has inverse relationship with sediment production of loesses.

In investigation of physical and chemical characteristics of loesses between surface and rill erosional features, it is found that there are not significant differences between these characteristics and the formation of special kind of erosion feature is mainly affected by slope amount and landuse type. The range lands are under overgrazing and without a plan throughout the year. This subject has caused many problems for natural reproduction of important and effected rangeland plants, the result of which being acceleration of erosion and sediment production. Construction of roads for access to cultivated lands across rangelands also has caused accelerated erosion. Also in recent years with promotion of technology, native people of the area use tractor and plough the lands in the direction of slope. These also cause intensification of erosion and sediment production.

20. Suggestion

The independent variables which were studied in this research explain only part of sediment production of loesses. Therefore, is necessary that in future researches, the role of Micro-organisms, Atterberg Limits and aggregate stability would also be studied. With regard to chemical properties of loesses and their erodibility, finding suitable measures for decreasing erosion and runoff through selection of suitable chemical fertilizers in cultivated lands which cause improvement of chemical characteristics of loesses, is recommendable. Performing landuse Planning on loesses and investigating economical and social conditions of the region for adjusting present landuses with the capability of loess are also important. Development of agro-forestry is also an effective way to control erosion of loesses.

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Plot-Scale Experimental Studies

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1. Introduction

1.1 Plot-scale experimental studies: structure, equipment, hydrologic monitoring

Plot-scale experimental studies are generally part of broader research projects aimed at improving the understanding of interrelations between processes involving hydrological, climatic and biological factors (Wainwright et al., 2000). Recently, these studies have become multidisciplinary, integrating fields such as hydrology, ecology and geomorphology. In a global environmental change and degradation context, plot-scale studies may provide information about runoff mechanisms, soil erosion and vegetation dynamics processes that result from these changes (Abrahams et al., 1995; Parsons et al., 1996). Furthermore, plot-scale studies may focus on water fluxes and sediment transport processes at controlled conditions using rainfall simulation (Wainwright et al., 2000; Rickson, 2001). It is important to note that process control generally involves simplifying a complex system that is highly variable in time and space (Wainwright et al., 2000; Abrahams et al., 1998; Parsons et al., 1998). However, plot-scale studies have the advantage of allowing for detailed process monitoring at small scale, providing a basic description of the most relevant aspects (Michaelides et al., 2009).

Plot-scale studies are also useful in providing experimental data involving rainfall, surface runoff and soil erosion. These data are used as reference in modeling conception, calibration and validation. However, there can be considerable variability in soil erosion processes, as well as limitations of models atempting to simulate these complexities (Nearing, 2004). For example, in a study using 40 cultivated plots in the United States the experimental data coefficient of variation ranged between 18-91%. In addition, this variation was found to decrease with increasing rainfall erosive power (Wendt et al., 1986). Ruttimann et al. (1995) found that soil loss varied up to 173% between replicates under the same treatment. In general, the capacity of the model in representing local physical system can be tested by comparing observed and simulated model data, using regression analysis. Regression coefficient values from several studies demonstrate that model efficiency increases as erosion variability decreases, such as when mean annual soil loss data are used (Nearing, 1998; Risse et al., 1993; Zhang et al., 1996). The USLE-Universal Soil Loss Erosion (Wischmeyer & Smith, 1978) soil erosion model was originally conceived by using statistical analysis of 20 years soil erosion data in natural and cultivated experimental plots, installed at 49 stations across the United States. It incorporated approximately 1000 events, producing a significantly representative database. In fact, USLE soil erosion model was developed primarily for agricultural purposes, in an atempt to simplify complex erosive interactions. Indeed, it paved the way for more refined modeling structures which consider the physical characteristics of the process.

Establishing an experimental plot often involves hydrological monitoring by using manual and automatic devices and fieldwork surveys to collect information on details such as plot topography, soil hydraulic characteristics, flora and fauna. In general terms, it is hypothesized that the plot represents local climate, soil and plant conditions. A plot-scale experimental study involving precipitation, surface runoff, soil erosion processes as well as the biological dynamics of local fauna and flora was developed in the semi-arid Brazilian Northeast (Moreira et al., 2009). Plot-scale studies often include topographic survey, analysis of soil surface characteristics such as roughness, crusting, cracking, and soil as an environment of biological activity for arthropods and other organisms. The plot is delimited and identifies the study area.

Hydrologic monitoring involves the measurement of variables, often requiring the installation of manual and automatic devices. Indeed, plot-scale studies in uncontrolled conditions tipically require the use of automatic devices. Water discharge monitoring implies the use of a measurement structure such as a Parshall flume or a tank at the downstream end of the plot. If a Parshall flume is used, discharge is monitored by using a stage-discharge relationship. Once the measuring structure is established, water surface monitoring is conducted by using manual (graduated rule) or automatic devices (water level logger). In case a tank is used, discharge is monitored by water surface variation as a function of time during the storm. After each event, the tank must be emptied and the sediment and particulate organic matter is collected, dried and analyzed. For each storm event, runoff was obtained by applying water balance equations including runoff, rainfall and the variation of the tank water level during the storm.

A plot-scale study was developed in New Mexico-USA using 15 small plots composed of 5 different grassland and shrubland species. The aim was to identify the hydrological and erosional processes resulting from these species in a context of degraded environment caused by the advance of shrub species in the region. 54 small-scale rainfall simulations (125 $mm.h^{-1}$) found that shrub specie and canopy density were the main vegetation control on runoff and erosion. Significant interactions and feedbacks were found to occur between edaphic carachteristics and vegetation, which influenced both runoff and erosion responses (Michaelides et al., 2009; Wainwright et al., 2000).

Some researchers have highlighted the role of experimental studies at different scales, in light of the need to increase levels of complexity and connectivity in the study of processes (Bergkamp, 1998; Cammeraat, 2002). The results obtained on small-scale investigations present serious limitations and cannot be extrapolated to other scales without careful analysis. Experimental conditions at small-scale do not usually capture the interactions of a complex physical system (Kirkby, 1987; Zhang et al., 1999). Different processes can be dominant or observable at specific scales. For example, at a fine scale processes such as rain splash and rill and interill erosion are important, and at a larger scale, gully erosion, sediment deposition and other processes become more dominant (de Vente & Poesen, 2005).

Several plot-scale studies have also been developed under natural conditions. The aim of these studies is often to obtain data involving hydrologic and erosion processes and its relationship with biological factors, such as faunal and vegetation species dynamics (Reynolds et al., 1999). Although a reasonably long monitoring period is required, data obtained from these studies can produce a broader description of the actual system and existing interrelationships.

2. Plot-scale experimental study in semi-arid Brazil

An experimental plot-scale study subjected to natural conditions was carried out in the semi-arid municipality of Serra Negra do Norte, northeastern Brazil (Moreira et al., 2009). The study aimed to analyze interrelationships between surface runoff, sediment transport and the aspects of undisturbed native vegetation in this region. The plot was installed at the Seridó Ecological Station (coordinates 6°34′42″,S; 37°15′56″,W), an environmentally protected area located at approximately 300 km from the city of Natal. Plot area was bounded by a 0.3 m height brick wall. Plot relief and situation within the Seridó Ecological Station catchment are shown in Figure 1. During the rainy season, around 70% of the plot area is composed of annual xerophyte species. Climate factors such as rainfall and temperature regulate water availability and biological processes in the region. In the drought season, plants are subjected to water stress. At the end of this period, the permanent species Mimosa tenviflora covers about 20% of the plot, along with substrate accumulated at the soil surface composed of leaves, seeds and dry twigs. In semi-arid areas, native vegetation plays an important role in infiltration and rainfall interception. For example, the stem structure direct flow to the plant roots, enhancing both soil infiltration and soil water storage. Similarly, residue and organic matter accumulated on the surface protect soil from the impact of raindrops (Puigdefábregas, 2005).

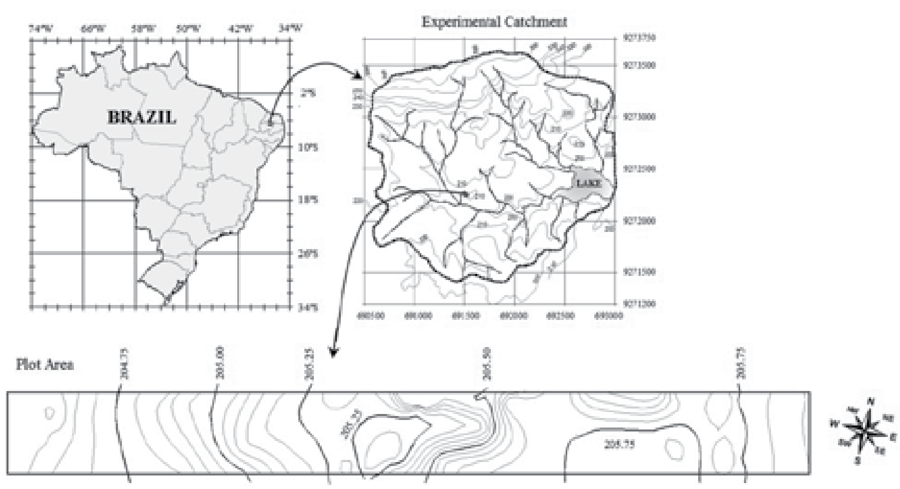


Fig. 1. Plot location within the catchment and terrain relief.

The average annual rainfall over the past 11 years (1995-2005) is 689 mm. Precipitation is highly variable from year to year in the area, where approximately 52% is high intensity thunderstorms of limited area extent. A study has shown the effect of high spatiotemporal rainfall heterogeneity on runoff in the watershed area (Moreira et al., 2006). Monthly rainfall shows considerable variation during the rainy season, especially in the period January-May. Daily rainfall data statistical analysis revealed that approximately 25% of the annual depth occurs during the maximum daily precipitation.

2.1 Biological fauna in the soil and substrate

The experimental plot-scale study enabled analysis of the biological fauna dynamics in the soil and substrate throughout the drought and rainy seasons in 2008-2009. For this purpose, five core sample collection campaigns were conducted at three randomly established points adjacent to the plot site. Soil samples were retrieved at 0.05 m depth and packed for subsequent laboratory analysis. Similarly, substrate samples were collected at three points, in squares measuring 0.30 x 0.30 m^2. Material was then submitted for biological analysis at the UFRN Entomology Laboratory to identify the main arthropod groups observed in the soil and substrate. To that end, specific taxonomic identification keys were used [Zeppelini-Filho & Bellini (2004), Buzzi (2005), Triplehorn & Johnson (2005)]. Screening, counting and organism identification was conducted using a tray, metal tongs, Petri dish, test tube and sterile microscope. Organisms not identified in the previous phase were removed with a Berlese-Tullgren funnel. After counting, arthropods were then stored in a test tube containing alcohol at 70° (v/v). Figure 2 presents daily precipitation data on the plot during the study period of 2008-2009. Samples were collected during drought and rainy periods.

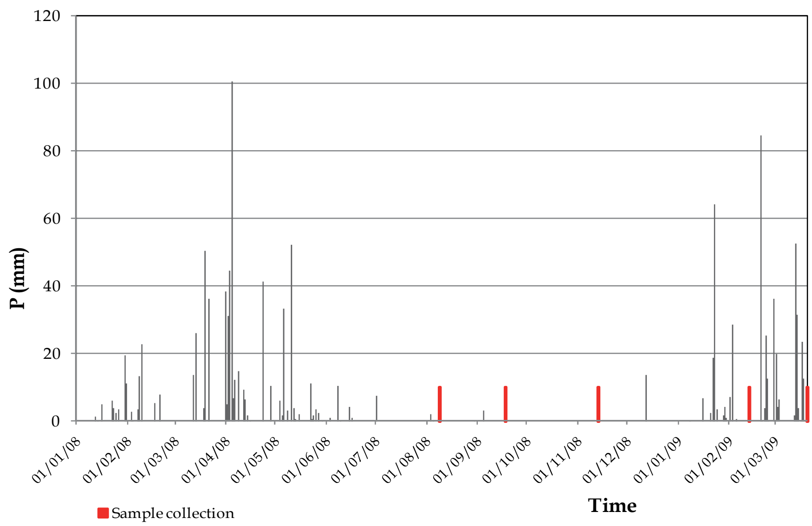


Fig. 2. Daily precipitation and sample collection as a function of time.

It is observed that after a period of several precipitation events during the first half of April 2008, further precipitation events occurred for the next couple of months. The first collection campaign was conducted on 08/08/2008. This was preceded by a period of sporadic low-magnitude rainfall, which produced a deficit on soil moisture and significant effects on annual species. The period between June and December 2008 received close to zero precipitation, with only an isolated event (13 mm) on 12/12/2008. A well-defined 165-day drought was observed during this period, which increased soil water stress level. The rainy period began in the second half of January 2009 when events of substantial magnitude occurred. This period was followed by high-magnitude events in February and March 2009. During the rainy period, soil water moisture increased and annual plants showed progressive changes over a period of aproximately 2-3 weeks. As the rainy period continued, vegetation and biological activity interacted with soil, increasing porosity and enhancing soil storage capacity. Indeed, vegetation may act as sinks of overland flow and sediment due to the velocity reduction as runoff encounters plants (Ludwig et al., 2005). Collection campaigns showed a vigorous transformation in the natural landscape, with soil water availability as a crucial factor.

Analysis of plot core samples provided quantification of the arthropod fauna and its effect on both seasonal periods. Organisms observed were classified into twelve different taxa: *Homoptera, Hemiptera, Hymenoptera, Coleoptera, Orthoptera, Psocoptera, Embioptera, Diptera, Collembola, Ácari, Araneae* and *Geophilomorpha*. Soil fauna demonstrated nine orders of insects, with a clear predominance of *Ácari* group, which occurred in the substrate mainly during the rainy season (Figure 3). It is important to note the mutual and positive relationship between the anual plant species and *Ácari, Collembola* and *Orthoptera*, found primarily in the organic substrate at the soil surface. The annual species offers suitable habitat for the arthropods, including provision of shade, refuge and food. However soil moisture is the most important factor for both the plants and arthopods. Accordingly, an increase in soil water moisture was followed by a marked increase in faunal activity during the rainy period in comparison with the drought period. The quantity of observed organisms in these 2 periods is classified by taxonomic rank and presented in Figure 3.

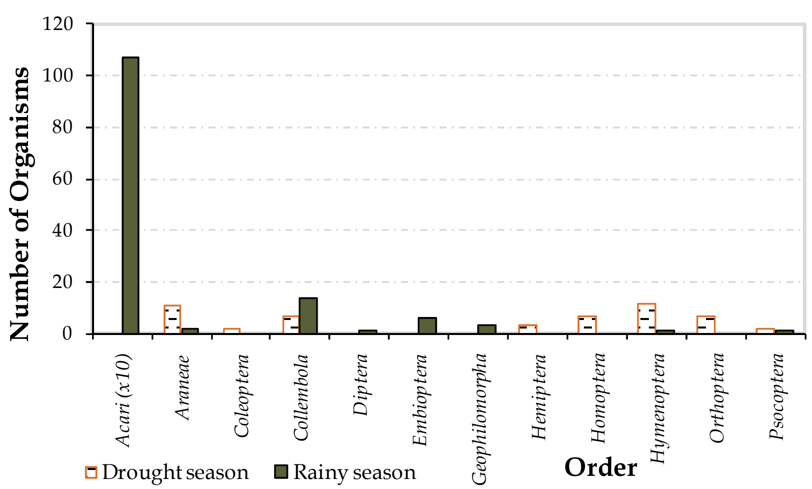


Fig. 3. Arthropod fauna observed in the plot during the dry and rainy seasons, classified by taxonomic rank.

2.2 Hydrological monitoring and sediment yield

With the aim of monitoring surface runoff and soil erosion processes, automatic devices (rainfall recorder and water level logger) were installed adjacent to the plot. A 5 m^3 tank was built at the downstream end of the plot in order to collect water discharge and sediment flowing from the plot during each event. The water level logger was programmed to take measurements every 5 minutes. After each event, the tank was emptied using a portable pump and sediment deposited at the bottom was collected, dried, weighed and analyzed. Calculation of surface runoff in the plot included precipitation and the variation of the tank water level during the storm, in accordance with the water balance Equation 1,

$$RO = \frac{1}{\Delta t}\left[A_{sw}(h_t - h_{t-1}) - (P_{sw}.A_{sw}) - (P_{ramp}.A_{ramp}) \right] \tag{1}$$

where RO ($L^3.T^{-1}$) is the surface runoff; Δt (T) is the interval between measurements; Psw and Pramp are the precipitation height on tank water surface and the paved ramp (L), respectively; Asw e Aramp are the tank and ramp water surface areas (L^2), respectively; h_t and h_{t-1} are the surface water levels in the tank (L) at times t and t-1, respectively.

2.3 Soil hydraulic properties

Soils in the plot site can be classified as a variation between clay-gravel textured Chromic Luvisol and the expansive clay Vertisoil. The soils in the plot site are well drained, shallow, gravelly, with depth varying from 0 to 1.40 m, with rocky outcrops on approximately 15% of its surface. Soil samples were collected from the top 0.1 m and taken to the laboratory for size distribution analysis, which allowed determination of the representative diameters D_{50}, D_{16}, D_{84} (in milimeters) and standard deviation, whose values are presented in Table 1.

Sample	A1	A2	A3	A4	A5	A6	A7
D_{84}	1.8	0.6	0.43	0.55	0.6	0.39	0.49
D_{16}	0.04	0.029	0.035	0.053	0.053	0.049	0.035
D_{50}	0.17	0.06	0.15	0.17	0.17	0.15	0.15
S.D.	6.71	4.55	3.51	3.22	3.36	2.82	3.74

Table 1. Soil representative diameters from the plot.

Table 1 indicates that soil size distribution is composed of gravel, fine, medium and coarse sand, silt and clay. Standard deviation values indicate bimodal composition of the soil (fine and coarse modes present in the bulk sample). The natural roughness of the surface area during the dry season is mainly due to the occurrence of randomly crusted rock fragments, which results from both physical and chemical weathering processes. During the first rainstorm events, readily mobilized sediment dominate sediment yield. Seeds and organic matter are also transported by overland flow across the plot.

To determine soil hydraulic properties in the plot, field infiltration experiments were conducted during the drought and rainy periods. Experiments were performed using a constant head disc permeameter at sixteen points, with care taken to avoid disturbing the native vegetation. The objective was to investigate vertical flow behavior through soil profile as a function of time. The field infiltration experimental data was used to adjust the Horton infiltration parameters, which characterise soil hydraulic properties as an unsaturated porous media. Infiltration curves exhibit declining behavior, with a constant and asymptotic tendency as a function of time. Thus, the profile achieved steady regime at soil saturation level. The Horton infiltration equation (1933) is as follows,

$$f(t) = f_c + (f_0 - f_c).e^{-k.t} \tag{2}$$

where f(t) represents infiltration capacity at time t ($L.T^{-1}$), fo is the initial infiltration rate ($L.T^{-1}$), fc is a final infiltration capacity ($L.T^{-1}$) and k is an empirical constant. Horton equation parameters reflect the spatial heterogeneity of soil hydraulics. In addition, the average observed saturated hydraulic conductivity rates in the rainy period are approximately six times higher than in the drought period, which indicates a marked difference in soil hydraulic behavior. Indeed, during the rainy season soil infiltration capacity is enhanced by an increase in soil moisture, roots osmotic effect, vegetation cover and faunal activity. Higher soil infiltration capacity rates were observed in areas beneath the canopy of permanent species such as *Mimosa tenviflora* (medium-sized trees). In these areas, a higher density of annual plants was observed, mainly due to canopy shade which provides protection from high temperatures and radiation.

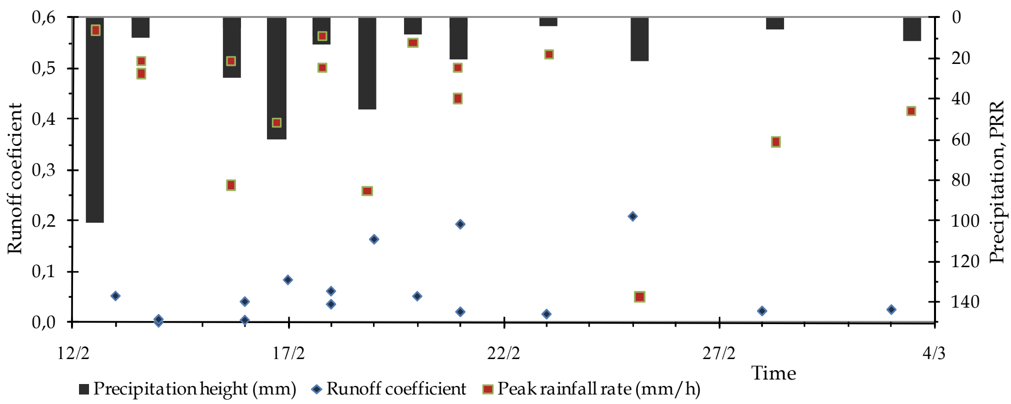
	Experimental run	Parameters			Experimental run	Parameters	
		fo	fc			fo	fc
Drought period	1	30	4	Rainy period	1	300	195
	2	25	3		2	160	85
	3	120	50		3	180	120
	4	60	6		4	35	10
	5	35	10		5	240	170
	6	36	12		6	170	155
	7	30	5		7	180	160
	8	80	57		8	90	40

Table 2. Infiltration parameters of the Horton equation ($mm.h^{-1}$).

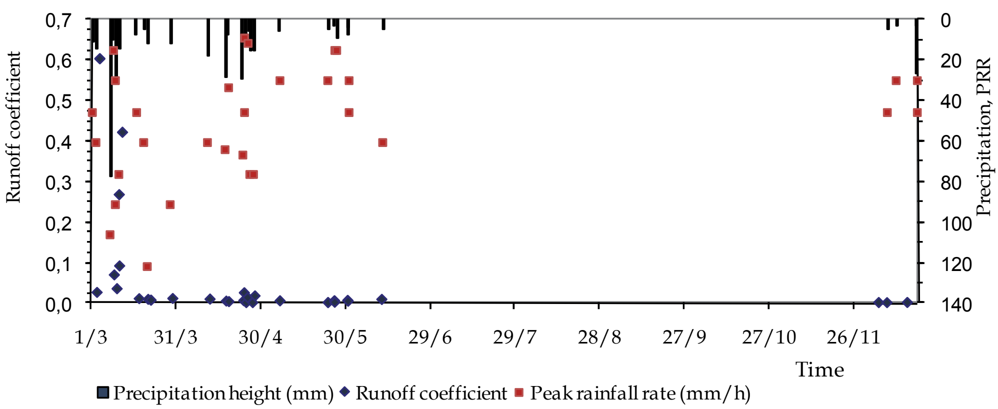
2.4 Runoff generation mechanisms

Surface runoff and erosion in semi-arid areas are the result of various factors associated with rainfall (duration and intensity), soil (moisture, cracking, crusting, and soil infiltration capacity), plant cover (density) and terrain relief. During the study period, 46 precipitation-runoff-sediment yield events were recorded and their main characteristics and the corresponding hydraulic responses were evaluated. 55% of the rainfall events duration were less than 60 minutes in duration and 66% between 18h00 and 06h00. Rainfall peak rate ranged between 9.14 and 137.16 $mm.h^{-1}$. In 56% of events peak rate surpassed 40 $mm.h^{-1}$ and in 5 events it exceeded 90 $mm.h^{-1}$. The runoff coefficient is the relationship between surface runoff and rainfall levels during the event. Observed values of runoff coefficient, rainfall peak rate and precipitation height are presented for the beginning and the end of the rainy periods in Figures 4(a) and 4(b), respectively.

33% of the observed events didn't produce runoff. Observed runoff coefficients were lower than 0.1 for 82% of events, which indicate high soil water storage capacity. Only 5 events exhibited runoff coefficients higher than 0.2; these higher values were possibly due to influence of antecedent rainfall, soil water storage capacity and the density of vegetation cover.



(a)



(b)

Fig. 4. Runoff coefficient, precipitation height and rainfall peak rate at the (a) beginning of the rainy period and (b) end of the rainy period.

Furthermore, these values above 0.2 were observed at the beginning of the rainy period when the vegetation cover density was low. Indeed, vegetation density increased as the rainy period progressed, thereby increasing infiltration capacity and soil water storage. During the rainy period, runoff coefficients were lower than 0.05, and seemed to be independent from rainfall characteristics. This demonstrates the role of native vegetation in improving infiltration capacity and soil water storage. Also, a feedback relationship seemed to control the regeneration of annual species influenced by soil moisture, intense faunal activity and seed supply followed the first week of the wet season. The graph in Figure 5 presents empirical relationships involving sediment yield and precipitation height in 2006 (plot installation) and 2007. The impact of disturbance to the soil surface during plot installation is clearly visible. In 2007, undisturbed natural conditions in the plot and a decrease in sediment supply are reflected in an empirical relationship that seems to be more independent from precipitation characteristics.

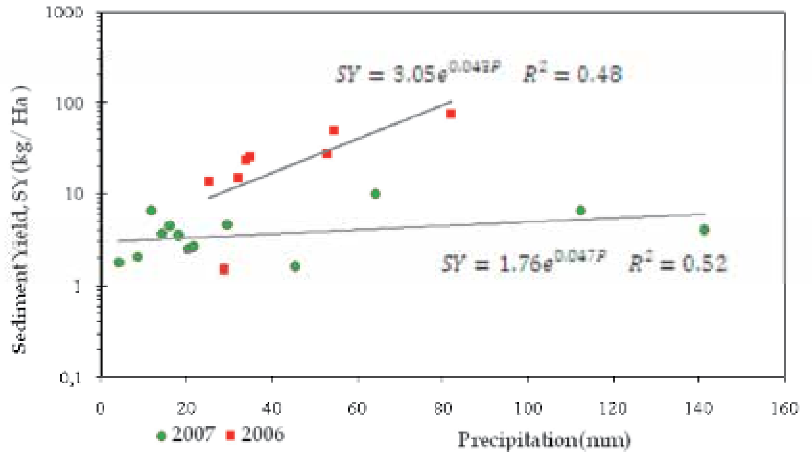


Fig. 5. Empirical relationships between sediment yield and precipitation height in 2006 and 2007.

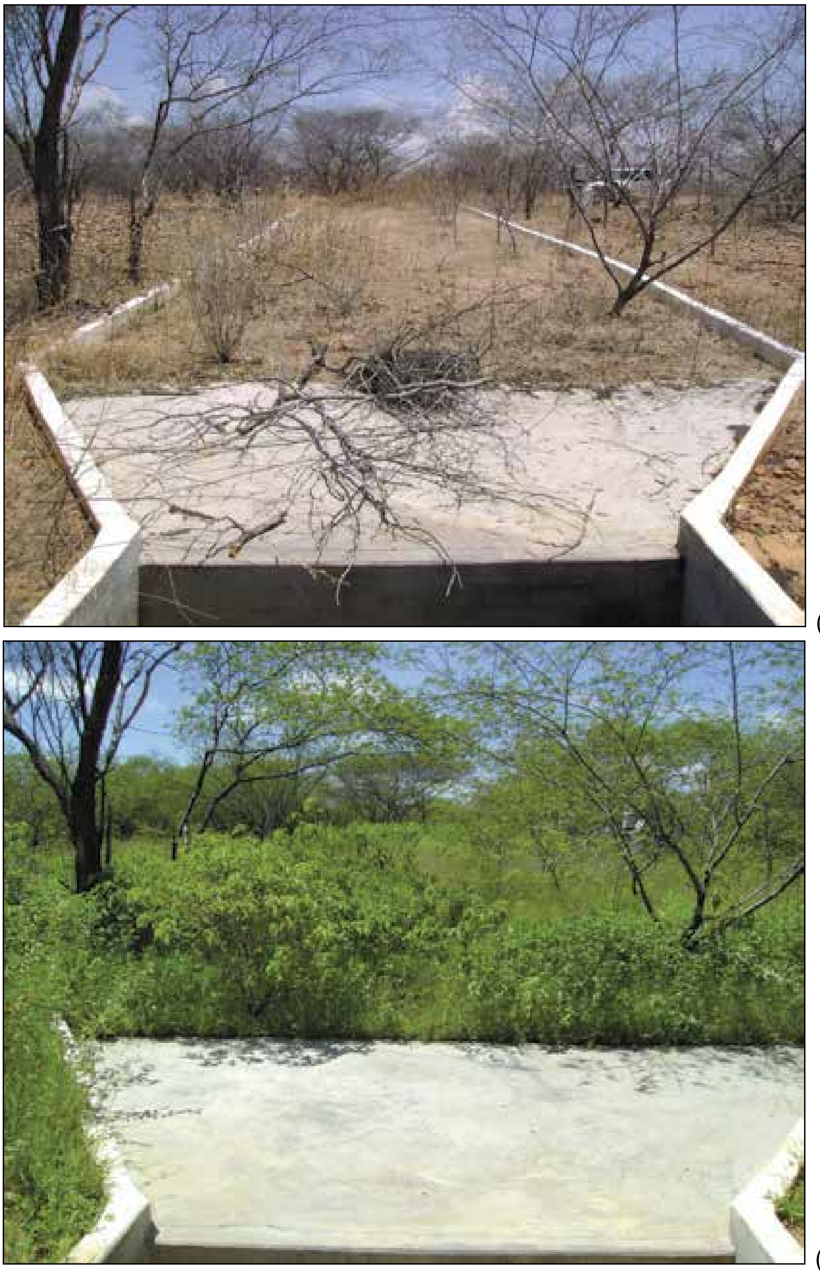
2.5 Vegetation cover

Flora in the plot is formed by the *Caatinga* biome composed of xerophilous species. These species possess mechanisms to adapt and cope with water dryness spells and their physiological processes are conditioned to water availability. Climate factors and the soil water availability are determinants of natural ecosystem functioning. Accordingly, two distinct landscape scenarios may be observed during the drought and rainy periods. In the dry season, annual species typically become absent (herbaceous); permanent species survive due to their root structure and ability to store water during this period. Another adaptation of the permanent species in the area is their ability to lose their leaves when water is scarce to avoid water loss through transpiration. Figures 6(a) and 6(b) illustrate the vegetation landscape scenario during the wet and dry seasons.

Vegetation cover in the plot is most dense at the end of the rainy season. A survey of existing species in the plot identified 31 individuals of the *Mimosa Tenuiflora* species (medium-sized tree) and 15 *Cróton campestris* (shrub). A predominance of annual species was observed, whose life cycle (germination, flowering, fruiting and death) is completed in less than one year. Table 3 depicts the observed vegetation species in the plot during the rainy period.

2.6 Summary of plot-scale experimental observations

The results from the analyses highlight the stark difference between the soil hydraulic properties, faunal activity and vegetation cover in the rainy season and dry season. This is consistent with other studies in semi-arid regions, which have also found that water availability is the key driving factor of biological and geomorphological processes (Cammeraat, 2002; Cerda 2002). In contrast, Cammeraat (2002) found that in a humid temperate climate (Luxembourg) these processes were dominated by water surplus. In this semi-arid Brazilian plot study, the soils were composed of gravel, fine, medium and coarse sand, and also rock fragments, which provides natural roughness to the soil surface. This natural roughness is particularly important in reducing water and soil loss during the dry season, when vegetation cover is sparse.



(a)

(b)

Fig. 6. Vegetation landscapes in the (a) drought and (b) rainy periods.

Strata	Family	Scientific name	Popular name
Arboreo	Leguminosae-mimosoideae	*Mimosa tenuiflora*	Jurema Preta
Shrubby	Euphorbiaceae	*Cróton campestris*	Velame
	Sterculiaceae	*Waltheria bracteosa*	Corre-campo
	Sterculiaceae	*Waltheria indica*	Malva-branca
Annual species	Amaranthaceae	*Froelichia humboldtiana*	Ervanço
	Euphorbiaceae	*Acalypha communis*	Algodãozinho
	Asteraceae	*Hyptis suaveolens*	Alfazema-braba
	Leg. Papilionoideae	Stylozanthes	Stylozanthes
		Sida rhombifolia	Relógio
	Malvaceae	Pavonia cancellata	Malva-rasteira
	Leg. Mimosoideae	*Mimosa ursina*	Jureminha
	Turneraceae	*Turnera subulata*	Chanana
	Rubiaceae	*Diodia teres*	Quebra-tijela
	Asteraceae	Centratherum punctatum	Perpétua-roxa
	Poaceae	*Aristida adscensionu L.*	Capim Panasco

Table 3. Observed vegetation species in the plot during the rainy period.

The runoff coefficient values were generally quite low for the study site, with a third of events not resulting in any runoff and the majority (82%) of events producing values less than 0.1. The 5 events that produced runoff coefficient values over 0.2 occurred at the beginning of the rainy period when vegetation cover was low. It was observed that as the rainy period progressed, the vegetation density increased, along with increased infiltration capacity and soil water storage, and consequently the runoff coefficients dropped to below 0.05. Indeed, the saturated hydraulic conductivity rates in the rainy period were approximately six times higher than that observed during the drought period. Also, the soils beneath the permanent plant species were found to have higher infiltration capacity rates. Another important observation from this study was the higher sediment yields in 2006 following the installation of the plot, compared to 2007. In 2007, the soils were relatively undisturbed and accordingly there was a decrease in sediment yield. A significant increase in the number of arthropods was also observed during the rainy season. This phenomenon between microbial and hydrological processes in arid and semi-arid environments was explored by Belnap et al. (2005) using the *trigger-transfer-reserve-pulse* framework (Ludwig et al., 1997). Under this framework, rainfall can be considered as the *trigger* which results in the *transfer* of resources such as water, nutrients and soil to the receiving patch (referred to as the *reserve*) downslope. Patches within a semi-arid landscape are typically formed by plants, under which soils tend to have higher organic matter, nutrients and microbial activity. The rainfall and subsequent transfer of materials to the patch triggers a *pulse* of biological activity, which in turn produces positive feedbacks including the formation of stronger or new soil aggregates that improve soil stability and water infiltration (Belnap et al., 2005). Human activities that disrupt this positive feedback loop between the abiotic and biological activities, for example native vegetation clearance or overgrazing, can lead to negative impacts on the system. For example, removal of vegetation will reduce organic matter input to the soil, which can lead to decreased microbial activity and poorer soil structure and lower soil storage capacity.

3. Impact of human activities on erosion processes and the effect on the environment

Sedimentological processes operate on the earth's crust over thousands of years. Climatic factors are the main drivers of the processes of erosion, sediment transport and deposition over different time-scales. When subjected to the action of natural forces, soil particles are transferred to other sites within the watershed. Sediment processes may occur in several forms: surface erosion, erosive formations such as channels and gullies, mass transfer including collapsed riverbanks and hillside landslides. When incorporated into the river system, sediment is carried by the flow to downstream areas, where sedimentation may occur. It is important to note that erosion processes occur in a continuous and dynamic system, which is in constant reworking and subject to geomorphologic changes (Walling, 2006). Therefore, erosion processes can be due to storm events or the wind action over dunes formations. Extreme events such as high magnitude floods may produce highly significant geomorphologic changes unrelated to human intervention. Natural events cause weathering processes on mineral rocks, which are subjected to erosion and transported to sedimentary formations, where they are subjected to other chemical processes.

Although erosion processes are directly linked to climate factors, human activity tends to accelerate their impact on the environment, provoking considerable negative effects (Dedkov & Moszherin, 1992). According to Panin (2004), the suspended sediment load released into oceans annually in continental regions varies between 15-20 GT.year-1. Historically, erosion processes have increased worldwide as a result of several different types of human activities, including agriculture, mining, urbanization and industry (Walling & Fang, 2003). Intensification of these erosion processes has led to long-term negative social and economic impacts. For example, siltation of reservoirs built for hydropower production can cause economic losses that affect society as a whole. Mahmood (1987) estimated that reservoir storage capacity in the world decreased by approximately 1% every year as a result of siltation, causing an annual loss of US$ 6 billion. This impact is far-reaching considering that approximately 40% of the worldwide river system capacity is stored in large dams (Vörösmarty et al. 2003).

Deforestation of native vegetation for agriculture and wood extraction are the main causes of erosion over the world. Ives & Messerli (1989) presented a model illustrating how changes in the population structure of Nepal in the 1950s affected natural processes on several scales. It is estimated that the global area dedicated to agriculture has increased five times over the last 200 years, prompted by population growth and higher food demand (UNEP, 1995). On the other hand, reservoir construction and the damming of water and sediment significantly reduce the amount of sediment reaching floodplains and estuaries. A recent survey using long-term records of large basins subjected to the impact of human activity found that, in some cases, increased sediment in river systems may not impact deltas and estuaries (Dai & Tan, 1996; Walling, 2000; Walling & Fang, 2003) due to sediment retention in reservoirs located upstream. Thus, erosion processes reflect the combined action of climate factors and disturbances in the basin as a result of unsustainable human activities.

Urbanization may also cause substantial changes in hydrologic behavior and erosive processes (Taylor, 2007). Land occupation of urban areas brings together the production of liquid and solid residues that, if not adequately collected, may be detrimental to water and sediment quality. Urbanization is associated with building construction and infrastructure service. Paved surfaces in urban environments result in lower amounts of water infiltration, which, in turn, can produce adverse social and economic impacts such as floods. In developing countries, it can be observed that urban development does not commonly occur in line with infrastructure and urban services investments. Often public services such as health and education are inadequate and planning and provisions to prevent or cope with extreme events (e.g. prevention measures and land occupation control) are lacking. In addition, urban occupation generates sediment contaminated by toxic substances (heavy metals, pesticides, oils, organic compounds), which can adhere to the fine fractions in the fluvial environment (Robertson et al., 2003; Lecoanet et al., 2003). Primary sources of sediment contamination in urban areas are domestic sewage and the construction of buildings and roadways. The presence of contaminants significantly affects aquatic organisms that feed on the sediment, which highlights the implications of land management on other parts of the system.

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8

Impact of Rainfall Microstructure on Erosivity and Splash Soil Erosion Under Simulated Rainfall

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1. Introduction

Rainfall represents the major driver of soil detachment in erosion processes. The potential of rainfall to detach soil has been defined as rainfall erosivity. The relationship between rainfall intensity and rainfall drop size distribution (DSD) controls various rainfall characteristics including the rainfall erosivity (Abd Elbasit et al., 2010). The relationship between rainfall intensity and rainfall erosivity differs due to geographical location under natural rainfall (Hudson 1965; Wischmeier and Smith, 1978; Zanchi and Torri, 1980; Van Dijk et al., 2002) and due to type and configuration of rainfall simulators under simulated rainfall (Hall, 1970; Olayemi and Yadav, 1983; Auerswald et al., 1992; Salles and Poesen, 2000). The role of rainfall microstructure on the determination of rainfall erosivity has attracted several researchers in the past. However, our understanding on this subject is still limited due to the lack of equipments that are able to measure the rainfall drop parameters and ultimately the rainfall kinetic energy. Several indices have been suggested to quantify the rainfall erosivity (Abd Elbasit et al., 2010). Generally, the suitable erosivity index must include the drop mass and velocity as major variables for raindrop power determination. The erosivity index has been described by Epema and Riezebos, 1983 as follows:

$$E \propto m^{\alpha}\ v^{\beta} \tag{1}$$

where m is drop mass in (kg); v is fall-velocity (m s^{-1}); α and β are coefficients.
The most used indices are raindrop kinetic energy (KE) and momentum (M). In the KE and M the α is equal to one where the β is equal to two in KE and one in M. In general, the raindrop fall velocity can be related to drop size by a power relationship. Accordingly, the raindrop size distribution affect both constituents of rainfall erosivity. Thus, theoretically the rainfall DSD (or rainfall micro-structure) has a great impact on rainfall erosivity. In this study, the impact of rainfall microstructure on rainfall erosivity and splash soil erosion

under simulated rainfall condition will be discussed. A dripper-type rainfall simulator located at the Arid Land Research Center, Tottori University, Japan has been used to simulate events with rainfall intensity ranged between 10 to 30 mm h^{-1}. The splash soil erosion has been evaluated using splash cup method. The rainfall kinetic energy and drop size distribution have been measured using piezoelectric sensor.

1.1 Rainfall erosivity evaluation

R- factor in the Universal Soil Loss Equation (USLE) and its revised and modified versions represents the major rainfall erosivity, which can be defined as the product of total kinetic energy of storm times its 30 min maximum intensity(EI_{30}) and annual average can be calculated as follow:

$$R - factor = \frac{1}{n}\sum_{i=1}^{n}\left[\sum_{k=1}^{m} KE\left(I_{30}\right)_k\right]_j \quad (2)$$

R-factor is average annual rainfall and runoff erosivity (MJ mm ha^{-1} h^{-1} $year^{-1}$); KE is total kinetic energy of single storm (MJ ha^{-1}); I_{30} is the maximum 30 min rainfall intensity (mm h^{-1}); m is the number of k erosive storms in each j year; n is the number of years used to obtain average R (Renard and Freimund, 1994). Several I-KE relationships can be applied in order to determine the storm kinetic energy depending on the geographical location and dominant type of rainfall. For example:

$$KE = (11.89 + 8.73\log_{10} I) \times I \quad (2a)$$

(Wischmeier and Smith, 1958), USA

$$KE = 29.86(I - 4.29) \quad (2b)$$

(Hudson, 1965), Zimbabwe

$$KE = 36.8I(1 - 0.691e^{-0.038I}) \quad (2c)$$

(Jayawardena and Rezaur, 2000a), Hong Kong
where KE is rainfall time-specific kinetic energy (KE_{time}) in J m^{-2} h^{-1}.
Determination of the I-KE relationships under certain geographical location or simulated rainfall requires information about the rainfall KE or at least the rainfall DSD.

1.2 Raindrop erosivity evaluation

Rainfall drop size distribution (DSD) represents the primary rainfall data that can be used in order to quantify the rainfall erosivity. However, devices for continuous determination of the KE and DSD during rainfall event have been used in few meteorological stations. For this reason, several indices have been suggested to estimate the rainfall erosivity from common rainfall parameters (rainfall macro-structure), such as daily, and monthly rainfall data. Raindrop erosivity can be determine directly by using piezoelectric transducer where the measured water drop kinetic energy or momentum related with output voltage from the transducer due to the drop impact (Madden et al., 1998; Jayawardena and Rezaur, 2000b; Abd Elbasit et al., 2007; Abd Elbasit et al., 2010; Abd Elbasit et al., 2011). Anologously, optical methods have, also been utilized, where raindrop size and velocity are monitored simultaneously and then the erosivity indices are calculated directly from these two parameters (Salles and Poesen, 2000; Nanko et al., 2004). The raindrop erosivity can be evaluated from the rainfall DSD measured by different methods (continuous, disdrometers or non-continuous, filter paper and flour-pellet) and use of drop fall velocity values derived from empirical and physical relationships.

1.3 Rainfall simulation

Rainfall simulators are developed to mimic natural rainfall in its different characteristics. The rainfall properties including rainfall intensity and energy are the important parameters for determining the rainfall erosivity. Generally, rainfall simulators can be divided in two categories: single drop simulators (SDS) and multiple drop simulators (MDS). The SDS have been used intensively to investigate the splash erosion processes (e.g. Al-Durrah and Bradford, 1982; Cruse and Francis, 1984; Gantzer et al., 1985; Nearing and Bradford, 1985; Bradford et al., 1986; Nearing et al., 1986; Sharma and Gupta, 1989; Mouzai and Bouhadef, 2003; Furbish et al., 2007). Although these studies have improved our understanding for splash soil erosion, they fail to extrapolate these results to natural field condition (Abd Elbasit et al., 2010). The MDS produced range of raindrops similar to that found under natural rainfall. However, the big challenge for these simulators is to generate rainfall similar to natural rainfall or at least with I-KE trend similar to natural rainfall. The MDS can be categorized into three main groups: the drip-screen type (dripper type, dripolator), vertical spray type or nozzle-type and sprinkler or rotating spray-types. In this study, a dripper-type rainfall simulator has been used to simulate rainfall with different intensities.

1.4 Dripper-type rainfall simulators

A dripper type rainfall simulator located at the Arid Land Research Center, Tottori University, Japan was used to simulate rainfall with intensities ranging between 10 to 30 mm h^{-1} (Figure 1). The simulator is 12 m in height, which is theoretically enough for most of the drop sizes to reach their terminal velocity (Wang and Pruppacher, 1977) experimental results. The simulator consisted of a main steel frame, a dripper system, a positive displacement pump, a set of solenoid water valves to control water flow, and a computerized control system for various operations. The height of the main frame was 12.5 m and the dripper system was fixed on the top of this frame (Figure 1). The dripper system consisted of 16 disc-type water distributors attached to a horizontal steel frame (2.55 x 1.5 m) in six rows (Abd Elbasit et al., 2010). Each distributor had 45 tubes with inner and outer diameters of 2 and 3.5 mm respectively and at the end of each tube, a flat cut hypodermic needle was fixed (Figure 1). The inner and outer diameter of the needles was 0.4 and 0.6 mm respectively. The other end of the needle was attached to a metallic plate in such a way that the needle protruded 2.6 cm (Abd Elbasit et al., 2010). There were 18 metallic plates in total and each plate had two rows of needles. The distance between the rows was 6 cm, and the needles were arranged in 6 cm offset pattern with a needle to needle distance of 6 cm within the row. Under the needles, an oscillating screen was fixed in order to distribute the rainfall evenly, improve the drop size distribution and to prevent continuous water flow (Figure 3). The oscillating screen (2.35 x 1.33 m) consisted of two sheets of metallic mesh (10 mm) moving horizontally and in opposite directions of each other, driven by an electric motor (Abd Elbasit et al., 2010).

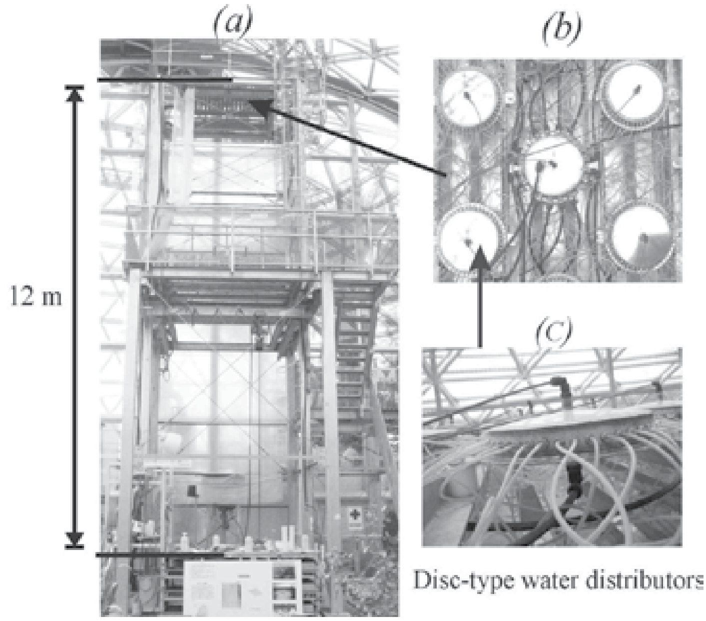

Fig. 1. Dripper-type rainfall simulator. (a) main frame, (b) dripper system, and (c) disc-type water distributor

The water pump used to supply water to the dripper system of the rainfall simulator was a positive displacement type. The water flow rate was controlled by adjusting the rotational speed of the pump (Abd Elbasit et al., 2010). The rainfall simulator was equipped with four 1 m^3 water tanks and the water flow in and out these tanks was controlled by the solenoid water valves. A high-performance water filtering system was connected to the water supply flowing to the tanks to avoid needle clogging. A computer system controlled the solenoid water valves, pump rotational speed, and oscillating screen. Before using the rainfall simulator for experiments, a priming system was used to remove all the air from the pipe system. The rainfall simulator was calibrated for the rainfall spatial distribution on the experimental area (2.1 x 1.1 m), and to determine the relationship between the flow rate and rainfall intensity (Abd Elbasit et al., 2008). In the experimental area, a table was placed at a height of 0.5 m on which the soil was placed when the splash experiment was conducted. The rainfall simulator was able to simulate rainfall intensities ranging from 1.0-200 mm h^{-1}.

2. Materials and methods

2.1 Application of piezoelectric transducer in erosivity quantification

The rainfall erosivity was measured using two piezoelectric sensors, one to measure the kinetic energy (KE, mJ) and the other to measure drop size distribution (DSD, mm), at 10 second interval. The both sensors were modified from the piezoelectric Vaisala RAINCAP® rain sensor. The measurement principle of the sensor is based on the acoustic detection of individual raindrop impact (Salmi and Ikonen, 2005). The drop impact generates acoustic waves to the piezoelectric detector (Figure 2). Resulting mechanical stresses in the piezoelectric material causes a voltage between the sensor electrodes. Due to the well known dependence between terminal velocity and mass of the drop, the drop size can be determined from the voltage signal (Abd Elbasit et al., 2010).

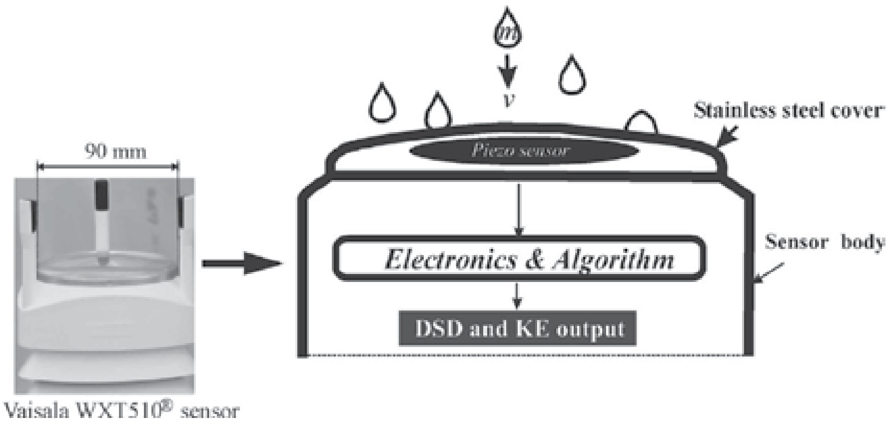

Fig. 2. Schematic view for the piezoelectric kinetic energy and drop size distribution sensors modified from Vaisala WXT510® sensor.

The sensor is constructed from a piezoelectric detector covered by stainless steel shell (Figure 2). The voltage pulses delivered by the piezoelectric element are filtered, amplified, digitized, and finally analyzed as to their selected parameters related to the raindrop size. Final computations are performed by the micro-processor system (Abd Elbasit et al., 2010). The DSD sensor was calibrated at Vaisala Rain Laboratory; Finland using controlled drop sizes falling from a height of 14 m and the velocity of each drop size was measured using two parallel laser beams and a prism. The received optical signal was converted to a voltage signal, which was proportional to the area of the laser beam intercepted by the raindrops (Salmi and Elomaa, 2007). The sensor was compared with a Joss-Waldvogel RD-69 disdrometer under natural rainfall conditions in Finland (Pohjola et al., 2008) and the results of the two methods showed significant agreement for raindrop size greater than 0.80 mm. The KE sensor was calibrated using rain drops with known kinetic energy values. The simulator and optical method used for the DSD sensor calibration were also used to calibrate the KE sensor. The raindrops' KE that was used for the KE sensor calibration was calculated from the raindrop size (controlled by the rainfall simulator) and fall velocity (measured using the optical method). The KE sensor was also validated under simulated rainfall and the sensor output (direct KE measurement) was compared with the calculated KE using rainfall DSD and empirically calculated velocity from drop size. The correlation between directly measured KE using the KE sensor and estimated KE was statistically highly significant under different rainfall intensities and empirical relationships (Abd Elbasit et al., 2007, Abd Elbasit et al., 2011). Moreover, there was agreement between the two methods in terms of the shape of the relationship between rainfall intensity and measured and estimated KE. The signals from the two sensors were logged in two notebook computers using the RS-232 serial interface and data logging software. The rainfall intensity was measured using a tipping-bucket rain gauge (Davis rain collector II, CA, USA) with 0.2-mm resolution. The rain gauge was attached to event data logger (HOBO Event Logger; Onset Computer Corp., MA, USA) with 0.5 s interval recording accuracy.

2.2 Measurement of splash soil erosion

The splash measurement was repeated three times for each rainfall intensity level. In each study three splash cups were used. The mean value for each intensity was used for determining the impact of rainfall micro-structure on soil splash erosion. The splash-cups were prepared using PVC pipe-connectors with a diameter of 10 cm and height of 20 cm (Figure 3). At a height of 10 cm, a metal screen was fixed in the cup using silicon sealant (Abd Elbasit et al., 2010). A filter paper was placed on top of the screen and then the cup was filled up to the edge with silty clay loam soil collected from the Tohaku area, Tottori Prefecture, Japan. The fine sand, silt and clay percentage was 8.24, 61.78, and 29.98%, respectively.

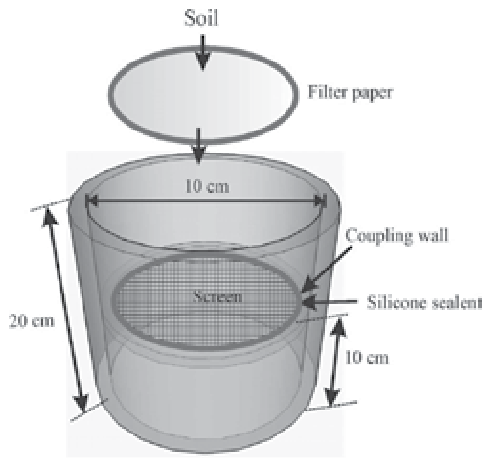

Fig. 3. Schematic view of splash cup.

The soil was air dried in a glasshouse and then mechanically crushed and sieved through 2 mm mesh. Before starting the experiment, the soil was again dried in an oven at 105 °C for 24 hours. The bulk density of the soil in the cup was 1.10 ± 0.01 g cm^{-3}. The cups were then exposed to the simulated rainfall for different durations depending on the rainfall intensity to be tested. The rainfall duration ranged from 18 minutes for 10 mm h^{-1} rainfall intensity to 6 minutes for 30 mm h^{-1}. The rainfall depth was kept constant at 3 mm to avoid any surface pond formation that would have reduced the rainfall energy striking the soil surface. The splash was measured by the difference in the total oven dry weight of each splash cup before and after exposure to simulated rainfall.

3. Results and discussion

3.1 Evaluation of simulated rainfall micro-structure

The rainfall DSD represents the major micro-structural property. Figure 4 shows the DSD measured by the piezoelectric transducer under different rainfall intensities. This result shows that the rainfall simulator generate various drop size under different rainfall intensities, which represent an advantage of the dripper-type rainfall simulators. The large drops number percentage (drops with diameter >2.5) under different rainfall intensities was calculated from results in Figure 4. The simulated rainfall large drops content (%) showed increase pattern with the rainfall intensities. On the other hand, the small drops percentage showed decreasing trend with increasing the rainfall intensities. Figure 5 shows the KE percentage at different raindrop classes (8 classes).

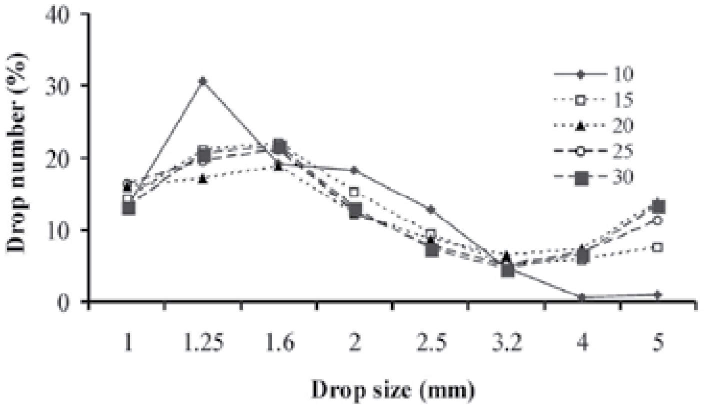

Fig. 4. Simulated rainfall drop size distribution under various rainfall intensities.

The KE pattern was highly different from drops number percentage as the KE resulted from large drops was very high compared to small drops classes. This can be attributed to two reasons: first, the drop mass increases exponentially with diameter; second the raindrop fall velocity has a non-linear relationship with drop diameter. The small drops number and KE percentage is shown in Figure 6. The small drops number and KE percentage showed relative agreement between each other. Both the drops number and KE percentage showed a decrease with rainfall intensities. The large drops number and KE percentage showed increasing pattern with the rainfall intensities. The large drops number percentage is approximately less than 30%, however, the KE produced by this percentage of raindrops was between 70 to 90%. These results emphasize that the large drops number percentage is a determination factor for rainfall KE. The correlation coefficient between the large drops number (%) and KE (%) was 0.78 and this correlation coefficient can be improved by increasing the number of sampled intensities (Figure 7).

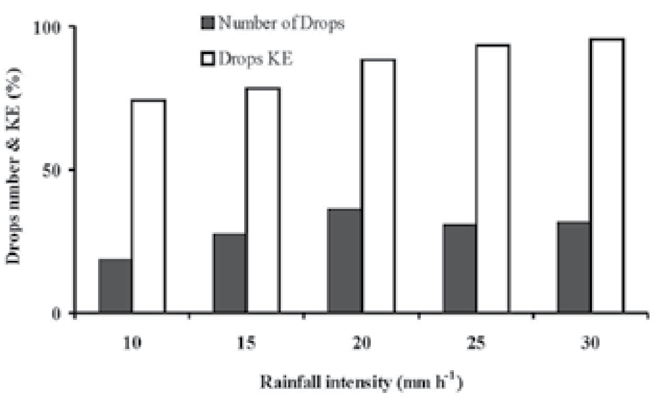

Fig. 5. Relationship between large drops number percentage and kinetic energy percentage under various simulated rainfall intensities.

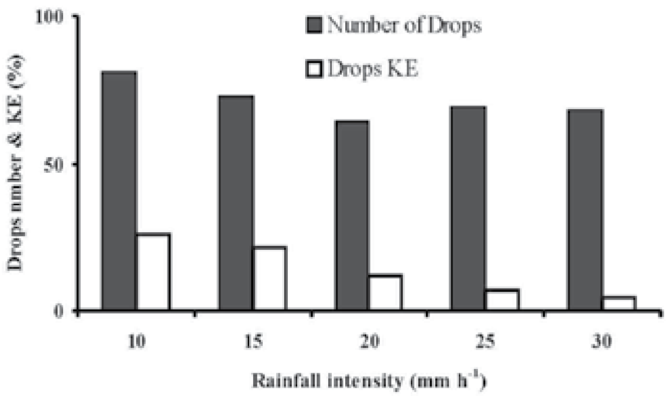

Fig. 6. Relationship between small drops number percentage and kinetic energy percentage under various simulated rainfall intensities.

3.2 Simulated rainfall erosivity

The rainfall erosivity has been represented in this study by the rainfall kinetic energy which was measured using a piezoelectric sensor. Figure 8 shows the relationship between the rainfall intensity and the kinetic energy (I-KE). The simulated rainfall I-KE was also compared with the natural rainfall relationships measured at different geographical locations (Figure 8). The simulated rainfall I-KE relationship showed agreement with the natural rainfall relationships under the observed rainfall intensity range (10 to 30 mm h^{-1}). Generally, I-KE relationship showed increasing and stabilizing pattern with different thresholds. However, different patterns have been also reported by various researchers under different environments (e.g. Hudson, 1963; Carter et al., 1974). The simulated rainfall I-KE relationship, in this study, showed significant agreement with natural rainfall trends.

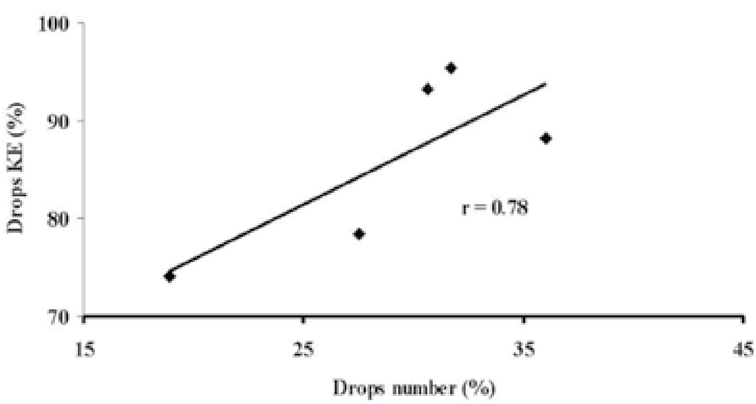

Fig. 7. Relationship between large drops number percentage and kinetic energy percentage under simulated rainfall.

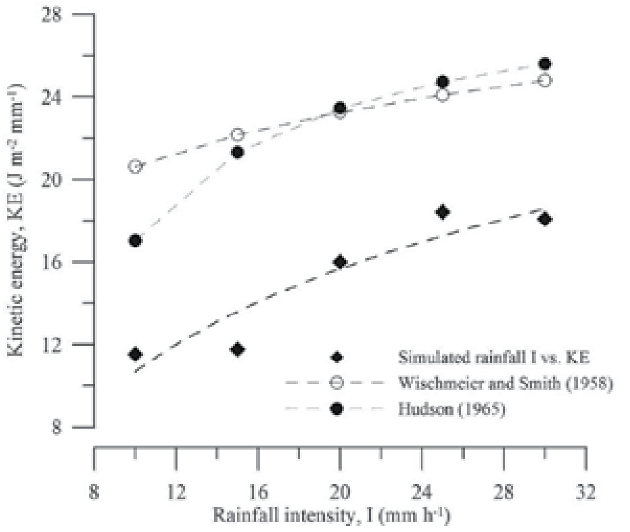

Fig. 8. Simulated rainfall intensity and kinetic energy relationship compared with natural rainfall.

3.3 Rainfall micro-structure and soil erosion

The soil splash erosion can be related directly to raindrop erosivity without any due consideration to the I-KE (Abd Elbasit et al., 2010). In other words, the rainfall erosivity can works as independent splash erosion predictor. As it was shown in the previous discussion, the rainfall micro-structure has significant effects on the rainfall erosivity and consequently on soil erosion. Figure 9 shows the relationship between splash soil erosion and large drops KE percentage.

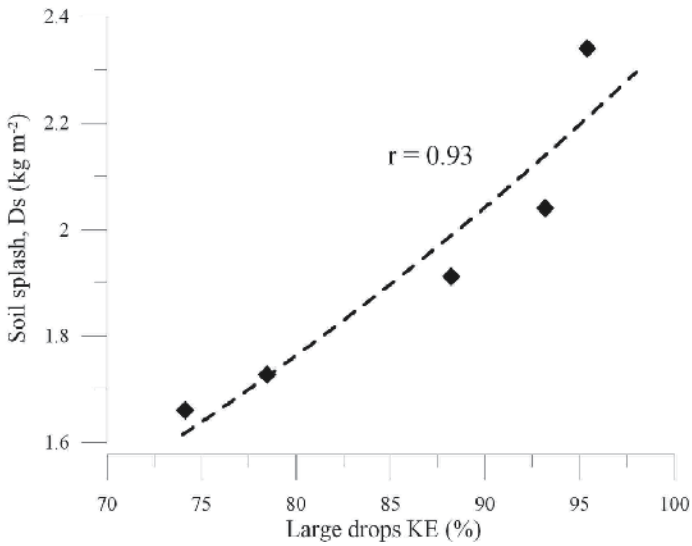

Fig. 9. Splash soil erosion as a function of large drops kinetic energy percentage under simulated rainfall.

4. Conclusions

Rainfall produced by dripper-type rainfall simulator has been charcterized using piezoelectric transducers. The rainfall drop size distribution and kinetic energy has been measured in 10 second time interval. The rainfall micro-structure has been eveluated by the changes in the drop size distribution at each rainfall intensity. The soil splash erosion has been evaluated using splash cup method under five rainfall intensities ranges between 10 to 30 mm h^{-1}. The rainfall kinetic energy was found to increase with the increase in large drops content (drops with diameter > 2.5). The splash soil loss was correlated with the large drop percentage which emphasize that the splash erosion is highly affected by the rainfall micro-structure.

5. Acknowledgments

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Soil Loss-Rainfall Duration Relations as Affected by Peat Content, Soil Type and Compaction Effort

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1. Introduction

Soil erosion, and its associated impacts, is a big environmental problem, globally. The resulting costs of this phenomenon are tremendous and originate from both on-site and of-site effects of erosion (Morgan, 2005). On-site effects are particularly important on agricultural lands. The outcome includes loss of soil fertility and productivity, breakdown in soil structure, and at times loss of life and property. This decline in fertility leads to increased costly fertilizer use, affects food production and food security and substantial declines in land values. Off-site problems generally result in downstream or downwind sedimentation. There is also the issue of pollution transfer from place to place.

It is thus very important that new methods and practices for reducing and/or controlling erosion be developed and existing ones improved so as to combat this very important problem. There is also the need to encourage the use of existing agri-environmental management methods like the use of geotextiles and soil conditioners. Basically, all strategies for soil conservation include the following: providing a barrier against raindrop impact, increasing soil aggregate stability, increasing infiltration capacity of the soil to reduce runoff and/or increasing surface roughness to reduce velocity of runoff and wind (Morgan, 2005).

Peat is sometimes used as a source of organic matter for the soil. In Trinidad, peat is particularly used in nurseries, because unlike other organic materials like FYM, its incorporation is not accompanied by weeds infestation. Peat increases soil fertility and improves physical properties like saturated hydraulic conductivity (Ohu et al., 1985) and available water and reduces bulk density (Lebeau et al., 2003; Ekwue and Harrilal, 2010).

Soil erosion by water consists of two basic processes: splash detachment and transport by raindrops and runoff. Splash erosion is the first step in the soil erosion process and control measures are best targeted at reducing it. Ekwue (1990, 1992) found that splash detachment by raindrops declined with increasing peat content of soils and noted that the relationship was negatively exponential over a range of organic matter content (1.50 – 18.23%). Peat was found to act as mulch and thereby protecting the soil surface from the direct impact of raindrops. Ekwue et al. (2009) further found that peat decreased soil transport by runoff or overland flow (wash erosion). However, it was not clear why peat reduced soil transport since it is known to reduce inter-aggregate stability and soil strength which affects the soil erosion process. Ekwue and Harrilal (2010) followed it up by studying the effect of peat on wash erosion by raindrop impact and observed that peat decreased wash erosion by reducing soil bulk density, increasing infiltration rates and decreasing runoff. The effect of peat incorporation on the overall soil erosion process is therefore now clearly understood. Soil erosion by raindrops is also known to be affected by rainfall duration but it is not clear how this relationship is affected by other parameters that affect the soil erosion process including peat content, soil compaction and soil type. This paper reports the results of an interaction experiment set up to examine the relative effects of peat content, soil type, rainfall duration and compaction efforts on raindrop erosion. The aim is to further increase the general understanding of how peat affects the soil erosion process.

2. Materials and methods

Three soils, Piarco sandy loam, Maracas clay loam and Talparo clay (Table 1) were used for the study. They were the same soils used in the earlier studies by Ekwue et al. (2009) and Ekwue and Harrilal (2010). Air-dry soil samples were ground to pass a 5 mm sieve. Particle size distribution (Table 1) was performed using the hydrometer method (Lambe, 1951). Organic matter content in the samples was measured using the Walkley and Black (1934) method. Organic matter content in the samples was increased by adding air-dry sphagnum peat moss (with 0.15 t m^{-3} air-dry density) at rates of 5%, and 10%, air-dry mass basis.

Soil Series	Classification*	Organic Matter Content (%)	Sand (0.06-0.002) mm	Silt (0.06-0.002) mm	Clay (<0.002) mm
Piarco	Aquoxic Tropudults	1.7**	64.9	17.0	18.1
Maracas	Orthoxic Tropudults	4.7	44.7	24.7	30.6
Talparo	Aquentic Chromuderts	2.7	25.4	28.3	46.3

* Classification according to the Soil Taxonomy System (Soil Survey Staff, 1999).

** All values are means of three replicates

Table 1. Classification, organic matter, and the particle size distribution (%) of the soils

Raindrop erosion was measured with a soil erosion assessment facility whose soil test bed (Figure 1) was fully described by Ekwue et al. (2009). The difference is that this has now been added a rainfall simulator (Figure 2) designed using the original design of Tossel et al. (1990). The simulator utilized three continuous spray full jet nozzles (6.35 mm diameter) placed along the length of a 2 m high, ½ inch diameter P.V.C. frame mounted onto the frame of the test bed. The intensity of the simulated rainfall from each nozzle was 90 mm hr^{-1} with a Christiansen (1942) coefficient of uniformity of 89%, median drop size of 2.03 mm and a kinetic energy of 29.38 J m^{-2} mm^{-1}. The rainfall intensity was chosen as a compromise between what is expected in temperate and tropical climates. During the erosion test period, the simulator frame was covered with a transparent material to limit the effect of wind on the raindrops falling to the test bed.

The apparatus measures erosion on surfaces with slopes varying from 0% to 30%. The soil tray has a flexible drainage hose added to the bottom end throughout the length of it. Gravel was placed at the bottom of the soil tray to a depth of 8 cm before putting the soil to be tested, such that water that infiltrated through the soil first passed through the layer of gravel, which acted as a filter, and ensured that clean water flowed down the drain preventing the siltation of the drain pipes. During testing, the eroded soil and overflow water (runoff) flowed into the soil collection pan. Here soil settled under its own weight. From this compartment, the water flowed through a drainpipe and into a drain where the runoff was measured. Sediments were collected from the collection tray after the tests and oven dried to determine the mass of soil eroded.

For each test, soil was added to the soil tray to a depth of 2 cm. This is the depth of soil that is normally involved in the soil erosion process. Soil was then compacted at three levels (100 kPa, 150 kPa and 185 kPa). The three compaction levels were obtained using a 3.6 kg roller 2, 3, and 4 times each followed by a 5.8 kg roller 3, 4 and 5 times respectively. The aim was to produce a compacted soil similar to field conditions and to determine the effect of these levels of compaction on soil erosion. Bulk density and penetration resistance achieved after soil preparation were measured using a hand pushed spring-type Proctor penetrometer (ASTM, 1985). Erosion by simulated rainfall was assessed using a factorial experiment involving the three soils with the three peat contents, and exposed to four rainfall durations (5, 10, 20 and 30 min) with two replications giving a total of 216 tests. The slope gradient was fixed at 9% which is prevalent in agricultural soils in Trinidad (Gumbs, 1987). Analysis of variance of soil erosion values was performed using the MINITAB computer software.

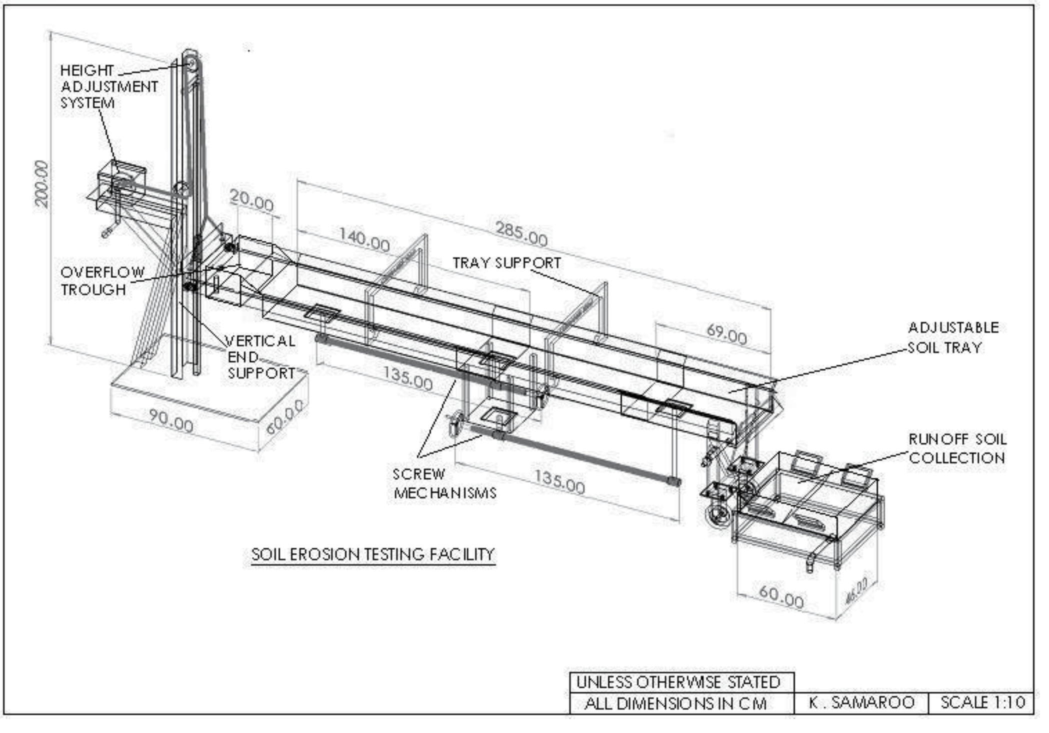


Fig. 1. The soil bed of the erosion facility

Fig. 2. The rainfall simulator with the soil bed

3. Results and discussion

3.1 Factors affecting runoff and soil loss

Table 2 shows the value of soil loss for the three soils. Soil loss decreased with increasing peat contents for all combinations of soil type, rainfall duration and compaction effort. Soil loss also decreased with increasing compaction effort and increased with increasing rainfall duration. Soil loss was consistently highest in the sandy soil, intermediate in the clay soil and lowest in the clay loam soil. Table 3 shows that cumulative runoff increased with increasing rainfall duration and compaction levels but decreased with increasing peat content. Runoff was highest in the clay, followed by clay loam and lowest in the sandy loam soil.

Soil	Peat content (%)	Compaction effort, 100 kPa				Compaction effort, 150 kPa				Compaction effort, 185 kPa			
		Rainfall duration (min)				Rainfall duration (min)				Rainfall duration(min)			
		5	10	20	30	5	10	20	30	5	10	20	30
Piarco sandy loam	0	0.48	0.85	2.10	3.39	0.49	0.82	1.85	3.30	0.42	0.85	1.66	2.39
	5	0.45	0.81	1.84	2.95	0.45	0.79	1.66	2.76	0.38	0.75	1.51	2.03
	10	0.42	0.79	1.60	2.74	0.42	0.75	1.44	2.53	0.34	0.68	1.30	1.78
Maracas clay loam	0	0.40	0.81	1.47	2.51	0.40	0.72	1.16	2.01	0.31	0.63	1.19	1.62
	5	0.36	0.68	1.30	2.11	0.32	0.66	1.10	1.88	0.25	0.49	1.02	1.37
	10	0.28	0.563	1.17	1.87	0.24	0.50	0.851	1.43	0.17	0.39	0.81	1.21
Talparo clay	0	0.46	0.81	1.97	2.86	0.46	0.78	1.88	2.81	0.39	0.74	1.49	2.29
	5	0.42	0.78	1.77	2.67	0.40	0.71	1.54	2.64	0.35	0.69	1.39	1.91
	10	0.39	0.76	1.52	2.43	0.36	0.66	1.21	2.21	0.28	0.58	1.16	1.67

[a]Values are means of two replicates.

Table 2. Soil loss[a] (kg) for three soils with and without peat compacted and exposed to four rainfall durations

Table 4 summarizes the mean values of cumulative runoff and soil loss for the different experimental factors. Mean runoff increased with increasing clay content, compaction effort and rainfall duration but decreased with increasing peat content. For soil loss, mean values of soil loss varied from 1.36 kg in the sandy soil to 0.95 kg in the clay loam soil. The analysis of variance (Table 5) showed that the main effects of soil type, peat content, compaction effort and rainfall duration were all significant (P = 0.001) for the two parameters as depicted by the 'F' values. Rainfall duration was the most important factor that affected the two parameters. In addition, the most significant interaction that affected the two parameters was that between soil type and rainfall duration which was significant at 0.1% level. This was followed by the interactions between compaction effort and rainfall duration and between peat content and rainfall duration in that order for the two parameters. These interactions and the main effects will be described below.

3.1.1 Peat content

Soil loss decreased with increasing levels of peat in the three soils. This was true irrespective of the compaction effort, and the rainfall duration that the three soils were exposed to. The decrease in soil loss by peat content confirms the earlier findings in the previous papers by Ekwue et al. (2009) and Ekwue and Harrilal (2010) that peat decreases soil erosion by water. This can be attributed to its reduction of soil bulk density (Table 6).

Soil Type	Peat Content (%)	Compaction Effort, 100 kPa				Compaction Effort, 150 kPa				Compaction Effort, 185 kPa			
		Rainfall duration (min)				Rainfall duration (min)				Rainfall duration (min)			
		5	10	20	30	5	10	20	30	5	10	20	30
Piarco	0	12.6	24.3	50.2	75.8	13.7	25.1	52.8	77.8	15.1	28.0	54.3	82.2
sandy	5	10.3	21.4	45.8	68.3	11.5	23.0	46.9	70.6	13.4	25.0	48.7	76.1
loam	10	7.1	17.2	38.3	58.1	8.3	18.3	38.1	63.3	10.5	20.1	44.0	70.5
Maracas	0	14.1	26.7	53.2	80.0	15.2	28.7	55.1	82.3	16.2	30.1	61.7	84.2
clay	5	12.3	23.8	48.2	73.7	13.1	26.0	51.3	76.8	14.0	27.3	55.1	78.3
loam	10	9.8	19.3	42.1	65.2	11.3	23.8	47.9	70.3	12.1	24.9	49.0	74.1
Talparo	0	16.9	28.3	55.2	84.2	16.4	31.9	59.4	87.7	17.1	31.4	63.0	90.1
clay	5	15.0	25.1	51.1	79.0	14.3	27.1	54.8	82.0	15.2	28.1	58.1	84.0
	10	12.3	23.8	47.8	72.7	12.6	25.0	50.7	75.7	14.1	26.3	53.1	79.9

Table 3. Surface runoff (mm) of soils at varying peat, compaction levels and rainfall durations

This is in line with the findings of Ekwue and Stone (1995) and Ekwue et al. (2009) which showed that peat reduces bulk density of soils by diluting the soil matrix with its own less dense material. This reduction in soil bulk density ensured that peat increased the infiltration capacity of the soils, and therefore reduced runoff and soil loss as was further confirmed in this study (Tables 2, 3, and 4). Ekwue (1987, 1992) reported increases in infiltration rates as a result of peat incorporation to the soil. Table 6 shows that penetration resistance decreased with increasing peat contents in all the soils. This result is in agreement with the findings of Ekwue (1990) and Zhang et al. (2005) which showed that peat reduces soil strength. Peat reduces soil strength by just adding to the soil bulk, reducing its inter-aggregate stability and making the soil aggregates to fall apart (Ekwue, 1987). Although soil strength is known to increase the resistance of soils to erosion (Rachman et al., 2003; Wuddivira, 2008), the present results further confirm that peat reduces soil loss by increasing infiltration and decreasing runoff during rainfall rather than by strengthening the soil as was obtained for other organic materials like farmyard manure by Wuddivira et al. (2009) and Ekwue et al. (2009). Runoff and soil erosion are important not only for soil and water conservation, but also to reduce nutrient discharge with runoff (Bjorneberg et al., 2000). This means that the reduction of surface runoff and soil erosion by peat will not only aid soil conservation, but also reduce loss of plant nutrients in the soil. The interaction between peat content and rainfall duration (Fig. 3) shows that the effect of peat on soil loss increases with rainfall duration. A similar interaction was reported for soil detachment by Ekwue (1991) in connection to organic matter originating from grass.

3.1.2 Soil type

The main effect of soil type was the second most important of all the experimental factors on soil loss and runoff (Table 5). This was almost like the previous paper by Ekwue and Harrilal (2010) where it was the most important factor. This may be as a result of the same process involved in the raindrop erosion measured in the two studies. In a previous study by Ekwue et al. (2009), soil type was the least important factor and this may be because this study measured wash erosion by surface runoff, while the present and the Ekwue and Harrilal (2009) examined the total erosion process of transport of soil particles detached by raindrop which is commonly referred as interrill erosion (Levy et al., 2001). Piarco sandy loam had the largest quantity of mean soil loss and this has been consistent in the with these two recent studies. Although this soil had the least runoff as the rainfall duration increased (Tables 3 and 4), its low percentage clay content (18.1%, Table 1) decreased the soil strength (Table 6), thus decreasing the soil's ability to increase the cohesiveness of the particles. The larger size of the sandy loam soil led to greater presence of large pores which enhanced infiltration. Results show that this led to lower surface runoff. However, decreased soil cohesiveness, the presence of more loose detached sand particles ensured that the soil had greater soil loss than the other soils despite its maintenance of high infiltration and low runoff rates.

With the 46.3% clay content of the Talparo clay soil (Table 1), the soil cohesiveness and soil strength (Table 6) was the greatest as was measured by the soil penetration test. However, due to the low infiltration and high runoff rates recorded for this soil, the Talparo soil still had more soil loss than the Maracas clay loam soil. Although there was little raindrop detachment, due to the quantity of clay in the soils composition, the Talparo clay experienced the lowest infiltration and greatest amount of surface runoff of the three soils (Tables 3 and 4). This quantity of surface runoff was able to produce soil erosion, and as the rainfall duration increased, so too did the runoff and also the quantity of erosion. However, its high clay composition and high soil strength ensured that there was less erosion than the Piarco sandy loam. The Maracas clay loam had the least soil loss. This was mainly its evenly balanced composition of sand, silt and clay (Table 1). The Maracas clay loam had 30.6% clay content which was enough to produce good cohesive nature and soil strength for the particles so as to minimize splash erosion and easy detachment. The sand and silt composition allowed the soil to have steady infiltration throughout the testing period and leading to runoff which was closer to that recorded for the sandy loam soil (Table 4). These characteristics of low soil detachment and medium runoff made the Maracas clay soil to have the least soil loss of the three soils.

Factor level	Mean runoff (mm)	Mean soil loss (kg)
Soil type		
Piarco sandy loam	37.1 a	1.36 c
Maracas clay loam	41.6 b	0.95 a
Talparo clay	44.7 c	1.27 b
LSD (P = 0.001)	2.0	0.06
Peat content, %		
0	44.7 c	1.34 c
5	41.5 b	1.20 b
10	37.1 a	1.04 a
LSD (P = 0.001)	2.0	0.06
Compaction effort, kPa		
100	38.2 a	1.34 c
150	41.3 b	1.23 b
185	43.8 c	1.01 a
LSD (P = 0.001)	2.0	0.06
Rainfall duration (mins)		
5	13.1 a	0.38 a
10	25.1 b	0.71 b
20	51.0 c	1.42 c
30	75.3 d	2.27 d
LSD (P = 0.001)	2.5	0.08

[a] Mean values for each factor were obtained by averaging the measured values over the levels of the other three experimental factors. Values followed by different letters in each column are significantly different at the 0.1% level. Number of experimental points is 216 representing a factorial experiment with 3 soil types, 3 levels of added peat, 3 compaction levels, and 4 rainfall durations with 2 replications.

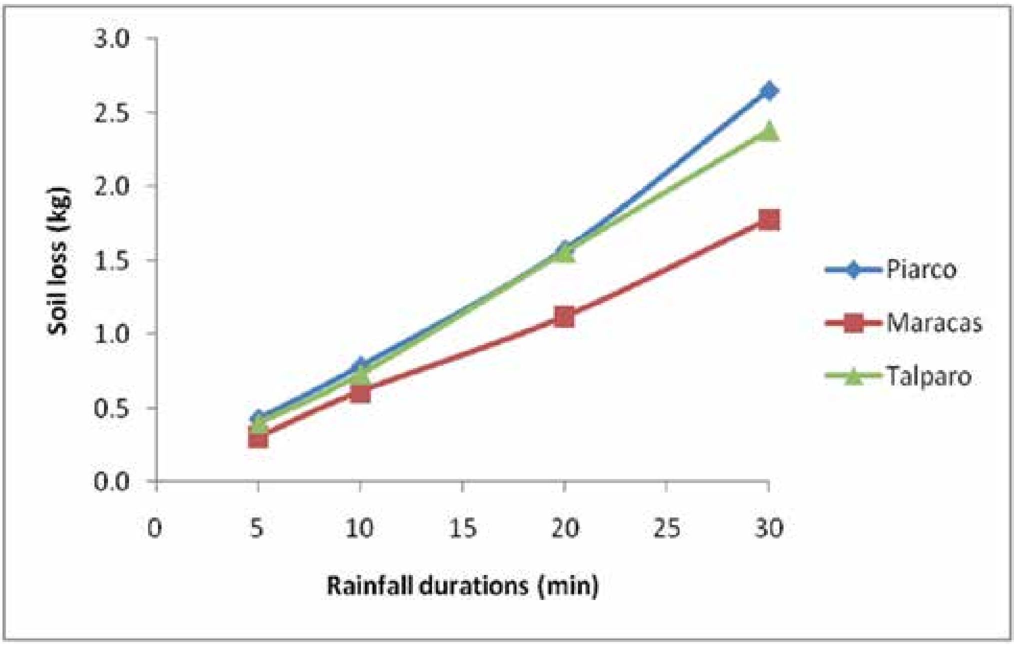
Table 4. Mean values of cumulative runoff and soil loss for different experimental factors[a]

Sources of variation	Degrees of freedom	Runoff	Soil loss
Soil type	2	50.3*	166.7*
Peat content	2	50.5*	79.1*
Compaction effort	2	27.1*	99.5*
Rainfall duration	3	2002.2*	1915.7*
Soil type x peat content	4	0.6	0.2
Soil type x compaction effort	4	0.8	1.9
Soil type x duration	6	4.5*	29.4*
Peat content x compaction effort	4	0.8	0.8
Peat content x duration	6	1.9	11.8
Compaction effort x duration	6	3.1*	27.2*
*Significant at 0.1% level			

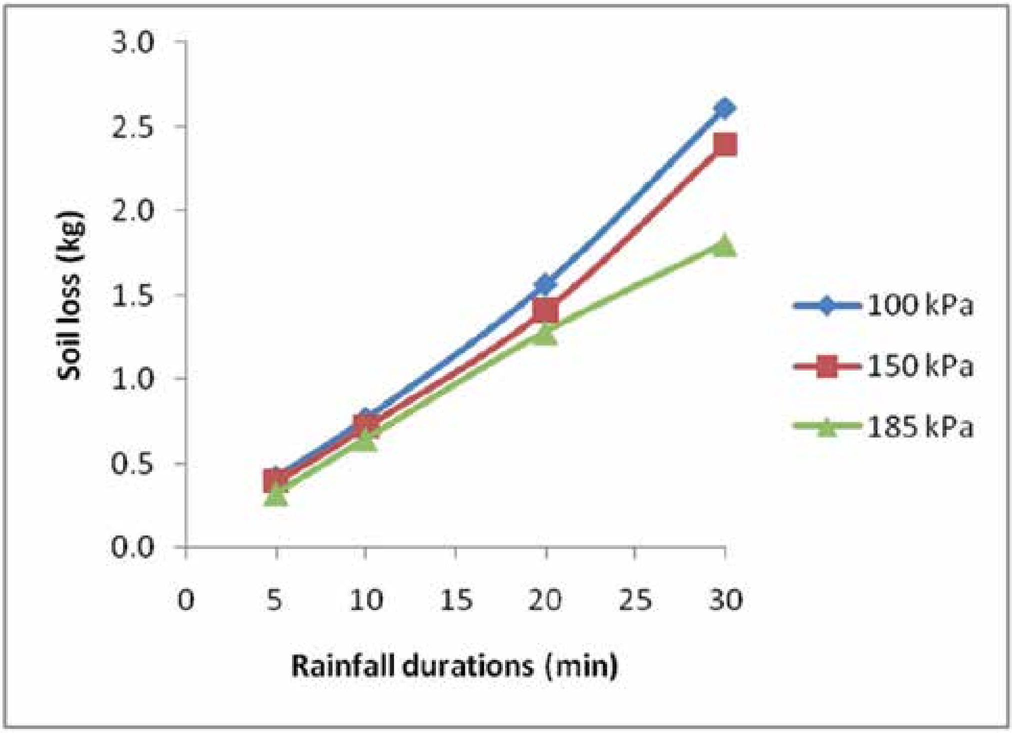
Table 5. 'F' values in the analysis of variance for cumulative runoff and soil loss

Soil type	Added peat Content, %	Bulk density, t m^{-3}			Penetration resistance, kPa		
		Compaction effort, kPa			Compaction effort, kPa		
		100	150	185	100	150	185
Piarco sandy loam	0	1.47	1.57	1.68	150.1	157.5	165.7
	5	1.37	1.47	1.56	147.2	152.8	160.5
	10	1.24	1.28	1.42	129.3	143.6	154.7
Maracas clay loam	0	1.42	1.45	1.51	160.0	171.0	180.1
	5	1.21	1.24	1.33	153.6	165.9	172.4
	10	1.04	1.07	1.12	147.8	155.6	167.4
Talparo clay	0	1.20	1.25	1.28	172.8	184.8	205.1
	5	1.15	1.21	1.23	163.5	170.7	189.2
	10	1.12	1.17	1.20	156.7	163.0	174.1

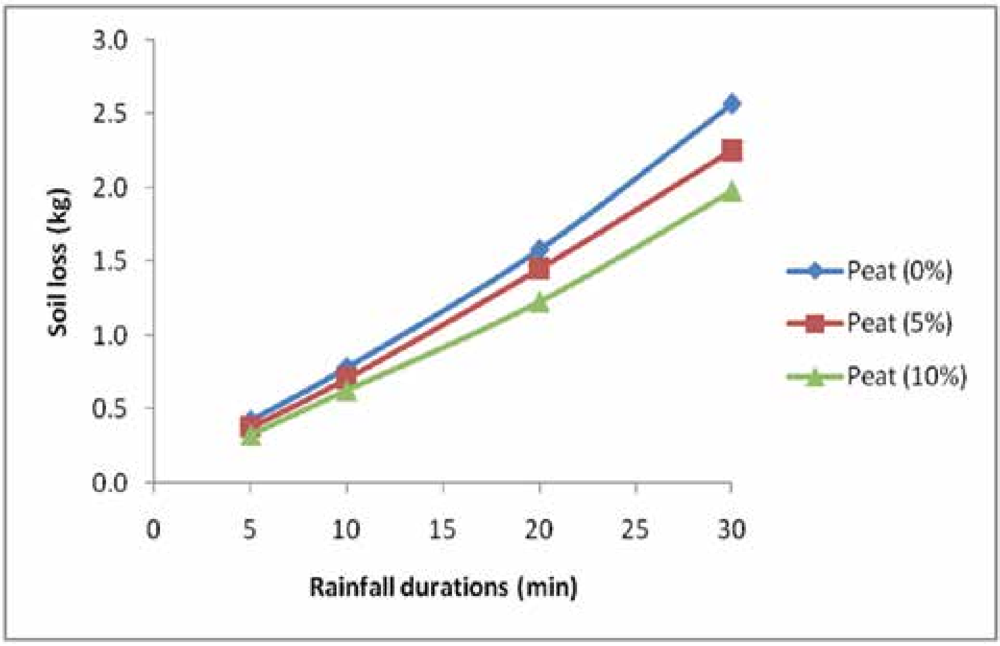
Table 6. Values of bulk density and penetration resistance of soils prior to testing for soil loss


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Soil loss (kg)
0
5
10
15
20
25
30
Rainfall durations (min)
Piarco
Maracas
Talparo

(a)


3.0
2.5
2.0
1.5
1.0
0.5
0.0
Soil loss (kg)
0
5
10
15
20
25
30
Rainfall durations (min)
100 kPa
150 kPa
185 kPa

(b)



(c)

Fig. 3. Effect of the interactions between rainfall duration and (a)soil type, (b) compaction effort and(c) peat content on soil loss.

The interaction between soil type and rainfall duration (Fig. 3), was significant and shows that as the rainfall duration increased the differences in soil loss between the sandy soil and the clay loam and clay widened. This was similar to the results obtained by Ekwue (1991). Results, therefore, confirm that the effect of soil type on soil erosion depends on the rainfall duration.

3.1.3 Rainfall duration

As expected, soil loss increased, in each case with rainfall duration. At higher rainfall duration, there was a greater breakdown in soil aggregates as well as greater cumulative runoff on the soil surface. The magnitude of increase of soil loss with increasing rainfall duration was, however, reduced by increasing peat content, clay content and soil compaction effort as the interactions between rainfall duration and these three parameters showed (Fig. 3). These results are not very explicit in previous studies of soil erosion.

3.1.4 Compaction effort

Generally, soil loss decreased with increasing compaction effort in all the soils and this further clarifies the effect of compaction on soil loss. Soil compaction is a process by which soil particles are rearranged into a denser state. This is normally caused by natural forces or human induced mechanical loads such as wheel traffic and tillage. It results in reduction in soil porosity mainly its air-filled fraction, decrease in aeration and water infiltration, and increase in soil strength (Tekeste et al., 2006**).** Although surface runoff increased with increasing compaction effort (Table 3), the greater soil strength which resulted from compaction (Table 6) ensured that soil loss declined with increasing compaction levels. This result is not always certain since it is always feared that greater surface runoff as a result of soil compaction could increase soil erosion.

3.2 Derivation of regression equation relating soil loss to experimental factors

The soil loss for the three soils with three levels of peat content compacted at three levels and exposed to four rainfall durations was used to generate a multiple linear regression equation that could be used to predict soil loss. The equation was of the form:

$$SL = 0.767 - 0.00276\, C_t \;\; 0.0307\, P_t - 0.00386\, P_c + 0.00172\, KE \qquad (1)$$

Student 't' (11.34) (-7.62) (- 4.43) (-3.69) (8.70)

(R = 0.878; N = 216)

Where: SL is soil loss (kg); C_t is clay content of the soil (%); Pt is the peat content (%), Pc is compaction effort (kPa) and KE is raindrop kinetic energy (J m^{-2}). R is the coefficient of multiple regression and N is the number of experimental data points. The signs of the experimental factors obtained confirm how the factors affected the soil loss. The R is significant at the 0.1% level. The student 't' values for all the experimental factors shown beneath them in the equation were all significant at 0.1% level. The relative 't' values for all the factors also confirm the findings in the analysis of variance which showed that the most important factors that affected soil loss were rainfall duration, soil type, compaction effort and peat content.

4. Conclusion

Soil loss by simulated rainfall was measured for three Trinidadian soils in the laboratory using a specially constructed soil erosion apparatus. Soil loss decreased with increasing peat content in all cases and was smallest in the clay loam soil and highest in the sandy loam. Peat decreased soil loss by decreasing runoff during rainfall. Soil loss declined with increasing compaction effort. The interactions involving rainfall duration showed that although soil erosion increases with rainfall duration, these increases will be reduced by increasing clay, and peat contents of the soil as well as the increasing level of soil compaction. A multiple regression equation derived to relate soil loss to the experimental factors was highly significant and confirmed that the most important factors that affected soil loss were rainfall duration, soil type, compaction effort and peat content. The implication of this study is that while land use zoning of soils based on slopes is very essential in soil conservation, the incorporation of organic materials particularly in form of peat in steep arable slopes will greatly minimize soil erosion by water. It will also minimize surface runoff which will decrease the loss of nutrients from farmlands.

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10

Soil Erosion and Surface Runoff on Slopes in Mountain Environment Depending on Application Technique and Seed Mixture – A Case-Study

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1. Introduction

Erosion is a basic problem found in the entire mountainous regions around the globe. Within the whole alpine area of Europe, thousands of hectares are affected every year, e.g. by construction of ski runs, ski lifts, tourists infrastructure and roads (CIPRA 1998). Besides, natural erosion causes increasingly more problems. According to estimates, 5,000 hectares have to be restored yearly following interventions in high altitudes, more than 50,000 hectares of insufficiently restored areas would need imperative improvement.

High altitudes as the most sensible part of the Alps can be defined as areas within the pre-alpine and alpine belt i.e. areas above 1,600 msm in the Eastern Alps and areas above 1,800 msm in the Central Alps (Krautzer et al. 2006). Every disturbance in such alpine ecosystems leads to interference that requires different technical and ecological measurements. For lack of plant material in most cases, seed mixtures containing grasses and clover are normally used to establish vegetation again. Restoration of damaged areas in high altitudes is much too often done with an inadequate combination of technical and biological measurements. Cheap application techniques and cheap seed mixtures from species that are not adapted for high altitudes are state of the art. The resulting ecological and economical damage is considerable: soil erosion, extreme surface runoff, degradation of the vegetation, frequent reseeding, constant fertilising, flora falsification, expensive maintenance (Greif 1985, Bittermann 1993). Due to this situation, especially the economically important winter and summer tourism got a very negative image.

The research project “Seed Propagation of Indigenous Species and their Use for Restoration of Eroded Areas in the Alps” (FAIR CT98-4024, short title “Alperos”), supported by the EU, was dealing with the thematic to restore damaged areas using a combination of improved application techniques combined with seed mixtures of indigenous species. The goal of this project was to create a new state of the art in ecological restoration of damaged areas in high altitudes of the Alps. Results obtained during the four years 1999 to 2002 at 8 different locations in altitudes between 1,200 and 2,300 metres clearly showed multiple positive effects if indigenous sub-alpine and alpine species are used for restoration. Up to 20 %

higher vegetation cover and thus better protection against erosion three years after sowing, no need for further fertilisation and maintenance on most sites and a much higher percentage of sustainable species are only some of the essential advantages (Krautzer et al. 2010). However, the most risky period where erosion processes can cause considerable damage are the weeks after sowing. Especially indigenous species are germinating and growing very slow. Depending on altitude, vegetation needs 8 to 12 weeks to reach a vegetation cover that is able to reduce erosion to an acceptable degree (Stocking & Elwell 1976, Mosimann 1984). During this period, the vegetation technique has a substantial influence on erosion processes. During the last years, essential work has been done to create simulations and predicting models for soil erosion by water (Morgan et al. 1991, Renard et al. 1997, Klik et al. 1998). Important investigations have been made in order to get knowledge about the influence of different soils and vegetation on erosion and surface runoff in high altitudes (Czell 1972, Schaffhauser 1982, Bunza 1989, Markart et al. 1997). But up to now only little data is available, describing the relations between precipitation, surface runoff and soil erosion during the period after restoration of alpine locations, what is strongly influenced by the chosen application technique (Florineth 2000). On the other hand, restoration companies assure that cheap application methods like normal hand sowing combined with cover crops or plain hydroseeding can be used in most cases (Neuschmid 1996).Up to now we lack on data clearly stating the effects of restoration with different application techniques and seed material on erosion processes on slopes in high altitudes.

In the course of the EC project “Alperos”, the Agricultural Research and Education Centre Raumberg-Gumpenstein tried to acquire special information about the effects of different common and improved application techniques on surface runoff and soil losses as a basis for further recommendations or stipulations. A special erosion facility was built up in order to measure erosion in dependency on different application techniques after restoration in high altitudes. Three different trials were carried out in order to answer the following main questions: Water flow and soil losses depending on precipitation, influence of seed mixtures on soil erosion, effect of cover grass and cover crop in comparison to hydroseeding and additional protection of soil surface.

2. Material and methods

2.1 Site conditions

The trial were carried out at the location Hochwurzen (1,830 m), a part of the famous skiing centre of Schladming, Austria (13.64° E, 47.36° N). The erosion facility with the plots were set up directly on a ski run with an average inclination of 38 % and an exposition of southeast (SE). The parent rock is Gneis, soil type Leptosol. The soil depth was measured with an average of 16 cm, the water regime can be described as fresh. The climax plant community around the experimental trial on the location Hochwurzen is the Larici-Piceetum; the antropogenic vegetation belongs to the Sieversio-Nardetum strictae. The soils are acid dystric cambisols and leptosols in the Al buffer range (Nestroy et al. 2000).

The classification and descriptions of the soil conditions were done according to the official Austrian guidelines for fertilization of grassland (BMLFUW 2006). The chemical soil conditions of the machine graded site were characterised by a slightly acidic soil pH (carbonate buffer range); relative high humus content (dry combustion) and a relative small C/N ratio (Table 1). The chemical analyses showed a low value of Calcium-Acetat-Lactat (CAL)-extract soluble P; a sufficient amount of Calcium-Acetat-Lactat (CAL)-extract soluble

K; a favourable base saturation of Ca and Mg and low K saturation. The soil contained a sufficient content of EDTA extractable Fe, Mn, Cu and Zn (BMLFUW 2006).

pH ($CaCl_2$)	6.6	P (CAL-extract mg kg^{-1} at pH > 6)	13.0
Humus %	4.0	K (CAL-extract mg kg^{-1})	47.5
N tot (%)	0.2	$CaCO_3$ %	2.2
Mg ($BaCl_2$-extract mval $100g^{-1}$)	2.3	K ($BaCl_2$-extract mval $100g^{-1}$)	0.1
Ca ($BaCl_2$-extract mval $100g^{-1}$)	9.2	Na ($BaCl_2$-extract mval $100g^{-1}$)	0.1
Fe (EDTA-extract mg kg^{-1})	260.7	Cu (EDTA-extract mg kg^{-1})	9.3
Mn (EDTA-extract mg kg^{-1})	86.0	Zn (EDTA-extract mg kg^{-1})	4.0

Table 1. Soil parameters of site “Hochwurzen”

The average yearly temperature of the site lies at 3.5° centigrade, precipitation at about 1200 mm per year. A meteorological station was installed about 60 m faraway from the experimental plots. Rainfall was measured every 10 seconds and an hourly average was calculated and stored on the data logger. On site Hochwurzen, snow melt ended during the last third of May.

2.2 Description of the erosion facility

In order to measure the effects of different techniques on erosion, a mobile erosion facility with three chambers was set up. Figure 1 shows a sketch of the erosion facility. The surface runoff and soil losses from 3 different plots (40 m² each) were collected at the bottom of the plots and passed through a tube to 3 deposit containers for heavy soil components. Water, containing dissolved soil components ran to tip pans of 0.5 and 2 litres (working in dependence on the amount of water) for each plot. The tip pans were connected to a data logger. A bypass was collecting samples automatically. Together with the data of the climatic station, the relation between precipitation and surface runoff was worked out. Measuring the heavy soil components and the dissolved components in the sample container, soil losses were calculated too. For this was very time consuming, soil losses were measured only three times a year for each trial. Therefore, detailed information about soil losses during single raining events was not available.

2.3 Description of the trials

In general, our available equipment restricted us to three chambers per year. Therefore, no replications and no statistic evaluation of the results were possible. To make our results more precise, we tried to repeat some techniques (with minor modifications). In order to guarantee comparable conditions, vegetation was killed in autumn using 4 l ha^{-1} of an herbicide with the active substance Glyphosate. In spring 2000 and 2001, the first 5 cm of soil surface were removed and stored soil surface from a depot near the trial was applied. Table 2 gives a short overall view of the three different trials in 1999, 2000 and 2001-2002. Over all four investigation periods, each chamber was fertilised with 2,000 kg ha^{-1} of the organic fertiliser “Biosol”, one of the most common organic fertiliser for restoration in high altitudes (Naschberger & Köck 1983).

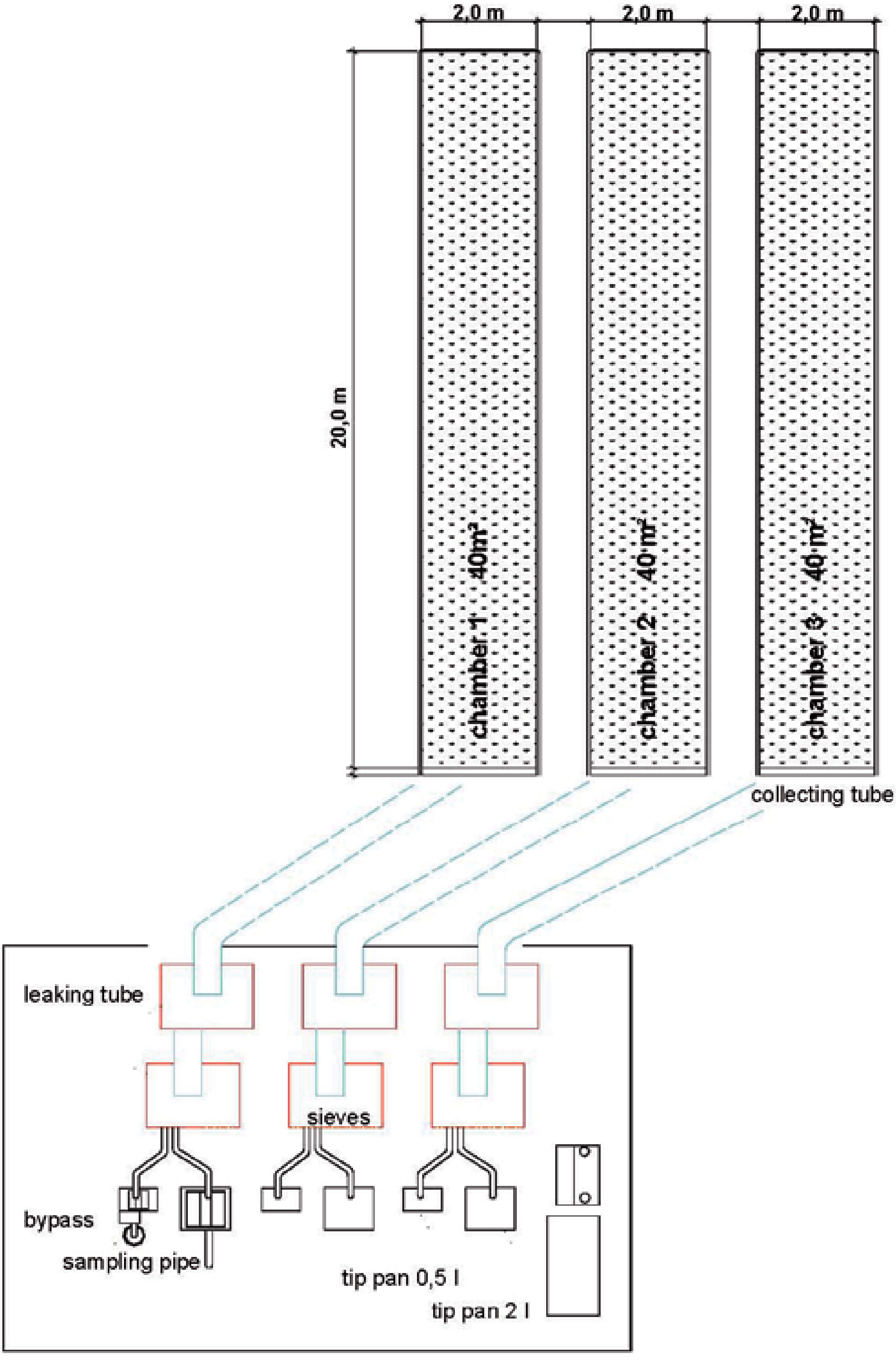

Fig. 1. Sketch of erosion facility "Hochwurzen"

Photo 1. Tip pans of 0.5 and 2 litres of the erosion facility "Hochwurzen"

Photo 2. The collecting tube at the bottom of the plots

Year	I	II	III
1999	hand sowing commercial mixture	hand sowing+straw mat (indigenous mixture)	hand sowing (indigenous mixture)
2000	hand sowing	hand sowing+cover grass (5% *Lolium perenne*)	hand sowing+cover crop (70 kg ha^{-1} rye)
2001-2002	hand sowing+cover crop (70 kg ha^{-1} oat)	hydroseed (gluten, cellulose, seeds, organic fertilizer)	hydroseed+straw mat

Table 2. Overview of the different trials (application techniques) from 1999 to 2002 on the erosion facility

In 1999, a pilot trial with 3 plots was set up in order to compare a seed mixture of commercial lowland species with an indigenous seed mixture of alpine species (Table 3). The commercial seed mixture in chamber 1 contained 11 species of grasses and herbs, bred for the demands of grassland production. In comparison, the indigenous seed mixture contained 16 species of pre-alpine and alpine species, adapted to the harsh site conditions. All three plots were hand sown, using 15 g seeds m^{-2}. Chamber 2, sown with the indigenous seed mixture like chamber 3, was covered by the straw net "Greenfield S 100" (350 g m^{-2} straw, interweaved with a jute thread). During June, the equipment was calibrated and optimised. The first trial was assessed from 02-08-1999 to 02-09-1999 in order to test the influence of the two different seed mixtures and in addition the effect of covered soil surface on surface runoff and soil losses. During the investigation period of 1999, a precipitation of 350 mm was registered by our climatic station.

commercial mixture	% of weight	indigenous seed mixture	% of weight
grasses			
Agrostis capillaris	4.60	*Agrostis capillaris*	4.00
Festuca ovina	2.50	*Festuca nigrescens*	35.00
Festuca rubra	31.00	*Festuca violacea*	5.00
Lolium perenne	15.70	*Lolium perenne*	3.00
Phleum pratense	19.90	*Phleum alpinum*	10.00
Poa pratensis	10.60	*Poa alpina*	15.00
		Poa supina	5.00
leguminosae			
Lotus corniculatus	5.00	*Anthyllis vulneraria*	5.00
Trifolium hybridum	2.40	*Lotus corniculatus*	3.00
Trifolium repens	4.20	*Trifolium badium*	5.00
Vicia sativa	3.40	*Trifolium nivale*	3.50
herbs			
Achillea millefolium	0.70	*Achillea millefolium*	1.00
		Dianthus superbus	0.50
		Leontodon hispidus	1.00
		Silene vulgaris	0.50

Table 3. Composition of commercial and indigenous seed mixture

In 2000, the second trial was set up in order to prove the efficiency of the additional use of nursery grasses and cover crops in comparison to normal hand seed. All described techniques are often used in alpine areas, especially on small scale restoration sites. The trial was assessed from 21-06-2000 to 25-10-2000. For this comparison, 15 g m^{-2} of the indigenous seed mixture were used for all three plots. On chamber 2, *Lolium perenne* (variety "Guru") with an amount of 5 % was added as nursery grass to the mixture. 70 kg m^{-2} of summer rye (variety "Tyrolean summer-rye") was used as cover crop for chamber 3. This trial should give an answer to the usefulness of nursery grasses or cover crops to prevent restored areas with an inclination of more than 30 % from erosion. Water samples were collected three times (13-07, 21-08, 25-10). During this investigation period, the nutrient losses of P and K by surface runoff were calculated as the product of the volume of water (l m^{-2}) running off the plot and its concentration (mg l^{-1}). Soil texture and nutrient content of the eroded soil material were analysed at the end of the observation period. The humus- and nutrient loss by soil erosion were calculated from the eroded soil material (particles smaller than 2 mm in diameter; g m^{-2}) and its nutrient content (%, mg kg^{-1}). During the investigation period of 2000, a precipitation of 810 mm was registered by our climatic station.

Photo 3. The setup of the three chambers of the trial

From 2000 to 2001, a third trial was set up in order to assess the efficiency of an additional protection of soil surface (chamber 3) in comparison to the common used techniques hand sowing plus cover crop oat (70 kg ha^{-1}, chamber 1) and hydroseeding (chamber 2). The hydroseeding contained cellulose (80 g m^{-2}) and gluten ("Curasol", 15 g m^{-2}). For all chambers we used organic fertiliser "Biosol" (200 g m^{-2}) and indigenous seeds (15 g m^{-2}). On chamber 3, again the straw net "Greenfield S 100" (350 g m^{-2}) was applied on the soil surface. The first observation period lasted from 27-06-2001 to 11-10-2001. We decided to run this trial also for a second investigation period from 23-05-2002 to 28-08-2002 in order to measure possible differences in surface runoff and soil losses of the described application techniques during the second vegetation period after sowing. The corresponding vegetation cover of the three chambers was measured at the end of June 2002. During the investigation period of 2001, a precipitation of 568 mm, during 2002 a precipitation of 1,066 mm was registered by our climatic station.

Photo 4. The experimental trial after the application of the different techniques

3. Results

In 1999 we managed the set up of the erosion facility during June. Facing some problems with the equipment, necessary adjustments were carried out during July. With our first trial in 1999 we wanted to measure the effects of commercial and indigenous seed mixtures as well as the effect of an additional protection of soil surface. In order to avoid interactions with application techniques, we used normal hand sowing. During the investigation period, 2 heavy raining events with a precipitation of more than 15 mm h^{-1} took place. Figure 2 shows the summarized surface runoff and soil losses depending on 362 mm precipitation. During our first inspection we noticed a blockage of the sampling tube of chamber three. Therefore, surface runoff from this plot did not describe the actual amount. However, between 6 % and 11 % of the precipitation did not infiltrate to the soil. In comparison, the additional cover of soil surface was able to reduce surface runoff to 1 % of corresponding precipitation. A similar relation was observed with soil losses. On the two chambers with hand sown seed mixtures soil losses from 640 kg ha^{-1} (commercial mixture) up to 780 kg ha^{-1} (indigenous seed mixture) were measured. The straw mat was able to reduce soil losses to 26 kg ha^{-1}, an amount of 4 % compared to chamber 1.

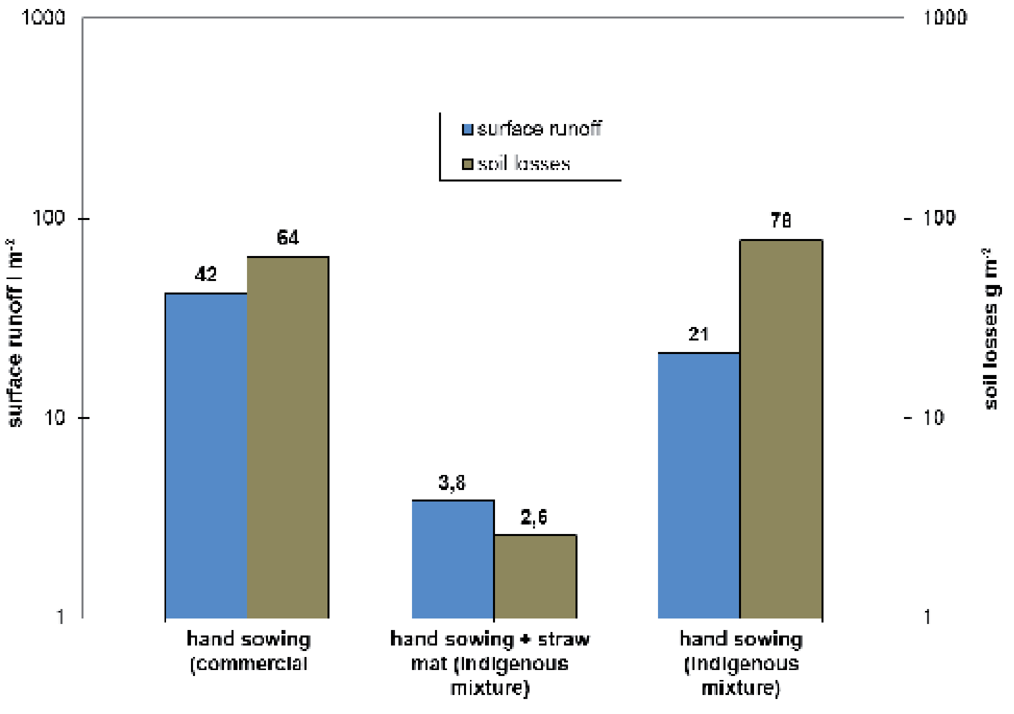

Fig. 2. Soil losses and surface runoff depending on precipitation (362 mm), observation period from 02-08-99 to 02-09-99

In the last week of June 2000, the second trial started. This year the investigation period lasted for 18 weeks with a precipitation of 810 mm. During the investigation period, 3 heavy raining events took place. The equipment worked without technical problems. This year we wanted to measure the effects of normal hand sowing in comparison to the very common techniques of hand sowing plus cover crop and hand sowing plus nursery grass as typical cover crop, we used rye of the old landrace “Tyrolean summer rye”. As nursery grass, we chose *Lolium perenne* of the variety “Guru”, a variety with very good winter hardiness. Corresponding to the extended investigation period, total surface runoff and soil losses were higher in comparison to the year before. Surface runoff of normal hand sowing reached 9.6 % of precipitation, 2 % less than the year before (Figure 3). The effect of cover crop and nursery grass was visible. However, surface runoff decreased only to a percentage of 8.9 for nursery grass and 8.6 for cover crop. Soil losses of chamber 1 reached nearby 2.8 t ha^{-1}. Again, a bit lower values were measured for hand sowing plus cover crop (2.68 t ha^{-1}) and the technique using nursery grass (2.37 t ha^{-1}). In a general view, the reduction of surface runoff and soil losses with the help of fast growing but short living components of the seed mixtures was not substantial. The available water samples and the eroded soil material (particles smaller than 2 mm in diameter; g m^{-2}) were analysed in order to get information about nutrient losses.

Differences in nutrient value of single samples were very high. Therefore, no exact interpretation of results was possible. In a general view, nutrient losses were below 0.5 kg ha^{-1} for P and from 1 to 1.5 kg ha^{-1} for K, corresponding to the poor nutrient content of the soil (Table 1). A comparison of the amounts of losses of N, P, K and Mg between the single trials approximately reflected their different stability against erosion.

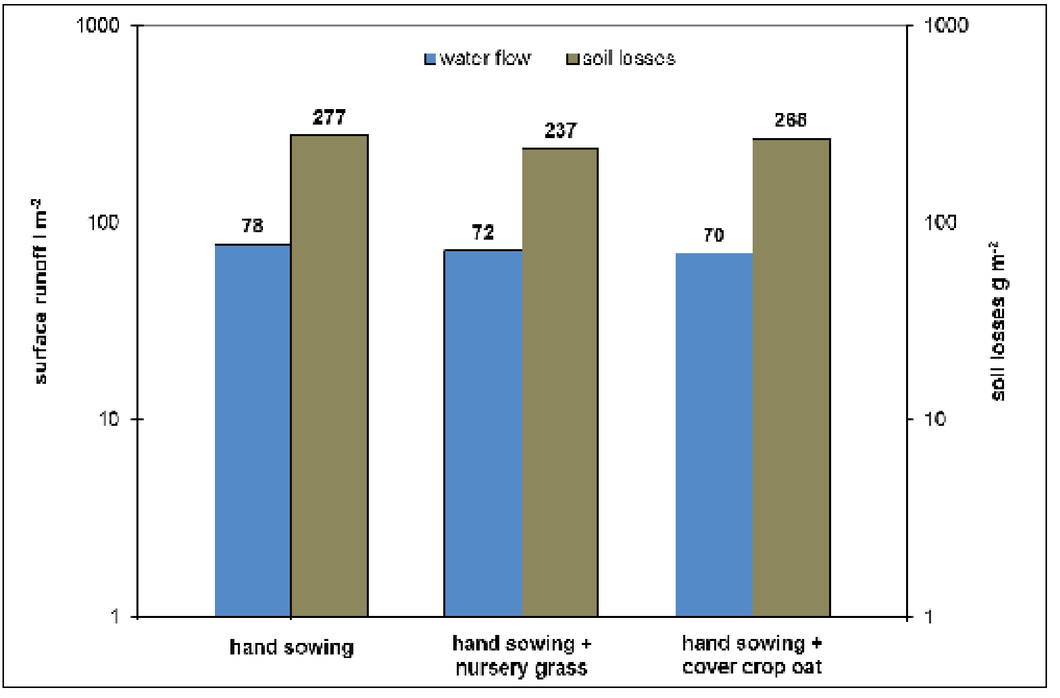

Fig. 3. Soil losses and surface runoff depending on precipitation (810 mm), observation period from 21-06-00 to 25-10-00

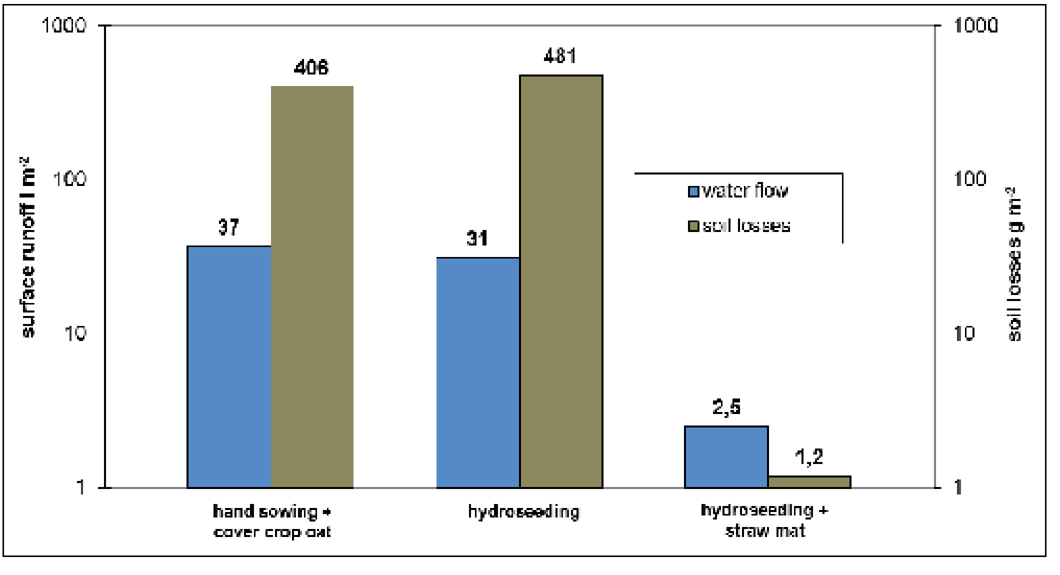

Fig. 4. Soil losses and surface runoff depending on precipitation (568 mm), observation period from 27-06-01 to 11-10-01

The third trial was set up at the end of June 2001. It was decided to run the erosion facility up to the end of vegetation period 2002 in order to get information about erosion processes the year after restoration. The first period lasted for 15 weeks with a precipitation of 568 mm and 1 heavy raining event. The equipment worked without technical problems. With this final trial we compared the technique hand sowing plus cover crop (this year oat, also a very common cover crop for restoration) to the world wide most used technique hydroseeding. As third technique, we chose hydroseeding with an additional cover of soil surface by the straw mat in order to measure the influence of protection by organic material a second time. Surface runoff from chamber 1 (hand sowing) reached 6.5 % of corresponding precipitation (Figure 4). For application technique hydroseeding, 5.5 % were measured. Again, the additional protection of soil surface led to a clear reduction of surface runoff, this time below 0.5 %. Results obtained showed soil losses of more than 4 t ha^{-1} for chambers 1 and 2. In comparison, only 12 kg ha^{-1} soil was washed out below the straw net.
Figure 5 shows the connection between precipitation and surface runoff depending on application technique during a raining event that took place on 10th August 2001, described as hourly sum total. From 9:00 to 24:00, a precipitation of 47 mm was measured.

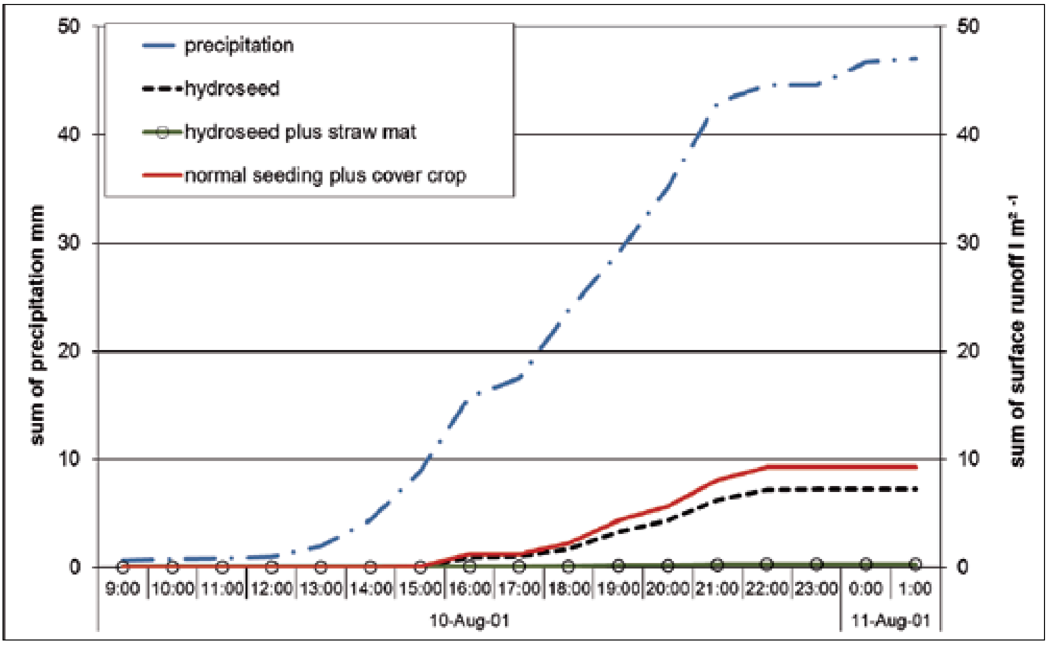

Fig. 5. Sum of precipitation and surface runoff in comparison of different application techniques during a raining event (Krautzer & Klug 2009).

The sum up of surface runoff for chamber one reached 15.8 % of precipitation, for chamber two 12.3 % and for chamber three only 1.8 %. This example showed that during periods with heavy raining events the proportion of surface runoff and therefore soil losses increases, compared to average precipitation. Figure 6 shows the same correlation between precipitation and surface runoff depending on application technique described as hourly mean values. With this figure it can be observed, that there is a delay between precipitation and surface runoff from half an hour to two hours, depending on intensity of precipitation and absorbability of the soil.

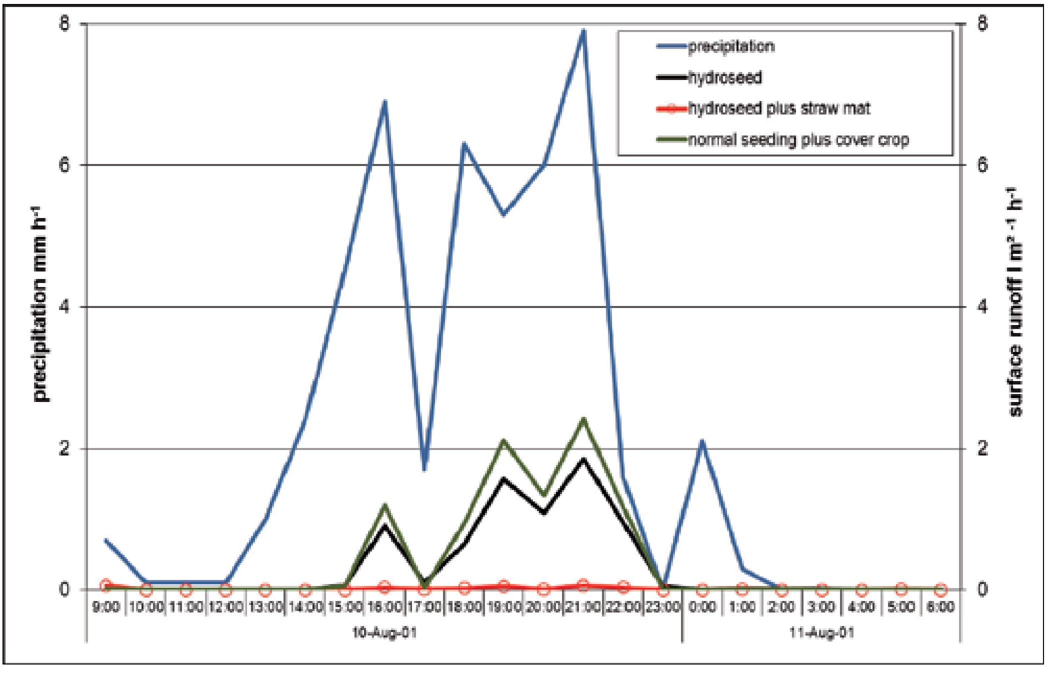

Fig. 6. Hourly values of precipitation and surface runoff in comparison of different application techniques during a raining event

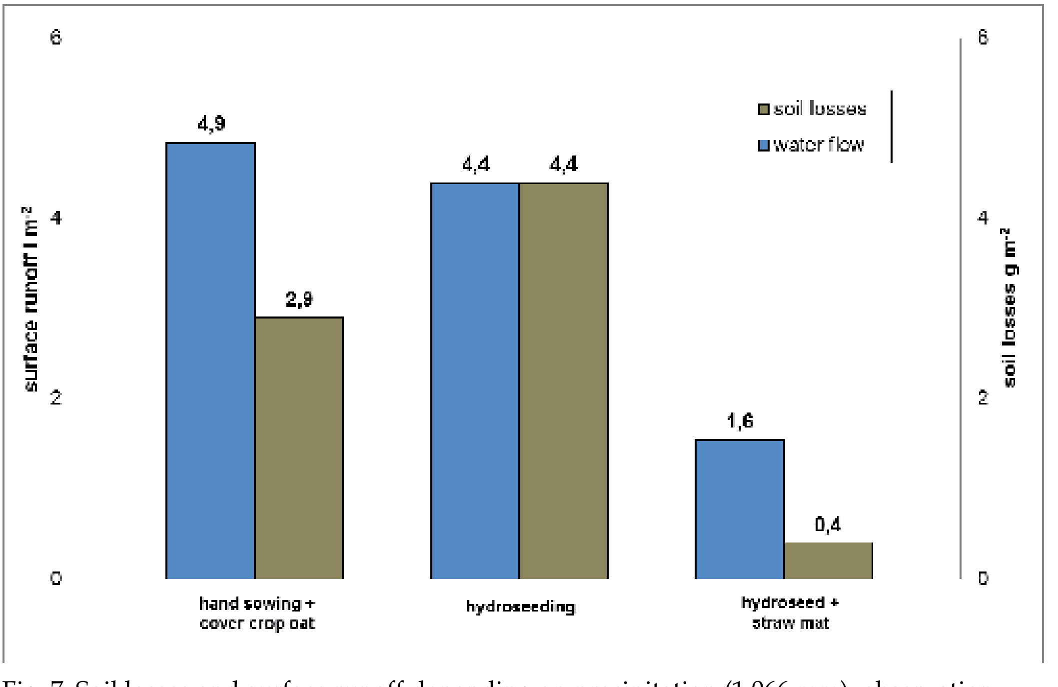

Fig. 7. Soil losses and surface runoff depending on precipitation (1,066 mm), observation period from 23-05-02 to 28-08-02

We extended the trial for one more vegetation period in order to get information about erosion processes the year after restoration. The second period of this trial lasted for 13 weeks with a precipitation of 1,066 mm, a wet summer with 14 heavy raining events. In June 2002, a vegetation cover of 70 % on chamber 1, 75 % on chamber 2 and 80 % on chamber 3 (plus 16 % additional cover from the residual material of the straw mat) was observed. The results show a clear reduction of surface runoff in comparison to 2001 (Figure 7).

Photo 5. Vegetation cover on the plot with the technique hand sowing plus cover crop a year after setup (2002), the fine-grained material was washed out

Again, for the techniques hand sowing and hydroseeding the highest water flow was measured, but in relation to total precipitation only 0.5 % respectively 0.4 % of total precipitation. The soil losses for both techniques were between 29 and 44 kg ha^{-1}, an amount that is neglectable. However, again the technique with straw mat performed much better in comparison, with surface runoff of less than 0.2 % of total precipitation and soil losses of 4 kg ha^{-1}.

Water flow and soil losses are not only a result from total precipitation. Both the intensity of the raining event and the kinetic energy from the raindrops reaching the soil surface are responsible for erosion. Therefore, a direct comparison of all assessed application techniques between years is not possible. However, Figure 8 gives a general view of surface runoff caused by all compared application techniques from 1999 to 2001, referring to 500 mm precipitation. Using cheap application techniques like hand sowing, cover crop or nursery grass as well as hydroseeding, surface runoff from 28-58 l m^{-2} was measured. Only the additional protection of soil surface was able to cause a clear reduction to a surface runoff from 2-5 l m^{-2}.

Photo 6. Vegetation cover on the plot with the technique Hydroseed a year after setup (2002), the fine-grained material was washed out

Photo 7. Vegetation cover on the plot with the technique Hydroseed with straw mat a year after setup (2002), no soil losses was visible

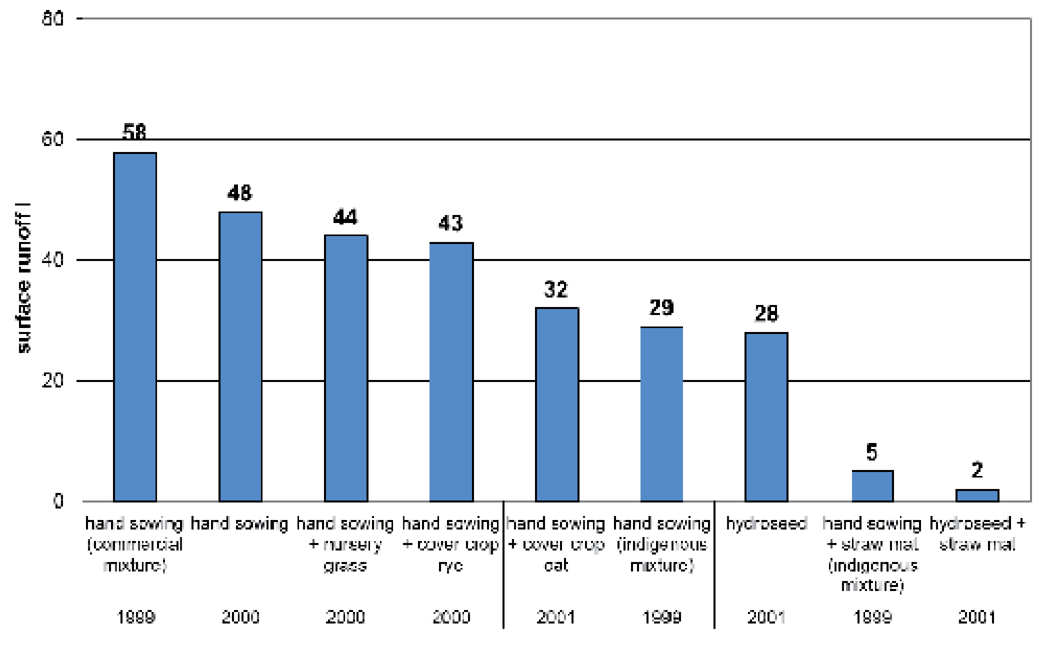

Fig. 8. Surface runoff referring to 500 mm precipitation, comparison of all sites (1999-2001)

A comparable proportion between soil losses and application techniques referring to 500 mm precipitation is visible in Figure 9. Corresponding to the climatic conditions during the investigation periods, the use of cheap and simple application techniques caused soil losses between 890 and 4,230 kg ha^{-1}. The expensive additional cover with the straw mat was able to reduce soil losses to an irrelevant amount of 11 to 46 kg ha^{-1}.

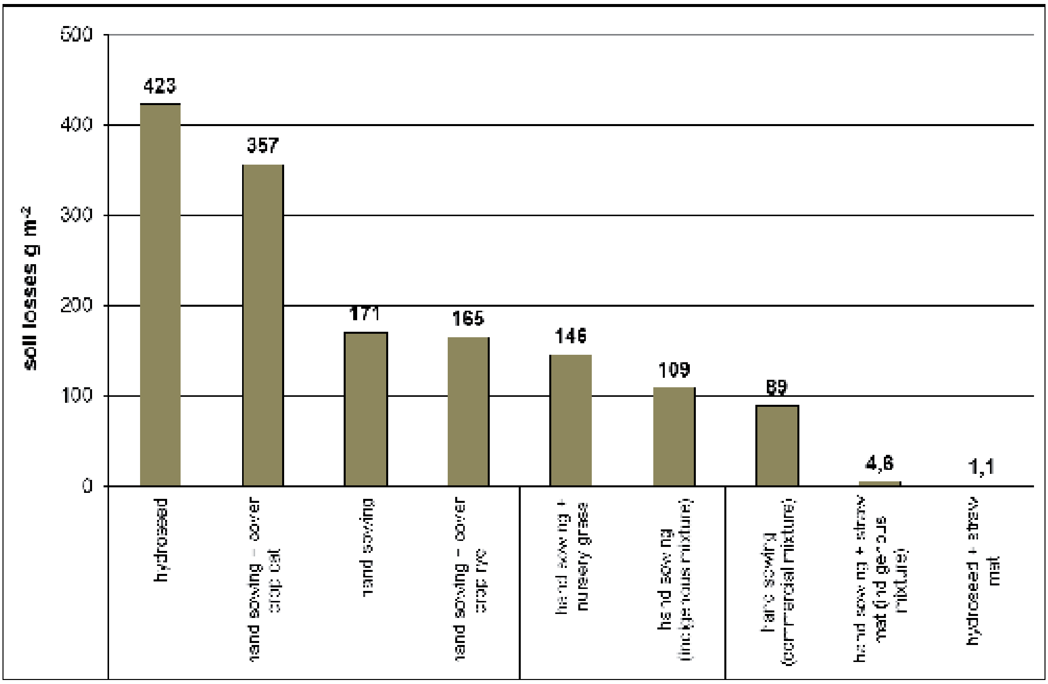

Fig. 9. Soil losses referring to 500 mm precipitation, comparison of all sites (1999-2001)

4. Discussion

The goal behind all restoration activities following interventions is to establish a dense vegetation cover as fast as possible. First and foremost, vegetation protects the soil from erosion by intercepting raindrops and absorbing their kinetic energy harmlessly. If rain drops reach the ground unimpeded, the kinetic energy damages the soil aggregates. This also reduces the water receptivity of the soil. Water not infiltrated the soil is running down the slope, causing erosion. A higher surface runoff is not definitely associated with higher soil erosion. Not only the amount of surface runoff but also other factors (type and coverage of vegetation, soil conditions) determine the extent of soil erosion (Stocking & Elwell 1976). Mosimann (1984) calculated a clear connection between vegetation cover and intensity of erosion. Up to altitudes of 1,600 m a minimum of 70 % vegetation cover is required to avoid erosion. Above timberline, more dense vegetation with a cover of about 80 % is recommended. Results of our EU-project Alperos clearly showed multiple positive ecological effects up from the 2nd year after sowing, if indigenous species were used. To reach sustainable vegetation with a cover exceeding the minimum requirement of 80 %, the use of indigenous seed mixtures is a precondition (Krautzer & Wittmann 2006).

The best period for restoration activities in high altitudes would be the first 4 weeks after snow melt (Lichtenegger 1994). During this period, most soils have a satisfying water content, also on exposed sites. In alpine environments, vegetation has a growing season of two to three months to establish. Especially the generally slow growing indigenous species need 4 to 6 weeks of satisfying growing conditions to germinate and to establish

(Urbanska & Schütz 1986). Our assessment on vegetation cover of the plots showed, that under average conditions of high altitudes this minimum cover can be reached the second vegetation period at the earliest. This requires application techniques with additional protection of soil surface for the first vegetation period. From an economic point of view, restoration companies will always try to reach minimum requirements with a minimum of costs. Therefore it is important to give clear answers and stipulations for successful application techniques under average conditions. It is evident that a direct comparison between trials and years is not possible. Hence only clear differences or correlations are discussed.

With our first trial 1999, we also wanted to measure the influence of different seed mixtures on erosion. Due to the faster germination and early growth of commercial varieties, an increase of surface runoff and soil losses the weeks after sowing was expected for indigenous seed mixtures. However, the harsh conditions in high altitudes (low soil and air temperature, short vegetation period, frequent frost) are causing environmental stress to the vegetation, reducing the competitiveness of commercial forage grasses and herbs and neutralizing their greater productivity (Jones et al. 1989) Therefore, results obtained during the investigation period did not show substantial differences between seed mixtures on erosion processes during the first weeks after restoration.

The use of cover crops and in recent time also nursery grasses as additional protection against erosion is often used for restoration activities. Due to positive, longstanding experiences of restoration companies, those techniques were compared to normal hand sowing. Again we noticed that the admixture of fast growing components did not have positive influence on surface runoff and soil erosion. Compared to normal hand seeding, the reduction was poor. Once again, the environmental stress compensated the capability of fast early growth, reducing the positive effects towards zero. Results obtained clearly showed that the use of cover crops and nursery grasses did not have positive influence in view of a necessary reduction of surface runoff and soil losses during the first weeks after restoration.

Hydroseeding is described as one of the best application techniques for steep slopes with good properties in order to prevent erosion. To our surprise, the comparison of hydroseeding to hand sowing plus cover crop showed comparable results. The hydroseeding was carried out by a professional restoration company. Therefore, conditions close to practice can be assumed. One hour after application, we were faced with a raining event of two hours with a precipitation of app. 15 mm. This could have caused some wash out of not yet stabilized gluten, reducing the effect of building a protective layer on soil surface. Even if we take this possible problem into account, results obtained at least indicate a big risk in using this application technique without additional protection of soil surface.

Depending on soil physical properties, climate and altitude, varying characteristics of runoff, infiltration and erosion can be expected (Markart & Kohl 1995). Especially in high altitudes, the main goal behind the choice of a certain application method has to be a reduction of surface runoff and soil erosion to an acceptable degree. A comparison of all used application techniques during our assessments shows clear results. Only an additional cover of soil surface is able to reduce surface runoff and soil losses to an acceptable degree. For our trials in 1999 and 2001-2002 we used a straw mat. But there are a lot of different techniques available that guarantee a sufficient protection of soil surface. Straw mulching, hay mulching, different mats, nets made from jute or coco, three-dimensional mats etc. With the first series of trials, we were not able to work out differences between the materials. But a comparison can be made to results gained from field trials in South Tyrol (Waldner 1999, Graiss 2000). There, erosion was measured for different application techniques with and without covered soil surface, regarding to precipitation. A measurement of surface runoff was not possible. However, differences between the used techniques with covered soil surface (straw, hay, with or without bitumen emulsion to glue the organic matter) were low. The proportion between soil losses of covered plots to hand sowing plus cover crop (average proportion of 1:110) is comparable to the results of our project.

5. Conclusion

Our assessment on vegetation cover of the plots showed, that under average conditions of high altitudes the necessary minimum vegetation cover between 70 % and 80 % can be reached the second vegetation period at the earliest. This requires application techniques with sufficient protection of soil surface for the first vegetation period.

During the second vegetation period, differences between used application technique are still visible but a satisfying developed vegetation cover reduces the total surface runoff and soil losses to an acceptable degree.

Due to the faster germination and early growth of commercial varieties, an increase of surface runoff and soil losses the weeks after sowing was expected for indigenous seed mixtures. However, the harsh conditions in high altitudes (low soil and air temperature, short vegetation period, frequent frost), causing environmental stress to the vegetation, reduced the competitiveness of commercial forage grasses and herbs and neutralized their greater productivity. Results obtained did not show substantial differences between seed mixtures on erosion processes during the first weeks after restoration. However, to reach sustainable vegetation with a cover exceeding the minimum requirement of 80 %, the use of indigenous seed mixtures would be a precondition.

The use of cover crops and nursery grasses did not have positive influence in view of a necessary reduction of surface runoff and soil losses during the first weeks after restoration. The environmental stress compensated also their capability of fast early growth, reducing the positive effects towards zero.

The comparison of hydroseeding to a simple hand sowing plus cover crop showed comparable results. This at least indicated a big risk in using this application technique in high altitudes without additional protection of soil surface.

A general comparison of all used application techniques during our assessments showed clear results. Only an additional cover of soil surface was able to reduce surface runoff and soil losses to an acceptable degree. Straw mulching as well as hay mulching, different mats, nets made from jute or coco, three-dimensional mats etc. could be applied. The use of application techniques with a satisfying additional cover of soil surface should be generally recommended for restoration of slopes in high altitudes.

6. Acknowledgements

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11

Combined Hydroseeding and Coconet Reinforcement for Soil Erosion Control

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1. Introduction

Soil erosion is a worldwide problem that washes away fertile farmlands, slopes of roadway cuts and embankments, produces undesirable deposits in rivers and reservoirs, and at a larger scale result to landslides (Kothyari, 1996 and Thakur, 1996) . Soil is eroded by water and wind (Toy, et.al, 2002). In tropical countries like the Philippines, precipitation is high and erosion by water is the dominant driving force based reported cases. Protection of soil surfaces especially of slopes is needed…

To protect the soil surface from erosion, it should be protected from direct contact with erosive forces. Plant cover helps protect the soil surface and provide supplemental soil stability (Morgan, 2005). Hydroseeding is an innovative method of growing vegetation and is designed for slope protection. In the Philippines, its effective application is showcased in the Subic-Clark-Tarlac Expressway (SCTEX) Project.

Another green technology being used is the application of coconut coirs or coconets. Coconets helped stabilize the slope and improved the growth of vegetation in pilot projects of the Department of Public Works and Highways (DPWH).

Newly planted vegetation on slopes could be easily washed away by heavy downpour of rain. Erosion of the slope and replanting of vegetation would be a costly consequence. Coconets, on the other hand, will show its full potential if coupled with a good growth of vegetation. Artificial vegetation is needed to facilitate the even growth of plants. Attempts of combining coconets with vegetation were done using grass (vetiver grass) and trees (Madre de Cacao and neem tree) (DPWH, 2005).

Limited and very little information about hydroseeding is available since it is newly introduced in the Philippines. Tests to assess this method were only made by private construction companies which makes the data's exclusive only for the company's use.

The use of combined hydroseeding and coconets in slope protection was investigated in this study. The study was aimed to assess the effectiveness of the combined technologies to control soil erosion in a representative slope at different series of tests.

The research involved an outdoor component of the experiment to facilitate growth of vegetation. Transportation of each representative slopes to the laboratory was by means of a forklift to minimize disturbance. To further minimize the disturbance factor, the test boxes were transported carefully. Only one type of soil, degree of slope and the intensity of rainfall were considered. However, results were captured at different times in the entire duration of the rainfall simulation.

2. Hydroseeding

Hydroseeding is one of the methods of ground re-vegetation to stabilize bare soil surface to prevent soil erosion. It calls for the use of cellulose mulch material mix with a tackifier acting as binder. The cellulose binder mulch, together with the grass seeds, fertilizer and water are mixed inside the tank of hydroseeding machine to form into consistent and homogeneous slurry and then hydraulically sprayed to the ground. When sprayed, the cellulose fiber mulch together with the fertilizer and the grass seed will act as an absorbent mat, holding enough moisture to allow proper germination of the grass seeds and the same time forming a firm blanket cover to the soil surface even before the grass seeds germinates to prevent soil erosion. The cementitious geobinder forms a permeable curst on the soil surface which control water, soil and wind erosion. The geobinder is a non toxic cementitious binder that safely holds the grass seeds uniformly in place, prevents surface erosion and water evaporation in the soil. The cellulose fiber mulch which is biodegradable and in time will revert back to organic matter, enhances vigorous establishment of the grass ground cover. The application of hydroseeding process can be considered for temporary and permanent erosion control, seeding and mulching.

Hydroseeding is now a widely used process of controlling soil erosion abroad. Countries like the United States use this type of grass planting since the process is fast, efficient, and economical. It is more effective than conventional seeding and more economical than conventional sodding. In the Philippines, hydroseeding is first introduced in the Subic-Clark-Tarlac Expressway Project. Reports show that the adoption of hydroseeding is advantageous to the said project. Centrocema Pubescens (Centro) and Calopogonium Muconoides (known as Calapo) are the plants used in the project. The application of hydroseeding method yields the following observations and conclusions: (a) Hydroseeding planting process is the fastest way of preventing soil erosion; (b) the temporary seeds will germinate forty-eight (48) hours after spraying and the planting seedbed of the embankment is already 100% stabilized even before the establishment of the permanent ground cover; (c) Aside from nursing the grass seeds, the planting seedbed stabilizer called "geobinder" holds the ground cover grass seed in place and other soil planting amelioration materials; (d) Less watering is needed once the ground cover grass seed is 100% established; (e) The mulch material serves as moisture retention absorbing mat and at the same time reduces the development of the undesirable weeds; (f) In hydroseeding, 10,000 to 15,000 square meters of planting seedbed can be accomplished in a day; (g) There is no rill or gully erosion in case of heavy rain once hydroseeding is in place; (h) The Pure Living Seed (PLS) population per square meter is guaranteed to be 70-75 Living Grass Seed; (i) Hydroseeding final end product will require only very little maintenance once the permanent ground cover is purely established. (BCDA, 2006)

3. Coconets

Coconets are made from 100% coir fiber twine woven into high strength nets for extreme slope stabilization, protection of high velocity stream banks and high velocity intermittent flow channels. The natural coconut coir material perform very well in applications such as erosion control blankets for landscaping. The mesh of woven coconut coir matting acts as miniature dams that prevents the seeds or seedlings to be washed away by rain and wind and facilites the growth. The netting breaks up runoff from heavy rains and dissipates the energy of flowing water. Once the growth of vegetation has occurred the function of the coir is over and the vegetation takes over the protection of the soil further. Coconut fiber also promotes the growth of new vegetations by absorbing water and preventing the topsoil from drying out.

In the study conducted by Bureau of Research and Standards (BRS) of DPWH, results showed that the method of using Geonets (specifically, coconets) to protect developing vegetation against water and wind erosion have proven to be essential since it provides the soil surface with partial shading, moderation of soil temperatures and moisture retention. These materials are prescribed to initially stabilize the soil but without live plants and trees, the effective erosion control would not be achieved. The benefits of applying

Bioengineering techniques such as the use of hydroseeding and coconets in accelerating vegetation helps control soil erosion and stabilize the soil. With the use coco coir products as slope protection, slope above the road will be prevented from caving in. Thus, damages triggered by soil erosion on infrastructure such as roads and bridges will be prevented if slope protection is present.

4. Methodology

To represent the slope covered with combined Hydroseeding and coconets, test boxes were constructed sloping at 65 degrees and having a surface area with dimension of 106 cm long by 63 cm wide as shown in Fig. 1. Three (3) trial boxes were constructed. The test boxes were covered with soil. These test boxes covered with soil only were all initially subjected to artificial rainfall simulator for the bare soil tests. After the bare soil tests, the test boxes were covered again with soil and covered with combined hydroseeding and coconets for another three (3) sets of samples. Vegetation was allowed to flourish for 21 days before subjected to the rainfall simulator.

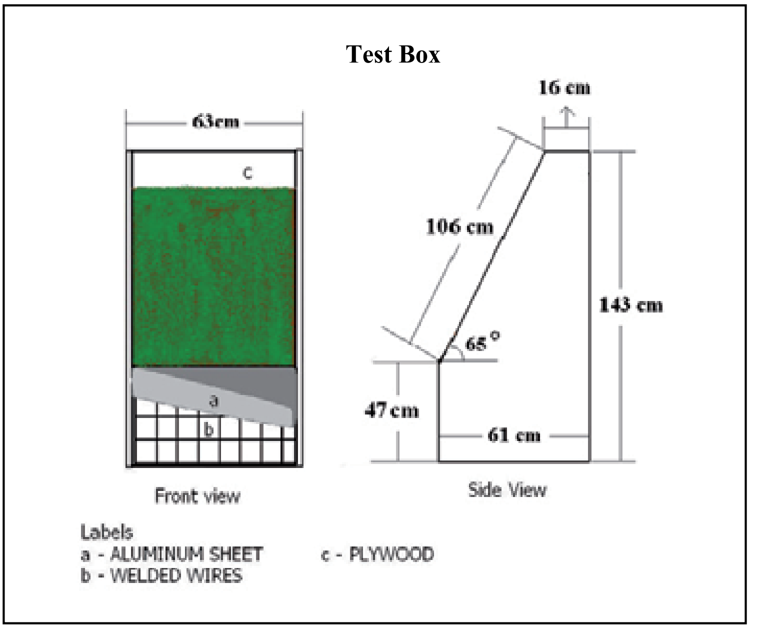

Fig. 1. Dimensions of the test box.

The amount of soil splashed out by runoff from the containers were collected and weighed. The data collected were used to compare erosion in mere bare soil to that with combined hydroseeding and coconet as slope protection.

4.1 Soil core test box

The soil core test box consists of water tight (leak free) container which holds the soil core specimen. The core is made up of wood that is capable to hold soil at a desired angle of the specimens. It includes gutter which is a runoff ramp for the routing of the soil and water that are washed out from the container to the bucket without spilling out. The dimensions are shown earlier in Fig. 1. The actual soil core test box is shown in Fig. 2.

Fig. 2. Test boxes shown with compacted soil.

4.1.1 Collection bucket

The collection bucket is used for the catchments and measurement of the eroded soil. This should have sufficient volume to collect the soil and water that is spilled out. Recycled 1-gallon mineral water containers were used to temporarily store the collected soil and water.

4.1.2 Filter

A filter for the separation of the sediment from soil and water solution is used. Recycled cloth used such as sack for flour, locally known as "katsa" was utilized.

4.2 Hydroseeding technical specifications

The hydroseeding mix has the following component:

4.2.1 Grass seeds

Approved seed varieties are those that are tested to withstand harsh weather conditions, characteristically aggressive, perennial, tropical, produce both runners and rhizomes, deep rooted, will rapidly colonize bare ground and form a dense mat of vegetation ground cover.

When established, it forms as an umbrella to dissipate rain drops impact and is environmental friendly and low - maintenance.

Permanent ground cover grass seed	- Centrosema (Pubescens)
Temporary grass nursing seed	- White Millet
Seed Purity	- 85%
Germination	- 80 to 90% average
Adaptability	- Tropical

4.2.2 Geobinder

Airtol geobinder is a low cost cementitious binder used in the study. When mixed with water and mulch, this geobinder sets in a predictable way to form an erosion resistant crust. Packed in 22.8 kilo bag, it is produced from high quality gypsum and is (fully) imported from the USA.

4.2.3 Cellulose fibre mulch

The cellulose fiber mulch is manufactured and processed from recycled paper. Made in USA, it is packed in 50 lbs. bag.

Moisture Content	- 15%
Organic Matter	- 99.5%
pH Level	- 5.5 to 6.0%
Water Holding Capacity	- 100 grams DW/will hold 1,000 grams of water.

4.2.4 Cocopeat

This is a by-product of coco fiber consisting of short coco fiber and dust available locally. Packed in 15 kilo bag, this acts as a soil conditioner.

4.2.5 Fertilizer

To enhance the growth of plants, chemical grade fertilizer, in accordance to Bureau of Soil Recommendation, is added in to ameliorate common soil nutrient deficiencies. It is an organic fertilizer locally produced in palletized form that is both environmental friendly and non-toxic.

4.3 The soil for the test box

To maintain good vegetation, the soil must meet certain requirements as a growth medium. It should meet the following conditions:

a. enough fine-grained (silt and clay) material to maintain adequate moisture content usually 15-20%. This is based from Unified Soils Classification System (ASTM Designation D-2487);
b. sufficient depth of soil to provide an adequate root zone;
c. favorable pH range for plant growth which is usually 5.5-6.0 ;
d. soil must be compacted like natural conditions soil slope; and
e. sufficient pore space to permit root penetration and it will be done by not compacting the last 4-6 inch of soil.

The soil used was sieved to separate large stone and other unnecessary things not needed. For every layer of 10 inch, the soil in the test box is compacted with use of ply board, a piece of wide flange or bricks. Compaction is done by placing the ply board on top of each layer to flatten the soil and will be compacted by dropping the wide flange five times with the height of 8 inch. If wide flange is unsuitable for compaction for small area, bricks may be used.

4.4 Hydroseeding mixing process

First, mix the cellulose fiber mulch and cocopeat together, followed with grass seeds, fertilizer amelioration materials and a geobinder tackifier in a pail full of water. Continue loading ingredients and mixing process until mixture forms a consistent, uniform and homogeneous slurry mixture ready to be applied. Fig. 3 shows the hydroseeding components and mixture.

(a) (b) (c)

Fig. 3. The hydroseeding components and mixture. (a)Hydroseeding Mix Components(b) Mixing the components(c) Hydroseeding Mixture

4.5 Hydroseeding application

The slurry was applied manually on the soil surface as shown in Fig. 4. Application started from the top of the slope down to the toe. Exposed area at the top and toe of the slope were completely covered by applying the mixture 15 inches beyond the top and toe of the slope. Spots that might not be covered with the hydroseeding mixture were simply hydroseeded again. Hydroseeded areas were regularly watered daily during the dry days for the first four (4) weeks of application.

Fig. 4. Hydroseeding by manual application

4.6 Installation of coconet

With the hydroseeding completed, the coconet is installed over the entire hydroseeded area as shown in Fig. 5. To ensure total coverage of the slope, nets are laid adjacent to each other and were anchored securely on the slope with bamboo pins or any other appropriate material(s) depending on the nature of the slopes.

Fig. 5. Hydroseeded test boxes covered with coconet. The green net is used for protection from birds and other factors.

4.7 Rainfall simulation

In this study, a laboratory test was performed using the Artificial Rainfall Simulation Apparatus at the Hydraulic Laboratory of the Flood Control and Sabo Engineering Center (FCSEC) of DPWH to assess the effectiveness of Hydroseeding with Coconet in erosion control and water run-off. The rainfall simulator is capable of creating uniform drops and desired intensities. This is used to apply uniform rain over the entire area of the specimen. In this study the researchers will use the worst rainfall rate which is 120 mm/hr. The rainfall simulator used is shown in Fig. 6.

The FCSEC artificial rainfall simulator is a device with adjustable /changeable nozzle for rainfall intensity variation. The said simulator has a dimension of 10m x 5m x 10m that produces drops simulating rainfall intensity of up to 235mm/hr. Raindrop sizes are representative of typical heavy rains/storms in the country. The spatial distribution of rain is essentially uniform, and the control of application rates is within the accuracy requirement of most experimental protocols.

For the rainfall simulation on the study's test specimen, the rainfall applied was at 120mm/hour for every 10 minutes. The sediment and water runoff from the test box were collected.

Fig. 6. Artificial Rainfall Simulation Apparatus at the Hydraulic Laboratory of the Flood Control and Sabo Engineering Center (FCSEC) of the Department of Public Works and Highways (DPWH).

5. Results and discussion

Table 1 and Figs. 7 and 8 present the sediment concentration accumulated on bare soil and on soil covered with combined hydroseeding and coconet.

Sediment Concentration (g/L)							
TRIAL	Time (mins)	0	10	20	30	40	50
TRIAL 1 BOX A	Bare Soil	0.000	5.823	20.146	18.553	12.319	9.585
	Hydroseeding with Coconet	0.000	10.740	2.690	2.670	1.060	1.340
TRIAL 2 BOX B	Bare Soil	0.000	63.501	39.723	35.130	26.274	21.320
	Hydroseeding with Coconet	0.000	4.990	2.900	4.340	3.330	2.730
TRIAL 3 BOX C	Bare Soil	0.000	75.443	68.321	40.743	42.553	33.551
	Hydroseeding with Coconet	0.000	18.970	4.520	2.780	1.500	0.610

Table 1. Sediment Concentration of Bare Soil and Soil Covered with Combined Hydroseeding and Coconet Reinforcement.

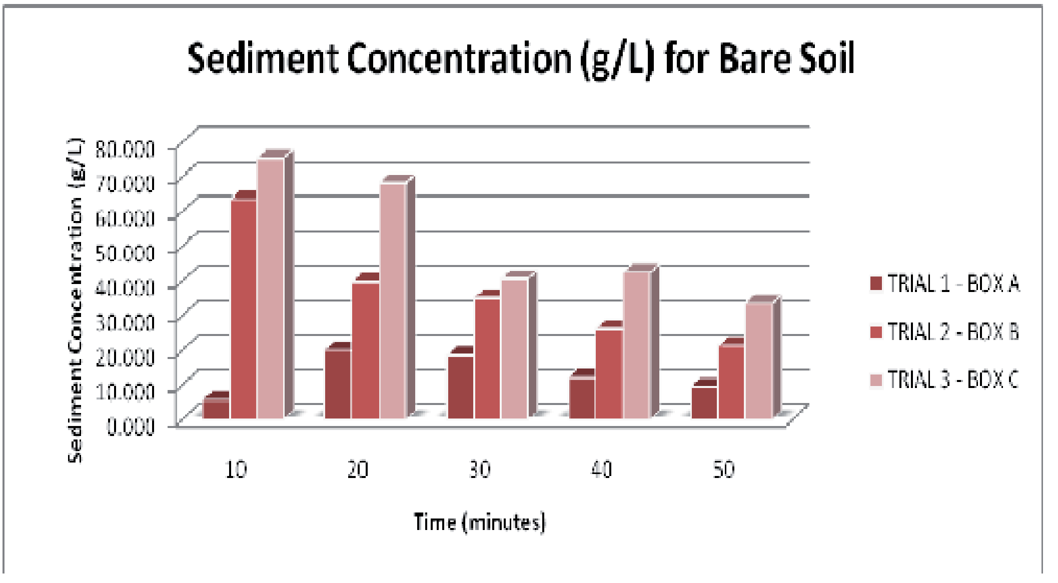

Fig. 7. Sediment Concentration (g/L) for Bare Soil

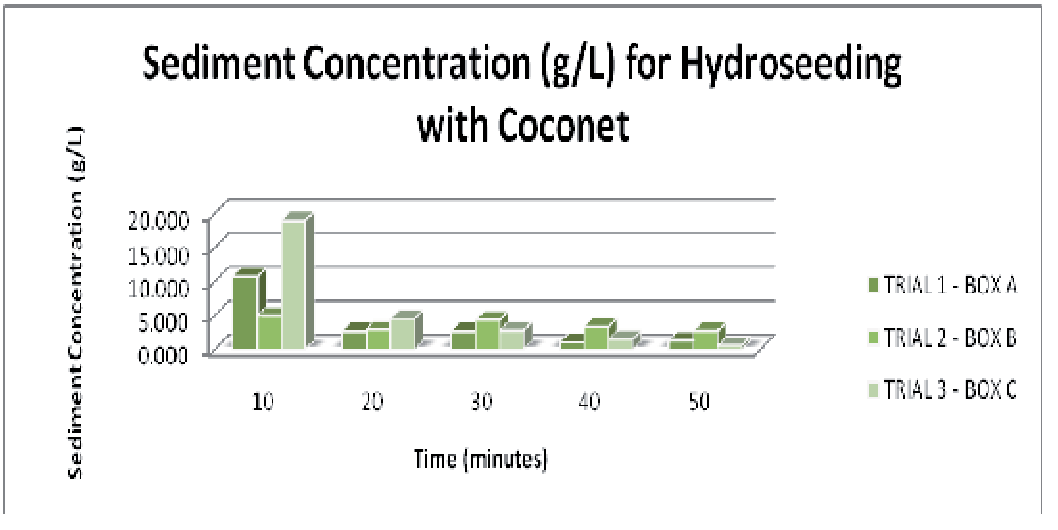

Fig. 8. Sediment Concentration (g/L) for Hydroseeding with Coconet Reinforcemen

It is shown that in each three trial boxes that were first used for bare soil specimen and the vegetated specimen, the first ten (10) minutes deposit higher sediment concentration. But, comparing the values obtained between bare soils and soil with hydroseeding and coconet reinforcement, it shows that as expected there is lower sediment concentration in the latter while higher sediment concentration in the former.

Table 2 and Figs. 9 and 10 present the sediment yield on bare soil and on soil covered with combined hydroseeding and coconet.

Sediment Yield (g/m²h)							
TRIAL	Time (mins)	0	10	20	30	40	50
TRIAL 1 BOX A	Bare Soil	0.000	73.873	272.503	225.529	126.809	78.247
	Hydroseeding with Coconet	0.000	155.330	34.380	18.010	5.650	5.930
TRIAL 2 BOX B	Bare Soil	0.000	1533.594	877.431	646.308	356.162	257.866
	Hydroseeding with Coconet	0.000	49.300	24.870	16.610	9.180	6.020
TRIAL 3 BOX C	Bare Soil	0.000	850.000	1169.062	581.067	472.833	227.832
	Hydroseeding with Coconet	0.000	226.670	83.370	35.430	13.560	5.210

Table 2. Sediment Yield (g/m²h) of Bare Soil and Hydroseeding with Coconet Reinforcement

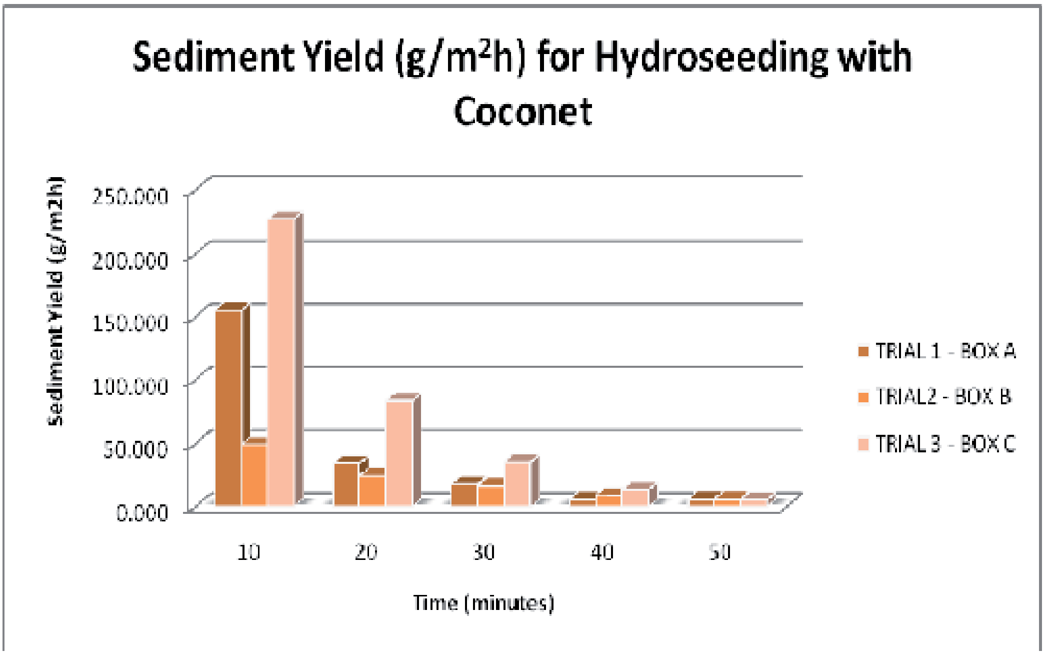

Fig. 9. Sediment Sediment Yield (g/m²h) for Bare Soil

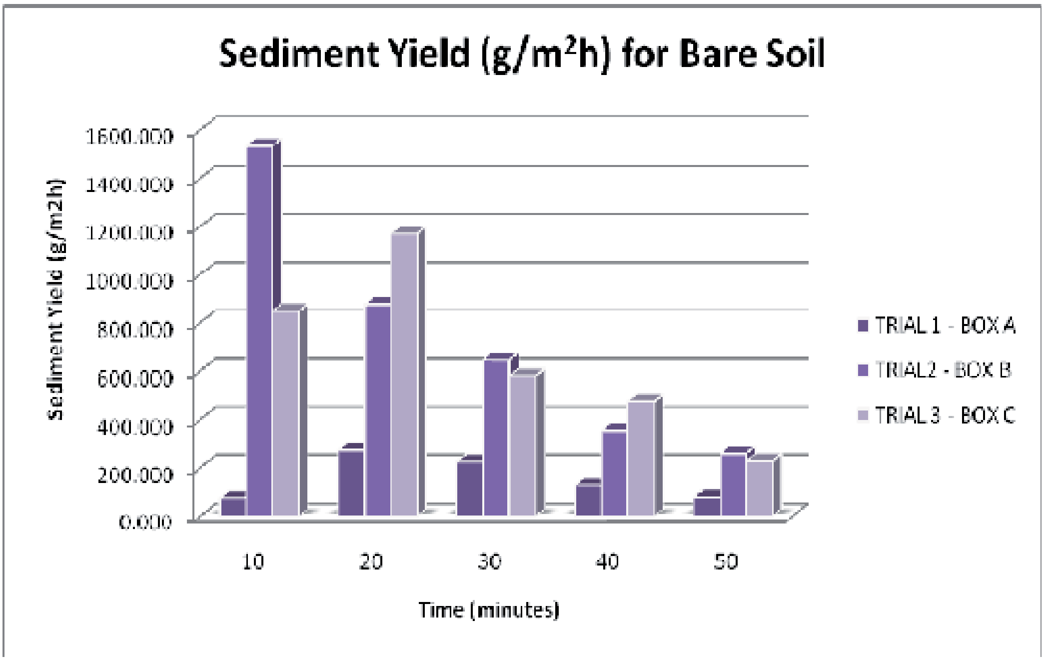

Fig. 10. Sediment Sediment Yield (g/m²h) for Hydroseeding with Coconet Reinforcement

As specified, the sediment yield determines the mass of the sediment over its plot area with respect to the time. The results of three trials from Table 2 show that the Hydroseeding with Coconet reinforcement obtained lesser sediment yields than the bare soil, which is already expected since soil without protection from rain splash would deposit greater amount of soil sediments.

The proceeding discussion presents the mean sediment concentration and sediment yield for the bare soil and for soil with combined hydroseeding and coconet.

Table 3 and Fig. 11 show the comparison of the mean sediment concentration of Bare Soil and hydroseeding and cocconet Reinforcement. As shown in the table, bare soil accumulates greater mass of soil sediment than of the hydroseeding and coconet Reinforcement.

Mean Sediment Concentration (g/L)							
Time (mins)	0	10	20	30	40	50	Average
Bare Soil	0	48.26	42.73	31.48	27.05	21.49	171.01
Hydroseeding with Coconet	0	11.57	3.37	3.27	1.97	1.56	3.694

Table 3. Mean Sediment Concentration of Bare Soil and Combination of Hydroseeding with Coconet Reinforcement

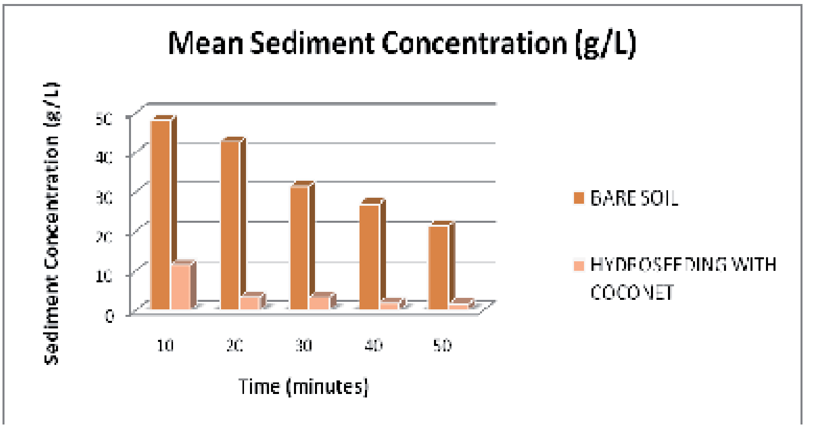

Fig. 11. Mean Sediment Concentrations of Bare Soil and Combination of Hydroseeding with Coconet Reinforcement

Mean Sediment Yield (g/m²h)							
Time (mins)	0	10	20	30	40	50	Total
Bare Soil	0	2457.47	2319	1452.91	955.81	563.95	7749.14
Hydroseeding with Coconet	0	143.77	47.54	23.35	9.47	5.72	229.85

Table 4. Mean Sediment Yield of Bare Soil and Combination of Hydroseeding with Coconet Reinforcement

The value projected in the Table 4 and Fig. 12 show that the mass of the bare soil with respect to the plot area and time is definitely greater than of the Hydroseeding with Coconet reinforcement.

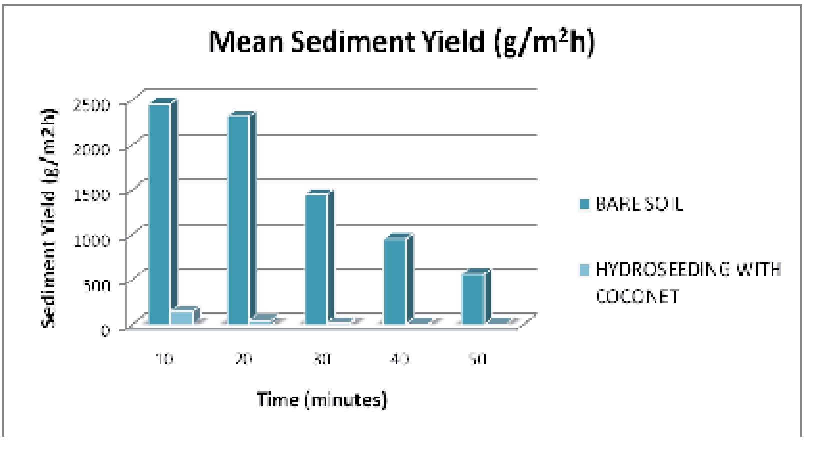

Fig. 12. Mean Sediment Yield of Bare Soil and Combination of Hydroseeding with Coconet Reinforcement

The following discussions summarize the total sediment concentration and total sediment yield.
Table 5 compares the sediment concentration and sediment yield of bare soil and hydroseeding with coconet reinforcement. From the numerical value indicated above, it was found out that the Hydroseeding with Coconet reinforcement lessen the mass of the soil eroded.

Total Sediment Concentration (g/L) and Sediment Yield (g/m^2h)		
Experiment	Sediment Concentration (g/L)	Sediment Yield (g/m^2h)
Bare Soil	21.49 ± 28.26	563.95 ± 2457.47
Hydroseeding with Coconet	1.56 ± 11.57	5.72 ± 143.77

Table 5. Total Sediment Concentration (g/L) and Sediment Yield (g/m^2h)

Table 6 presents the effectiveness of the applied hydroseeding with coconet reinforcement to control against soil erosion. From the results, it was found out that combined hydroseeding with coconet reinforcement is an effective soil erosion control instrument.

Effectiveness Of Hydroseeding with Coconet Reinforcement versus Bare Soil Against Soil Erosion (%)						
Time (mins)	0	10	20	30	40	50
Hydroseeding with Coconet versus Bare Soil	0	94.15	97.95	98.4	99.01	98.99

Table 6. Effectiveness of Hydroseeding with Coconet Reinforcement versus Bare Soil Against Soil Erosion (%)

6. Conclusion

Results of actual laboratory experiments that were conducted with the use of the DPWH Artificial Rainfall Simulation Apparatus showed that the specimen of soil covered with combination of hydroseeding and coconet passed the surface run-off tests. The said specimens did not show any sign of failure in the measurement of run-off in the surface of the slope. Erosion problem was not encountered in the specimen of combined hydroseeding with coconet. The primary effect is that water is absorbed by the hydroseeding materials as well as by the coconet that were put in place to hold the soil and control soil erosion.

7. Recommendations

The experiment conducted was limited only for a fixed slope of 65 degrees. The hydroseeding mix had a single set of mixture components. Rainfall simulation rate was at a constant 120mm/hr. Future studies on combined hydroseeding with coconet may consider variable slopes and different length to width and depth dimensions. Other plant varieties locally available in a particular area may be considered. Other rainfall intensities may be tested. Consideration of wind and other environmental factors could be included to simulate stormy weather.

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12

SCALES: An Original Model to Diagnose Soil Erosion Hazard and Assess the Impact of Climate Change on Its Evolution

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1. Introduction

In that they regulate the water supply, determine air quality, are an essential component of the biodiversity of environments, support biomass production, and are a factor in maintaining and developing populations, soils perform environmental, productive and societal functions which take part in maintaining the fragile balance of territories (EEA, 2008). Therefore, soils constitute a natural heritage which has to be sustainably managed at a local as well as global level. There is now an international consensus on this statement, as human-caused soil degradation has accelerated and taken on more diversified manifestations across the world over the past fifty years.

In Europe, water erosion of soils is seen as one of the main forms of degradation of arable land. The surface of European soil affected by erosion is estimated to be around 12%. From continental to local levels, territorial agencies need to avail of geo-referenced information to Fig.ht against or prevent soil erosion. The aim in particular is to map the areas most affected or likely to be affected, in order to formulate restorative or preventative measures (*Gobin* et al., 2004). Besides, in the current context dominated by a global warming which will in the mid and long term disrupt the natural components of habitats, it seems necessary to provide the representatives of civil society with new elements which facilitate rationalized anticipation of future evolutions and of consequences in terms of land management.

To that end, erosion risk maps are essential documents. They are the result in particular of the production of semi-quantitative erosion models such as PSIAC (PSIAC, 1968; Hadley et al., 1985), FSM (Verstraeten et al., 2003; de Vente et al., 2005), EHU (Stocking and Elwell, 1973), CORINE (EEA, 1992) or even INRA (Le Bissonnais and Daroussin, 2001) and PESERA (Kirkby et al., 2003).

Whereas all the semi-quantitative models can be characterized by their simplicity and their high application potential to global spatial and temporal scales, their degree of accuracy does not allow the mapping of erosion problems at local level. To overcome this difficulty, we have developed the SCALES model (Le Gouée et al., 2010). SCALES is a model which offers similarities with semi-quantitative models as regards structure of model, holistic positioning, and strong reproducibility potential, but also with physical and empirical models because of the great accuracy of the data used and of their spatial representation.

After having shown the operational capability of SCALES at the scale of the Calvados department (Le Gouée et al., 2008) which represents 5,500 km² (Fig. 1), we then focused our efforts on adapting this model to produce a diagnosis of the erosion hazard at seasonal and monthly scales (Stepkow, 2008). That approach enabled us most recently to offer a prospective insight into the effects of climate change in the distant future (scenario A1B of the IPCC for 2100) on the evolution of soil erosion hazard in Normandy (Goulet, 2010).

Fig. 1. The regional council of Basse-Normandie. A: Catchment of the Branche. B: Catchment of the Lingèvres.

2. The SCALES model

2.1 Background

SCALES provides a mapping of soil erosion hazard which offer local land managers spatialized data at regional scale while having high accuracy on the local scale. As a result, hazard assessment is carried out on erosion source areas identified by elementary spatial units such as agricultural parcels.

In many European regions, agricultural land is structured visually and physically by the juxtaposition of these parcels. Each of these units is an erosion system whose activation depends less on near environment than on the distinct features of each parcel. By mapping the hazard at the scale parcel, the aim is to provide land management organizations with data so as to rationalize the Fig.ht against erosion hazard not at catchment area scale, but directly at source area level.

Taking into account anthropic activity in assessing hazard means resorting to the concept of agricultural practices as opposed to that of land cover, unlike all others erosion models at regional scale. The idea here is to re-contextualize hazard by looking at agricultural practices strongly structured along annual cycles (duration and management of intercrop) and multiannual cycles (crop rotation).

Initial, intermediate and final data from the model needs to be implemented as numeric geo-referred informations, usable with GIS and presented at different spatial resolutions showing the main agricultural, administrative and hydrological divisions of the area.

Since diagnostic of erosion hazard is based on data susceptible to change on a short or medium time, the model needs to be designed in order to easily generate data and hazard level updates. This perspective will then offer the possibility to develop an exploratory approach aiming to measure the positive or negative effects of a climatic tendency or a planned change in agricultural practices.

The SCALES approach can be reproduced where such agricultural practices as descrubed above occur and where the climate is a mild maritime one. In Europe, the application of the model can be carried out all along the Oceanic façade from the N-W of Spain until the South of England.

2.2 The SCALES model characteristics

SCALES is displayed as a regional scale applicable model keeping high precision and high quality of information at local scale. This tool allows us to produce in a short time a diagnostic of erosion hazard using high resolution data coming from accurate data. This diagnostic is specific to arable lands. It cannot be proposed in context of "natural" vegetation such as woods or forests or for urbanized areas. SCALES is also designed to be accessible to a wide range of companies dealing with questions of environmental relevance. Furthermore, this model also displays the possibility to aggregate hazard data with administrative or hydrological units like municipality and elementary catchment, in order to adapt the diagnostic to intervention scales of local land managers.

2.2.1 Basic statements

SCALES is a tree form model based on the use of GIS in order to map the potential sensibility of areas and soil erosion hazard. Potential sensibility of areas represents the first fundamental concept of the model. This concept aims to precise if the studied area is able to generate erosive runoff when we integrate both erodibility of soils, land-use and topography. The computational model is therefore a global indicator.
Erosion hazard defines the probability of appearance of soil erosion by water when potential sensibility and rainfall erosivity are put together. The rainfall erosivity depends on meteoric conditions. The latter will be higher during wet years and lower during dry years. We thus estimate a mean of rainfall erosivity based on rainfall data originating from pluri-annual period. Therefore, the erosion hazard has to be considered as a mean hazard.
The factors of evaluation of soil erosion hazard (soil erosion, agricultural practices, topography and rainfall erosivity) are displayed by the input data which can be of quantitative or qualitative relevance. Each factor is defined by one or several types of input data. All data types are converted in measurable data which in turn will express levels of pressure on the erosive runoff trigger. Some input data are combined in order to obtain combined data which generate also level pressure. Levels of pressure from combined data will lead to the estimation of level of hazard.

2.2.2 Parameters and input data

The choice of input data (Fig. 2) in the view of characterizing factors of evaluation of erosion hazard result from well-established scientific concepts in the literature, expert opinions and by conclusions originating from numerous personal observations for two years in the Department of Calvados (Le Gouée et al., 2008).
In order to estimate the soil erodibility, we selected and considered the structual instability as input data. This characteristic corresponds to the soils sensibility to degradation of its superficial structure by rainfalls. The degradation by water can be explained by the different physical and physico-chemical mechanisms among which we can cite: bursting, mechanical disaggregation, disaggregation by differential blow, and the chemical spread. Mechanical disaggregation due to the impact of rain drops constitute, in the temperate regions influenced by the ocean, the main mechanism acting on the soil crusting.

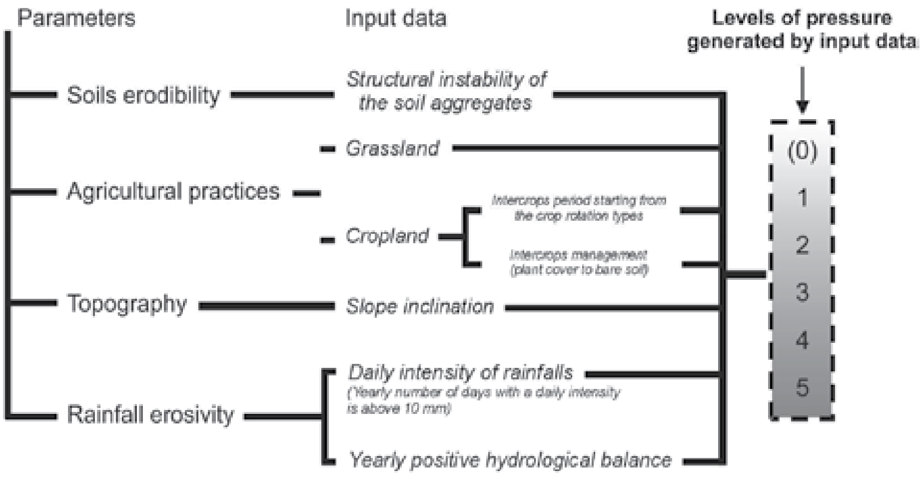

Fig. 2. Types of parameters and input data and levels of pressure concerning soil erosion

Soil erodibility

However, one must be aware that the sensibility of the soil to erosion is not always correlated with the soil crusting notion and a fortiori to the soil characteristics which lead to this phenomenon. In case of heavy rainfalls combined with water-saturated soils we will observe the establishment of a runoff on soils with stable structure able to transport heavy aggregates or stony load. This case will be integrated to the model when we will show input data relative to rainfall erosivity factors.

Agricultural practices

In temperate regions, soil erosion is linked to agricultural land. We can observe this erosion when soils are not protected by a permanent or well-developed plant cover. At this stage, a first distinction must be established between areas entirely and durably covered by agricultural vegetation i.e., permanent grassland and orchard, and the ones dedicated to crops. In the first case, water erosion remains absente or very anecdotic. In the second case, the risk to soil erosion is closely linked to the agricultural practices and their temporality.

The choice between crops or grassland and the technical management of cultivated parcels is integrated within the framework of logics of management of the farms fixed over several years. The assessment of the pressure generated by the agriculture on erosion hazard fulfills these logics. This is the reason why we prefer talking about agricultural practices more than land cover: the first term refers to the impact of agriculture at a multiannual scale when the second refers to plant covers (grassland, cereal crops, fodder crops) at a given moment. As we explained about rainfall erosivity, the role of agricultural practices on erosion is finally estimated by a mean pressure level characterizing the global erosive impact of technical practices during agricultural cycles. Therefore, the soil erosion hazard is an indicator of the soil degradation at multiannual scale.

The impact of agricultural practices in the modeling is established out of 3 types of input data. The first type of input data is related with the presence or absence of plant cover. A distinction is made between the areas characterized by permanent plant cover (grassland or orchards) and cultivated areas.

For the latter, another type of data aims to precise the profile of crop rotation. It allows us to gather information about the duration of the crop rotations and of the duration of the intercrop periods. This intercrop period data is essential for the application of SCALES because it specifies the amount of time during which the soil is directly subjected to the erosive action by the rainfalls. When the intercrop period is persisting, the risk of soil erosion increases. The mean duration of intercrop period has been chosen to estimate erosive pressure levels due to agricultural practices.
For cultivated lands, a third type of input data is used. It is related to intercrop management. This management is indeed leading to very different soil erosion responses whether keeping a bare soil or establishing temporary plant cover such as temporary crops or ray-grass. The duration and terms of intercrop management are linked to the types of crop rotations. The diversity of observed situations during the rotation cycle is integrated in the form of erosive pressure levels calculated for "intercrop period" and "intercrop management" input data.

Topography

The role of topography in the assessment of erosion hazard is expressed through the selection of only one type of input data which is slope inclination. Possibilities of runoff of the non-infiltrated water are depending on the slope at every point of space. These possibilities increase rapidly as soon as the slopes are strong.

Rainfall erosivity

Rain is the main factor of soil erosion by water. Its capacity to damage the soils depends on rainfall intensity, on volume of precipitations and on the hydrological response of the soil to rainfalls. This led us to propose two types of input data.
The first type defines the rainfalls ability to erode the soil based on its intensity. Among the indicators usually employed, we chose to considerate the yearly number of days with a Daily Intensity is above 10 mm (Fig. 2). Data comes from records of local meteorological stations of Météo France network.
The second type of data results from the response of the soils to the rainfalls. It refers to the concept of yearly positive hydrological balance and is given by applying the methods of hydrous budget. The positive hydrological balance is regarded as available water either for drainage or runoff. Data are resulting from the combination of potential evapotranspiration, rainfalls and available water content. If it is difficult to estimate the part of drainage and runoff, we can recognize that the risk of runoff increases with an increase of positive hydrological balance. These data are calculated at monthly scale and then cumulated to obtain results at yearly scale. The data used are means of climatic period. The main problem encountered to get this type of data comes from the methods implemented to gather accurate and reliable data about available water content. This problem is solved since it has been decided to start a wide program of soil mapping over the Calvados.

2.2.3 Steps of the modeling

The first step aims to convert all input data into erosive pressure levels (Fig. 3). 6 levels of pressure had been specified, from 0 to 5. Level 0 indicates absence of pressure and level 5 refers to a very high pressure level.
Some types of input data have only 5 levels. In this case, there is no level 0. This applies to "intercrop period", "daily intensity of rainfalls", "intercrop management" and, "yearly

positive hydrological balance" types. Regardless of their characteristics, these four types of data generate favorable conditions for triggering soil erosion. Therefore, even with very short intercrop periods, soils will always be exposed to the erosive effect of the rain. Also, in spite of protecting practices during intercrop period such as implantation of plant cover, the time required by the plants to grow gives a period during which the bare soil stays unprotected from erosion agents. Concerning rainfall erosivity, the weather conditions of a mild maritime climate rule out the absence of rainy events during the intercrop period, that is to say between September and April.

Level 0 has been affected to "grassland" and "slopes" input data. The presence of a permanent plant cover such as grassland always protects soil from erosion, even if it is common to observe some runoff on permanent grassland. Parcels dedicated to orchard culture are also included in this category. For slopes, the level 0 refers to topography with surface gradient lower than 1%. In that case, the slope does not cause the surface water to flow, preventing all possibilities of soil erosion by water.

The second step consists of combining the pressure levels of input data following an additive approach (Fig. 3). Between two types of input data, every combination is conceivable. Summations are included in an interval from 0 to 10. These values are subsequently classed in the following categories: ≤ 2, 3-4, 5-6, 7-8 and 9-10. Each category is then reclassified into simple value equivalent to a combined level of erosive pressure. Combined levels can later be combined again with other input data or other combined levels. In any case, the combination and simplification process remains the same.

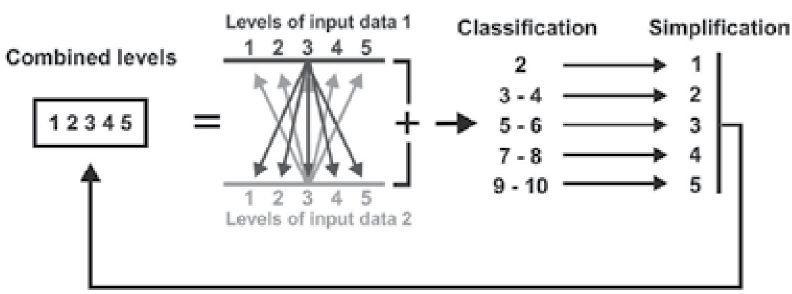

Fig. 3. Levels of erosive pressure and combination procedure in the SCALES model

The third step leads to the estimation of hazard levels. It implies to know the structure of the model (Fig. 4). SCALES is a tree form model, which means that input data are organized in a hierarchy according to their influence on the genesis of erosive runoff. Arguments in favor of this organization are the same as those previously exposed about the choice of input data. Therefore we can notice that the "intercrop period" type for example has a lower impact on triggering erosive runoff than the "slope" type, which has itself a lower impact than "structural instability".

Even if this organization differs from a weighting using coefficients, the classification of input data associated with additive approach make good case for this idea. The weighting occurs at every combination until the final hazard level. The weight of input data is always divided by two during the first combination, and then divided by two again with the next combination. According to this way of operating, we notice that the impact of pressure level of input data on final hazard is decreasing significantly when input data are lowered in the proposed hierarchy.

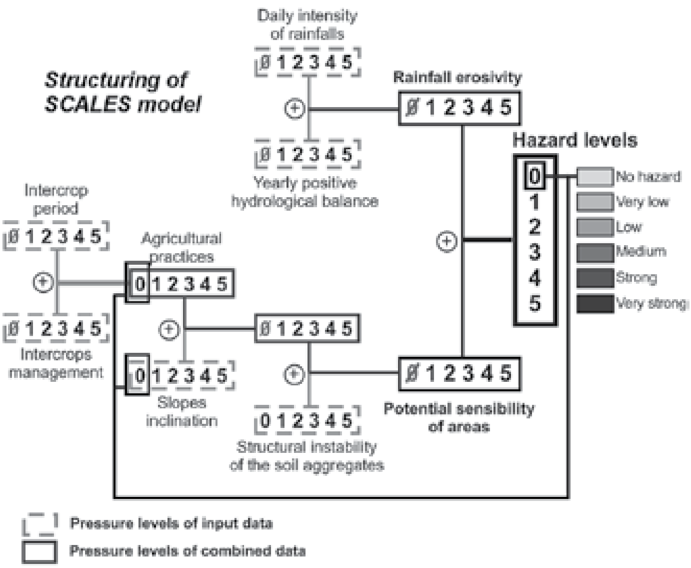

Fig. 4. Defining hazard levels using SCALES model

The SCALES model incorporates specific cases that don't follow the general rule. The level 0 of combined data, referring to agricultural practices for permanent grassland and orchards and the level 0 of "slope" type when gradient is lower than 1 %, are automatically excluded from the treatments. These levels are directly converted into level 0 of erosion hazard. This conversion does not require the agricultural areas to fulfill these two conditions.

2.2.4 Integration and aggregation of SCALES data

SCALES is a large-scale assessment model intended for mapping soil erosion hazard at the finest level of organization of the agricultural area. It supposes an integration of input data at parcel unit scale. Their area can exceed a few hectares but are generally lower than this unit of reference. This scale seems to be the better scale to determine the spatial context of soil erosion in Basse-Normandie. The layer of parcel units exists in the form of a vectorized and geo-referred database and such data came from the Inventory of Common Agricultural Politics given by the agricultural administration. Data inform on the land cover types in 2006 (source: Rpg_anonyme_014_AUP_2006). The parcels are classified in the three following: Grassland and arboriculture parcels (26,500 parcels, 111,000 ha) Temporary grassland parcels (13,200 parcels, 99,600 ha) and Crop parcels (25,800 parcels, 154,400 ha).

The integration of data in the parcel units requires beforehand a mapping of input data under raster format. We used the principle of allocating for each parcel unit and for each input data type, only one mode. When parcel unit holds several modes, we chose using a decision rule, to select the spatially most dominant mode. The application of the dominance rule has been carried out using the module *Spatial Analyst* in ESRI ® ArcView Gis 9.2. Obtained maps concerning the rainfall erosivity, the potential sensibility of areas and the soil erosion hazard are vector maps. Those are transformed to raster format for incorporating the output data in larger vector units as administrative units (approximately 800 ha) or as hydrologic units (approximately 2,000 ha).

2.3 Data processing

2.3.1 Topography

To calculate slopes inclination, we used Digital elevation Model of Calvados with a grid resolution of 20 X 20 m. The high resolution of DEM is essential because it allows us to carry out a topographical analysis of a very high degree of accuracy. Claessens et al. (2005) shows that DEM resolutions influence the slope inclination distribution: the coarser resolutions underline a larger contribution of lower slope angles (smoothing the effect on the landscape topographical representation). This report is in particular validated while comparing 50 m and 25 m DEMs. For Calvados, slope values result from the local cell-to-cell slope, rather than using a smoothing multiple cell windows, as done in major GIS procedures. Slopes were classified into six classes. Their limits were defined starting from values determined by statistics treatments of the cell slopes (classification according to the geometric progression method) and values coming from the literature (Le Bissonnais et al., 2002). In contrast to the latter, the slopes larger than 15% have been regrouped in one class because of the absence of major dissected relief.

The classes selected are as follows: [0-1%[; [1-2%[; [2-5%[; [5-10%[; [10-15%[; >=15%.

Those are respectively corresponding to the levels of pressure 0, 1, 2, 3, 4, 5.

2.3.2 Climate

Rainfalls are regarded as the average factor of water erosion. It is allowed that the amount and the intensity of rains characterize the rainfall erosivity. Climate data comes from records of local meteorological stations of Météo France network. Insofar as the number of stations decreases with the lengthening of rains recording period, we decided to limit the reference period to 15 years (1991-2004) to be able to profit from a solid network of meteorological stations. This is composed of 22 stations located inside the Calvados and 19 stations located in periphery of this one. The main climatic data used are daily rainfalls.

Variables selected to appreciate the erosivity are (1) the yearly number of days with a Daily Intensity is above 10 mm (DI10) according to De Bruyn et al. (2001) and (2) the Yearly Positive Hydrological Balance (YPHB). This last variable at the same time allows us to take into account the amount of rains and the available water content (AWC) of soils. Let us recall that one of the major causes of erosion in Basse-Normandie is due to the saturation of soil. Also, we have to calculate beforehand the AWCs starting from the soil database presented further. Concerning the first variable, data of stations were interpolated by kriging method. In order to avoid interpolation errors related to the edge effect, we integrated data of the stations located just at outside of Calvados.

Classes are the following.

For DI10: < 20; [20-25[; [25-32[; [32-40[; >=40

For YPHB: <150 mm; [150-250 mm[; [250-350 mm[; [350-450 mm[; >=450 mm

Those are respectively comparable with the levels of pressure 1, 2, 3, 4, 5.

2.3.3 Agricultural practices

In order to define the agricultural practices (Fig. 5), we had recourse to the data of the Agricultural census for 2000 realized at holding scale (source: Agricultural administration). 21 variables have been retained to evaluate the agricultural specialties of the 4844 holdings of the Calvados. They relate to socio-demographic characteristics of agricultural households, to juridical statute and economic dimension of the farms and to production systems (Dobremez and Bousset, 1996).

Adapted statistical treatments allowed us to draw up a typology of dairy farm (9 types) and non-dairy farm (13 types). A statistic aggregation (by summation) has been realized in order to assign them to the small administrative units (municipality scale). That led to the characterization of repartition profiles of different farm types for each municipality of Calvados which counts 706 of them. The following stage consisted in operating an Ascending Hierarchical Cluster followed by K-means method in order to reach a typology of farms (12 types) according to type repartition profiles (Bermond, 2004). Each type refers to modes of farm management, and to specific agricultural practices. A local farmer practice survey has been carried out in this direction, which enable us to produce our own data.

After selecting a sample of municipalities for each farm type, we interviewed the farmers about soil work methods used, plot localization and farm characteristics. This investigation showed that types of farm had notably evolved between 2000 and 2007. Thus, interviews have been used to update the 12 types of farm and to specify the current agricultural practices. This procedure has been applied to the sampled administrative units and, by extrapolation, generalized with all municipalities. Knowledge of crop rotations and management of intercrops allowed us to determine various modes concerning these agricultural input data of the SCALES model.

For crop rotations, the types are: winter crops, dominance of winter crop, balance winter crops/ spring crops, dominance of spring crops, spring crops. The passage of the first to the last type represents insofar the lengthening of the period during which soil is not protected. The duration of this period is in this way lower than 4 months for rotations based on winter crops and reaches a duration of 7 months in case of a succession of spring crops.

Those are respectively comparable with the levels of pressure 1, 2, 3, 4, 5.

Regarding the management of intercrops numerous publications underline the influence of different practices on soil erosion risks (Auzet, 1987; Martin, 1997; Martin 1999; Baumhardt and Jones, 2002; Le Bissonnais et al., 2002; Lipiec et al., 2006; Strudley et al., 2008). Therefore the creation of a temporal plant cover like oilseedrape or mustard, in the period between two crops, will effectively protect the soil against run-off erosion. This measure will be less effective in case the crop partially covers the soil like for example rye (concept of scarce plant cover). One also considers that the wheat stubble correspond to this concept. With the absence of a temporal crop, soil tillage will permit to temporally reduce the erosion risk because of a better infiltration and a higher soil roughness. More the tillage operations are deeper, more effective are infiltration and soil roughness against soil erosion. The most unfavorable condition occurs when there is no tillage during the intercrop period remaining the soil bare. These different practices between crops or their absence (plant cover, scarce plant cover, deep ploughing, superficial ploughing, bare soil) are respectively comparable with the levels of pressure 1, 2, 3, 4, 5. The level 0 corresponds at the grassland and arboriculture areas.

2.3.4 Soils

To achieve the aim of a fine diagnosis of soil erosion hazard, it was necessary to have a sufficiently precise soil database. It was not conceivable to exploit the Soil Geographical Database of France at scale 1 : 1 000 000. The regional BDSol-250 on a 1 : 250 000 scale (source INRA) does not exist. So we decided to create our own data.

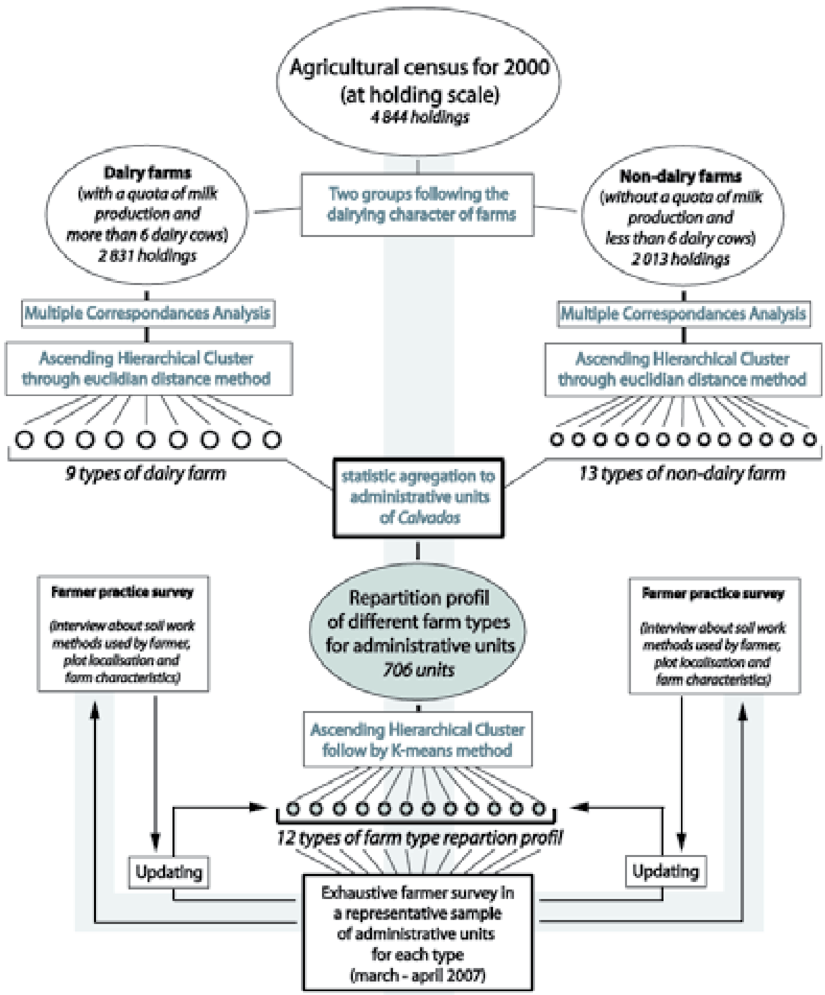

Fig. 5. Procedure for characterizing the agricultural practices in Calvados

During two years, we carried out nearly 8000 soil boreholes, which represent one borehole per 40 ha of agricultural land. Pedogenesis, soil thickness, coarse fragments, texture and hydromorphy have been registered. Data and Progressive knowledge of the soil landscape allowed us to produce a first soil map on which we selected 150 representative soil boreholes. Physical (granulometry, structural instability of surface horizon), hydrologic (AWC taking into account per cent of coarse fragments) and chemical properties have been determined. Structural instability has been evaluated starting from the INRA test of structural stability carried out on aggregates (Le Bissonnais and Le Souder, 1995).
Consequently, the soil features do not come from the application of the pedotransfer rules. This analytical step has been led us to finalize a global soil map on a 1 : 50 000 scale, to suggest at the same scale a map of soil structural instability, to propose another map in connection with spatial distribution of available water content of the soil, and, finally, combining the latter with interpolated rainfall data, to define the yearly positive hydrological balance. Classes of structural instability of the soil aggregates come from a

small adaptation of MWD (medium weight diameter of aggregates) classes found by Le Bissonnais and Le Souder (1995). This adaptation is based on the formation of two classes instead of one, which was initially provided for aggregates with a size larger than 2mm. For MWD of aggregate: > 3.5 mm; [3.5-2 mm[; [2-1.3 mm[; [1.3-0.8 mm[0.8-0.4 mm[; =<0.4 mm. Those are respectively comparable with the structural instability levels 0, 1, 2, 3, 4, 5.

2.4 Results

Combination of potential sensitivity of areas to erosion and rainfall erosivity in a "normal" climatic context leads to evaluation and mapping of mean erosion hazard (Fig. 6a). This document highlights of the existence of all levels of hazard. Level 0 shows parcels promoted with permanent grassland or orchards and/or with a slope lower than 1%. These parcels represent 1600 km² of agricultural surface (42 %). They are localized by the form of coherent spatial units in the north-west and center-east of the territory.

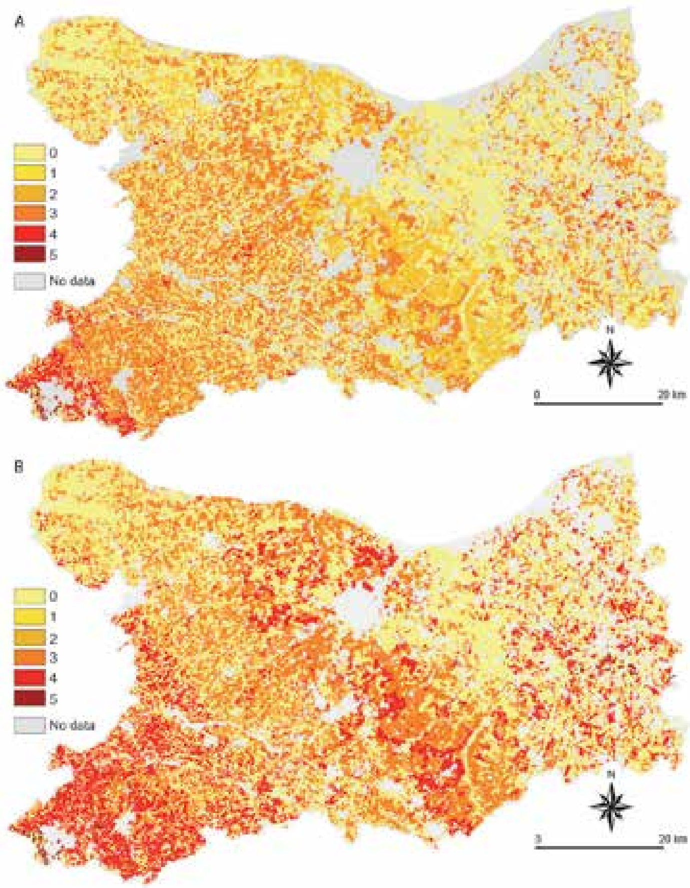

Fig. 6. Soil erosion hazard in Calvados at parcel scale (A) for a normal climatic contex, (B) for a rainy year

Levels 1 and 2 of soil erosion hazard cover more than 500 km² of agricultural surface (13 %). It is located in majority in the central part of the Calvados along a North/South axis. Level 3 is

the most represented since it covers 1400 km² (37%) of agricultural surface. It is located south-west of the department and locally in the East. The fourth level is the only one representing important hazard since the level 5 is absent. The affected parcels cover a surface of 100 km² (2,6%). They are essentially gathered at the extreme south-west of Calvados.
The assessment of the soil erosion hazard for a rainy year (2001, + 15% compared to the "normal" 1970-2000) has been achieved in order to study the potential impact of the rainfall conditions supporting high erosivity (Fig. 6b). Results are particularly interesting because they show that agricultural surfaces affected by a level 4 (strong hazard) extended more than 800 km² compared to a year with "normal" climatic conditions. The most affected areas are South-West, the central North/South axis and secondarly the eastern part of the territory. This brings us to considerate that Calvados is a department presenting a strong predisposition for the genesis of soil erosion by water, erosion which express itself as soon as climatic conditions induce strong erosivity.
Finer representation with zoom effect of levels of hazard at the scale of parcel unit reveals the occurrence of a mosaic of colors expressing very frequent spatial disjunction at local scale about erosion hazard (Fig. 7C). The rapid and brutal spatial variations of physic properties of the area associated with the interpenetration of grassland and crops parcels contribute to the strong heterogeneity of the results at local scale. The precision of input data of the model SCALES allows to obtain this type of conclusion. It also comes to the idea that the management of this issue assumes in priority an approach at the scale of a parcel or a group of parcels.
The aggregation of soil erosion hazard data at administrative and hydrologic scales (Fig. 7A-B) shows a significant loss of information when the basic scale is given up (Fig. 7C). SCALES model loses quickly its interest but can become a communication tool about the question of soil erosion.

3. Adaptation of the SCALES model at seasonal and monthly scales

The SCALES model leads to the production of soil erosion hazard levels on a very precise spatial scale and for region-size territories. However, the results enable at best to compare median annual situations in a normal climatic context and during years with rainfalls higher than the normal climatic context. Yet, these are tendencies that hide an intra-annual variability of the erosion hazard, which shall be necessary to evaluate in order to take into account the quick change of climate conditions and of the surface state of cultivated soils. The next step is hence about an adaptation of the initial model in order to be able to evaluate the erosion hazard on seasonal and monthly scales.

3.1 Data with intra-annual variability

The data of the initial model characterized by an intra-annual variability correspond to agricultural practices and to climatic and pedoclimatic parameters (rainfalls and yearly positive hydrological balance). The modalities of the yearly repartition of the daily high intensity rainfalls and precipitations' volumes will affect the variability of the rain erosivity during months and seasons. As well, the agricultural practices associated to climatic conditions will affect the rate of plant covering and its evolution. Yet, the plant covering of a bare soil strongly intervenes on the probability of soil erosion by water. The adaptation of the SCALES model needs to get the monthly and seasonal data about 1° rates of plant covering and their evolution for cultivated parcels and 2° rain erosivity conditions.

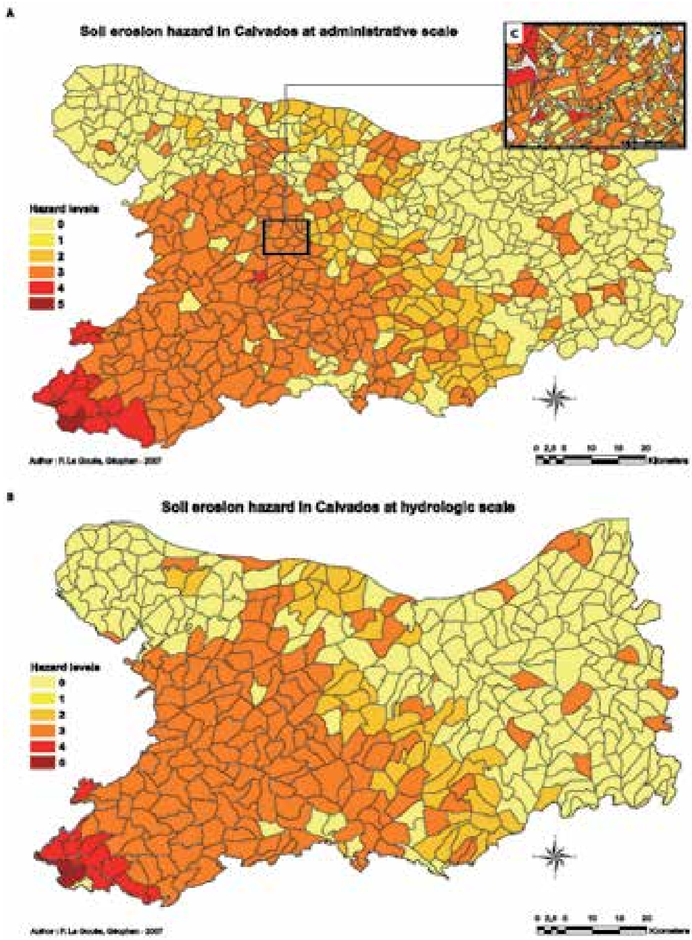

Fig. 7. Aggregation of the soil erosion hazard data: (A) at the administrative scale (municipality); (B) at the hydrologic scale; (C) significant deterioration of results from the parcel scale to the administrative scale due to aggregation procedure

3.1.1 Plant covering

The plant covering on cultivated areas can be estimated by the foliar surface of plants. In French regions with temperate climate, it is very difficult to get reliable data about monthly rates of plant covering and their intra-annual evolution. The data that we show (Fig. 8) have been sent by the Technical Institute for Plants specialized in the agronomic research (ARVALIS – Institut Technique du Végétal), a Calvados-based and nationally recognized organism. These data concern the principal plants cultivated annually or in intercrop periods, in Normandy.

Fig. 8 enables to show on a monthly scale three types of evolution for the plant covering by plants in crop areas. A first type gathers the plants characterized by a poor rate of plant covering at the end of the first month of growth and then by a very quick and totally covering rate at the end of the second month. This type concerns maize silage and ray grass. The following type refers to rapeseed and mustard. The rate of plant covering is very important at the end of the first month of growth and reaches 100% at the end of the second month. Finally, the third type is slightly different from the two others as it needs 4 months of growth to get a rate of plant covering of 50% and then 6 months for a complete rate. Cereals correspond to this type.

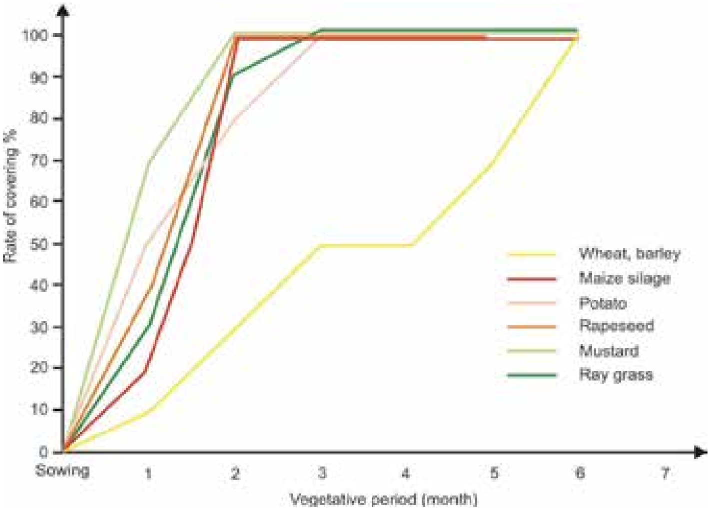

Fig. 8. rate of covering according to the vegetative period of various cultures (Arvalis)

A first adaptation of the SCALES model consisted then in replacing the initial data "intercrop period" and "intercrops management" by the data "rate of plant covering".
The monthly classes selected are as follows: >90%; [90-70%[; [70-50%[; [50-30%[; [30-10%[; <=10%. Those are respectively corresponding to the levels of pressure 0, 1, 2, 3, 4, 5.

3.1.2 Climate

The data of the initial model that characterized the rainfall erosivity have been conserved. Concerning the number of days when the rainfall intensity is above 10 mm, we made an average monthly counting for the 1991-2004 period starting from the network of meteorological stations presented previously. For the average monthly positive hydrological balance, we used the monthly data of hydrous budget reports used in the initial version of the SCALES model.
Monthly classes are the following.
For DI10: =1; =2;=3;=4; >=5
For YPHB: <30 mm; [30-60 mm[; [60-90 mm[; [90-120 mm[; >=120 mm
Those are respectively comparable with the levels of pressure 1, 2, 3, 4, 5.

3.1.3 From monthly data to seasonal data

In order to estimate the soil erosion hazard at seasonal scale, we calculated, for the initial data rate of plant covering, DI10 and YPHB, the average of values of the months that characterized each season. Thus, the value relative to the spring results from the average of values obtained for March, April and May. The values of June, July and August provide the summer value ; the ones from September, October and November give the autumnal value and the ones from December, January and February are the winter value. Thus, the monthly classes presented previously are reused to estimate the seasonal levels of pressure for the initial data that showed an intra-annual variability.

3.2 Application to the Branche catchment

The monthly and seasonal approach of the SCALES model has been tested in Basse-Normandie, on a catchment scale (Fig. 1A).

3.2.1 Study area

Localized in the French department of the Manche, the Branche catchment covers 1100 hectares and is a part of the Vire catchment, a larger hydrological area of 1270 km². The uphill of the test zone shows an undulating relief resulting of many small valleys. The slopes are between 1% and 5%. The downhill is marked by deeper steeply sided settings of the rivers. The slopes are more abrupt, between 5 and 15%. The study area is situated in the Armorican block, formed by Precambrian schist and sandstones. Umbric leptosols and cambisols cover the major parts of the slopes and gleysols can be found in the valleys bottoms. Their thickness varies from 40 cm to 120 cm. The local climate is characterized by abundant annual rainfalls, around 950 and 1000 mm.
The average size of the farms is 100 ha. The local agriculture shows a system of intensive pastures with a high proportion of ploughings dominated by spring crops. The grass surfaces represent 60% of the agricultural land. Crop and wheat respectively occupy 53% and 36% of the cultivated areas.

3.2.2 Acquisition of input data

To calculate slopes inclination, we used Digital elevation Model of Manche with a grid resolution of 50 X 50 m. The climate data start from the Torteval-Quesnay station, based 15 km East from our site. As for the general model, we collected the daily data for the 1991-2004 period. These data were used for mapping the soil erosion hazard on monthly, seasonal and annual scales within the framework of an average climatic year. The data related to the agricultural practices result from a survey carried out among farmers who exploited catchment lands between 2005 and 2008. Those were used to map the annual hazard. For the other temporal scales, the hazard was estimated from agricultural data from the 2007-august 2008 period. Finally, the soil data (structural stability, available water content) were obtained from soil boreholes according to a density of 1 hole for 10 ha about agricultural area and from laboratory analysis concerning the structural instability of the superficial horizons. The spatial units of integration of the SCALES data correspond to the agricultural parcels.

3.2.3 Results

The monthly maps obtained for the September 2007-august 2008 period primarily reveal a significant intra-annual variability of the soil erosion hazard (Fig. 9).
One note a first sequence, between September and October, characterized by quite a low hazard on the majority of the cultivated parcels (approximately 300 hectares). The surfaces with medium level represent 2% of the catchment area. During this period, the erosivity is low because of nonexistent or very low hydrological surplus and insofar as the plant covering is relatively important because of the presence of fast-growing temporary crop (mustard) and wheat stubble.

A second sequence goes from November to January, which is different because of the levels of soil erosion hazard increase, with maximum levels in December. During this month, the parcels associated to a high soil erosion hazard represent 7% of the agricultural surfaces. December combines bare soils after the maize silage with abundant hydrological surplus and more numerous daily rainfalls exceeding 10 mm.
The third sequence goes from February to Match. Its marks a fall of the hazard levels on all the cultivated parcels because of an increase of the rate of plant covering and an important decrease of hydrological surplus.
The fourth period corresponds to April and May. We can notice higher hazard levels than in the previous period. The razing of temporary crops comes with the soil baring of the parcels used for maize production. In addition, this culture has a slow plant covering during the beginning of its growth, which leads to a prolonged exposition to intense rainfalls for the soil. Nevertheless, in spite of a large increase of bare soils, the erosivity is low because the hydrological surplus are nil and the repetition of daily rainfalls that exceed 10 mm are very low.
The last period, from June to August, is characterized by the lowest hazard levels that don't change during those three months. This can be explained by a nonexistent or low erosivity and a complete plant covering for the cultivated parcels.
At seasonal scale, the temporal variability of levels of soil erosion hazard, observed at monthly scale, is significantly smoothed (Fig. 10). However, the evolution in time of the soil erosion hazard intensity remains sensible. Winter appears as the period in which hazard levels are the highest. Yet they don't exceed the average level. This level concerns 32% of the agricultural area in the test zone.

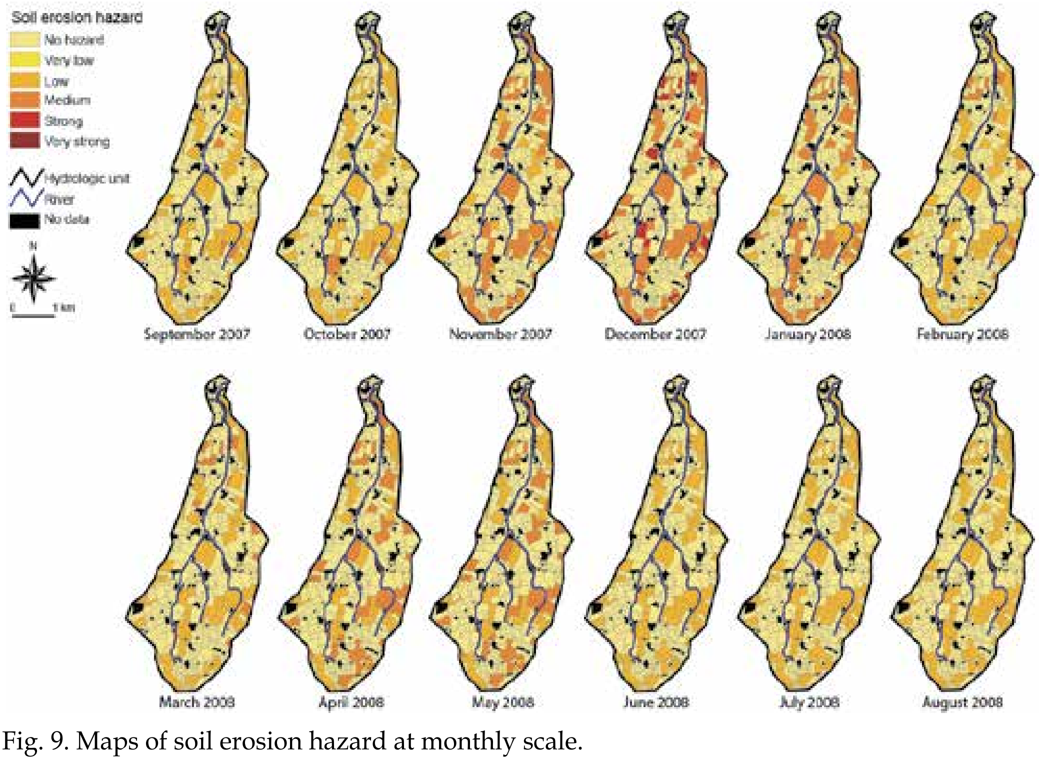

Fig. 9. Maps of soil erosion hazard at monthly scale.

Autumn comes at the second rank for the soil erosion's most favorable seasons, before spring. The low hazard level is observed in the main parts of the cultivated parcels. But the medium hazard is still highly represented as it concerns 12% of the agricultural surfaces. During summer, no cultivated parcel exceeds a low hazard level.

3.3 Discussions

The initial conception of SCALES enables us to consider an adaptation of the model to succeed in the mapping the soil erosion hazard at intra-annual time scales. The evolutionary character of the model proves that we can go from a static temporal vision of the soil erosion hazard within the framework of an annual approach to a dynamic point of view starting from monthly and seasonal representation of the hazard.

When we compare the monthly and seasonal data of the soil erosion hazard with the annual data (Fig. 11), we first notice that the initial version of the SCALES model doesn't enable to perceive the intra-annual variability of the hazard. In addition, the reading of the seasonal and annual hazards shows that the annual values are overestimated. Insofar as the input data of the initial model have changed, the results' comparison therefore appears to be delicate. However, we notice that the modularity of the SCALES model enables us to display the erosion hazard at different temporal scales and to get highly complementary results.

The adaptation of SCALES allows us to take into account the temporal as well as spatial variability of input data concerning climate and agricultural practices. Hence, for instance, the monthly erosive pressure of agricultural practices will move spatially from year to year according to the crop rotations decided by the farmer. Hazard levels will act in like manner. Thus, SCALES can be considered as a model which is spatially and temporally dynamic.

Fig. 10. Maps of soil erosion hazard at seasonal scale.

The monthly and seasonal approach of the soil erosion hazard needs to have local and precise information about agricultural practices. In addition, the characterization of the soil proprieties has to be based on field and laboratory data in a high spatial resolution. In these conditions, it is not possible to carry out a monthly mapping of the hazard erosion for territories that exceed several hundred or thousand of km². This work must be limited to areas recognized as sensitive through the initial model's representation of the hazard or by the intermediary of the land managers' knowledge.

4. SCALES, a model to consider the climate change impact on soil erosion by water

The structure and modularity of SCALES allows us to plan its use at long-term scale. This approach has been set as part of study of the impact of the climate change on the soil erosion hazard. We tried to compare at a monthly scale the present levels of hazard with those forecasted for the year 2100 based on a case study carried out in Normandy (Fig. 1B).

4.1 Study area

The study area is located in the north-west of Calvados. The catchment called the Lingèvre covers an area of 15 km². It is part of the Seulles, a larger catchment covering an area of 450 km² in the western part of the French department. The Lingèvres is located on a transition zone between the Armorican block upstream and the Paris basin downstream. At the periphery of the catchment, more particularly upstream, some thick patches of aeolian silt (loess) over clay and limestone formations from Secondary and Tertiary.

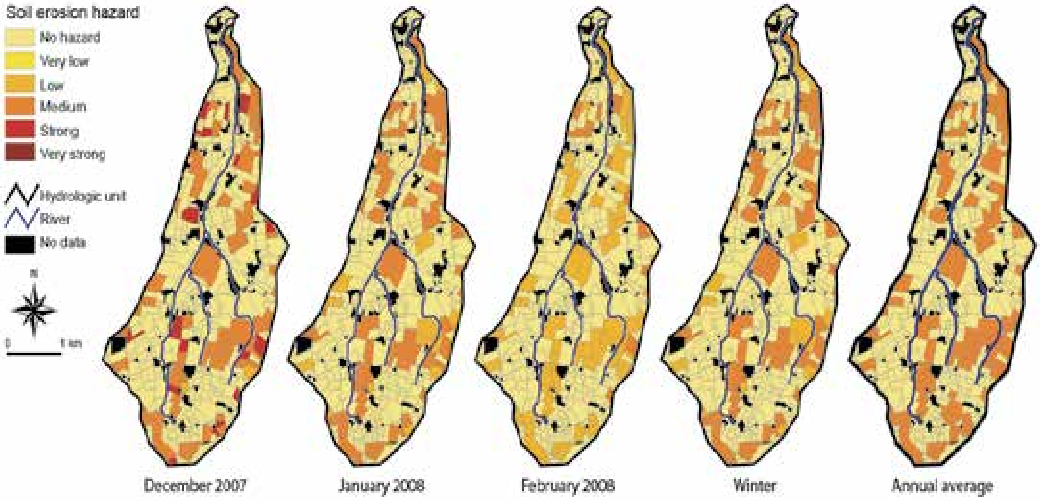

Fig. 11. Maps of soil erosion hazard at various temporal scales.

Slopes are generally gentle, especially on the higher parts reaching 130 meters high. The difference of height with the outlet is about 80 meters at the north of the basin. Slopes are increasing downstream of the Lingèvres.

Soils are predominantly hydromorphic. At the basin's periphery, on the higher slopes, we notice the presence of moderately to strongly redoxic silty luvic cambisols which thickness exceeds 1 meter. 70% of the Lingèvre's slopes are made of thin (40 cm) clayey redoxic soils. Umbric an rendzic leptosols less than 40 cm thick are sporadically localized. Gleysols are located in valley bottoms.

The climatic context is similar to the one described in the previous case study. Rainfall is quite constant all year long with an increase in autumn and winter. The annual accumulation of rain is around 950 mm.

Agriculture combines cereal crops, fodder crops, and bovine breeding gathered in huge farms intensively exploited. Grassland cover half of the agricultural land of the catchment. These are almost always permanent grassland. Crops are covering an area equivalent to the one of the grassland. Arable lands are fairly divided between spring crops (maize silage) and winter crops (wheat).

4.2 SCALES data for the current period and for 2100

4.2.1 Data for the current period

The digital elevation model of Calvados at 20 m scale was used to estimate the slopes of the Lingèvres. The local climatic data comes from the same weather station than the one mentioned in the case study of the Branche catchment. This weather station is located 5 km from the Lingèvres. The identification of the agricultural parcel network and agricultural practices was based on field work. The data collected covers the period from September 2009 to august 2010. The soil data used for calculation of available water content and hydrous budget were extracted from the database related to the 1/50000 map of Calvados soils described in the first part of this document. Additional survey with soil boreholes also allowed refining the spatial resolution of pedological characteristics of the Lingèvres. Therefore the structural instability of the catchment's soils was deducted from already existing administrative data and from 18 additional analysis on representative of the soils and agricultural practices diversity. Input data of the model and their treatment at monthly and seasonal scale for an average climatic year had been integrated in elementary spatial units represented by agricultural parcels.

4.2.2 Input data for a forecast of the soil erosion hazard to 2100

The agricultural and climatic data represent the two types of data that show a temporal variability. Nowadays, works relating to climate change allow us to have pieces of information that make consensus in the scientific community of climatologists for a distant future (GIEC, 2007a). Unfortunately, we cannot say the same for agricultural practices as the agricultural evolution depends at the same time on its interaction with climate, political choices and the socio-economic situation. Yet, it is not possible to precise with certainty what will be local agriculture in a distant future because we know little if nothing about the agricultural consequences of these interactions, political choices and socio-economic characteristics by 2100. So, our projection of the erosion hazard in 2100 leans on data from the GIEC that reproduce by default the current agricultural situation.

To characterize the Norman climatic context by 2100, we used and adapted the GIEC's simulation data (GIEC, 2007a) concerning the A1B scenario (Cantat et al., 2009). These ones reveal a annual increase of temperatures in Normandy on the order of 2.8° C from now to 2100 (Fig. 12A) with a global warming being more intense during summer (+ 3.2° C). With regard to rainfalls, the annual accumulations would remain stable, which would nevertheless hide differentiated seasonal behaviors: +9% during winter and -21% during summer (Fig. 12B). All these data were used to determine the conditions of rainfall erosivity in 2100.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
A. Temperature (°C)	2.5	2.5	2.5	2.6	2.8	3.1	3.3	3.2	3.1	2.8	2.7	2.5	2.0
B. Rainfall (%)	9	9	9	4	6	20	23	20	6	4	8	9	2

Fig. 12. Regional climatic projections at horizon 2100 starting from scenario A1B concerning temperatures (A) and rainfalls (B)

4.3 Results

4.3.1 Soil erosion hazard for the current period

In order to show the most interesting results, our comments will concern more specifically on the period that goes from September to February in which the temporal variability of the erosion hazard is the highest. The monthly mapping of the hazard according to the current climatic data shows that the cultivated parcels are characterized by a susceptibility to the soil erosion by water which is medium or high (Fig. 13).

In September, the hazard levels are quite low or medium. At this time, the available water contents in the soils are not refilled, which postpone the presence of hydrological surplus. In addition, the plan covering is assured by corn and wheat stubbles.

In October and November, the average level of the soil erosion hazard concerns nearly 90% of the cultivated parcels. The increase of the soil susceptibility to erosion results from the bare soil of areas ensilaged and sowed with wheat. This can also be explained by the appearance of the first poor hydrological surplus.

The soil erosion hazard reaches its highest level in December and January. It becomes important for half the cultivated parcels. If the rate of plant covering is not very different from the previous period, the erosivity has increased due to important hydrological surplus and to the increase of days in which rainfalls exceed 10 mm.

In February, the susceptibility to erosion comes back to medium on the catchment's uphill border and quite poor elsewhere. This is explained by a better plan covering and land use and by a significant decrease of the amount of days in which the rainfalls intensity is exceeding 10 mm.

4.3.2 Forecasts for 2100

The projection of the soil erosion hazard for September shows levels that are similar to those found for the current period (Fig. 14). In October, we notice that in 2100 the cultivated areas concerned by the low and very low hazard increase and that parcels characterized by a high hazard vanish. The reduction of the susceptibility of cultivated surfaces to soil erosion could be explained by a huge decrease of summer rainfalls (-21%). This would lead to a delay in the filling of available water contents and thus to differ until November for the beginning of the first hydrological positive balance.

For November, the projection highlights a reinforcement of medium and high levels of the erosion hazard. The tendency would be even more marked in December. The parcels characterized by a high hazard would represent 90% of the cultivated areas. The increase of the susceptibility fo the catchment to soil erosion would be discernable until February. The strong hazard would still be present and the medium hazard would concern more than 80% of the cultivated areas.

Comparing the foreseen climatic data for 2100 with the ones from our period of reference (1991-2004), we noticed that 1994 was a very comparable year to the climatic projection of

2100. Knowing the frequency of occurrence of the 1994 climatic conditions, it leads us to the conclusion that the hazard levels obtained for an average year by 2100 would correspond to a current period's year whose occurrence periodicity is 4 years.

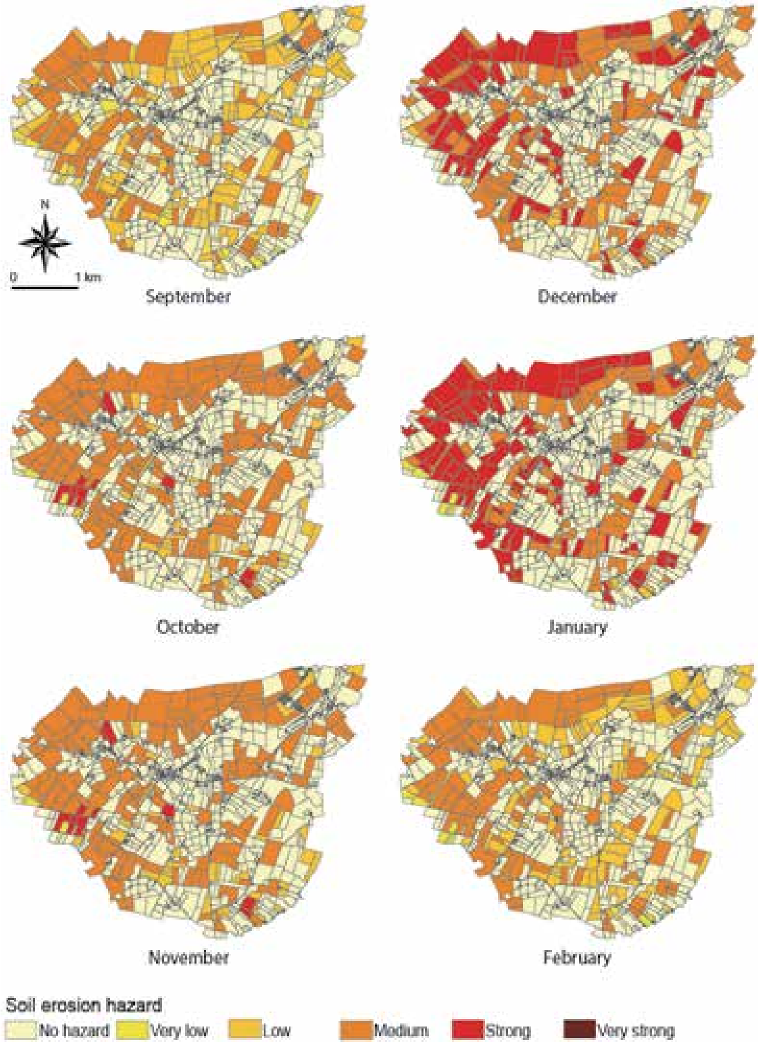

Fig. 13. Maps of soil erosion hazard in current climatic context at monthly scale.

4.4 Discussions

The climate change which has been observed in Europe from the pre-industrial to the current period resulted in an increase of temperatures in the order of 1°C and in a modification of rainfall distribution: +10% to +40% in Northern Europe during the 20th century and -20% in the South (EEA, 2008). On a world scale, we may not evade a climate warming in the order of 2 to 3°C by 2100 (Séguin, 2010).

Available data of the climate change effects on soils are very insufficient in European countries (EEA, 2008). However, according to some work, It seems that this leads to an

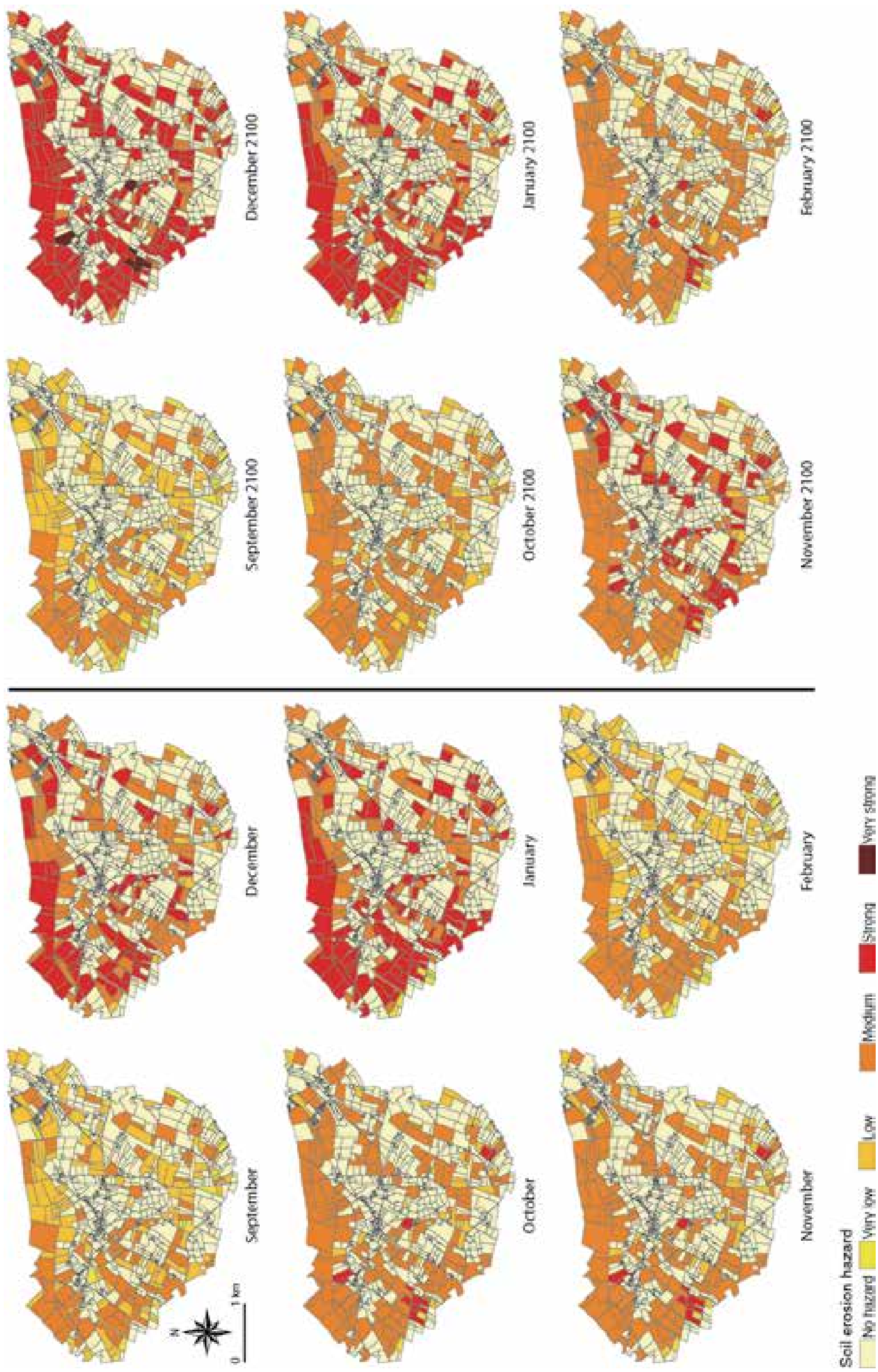

Fig. 14. Soil erosion hazard for current period and for 2100 at monthly scale.

increase of soils sensitiveness to erosion by water in Northern European areas on account of an increase of the rainfall frequency and intensity (Boardman, 1990; Boardman and Favis-Mortlock, 1993).

Nevertheless, this increase could be minimized under the influence of a modification of the vegetative cycles in the natural and cultivated areas (Ellis et al., 1990 ; Wheeler et al., 1993). We thus notice a significant progress of phenology in Europe (Séguin, 2010). In addition, a CO_2 multiplication by 2 at the end of the 21st century may lead to a 20 to 30% increase of photosynthesis (Séguin, 2010). The sensitiveness to erosion may even be lowered by conservative agricultural practices (Hulme et al., 1993; Zhang et al., 2009)

However, it is impossible to foresee the agricultural practices evolution for the 21st century because we know well yet the interactions between climate change and agricultural practices. Besides, agriculture depends on political direction and socio-economic contexts. In these conditions, it is not totally unrealistic to consider the climate change impact on the soils sensitiveness on erosion if we base on the current agricultural practices. This choice may also be justified by the fact that, in Europe, agricultural production systems are characterized by a large geographic stability (Seguin, 2010). In addition, the results we obtained deserve to be well examined.

Our work shows that the increase of erosive pressure on the cultivated soils which is forecast for an average year by 2100 would correspond to a scenario which the current frequency is one out of four. The fragility of cultivated soils may therefore be more important and more continuous over time. Although these results for a normal year are given, we must not forget that the climatic variability in a distant future may have consequences as harmful as the deep-rooted trend. Besides, it should be reminded that two climatically similar years may reach different erosive solutions (Favis-Mortlock and Boardman, 1995).

SCALES model helps to propose high spatial and temporal resolution custom-built scenarios of the climate change impact on the evolution of soils sensibility to erosion by water by 2100. Nevertheless, these data can only be produced on a local scale. However, our work is in the spirit of the European Environment Agency which reminds us the necessity to develop tools to assess the impact of climate change on soils (EEA, 2008).

5. Conclusions

Soil erosion is a major and growing cause of soil deterioration in many European countries. The main issue is that we must no longer consider soil as a renewable natural resource. Whatever the scale of intervention, the territorial structures need to have spatially spread information in order to overcome or prevent soil erosion. In this regard, maps of erosion hazard constitute essential documents.

Our goal was multiple when we developed SCALES model. Firstly, the point was to prove that it was reasonable to foresee a regional scale model and map while we have detailed local scale data. Then, we wanted to limit the model applicability to the European oceanic areas which are marked by a mutual pedoclimatic situation and a territorial dividing into agricultural parcels. Besides, our idea was to consider the soil erosion hazard within these parcels which are area sources: assuming that in this geographic context the erosion is more controlled by agricultural units rather than the environment where they dwell. We eventually had to take into consideration the weight of agricultural practices through their temporality when we assessed this hazard.

After we proved SCALES was operational in Calvados, we contemplated editing the model in order to achieve an assessment of the erosion hazard within intra-annual time scales. SCALES progressive nature allows us to consider this model as spatially and temporally dynamic. However, the required investment for produce the data in order to decline the model at the monthly and seasonal scales does not allow us to establish a mapping of the soil erosion hazard on a regional level. Consequently, this fine temporal approach must be held for sectors with strong environmental stake.

If SCALES can be used in a predictive approach, its structuring and its modularity also give opportunities within a prospective framework. It is what we did, in Basse-Normandie, concerning the topic of the impact of the climate change on the evolution of the cultivated soils susceptibility to erosion by water. In average year at horizon 2100, the results of this new application show that the levels of soil erosion hazard would be comparable with those currently obtained within the one year framework rainy of which the probability of return is once every 4 years. One would thus witness a reinforcement of the soil erosion hazard in average year.

We now wish to look further into the prospective application of SCALES starting from the studies which present, in comparable areas, the scenarios of agricultural practices evolution in a near future and a future distance. Our first results and the aim which we propose are altogether in the spirit of the recommendations of the GIEC (2007b) and the European Environment Agency which reminds us the necessity to develop tools to assess the impact of climate change on soils.

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SATEEC GIS System for Spatiotemporal Analysis of Soil Erosion and Sediment Yield

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1. Introduction

In recent years, severe rainfall events have been causing various negative impacts on environment and ecosystem at the receiving water bodies. Especially soil erosion and resulting muddy water problems driven by rainfall-runoff have been hot issues in many countries due to accompanying water quality impacts. Thus various efforts have been made to evaluate soil erosion and sediment yield spatially and temporarily to develop effective soil erosion best management practices. Among those, modeling approaches have been often utilized and many soil erosion models have been developed and evaluated worldwide. In the past couple of decades, these soil erosion models have been integrated with Geographic Information System (GIS) for spatiotemporal analysis of generation and transport of soil erosion/sediments. The Universal Soil Loss Equation (USLE), Water Erosion Prediction Project (WEPP), Soil and Water Assessment Tool (SWAT), European Soil Erosion Model (EUROSEM), Agricultural Non-Point Source Pollution (AGNPS) are widely used for various soil erosion studies. The input requirements for these models vary to some extents. The USLE model has been widely used because its input data are available in most countries and the model is relatively easy to implement. This USLE model has been integrated with GIS for spatiotemporal analysis of soil erosion by many researchers worldwide. The Sediment Assessment Tool for Effective Erosion Control (SATEEC) is one of them with several enhanced modules for sediment yield estimation at a watershed scale with higher accuracies in sediment evaluation. In this chapter, the development history of the SATEEC system and several SATEEC applications for soil erosion and sediment yield estimation will be introduced.

2. Development of SATEEC GIS system

The SATEEC system was developed in 2003 (Lim et al., 2003) and has been upgraded with various enhanced modules incorporated into the system (Lim et al., 2005; Park et al., 2010). It has been applied to various watersheds with diverse purposes (Yoo et al., 2007; Park et al., 2007; Park et al., 2008). In the current SATEEC 2.1 system, the soil erosion is estimated using USLE with time-variant R and C modules. The sediment delivery ratio (SDR) is estimated using area-based SDR module, channel slope-based SDR module, and Genetic Algorithm-based SDR module in the SATEEC system. In addition, several miscellaneous modules are available for various soil erosion and sediment yield applications.

2.1 SATEEC Version 1.0 ~ 1.8

2.1.1 USLE-based SATEEC for soil erosion and area-based sediment delivery ratio modules

The system requiring only USLE inputs was developed with the philosophy of "very limited dataset for reasonable soil erosion estimation accuracy with commonly available GIS interface" and "easy-to-use", To keep the philosophy and provide user with watershed assessment capabilities, the SATEEC version 1.x system utilized are area-based and slope-based SDR methods. The SDR in general is defined as a ratio of the soil which reaches the watershed outlet to soil detached from source area (Yin et al., 2005). The SDR is affected by various watershed characteristics such as watershed area, geomorphologic properties, precipitation pattern, total runoff and peak flow volume, land use properties, physical properties of soil, etc. These characteristics affect it not only with *spatial properties* also *temporal properties*. However, it is not feasible to reflect all of these in estimating SDR due to limited data sets. Empirical regression models to estimate SDR for watersheds were proposed by many researchers; one of them is to estimate SDR using watershed area as shown below (USDA, 1972, Boyce, 1975, USDA, 1972).

$$\mathrm{SDR} = 0.4720 \times \mathrm{A}^{-0.125} \text{ (Vanoni, 1975)} \tag{1}$$

$$\mathrm{SDR} = 0.5656 \times \mathrm{A}^{-0.11} \text{ (Boyce, 1975)} \tag{2}$$

$$\mathrm{SDR} = 0.3750 \times \mathrm{A}^{-0.2382} \text{ (USDA, 1972)} \tag{3}$$

Where, SDR is sediment delivery ratio, and A is watershed area (km^2).
These regression models with only watershed area as an input are useful for a watershed with very limited watershed characteristics data to estimate SDR. These area-based SDR is the first approach in SATEEC system to estimate sediment yield at the watershed outlet.
Yoo et al. (2007) reported that soil reconditioning in agricultural field could affect sediment yield at the watershed significantly. Thus area-based SDR was used to estimate sediment yield and it was found that soil loss could increase by 138.0 % per unit hectare while sediment yield could increase by 59.4 % per unit hectare with various activities in the watershed. It indicates that estimated soil loss and sediment yield may not show identical trend.

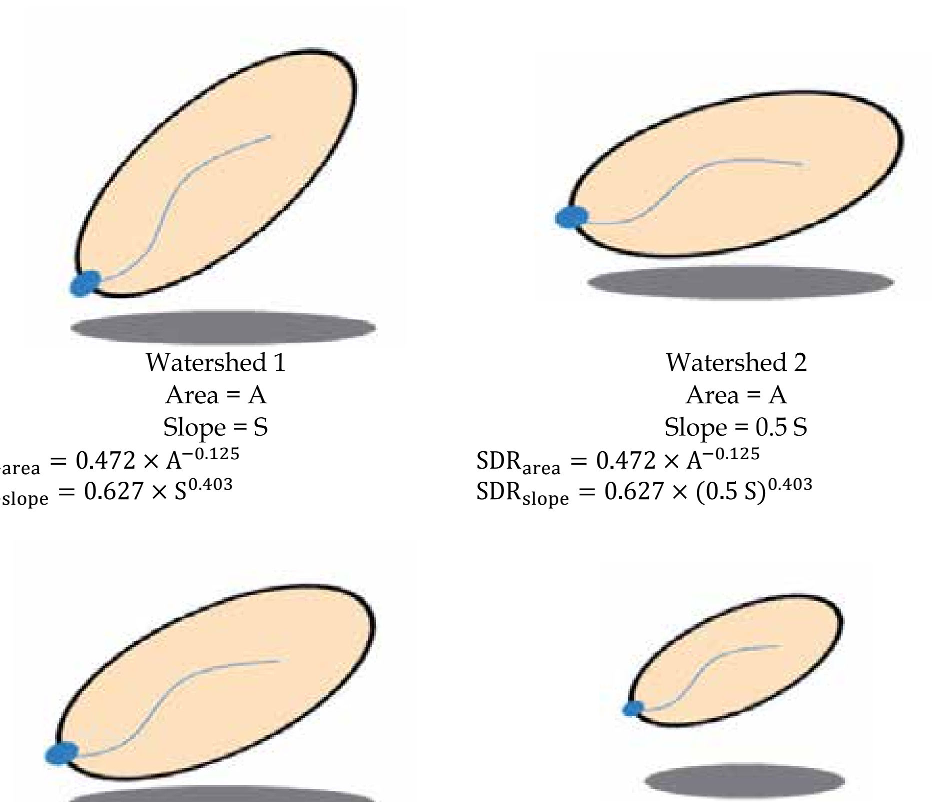
2.1.2 Slope-based Sediment Delivery Ratio modules

Area-based SDR module provides convenience to estimate SDR with limited data collection for a given watershed, The SDR in the watershed is affected by various geomorphologic properties such as average channel slope than watershed area. Thus, slope-based SDR module was incorporated into the SATEEC system to supplement limitation of area-based SDR module.

$$\mathrm{SDR} = 0.627 \times \mathrm{S}^{0.403} \text{ (Williams \& Berndt, 1977)} \tag{4}$$

Where, S is slope of watershed.

As indicated above, the SDR could be identical if the area-based SDR is applied to two different watersheds with the same area. Thus, the SATEEC was modified to integrate slope-based SDR module using equation (4). Park et al. (2007) reported that SDRs for 19 small watersheds having identical watershed area were different due to various average channel slope in each watershed, and sediment yields were different by not only USLE factors also estimated SDR for the watersheds. The SDRs by area-based SDR module were calculated as 0.762 for the same size watershed (0.0219 square kilometer). However, the SDRs by slope-based SDR module were from 0.553 to 0.999 with varying slope from 0.73 % to 3.17 %. It indicates that the SDR is one of watershed-specific conditions, thus, better ways to estimate SDR needs to be developed based on various characteristics of watershed and measured data, not just based on single parameter such as only area or only slope. The slope-based SDR module has similar limitation as area-based SDR module does (Figure 1).



Watershed 1
Area = A
Slope = S
$SDR_{area} = 0.472 \times A^{-0.125}$
$SDR_{slope} = 0.627 \times S^{0.403}$

Watershed 2
Area = A
Slope = 0.5 S
$SDR_{area} = 0.472 \times A^{-0.125}$
$SDR_{slope} = 0.627 \times (0.5\ S)^{0.403}$

Watershed 3
Area = A
Slope = S
$SDR_{area} = 0.472 \times A^{-0.125}$
$SDR_{slope} = 0.627 \times S^{0.403}$

Watershed 4
Area = 0.5 A
Slope = S
$SDR_{area} = 0.472 \times (0.5\ A)^{-0.125}$
$SDR_{slope} = 0.627 \times S^{0.403}$

Fig. 1. Comparison of SDR for watersheds

The research indicated the SDR is not always the most influential and fundamental factor in sediment yield estimations. However it is also one of very important factors to estimate sediment yield which is site-specific/watershed-specific. For instance with Figure 1, watershed areas for Watersheds 1 and 3 with different slope condition, the SDR based on area are identical, but the SDRs based on slope are different. As shown in this comparison, the influence of slope is ignored if SDR is calculated with only their area. In the other way, if the average channel for Watersheds 3 and 4 are the same, while the area of Watershed 3 is greater than that of Watershed 4, the slope-based SDR values are the same while the area-based SDRs are different. From these examples, area-based and slope-based SDR need to be enhanced by incorporating more watershed characteristics affecting generation and transportation of soil erosion and sediment to the watershed outlet.

2.2 SATEEC version 2.0 ~ 2.1

2.2.1 Time-variant SATEEC R and C modules for monthly and yearly soil erosion and sediment

One of highly beneficial modification in SATEEC ver. 2.0 is time-variant soil erosion simulation with temporal USLE factors to reflect surface condition of land and precipitation, represented by USLE C and R factors respectively. Soil loss or sediment yield represented with a single value using long-term precipitation data is not sufficient for various soil erosion studies to develop site-specific Best Management Practices. Soils erosion at the watershed is affected by not only total volume of precipitation but also precipitation intensity or patterns. The SATEEC ver. 2.0 was enhanced to reflect precipitation pattern for soil erosion estimation monthly and annually. Time-variant R module integrated into SATEEC ver. 2.1 derives monthly or yearly USLE R factors using daily precipitation data, using regression models suggested by Jung et al (1983).

$$\text{USLE monthly R factor: } \mathrm{R} = 0.0378 \times \mathrm{X}^{1.4190} \tag{5}$$

$$\text{USLE yearly R factor: } \mathrm{R} = 0.0115 \times \mathrm{Y}^{1.4947} \tag{6}$$

Where, X is monthly rainfall amount (mm) and Y is yearly rainfall amount (mm).

With this Time-Variant R module in the SATEEC ver. 2.0, the SATEEC could be used for temporal analysis of soil erosion with USLE input data and readily available rainfall data. In addition to the Time-Variant R module, the Time-Variant C module was developed to reflect crop growth and various management practices such as planting, growth, withering, and kill/harvest at the agricultural fields as well as forest. USLE factor representing land use condition is USLE C factor; they vary depending on land use.

$$\mathrm{C_{USLE}} = \exp\left(\left[\ln(0.8) - \ln\left(\mathrm{C_{USLE,mn}}\right)\right] \times \exp[-0.00115 \times \mathrm{rsd_{surf}}] + \ln\left(\mathrm{C_{USLE,mn}}\right)\right) \tag{7}$$

Where $C_{USLE,mn}$ is the minimum value for the cover and management for the land cover and rsd_{surf} is the amount of residue on the soil surface (kg/ha).

SWAT model estimates daily USLE C values for each crop (equation (7)). Instead of adding SWAT USLE C module for dynamic simulation of crop growth in the SATEEC system, the Time-Variant C module was developed in the SATEEC, allowing user to use daily-based USLE C DB containing 30 representative crops and adjust planting date of each crop for watersheds. The USLE C factor values in SATEEC ver. 2.0 represent crop growth well. For instance, the USLE C factor for potato shows the range from 0.370 to 0.659, from 0.644 to 0.784 for watermelon, from 0.491 to 0.689 for cucumber, and from 0.250 to 0.628 for tomato. Simple interface was developed to allow users to adjust a certain schedule of agricultural activities for each crop so that temporal land use change of the year in the given watershed can be considered. These Time-Variant R and C modules are available in SATEEC 2.0 system (Park et al., 2010). The application of SATEEC with these modules described in following section showed reasonable results, when compared with measured data.

2.2.2 Sediment yield estimation using genetic-algorithm-based SDR module

Additional and significant enhancement in the SATEEC is an integration of SDR module considering various watershed characteristics. One of benefits to use the SATEEC is to estimate sediment yield with only USLE factors and SDR; however, the SDRs in SATEEC ver. 1.x had limitation because it only estimated SDR based on either area or average slope. As indicated by Park et al. (2007), the SDR needs to be estimated with various watershed characteristics not with single factor because of complicated sediment yield mechanism. To derive SDR for a given watershed with given data for soil loss simulation, a SDR module was developed with optimization algorithm to determine coefficient and exponents of basic formula with watershed area, average slope, Curve Number as fundamental parameters for a given watershed. The modified SDR module in SATEEC ver. 2.0 estimates the SDR equation using three watershed parameters and four coefficient and exponents, that are watershed area, average slope, and curve number to explain sediment transport processes to the watershed outlet.

$$\mathrm{SDR} = \mathrm{A} \times \mathrm{Area}^{\mathrm{B}} \times \mathrm{Slope}^{\mathrm{C}} \times \mathrm{CN}^{\mathrm{D}} \tag{8}$$

Where, A-D are coefficient and exponents, Area is watershed area (km^2), Slope is average slope of watershed (%), and CN is average curve number of watershed.

The Genetic-Algorithm developed by Holland (1975) was utilized to derive these coefficient and exponents to derive the SDR (Genetic-Algorithm-based Sediment Delivery Ratio: GA-SDR) in the SATEEC system. It is available in the SATEEC 2.0 system. The genetic algorithm has been applied to many scientific studies to solve complex problems, based on the principle of 'survival of the fittest' and setting up a population of individuals.

Figure 2 shows how the GA-SDR module was integrated to SATEEC ver. 2.0; the module requires only the data for soil loss estimation in SATEEC. The basic formula of the module requires watershed area, watershed average slope, and CN, they are derived by Digital Elevation Model (DEM), land use, and soil map data, then the coefficient and exponents are determined by the algorithm, compared measured data.

SATEEC ver. 2.0 was applied to a watershed which has 1,361 square kilometers with the Time-Variant modules and GA-SDR modules, it showed reasonable results represented with 0.721 and 0.720 of determination coefficient (R^2) and Nash-Sutcliff efficiency index (NSE) in calibration, 0.906 and 0.881 of R^2 and NSE in validation (Park et al., 2010).

2.2.3 Daily USLE R modules for daily soil erosion estimation

The latest version of SATEEC through various modifications is the SATEEC ver. 2.1 that allows user to estimate daily soil loss and sediment yield with enhanced R_5 module. The SATEEC ver. 2.0 provides time-variant estimation of soil loss and sediment yield with the Time-Variant C and R modules and GA-SDR module, daily assessment of soil loss and sediment yield at the watershed outlet is in need due to the particularity of precipitation affecting to soil erosion in a single day or a few days, such as typhoon. But deriving USLE R

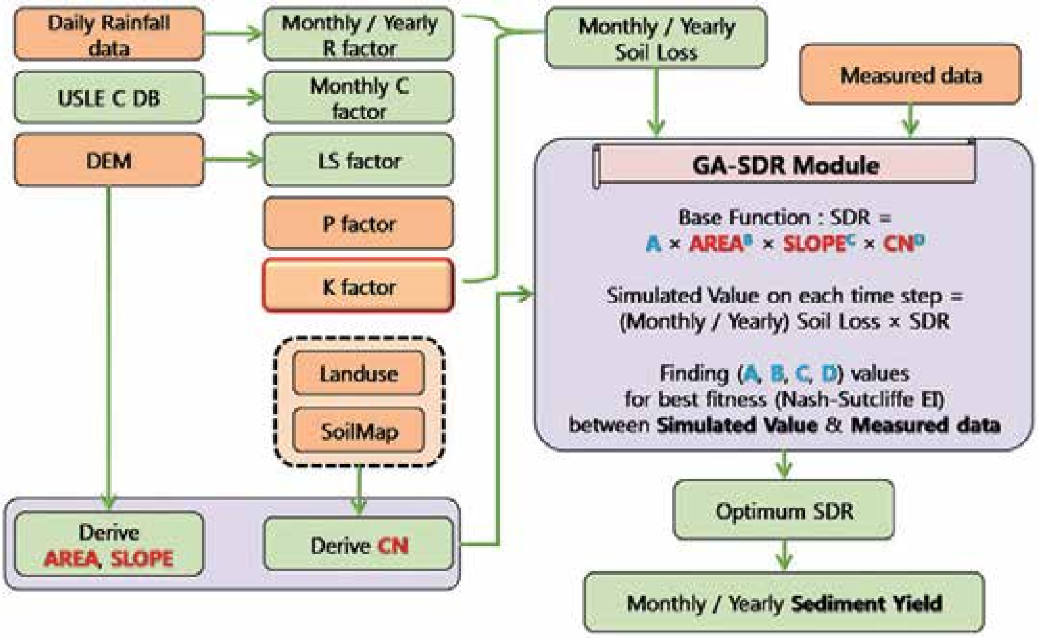


Fig. 2. Overview of SATEEC GA-SDR module (Park et al., 2010)

factor is not deemed as simple process, although daily assessment of soil erosion is strongly suggested to a hydrology model. Another module named R_5 module was integrated to SATEEC for the assessment, the module estimates daily USLE R factor with the process that distributes monthly USLE R factor to each day based on daily precipitation data values. Moreover, the module calculates 5-days antecedent rainfall values with observed daily precipitation data to consider soil moisture condition indirectly (Woo et al., 2010). Eventually, the process to estimate daily USLE R factor with this module can be represented by the equation (9).

$$\text{Daily USLE R factor} = \frac{\text{5 Days Antecedent Precipitation}}{\text{Monthly 5 days Antecedent Precipitation}} \times \text{Monthly USLE R factor} \times 0.172 \quad (9)$$

Woo et al. (2010) applied the SATEEC ver. 2.1 with the module to identical watershed to the watershed used for the application of SATEEC ver. 2.0. The application of SATEEC 2.1 showed more reasonable result represented with 0.776 and 0.776 of R^2 and NSE in calibration, 0.927 and 0.911 of R^2 and NSE in validation. The SATEEC ver. 2.1 allows user to estimate daily, monthly, and yearly soil loss and sediment yield with DEM, land use, soil map, and measured data (Figure 3). SATEEC, operating in ArcView GIS platform, provides various options selectively (Figure 4).

2.2.4 L modules for topography changes

USLE LS factor is derived based on the flow accumulation map and flow direction map which are derived using DEM. DEM represents the elevation of each cell so that hydrologic model estimates direction of flow in a given watershed. However the DEM is not detail enough to represent the forest roads of agricultural canals which affects the flow and soil erosion estimation to some degrees. The segmentation of slope length by human-made roads should be reflected in estimating USLE L factor. Thus a simple module to consider this effect was developed and integrated to the SATEEC system. By considering detailed characteristics such as segmentation of slope length in watershed, the SATEEC model can provide more realistic effects of field slope segmentation on soil erosion.

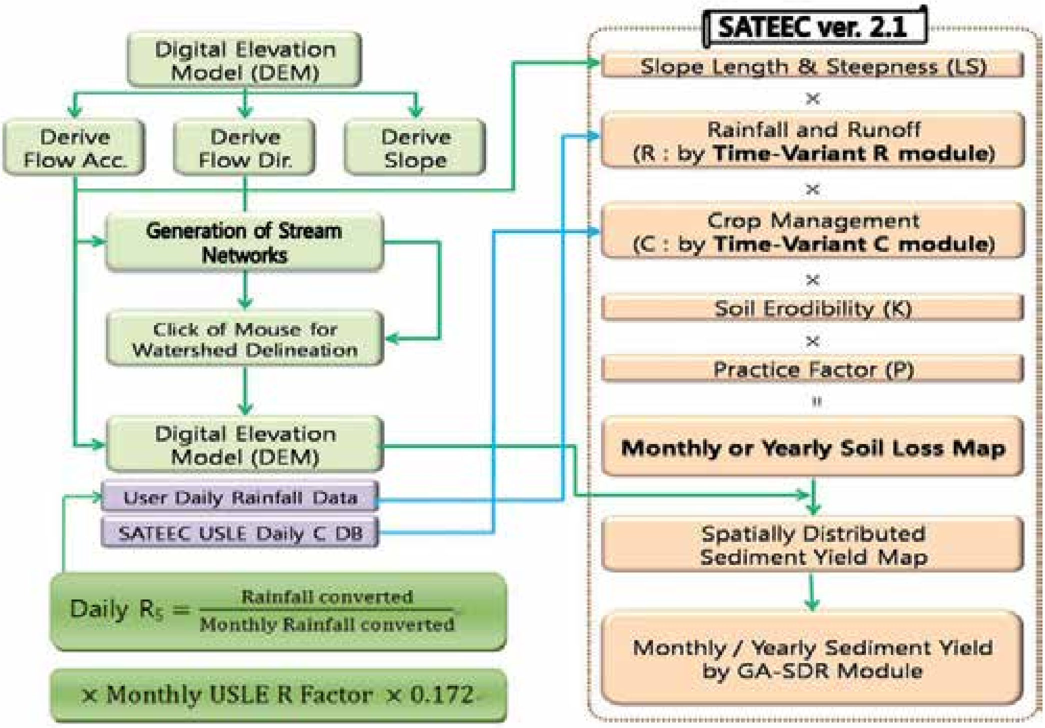


Fig. 3. Overview of the SATEEC ver. 2.1

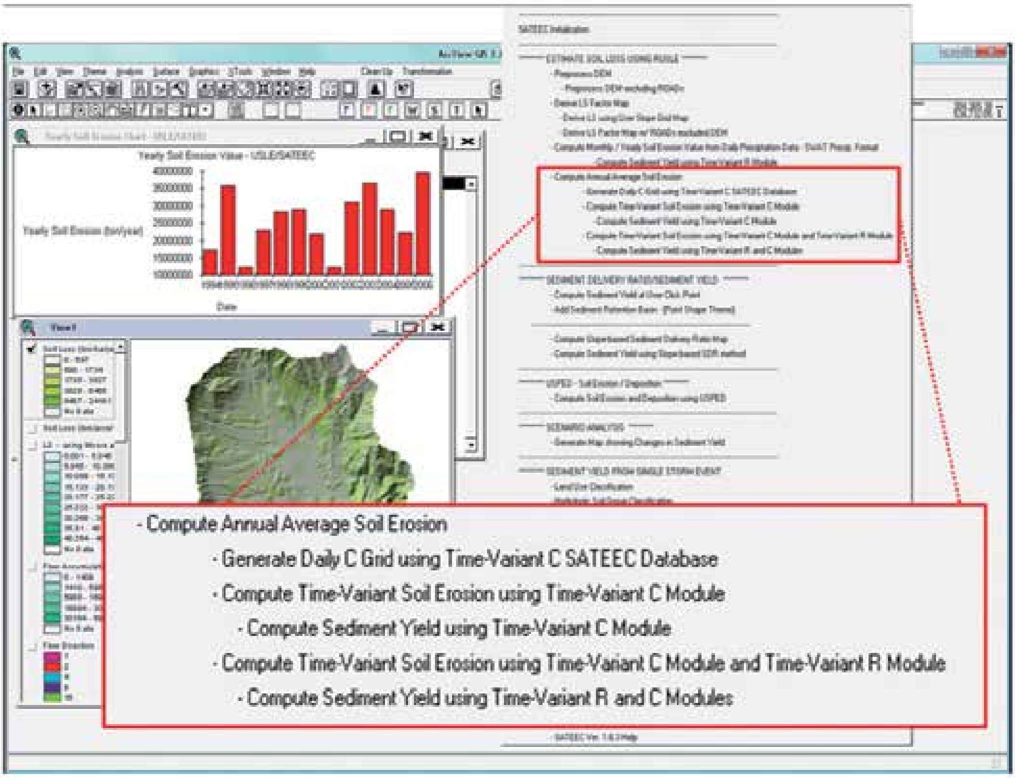
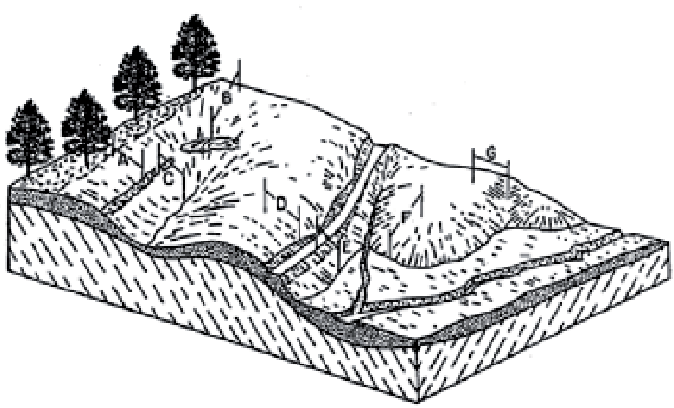


Fig. 4. SATEEC 2.x GIS Interface



(A-G: segmentation of slope length in real fields)

Fig. 5. Field Slope Length at Watershed (Foster et al., 1996)

2.2.5 nLS and USPED in SATEEC

USLE is a field-scale model to estimate soil erosion by sheet and rill erosion, therefore soil erosion estimated by SATEEC represents sheet and rill erosion, excluding gully erosion which is also one of the soil erosion types occurring in a watershed. To estimate soil erosion containing all of the erosion stated above, nLS model (McCuen & Spiess, 1995) for gully head detection and Unit Stream Power-based Erosion/Deposition (USPED, Mitas, L. & Mitasova, 1998; Mitasova et al., 1996) model for gully erosion was integrated with the SATEEC system. The nLS model detects gully head location based on the estimated nLS values, it requires Manning's n coefficient, length of overland flow, and slope (equation (10)) for gully head detection as described below.

$$\text{Gully head} = \frac{3.3 \times n \times L}{\sqrt{S}} \tag{10}$$

Where, n is Manning's n coefficient, L is the length of overland flow, and S is slope (m/m). The L and S parameters for the model are derived using DEM by SATEEC, and the other parameter can be set with Table 1.

Class	Land use	Manning's n coefficient
1	Water area	0.030
2	Urbanization	0.015
3	Eroded land	0.035
4	Marsh	0.050
5	Grassland	0.130
6	Forest	0.100
7	Paddy field	0.050
8	Cropland	0.035

Table 1. Manning's n coefficient for different land uses (Vieux et al., 2004)

The USPED model estimates soil erosion considering erosion and deposition based on tractive force (equation (11), Mitas, L. & Mitasova, 1998; Mitasova et al., 1996), most parameters are available to be defined with USLE input parameters.

$$T = R \times K \times C \times P \times A^m \times (\sin b)^n \tag{11}$$

Where, T is tractive force, R is USLE R factor, K is USLE K factor, C is USLE C factor, P is USLE P factor, A is area in square kilometer, and both m and b are coefficient for types of soil erosion.

The nLS and USPED model are used to estimate soil loss by gully erosion, nLS model defines the points which are gully head, USPED model estimates gully erosion, and then gully erosion map is developed using output with the nLS and USPED models.

3. Application of SATEEC GIS system

The SATEEC system has been applied for various soil erosion studies because it is available in GIS interface and is freely downloadable from the SATEEC website (http://www.EnvSys.co.kr/~sateec). In this chapter, several SATEEC applications will be introduced to give various insights of using SATEEC system to the readers.

3.1 SATEEC ver. 1.5 evaluation using area-based and channel slope-based SDR modules

The comparison of area-based and slope-based SDR modules was performed by Park et al. (2007). The SATEEC provides two SDR modules to estimate sediment yield using soil loss estimated with USLE. The SATEEC was applied to 19 sub-watersheds in South-Korea (Figure 6) which have identical area with various slopes. The study area is located at Chuncheon-si in South-Korea, total area of the watershed is 11.17 square kilometers.

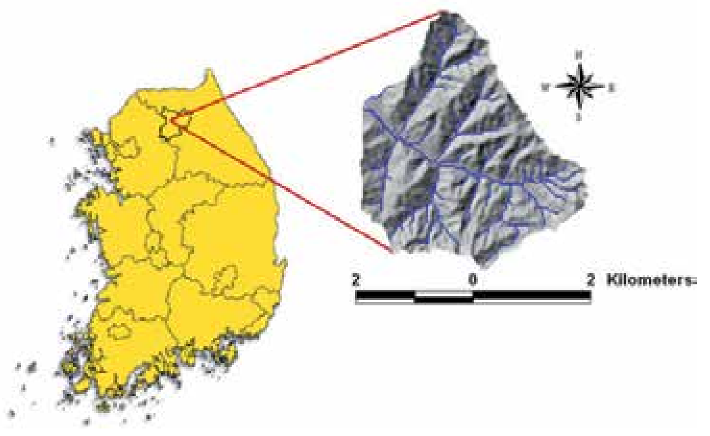


Fig. 6. Location and figure of Sudong watershed (Park et al., 2007)

The USLE R factor suggested by Jung et al. (1999) was used for this study. Table 2 shows USLE R factors of Gangwon province in which Chuncheon-si is located.

Administrative district	R factor	Administrative district	R factor
Kangnung	297	Kosung	250
Samchok	215	Sokcho	255
Yangyang	255	Yongwol	350
Wonju	578	Inje	294
Cheolwon	400	Chuncheon	464
Hwacheon	450	Hongcheon	417
Yanggu	350	Pyongchang	269
Chongson	250	Hoengsung	400

Table 2. USLE R factors for administrative districts in Gangwon province (Jung et al., 1999)

USLE K factor indicating soil erodibility was calculated with equation suggested by Williams (1975), which requires the percentage of sand, silt, and clay (equation (12)).

$$\text{USLE K} = \left[0.2 + 0.3 \times \exp\left(-0.0256 \times \text{SAN} \times \left(1 - \left(\frac{\text{SIL}}{100}\right)\right)\right)\right] \times \left[\left(1.0 - \left(\frac{0.25\times\text{CLA}}{\text{CLA}+\exp(3.72-2.95\times\text{CLA}}\right)\right)\right] \times \left[1.0 - \left(0.7 \times \frac{\text{SN1}}{\text{SN1}+\exp(-5.51+22.9\times\text{SN1})}\right)\right] \tag{12}$$

Where, SAN is the percentage of sand (%), SIL is the percentage of silt (%), CLA is the percentage of clay (%), and SN1 is (1-SAN/100).

Then the USLE C factor reflects the effects on soil erosion of surface condition of watershed, rainfall drop impact and flow velocity are affected by the surface condition of watershed in real field. Jung et al. (1984) suggested the values of the factor to apply non-crop area such as urbanized area (Table 3). It has the range 0 to 1 as a fraction; lower value indicates that the surface is covered well so that less soil erosion occurs, while higher value indicates that the surface is covered roughly which has higher possibility of much soil erosion.

Land use	USLE C factor
Water	0.000
Forest	0.001
Pasture	0.010
Agriculture	0.260
Urbanization	0.010
Bare Ground	1.000

Table 3. C Factor for Various Land uses (Jung et al., 1984)

USLE P factor represents a conservation or support practice such as contouring, strip cropping, terracing, and etc (Table 4).

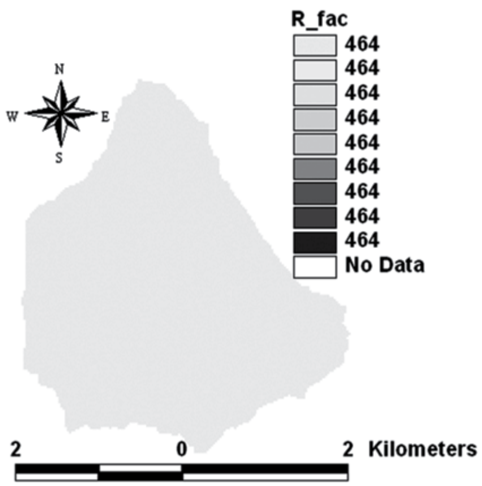
Land use	P Factor	
Paddy land	0.20	
Upland	Slope	P factor
	0 % – 2 %	0.60
	2 % – 7 %	0.50
	7 % – 12 %	0.60
	12 % – 18 %	0.80
	18 % – 24 %	0.90
	24 % – 30 %	0.95
	> 30 %	1.00

Table 4. USLE P Factors for Various Land uses and Slopes

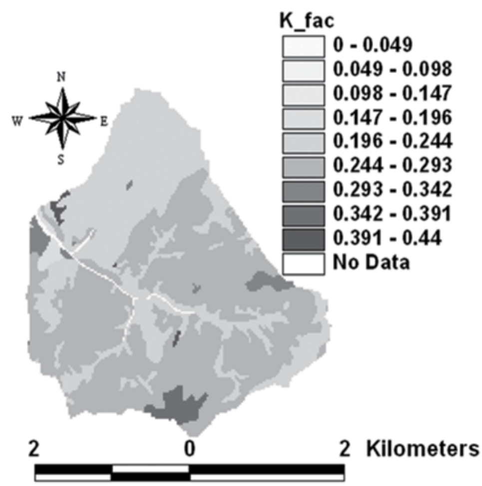
SATEEC computed the LS factor map based on DEM and the method suggested by Moore and Burch (1986, equation (13). The length of hill slope in the USLE experimental plots ranged from 10.7 m (35ft) to 91.4 m (300 ft), thus, it was recommended to use of slope lengths less than 122 m (400 ft) because overland flow becomes concentrated into the rills in less than 122 m (400 ft) under natural condition (Foster et al., 1996).

$$\mathrm{LS} = \left(\frac{A}{22.13}\right)^{0.6} \times \left(\frac{\sin\theta}{0.0896}\right)^{1.3} \tag{13}$$

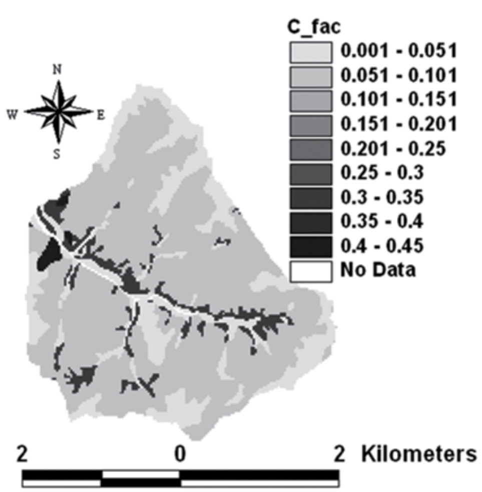
To compare sediment yield by both area-based and slope-based SDRs, which was main purpose of the study, 19 small sub-watershed having 0.0219 square kilometers were selected (Figure 8), they had different watershed characteristics (Table 5). As shown in Table 5, areas of 19 sub-watersheds were identical to investigate effect of different SDR methods. However the slopes for these watersheds ranged from 0.73 % to 3.17 %. The 'Distance (km)' in the table indicates length of the sub-watershed which is from the outlet to the farthest point, and the 'Unity shape factor' indicates a water shape factor which is ratio of the longest distance to the shortest distance in the sub-watershed.



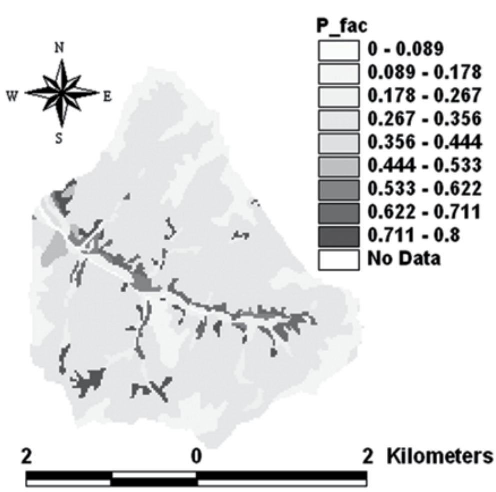
(a) USLE R Factor Map



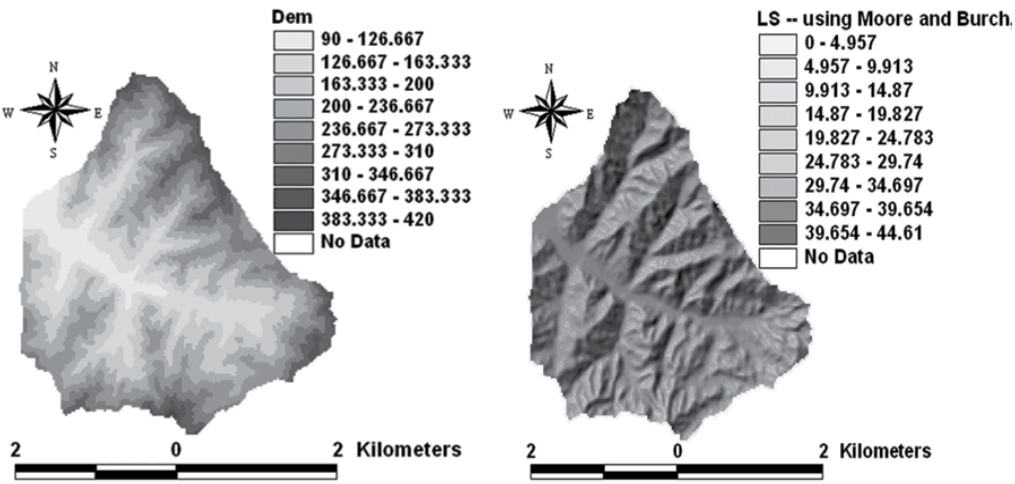
(b) USLE K Factor Map



(c) USLE C Factor Map



(d) USLE P Factor Map



(e) DEM (f) USLE LS Factor Map derived using DEM

Fig. 7. Input data for Soil loss in SATEEC (Park et al., 2007)

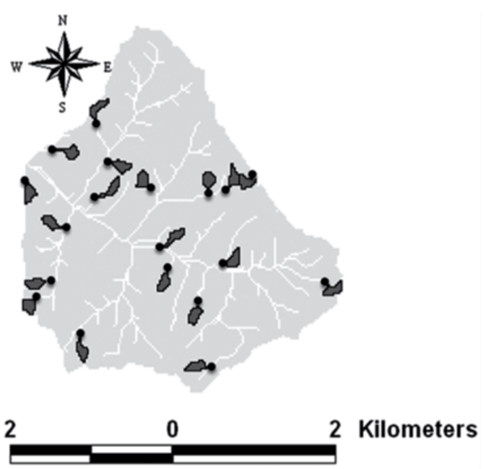


Fig. 8. Location of 19 watersheds in study area (Park et al., 2007)

As shown in Table 6, soil loss for each sub-watershed was different due to different sub-watershed characteristics. However sediment yield estimation was also affected by the SDR methods utilized. Area-based SDRs showed the same results due to identical watershed area, while slope-based SDRs for study watershed ranged from 0.553 to 0.999. The sub-watershed 9 and 11, which are pasture-dominant sub-watershed, showed relatively less soil loss, though, the difference of sediment yield by SDR module was -79.74 %. The difference in percentage ranged from -79.74 % (sub-watershed 11) to 27.45 % (sub-watershed 1), and the difference in 'ton/ha' showed from -89.61 ton/ha (sub-watershed 16) to 73.84 ton/ha (sub-watershed 1).

Sub-watershed	Slope (%)	Area (sq. km)	Distance (km)	Unity shape factor
1	0.73	0.0219	0.207	1.399
2	0.76	0.0219	0.181	1.223
3	0.85	0.0219	0.252	1.703
4	0.86	0.0219	0.216	1.46
5	1.01	0.0219	0.203	1.372
6	1.12	0.0219	0.235	1.588
7	1.21	0.0219	0.252	1.703
8	1.46	0.0219	0.195	1.318
9	1.52	0.0219	0.185	1.25
10	1.58	0.0219	0.309	2.088
11	1.75	0.0219	0.277	1.872
12	2.12	0.0219	0.356	2.406
13	2.49	0.0219	0.302	2.041
14	2.55	0.0219	0.349	2.358
15	2.66	0.0219	0.282	1.906
16	2.67	0.0219	0.285	1.926
17	2.87	0.0219	0.304	2.054
18	3.07	0.0219	0.307	2.075
19	3.17	0.0219	0.251	1.696

Table 5. Subwatershed, slope, area, distance and unity shape factor characteristics (Park et al., 2007)

Sub-watershed	Area (sq. kilometer)	Slope (%)	Soil loss (ton/yr)	Area-Based		Slope-Based	
				SDR	Sediment Yield (ton/yr)	SDR	Sediment Yield (ton/yr)
1	0.0219	0.73	353.125	0.762	268.995	0.553	195.160
2	0.0219	0.76	196.000	0.762	149.304	0.56	109.790
3	0.0219	0.85	311.250	0.762	237.097	0.587	182.551
4	0.0219	0.86	169.688	0.762	129.261	0.59	100.069
5	0.0219	1.01	180.125	0.762	137.211	0.629	113.278
6	0.0219	1.12	100.813	0.762	76.795	0.657	66.227
7	0.0219	1.21	37.375	0.762	28.471	0.678	25.339
8	0.0219	1.46	99.188	0.762	75.557	0.731	72.457
9	0.0219	1.52	1.938	0.762	1.476	0.742	1.438
10	0.0219	1.58	161.938	0.762	123.357	0.754	122.031
11	0.0219	1.75	27.750	0.762	12.139	0.786	21.818
12	0.0219	2.12	354.125	0.762	269.757	0.849	300.581
13	0.0219	2.49	153.438	0.762	116.882	0.905	138.910
14	0.0219	2.55	214.688	0.762	163.540	0.914	196.194
15	0.0219	2.66	134.500	0.762	102.456	0.93	125.121
16	0.0219	2.67	527.250	0.762	401.636	0.932	491.243
17	0.0219	2.87	62.438	0.762	47.562	0.959	59.883
18	0.0219	3.07	141.813	0.762	108.027	0.985	139.652
19	0.0219	3.17	167.938	0.762	127.928	0.999	167.711

Table 6. Soil loss, sediment yield using SDR_A and SDR_S for 19 Sub-watersheds (Park et al., 2007)

This application study indicated that the SDR method could affect sediment yield estimation significantly than the USLE factors do. Thus, soil erosion assessment needs to be performed with not only meticulous collection of USLE input data but also appropriate SDR estimation method.

3.2 SATEEC ver. 1.5 and USPED applications for soil erosion hot spot areas

To determine of soil erosion hot spot watershed, the SATEEC with USPED was applied to a watershed that was referred as requiring BMPs by the Korean government to reduce soil erosion due to severe sediment-laden water problem in the stream. The study watershed is located at Jawoon-ri, Hongcheon-gun in South-Korea, watershed area is 6,906 ha, containing 82.93 % of forest, 12.32 % of agricultural area, 2.02 % of water, 1.62 % of pasture, and 1.09 % of urbanized area.

Table 2 shows USLE R factors of Gangwon province in which Hongcheon-gun is located. USLE K factor indicates soil erodibility, was calculated by the equation suggested by Williams (1975). The USLE K map was developed with the soil map for the study. USLE C factor map was developed using the values suggested by Jung et al. (1984) (Table 3), and USLE P factor map was developed based on slope (Table 4). USLE LS factor map was developed with the module in SATEEC using DEM. To determine hot spot area in the watershed and decide the order of priority in BMP implementation, the given watershed was divided into 54 sub-watersheds (Figure 10, Table 7), soil loss for each sub-watershed was estimated with SATEEC and USPED.

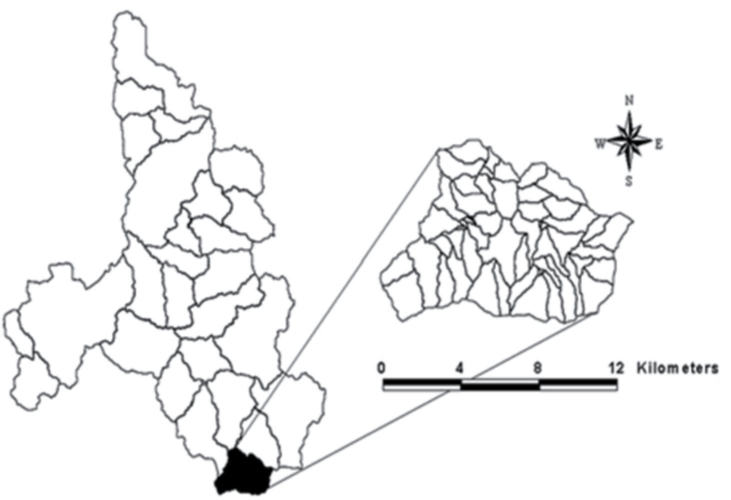


Fig. 9. Location of watershed in Hongcheon-gun (Seo et al.,2010)

The estimated soil erosion values for each sub-watershed are different although these SATEEC and USPED estimate soil erosion with the USLE input data set. However, they showed similar trends for the order of priority in BMP implementation. The soil loss (ton/ha/year) estimated with SATEEC showed higher values in the sub-watershed 2, 1, 25, 21, and 17, the soil loss with USPED considering both erosion and deposition showed higher values in the sub-watershed 2, 1, 7, 35, and 39, and the soil loss by USPED considering only erosion showed higher values in the sub-watershed 46, 2, 3, 1, and 17. The order of priority in BMP implementation is different based on each model, however, both models indicates that BMPs should be applied to reduce soil erosion for sub-watershed 2 and 1.

Fig. 10. Location of 54 sub-watersheds at Jawoon-ri Watershed (Seo et al.,2010)

Sub-watershed	SATEEC	Sub-watershed	$USPED_{ED}$	Sub-watershed	$USPED_{E}$
2	265.41	2	3.46	46	28.29
1	199.71	1	3.27	2	24.50
25	167.18	7	2.47	3	18.75
21	153.05	35	2.00	1	18.70
17	87.82	39	1.99	17	18.15

Table 7. 5 Sub-watersheds Requiring BMPs and Soil Loss (ton/ha/year)

3.3 SATEEC ver. 1.8 with USPED, nLS for gully erosion evaluation

It is not possible to estimate gully erosion with USLE model because it estimates sheet and rill erosion. Kang et al. (2010) applied the SATEEC with nLS and USPED to estimate sheet/rill and gully erosion. These models were applied to the study watershed located at Haean-myeon Yanggu-gun in South-Korea (Figure11). Watershed area is 61.78 square kilometers, containing 58.8 % of forest, 37.2 % of agricultural area, 1.9 % of urbanized area, 1.3 % of water, 0.6 % of bare land, and 0.2 % of pasture.

Soil Loss considering sheet/rill erosion and gully erosion can be estimated by the process showed in Figure 12. The processes show how to develop input for nLS and USPED using USLE inputs, determine gully head determined with nLS, gully erosion by USPED, develop gully erosion map combining gully head map by nLS and gully erosion map by USPED, and to combine the map with sheet/rill erosion map by SATEEC.

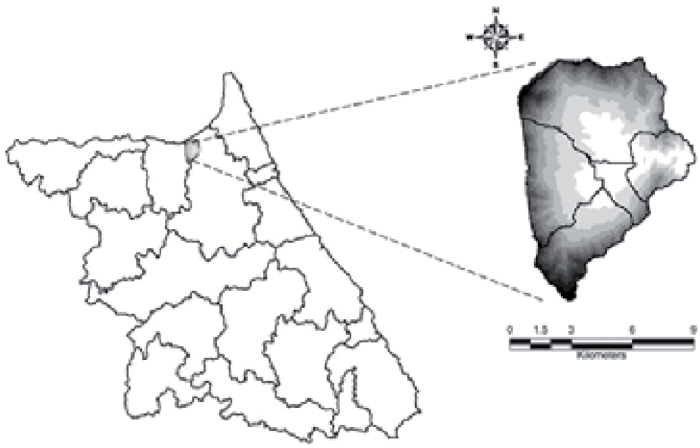


Fig. 11. Location of Haean-myeon watershed (Kang et al., 2010)

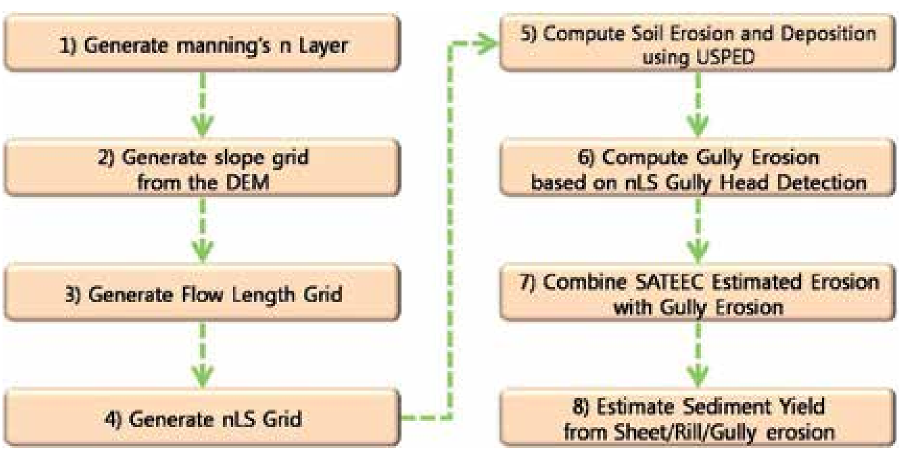
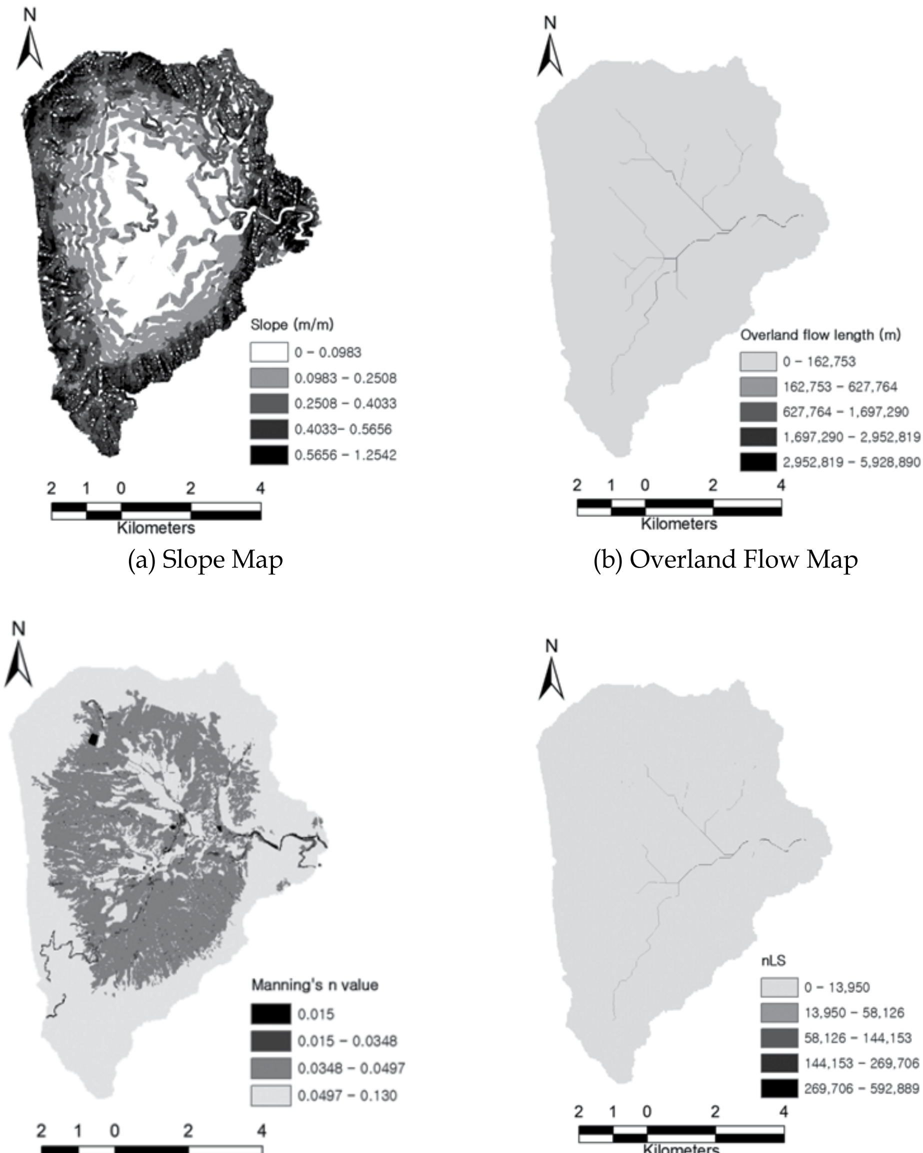


Fig. 12. Modeling process of integrated system using SATEEC, nLS, and USPED (Kang et al., 2010)

USLE input data maps were used for SATEEC and USPED to estimate sheet/rill and gully erosion, the gully head map was developed by nLS model. The nLS map (Figure 13 (d)) was developed using slope map (Figure 13 (a)), overland flow map (Figure 13 (b)), and manning's n map (Figure 13 (c)), the values over 100 in the nLS map indicate gully head.



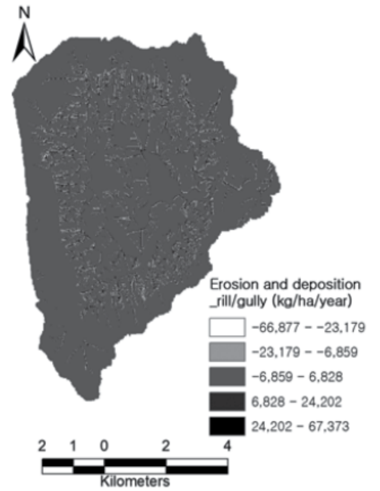
(a) Slope Map (b) Overland Flow Map

(c) Manning's n Map (d) nLS Map

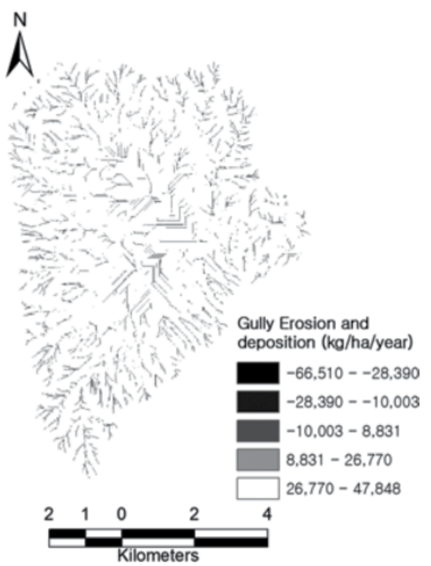
Fig. 13. Maps to develop Gully Head Map (Kang et al., 2010)

Gully head map (Figure 14(a)) was derived from nLS map (Figure 13 (d)) of which cell values are greater than 100, which indicates potential gully head location. Using the Gully head map and soil erosion map by USPED (Figure 14 (b)), the map representing only gully erosion (Figure 14 (c)) was derived. And then the soil erosion map considering sheet/rill and gully erosion map was derived from gully erosion map and sheep/rill erosion map by SATEEC. The negative values in the maps indicate deposition, and positive values indicate erosion.

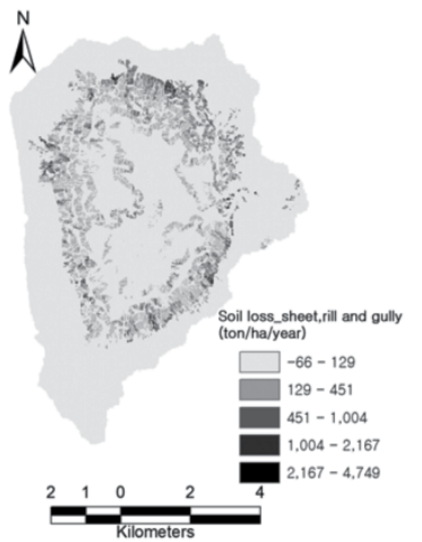
(a) Gully Head Map



(b) Soil Erosion Map by USPED



(c) Gully Erosion Map



(d) Sheet/Rill and Gully Erosion Map

Fig. 14. Soil Erosion Map (Kang et al., 2010)

3.4 SATEEC ver. 2.0 for sediment evaluation using time-variant R and C modules

One of significant modification in SATEEC was development and integration of Time-Variant Modules and GA-SDR modules that are to estimate monthly/yearly sediment yield at the watershed outlet using USLE model which is field-scale. Park et al. (2010) applied the modules to Imha watershed located in South-Korea (Figure 15), the area of the watershed is 1,361 square kilometers containing 79.8 % of forest, 16.0 % of agricultural areas, 1.4 % of residential areas, 2.4 % of water, and 0.4 % of pasture. The watershed is forest-dominant, but much of agricultural areas are located nearby stream, increasing chance of being transported into the stream after soil eroded from the agricultural areas.

Park et al. (2010) set USLE K, P, and LS factor map with similar method and process to previous one in SATEEC, but USLE R factor was estimated using Time-Variant R module with daily precipitation data from Jan/1/1999 to Oct/31/2004 (Figure 16(a)), and USLE C factor was estimated using Time-Variant C module with SATEEC DB (Figure 16(b)) and land use map (Figure 16(c)). To estimate sediment yield at the watershed outlet, GA-SDR module was applied.

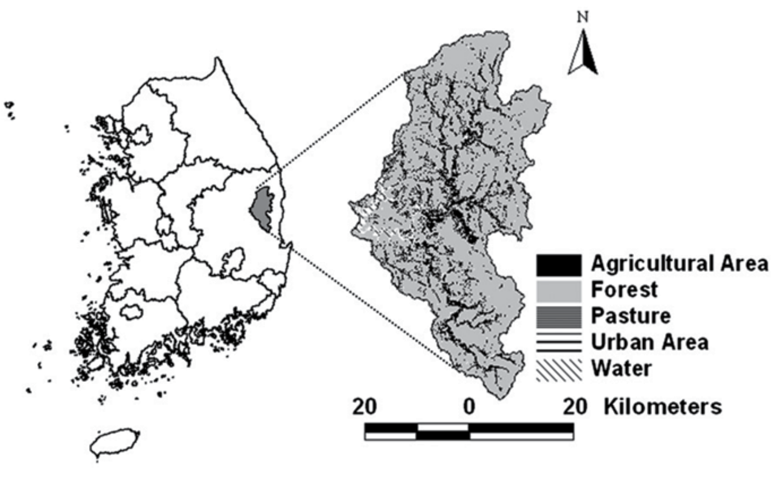
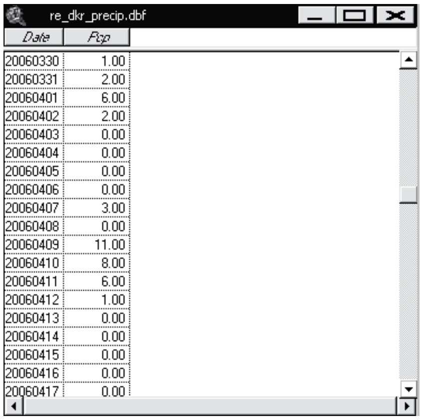


Fig. 15. Location and land-use at Imha Watershed, Gyeongsangbuk-do, South-Korea (Park et al., 2010)

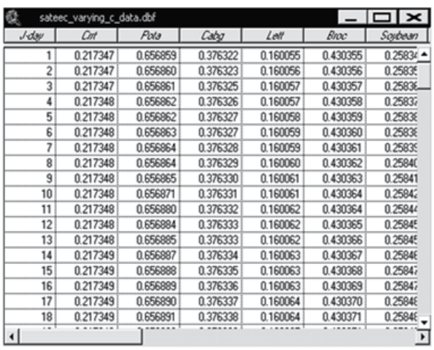
GA-SDR module estimated the coefficient and exponents for the formula to calculate SDR of the watershed (equation (14)), comparing to measured data. SATEEC was calibrated with measured data from 1999 to 2004, was validated with measured data from 2005-2008, it showed 0.721 and 0.720 of R^2 and NSE in calibration, 0.906 and 0.881 for R^2 and NSE in validation (Figure 17).



re_dkr_precip.dbf

Date	Pcp
20060330	1.00
20060331	2.00
20060401	6.00
20060402	2.00
20060403	0.00
20060404	0.00
20060405	0.00
20060406	0.00
20060407	3.00
20060408	0.00
20060409	11.00
20060410	8.00
20060411	6.00
20060412	1.00
20060413	0.00
20060414	0.00
20060415	0.00
20060416	0.00
20060417	0.00

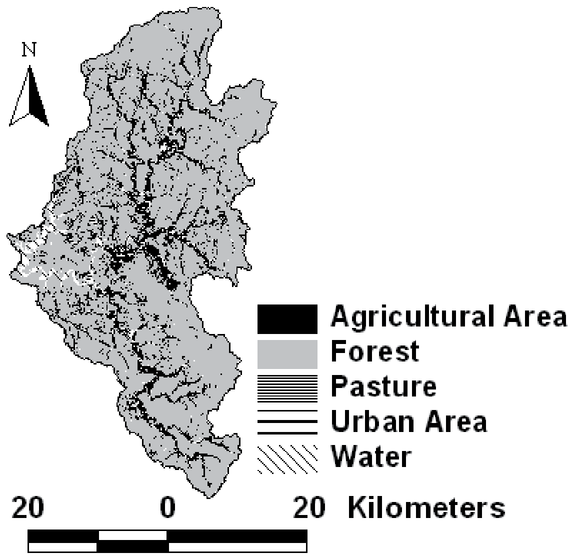
(a) Daily Precipitation Data



sateec_varying_c_data.dbf

J-day	Cnt	Pota	Cabg	Lett	Broc	Soybean
1	0.217347	0.656859	0.376322	0.160055	0.430355	0.25834
2	0.217347	0.656860	0.376323	0.160056	0.430356	0.25835
3	0.217347	0.656861	0.376325	0.160057	0.430357	0.25836
4	0.217348	0.656862	0.376326	0.160057	0.430358	0.25837
5	0.217348	0.656862	0.376327	0.160058	0.430359	0.25838
6	0.217348	0.656863	0.376327	0.160059	0.430360	0.25838
7	0.217348	0.656864	0.376328	0.160059	0.430361	0.25839
8	0.217348	0.656864	0.376329	0.160060	0.430362	0.25840
9	0.217348	0.656865	0.376330	0.160061	0.430363	0.25841
10	0.217348	0.656871	0.376331	0.160061	0.430364	0.25842
11	0.217348	0.656880	0.376332	0.160062	0.430364	0.25844
12	0.217348	0.656884	0.376333	0.160062	0.430365	0.25845
13	0.217348	0.656885	0.376333	0.160062	0.430366	0.25845
14	0.217349	0.656887	0.376334	0.160063	0.430367	0.25846
15	0.217349	0.656888	0.376335	0.160063	0.430368	0.25847
16	0.217349	0.656889	0.376336	0.160063	0.430369	0.25847
17	0.217349	0.656890	0.376337	0.160064	0.430370	0.25848
18	0.217349	0.656891	0.376338	0.160064	0.430371	0.25848

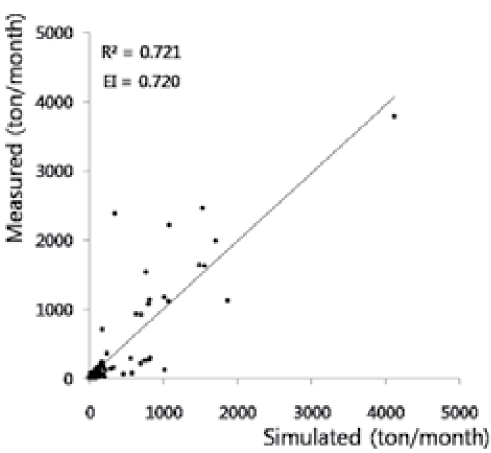
(b) Daily USLE C factor DB



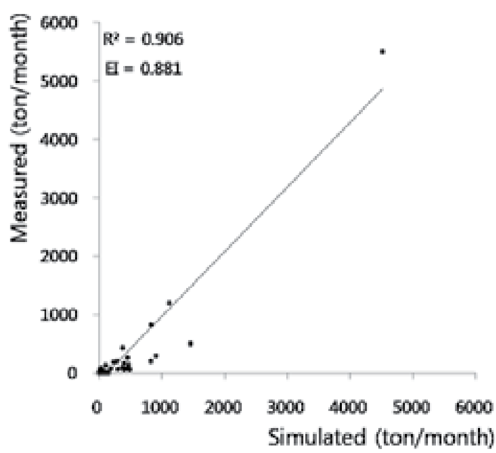
(c) Land use Map

Fig. 16. Data for Time-Variant modules (Park et al., 2010)

$$\mathrm{SDR} = (6 \times 10^{-4}) \times \mathrm{AREA}^{0.022} \times \mathrm{SLOPE}^{0.1901} \times \mathrm{CN}^{0.0267} \tag{14}$$



(a) Calibration (1999–2004)



(b) Validation (2005-2008)

Fig. 17. Calibration and Validation of SATEEC

SATEEC requires USLE input data, though, it has various modules to estimate time-variant soil erosion and sediment yield at the outlet, and moreover it showed reasonable result.

3.5 SATEEC ver. 2.0 with L modules for topography changes due to forest roads

The application of L module in SATEEC was applied to study watershed located at Haean-myeon Yanggu-gun in South-Korea (Figure 12, Kang et al., 2009). Watershed area is 61.78 square kilometers, containing 58.8 % of forest, 37.2 % of agricultural area, 1.9 % of urbanized area, 1.3 % of water, 0.6 % of bare land, and 0.2 % of pasture. The interference to slope length in the watershed are the boundaries of agricultural areas and roads, the data was built based on Gangwon Development Research Institute's measured data in Haean-myeon watershed (Figure 18).

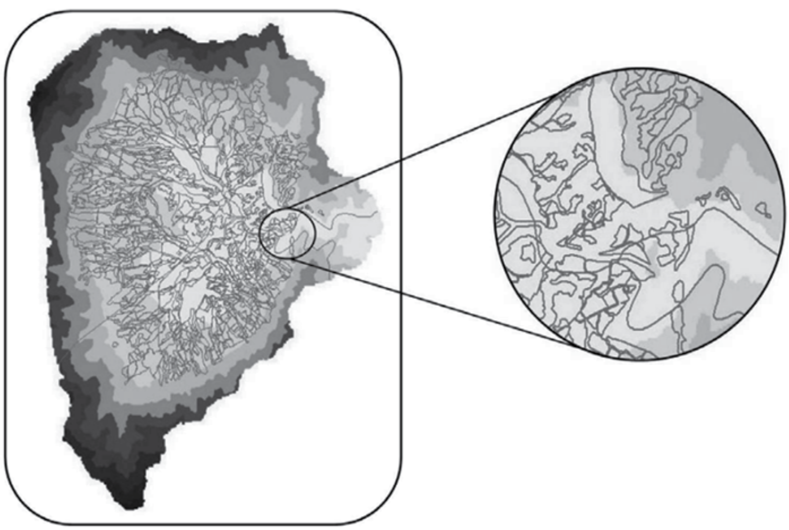
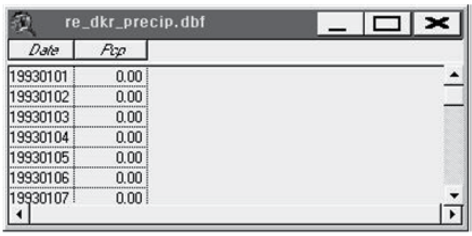


Fig. 18. Slope Length Segmentation due to Agricultural Field Boundaries (Kang et al., 2009)

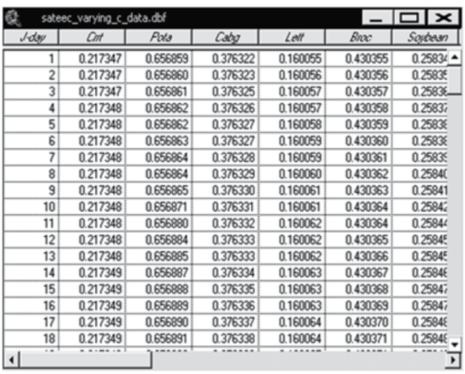
Kang et al. (2009) developed the USLE K and P factor maps with similar method and process to previous one by SATEEC, but USLE R factor was estimated using Time-Variant R module with daily precipitation data from Jan/1/1993 to Jul/31/2007 (Figure 19 (a)), and USLE C factor was estimated using Time-Variant C module with SATEEC DB (Figure 19 (b)) and land use map (Figure 19 (c)).



re_dkr_precip.dbf

Date	Pcp
19930101	0.00
19930102	0.00
19930103	0.00
19930104	0.00
19930105	0.00
19930106	0.00
19930107	0.00

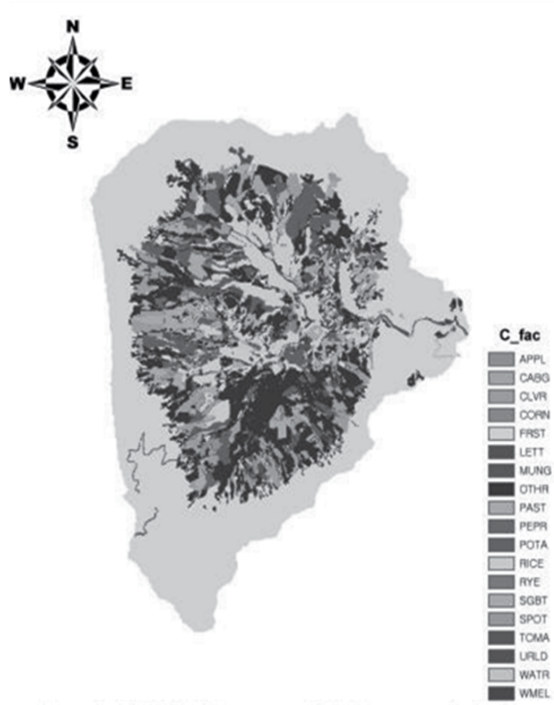
(a) Daily Precipitation Data



sateec_varying_c_data.dbf

J-day	Cnt	Pota	Cabg	Lett	Broc	Soybean
1	0.217347	0.656859	0.376322	0.160055	0.430355	0.25834
2	0.217347	0.656860	0.376323	0.160056	0.430356	0.25835
3	0.217347	0.656861	0.376325	0.160057	0.430357	0.25836
4	0.217348	0.656862	0.376326	0.160057	0.430358	0.25837
5	0.217348	0.656862	0.376327	0.160058	0.430359	0.25838
6	0.217348	0.656863	0.376327	0.160059	0.430360	0.25838
7	0.217348	0.656864	0.376328	0.160059	0.430361	0.25839
8	0.217348	0.656864	0.376329	0.160060	0.430362	0.25840
9	0.217348	0.656865	0.376330	0.160061	0.430363	0.25841
10	0.217348	0.656871	0.376331	0.160061	0.430364	0.25842
11	0.217348	0.656880	0.376332	0.160062	0.430364	0.25844
12	0.217348	0.656884	0.376333	0.160062	0.430365	0.25845
13	0.217348	0.656885	0.376333	0.160062	0.430366	0.25845
14	0.217349	0.656887	0.376334	0.160063	0.430367	0.25846
15	0.217349	0.656888	0.376335	0.160063	0.430368	0.25847
16	0.217349	0.656889	0.376336	0.160063	0.430369	0.25847
17	0.217349	0.656890	0.376337	0.160064	0.430370	0.25848
18	0.217349	0.656891	0.376338	0.160064	0.430371	0.25848

(b) Daily USLE C factor DB



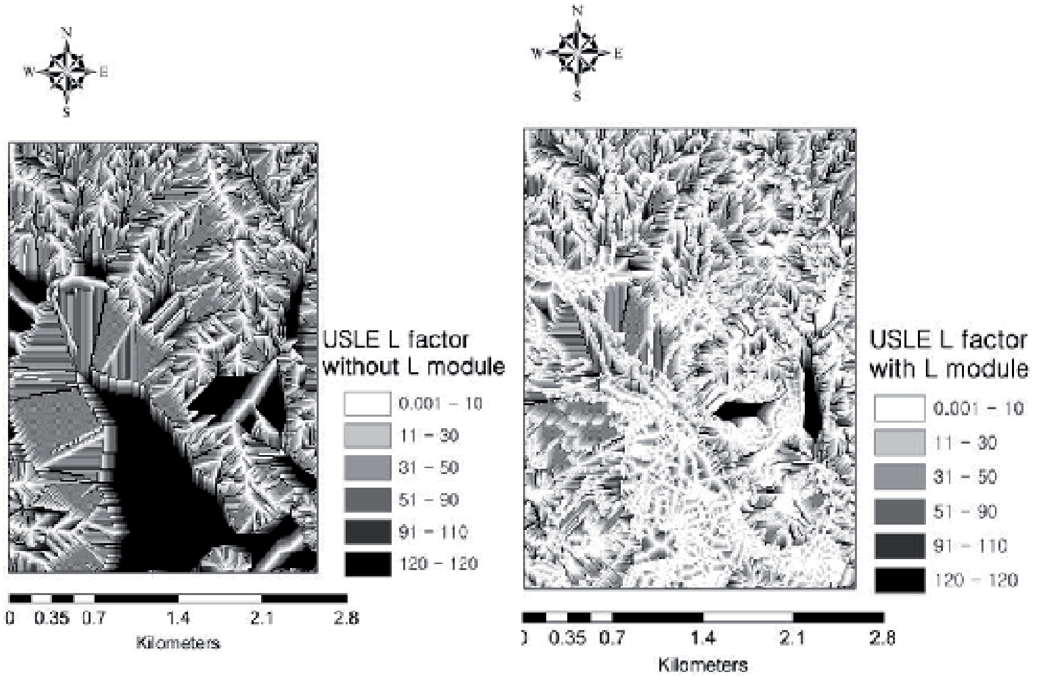
(c) Land use Map

Fig. 19. Data for Time-Variant modules (Kang et al., 2009)

Kang et al. (2009) compared USLE L factor maps without and with SATEEC L module as shown in Figure 20(a) and 20(b). With agricultural field boundaries and roads considered in L factor estimation, flow length segmentation could be considered in soil erosion estimation.

Annual soil erosion with and without SATEEC L module were shown in (Figure 21). The average annual soil loss estimated without L module was 91,714.71 ton, while the average annual soil loss estimated with L module was 68,469.49 ton. The application indicates that soil erosion could be overestimated if the flow segmentation was not considered with the SATEEC L module.

In addition, the estimated sediment yields with SATEEC were compared with SWAT monthly simulation since no measured sediment values available. The R^2 and NSE were 0.729 and 0.719 for calibration period, 0.818 and 0.800 of R^2 and NSE for validation period, when the module was not applied. Sediment yield estimated with the L module showed 0.730 and 0.720 of R^2 and NSE in calibration, 0.818 and 0.800 of R^2 and NSE in validation.



(a) USLE L factor without L module (b) USLE L factor with L module

Fig. 20. Comparison of USLE L factor with L module and without L module (Kang et al., 2009)

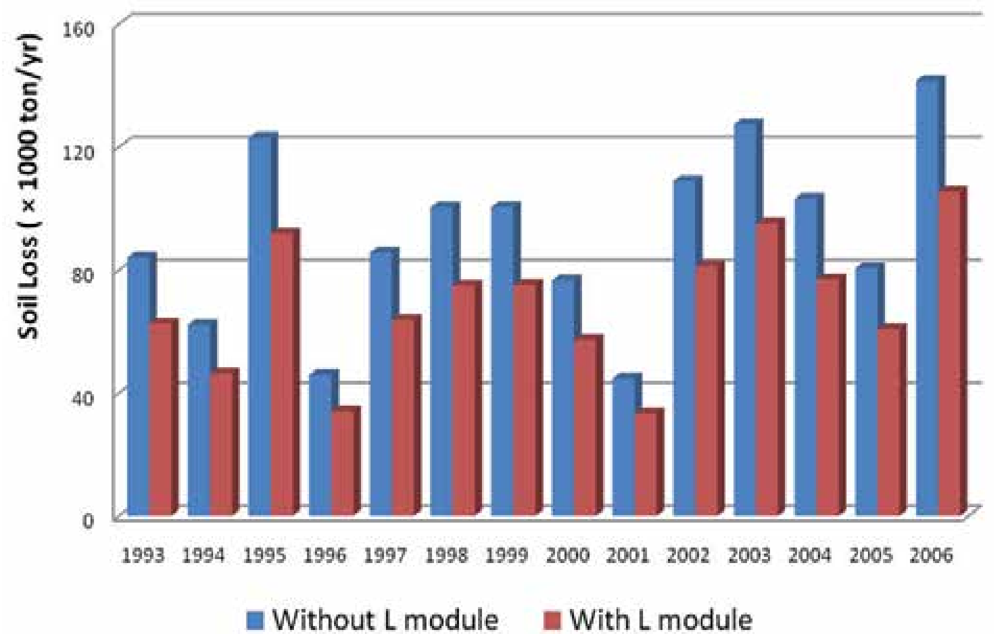
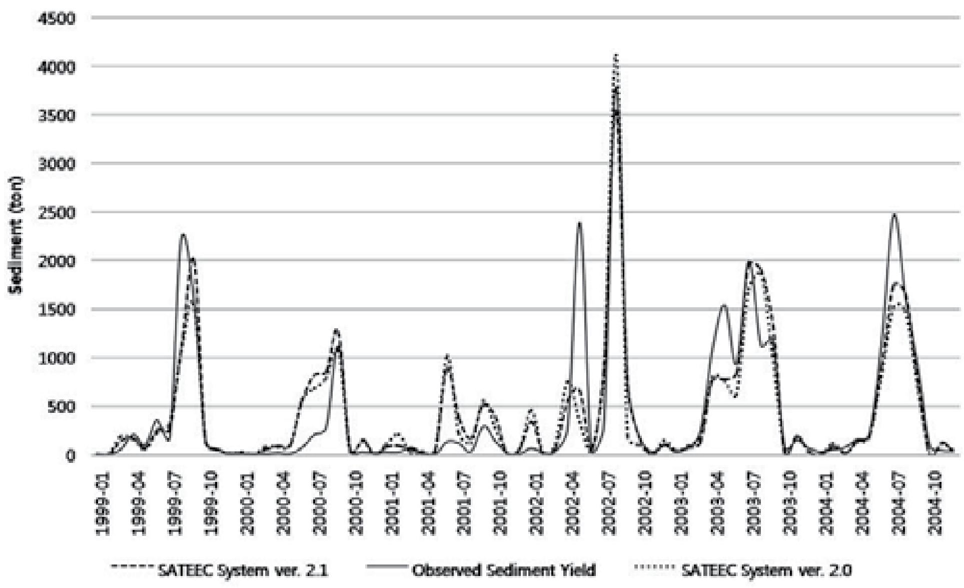


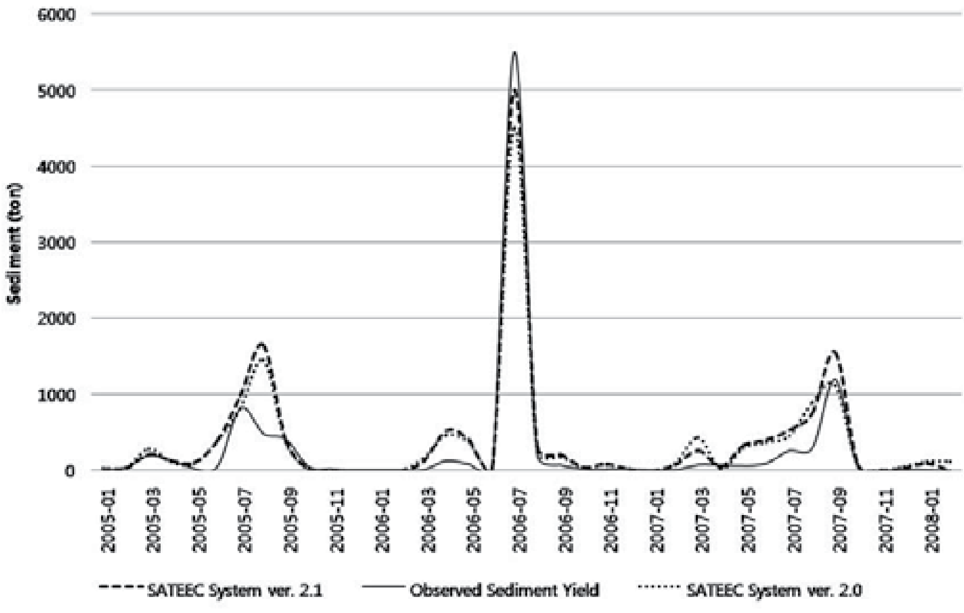
Fig. 21. Comparison of Annual Soil Erosion using SATEEC 2.0. with L Module and without L Module (Kang et al., 2009)

3.6 SATEEC ver. 2.1 for daily sediment estimation using daily USLE R modules

Although, with integration of Time-Variant C and R modules, the SATEEC allows user to estimate monthly/yearly soil erosion and sediment yield, daily assessment of soil loss and sediment yield at the watershed outlet is in need due to the particularity of precipitation affecting to soil erosion in a single day or a few days, such as typhoon. Woo et al. (2010) applied SATEEC with R_5 module to estimate daily USLE R factor to Imha watershed stated above (Figure 16). Most of input data was set with identical method to Park et al. (2010), but R_5 module was applied to estimate daily USLE R factor, and to validate the module. As shown in Figures 22 (a) and (b), the estimated sediment yield by SATEEC ver. 2.1 using R_5 module showed less difference than the estimated sediment yield by SATEEC ver. 2.0 using Time-Variant R module, compared to measured data in both calibration and validation periods.



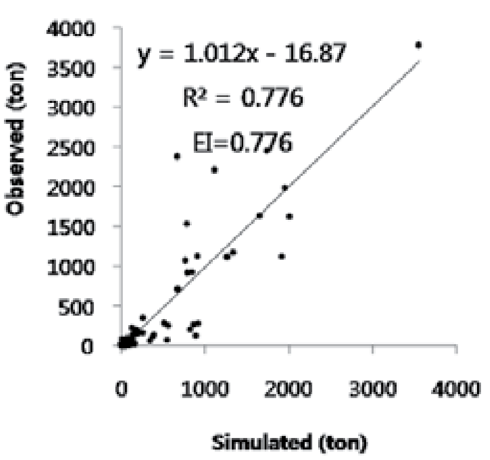
(a) Calibration Period (Jan/1999 – Dec/2004)



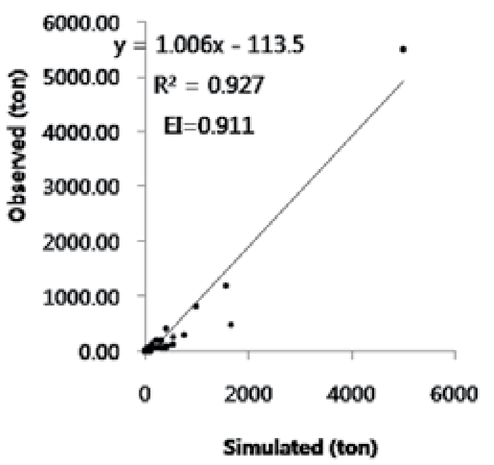
(b) Validation Period (Jan/2005 – Dec/2008)

Fig. 22. Comparison in Time-Series Plot

R^2 and NSE of the sediment yield by SATEEC ver. 2.1 were 0.776 and 0.776 in calibration, and 0.927 and 0.911 in validation (Figure 23). Compared to the criteria of SATEEC ver. 2.0 results, SATEEC ver. 2.1 showed more reasonable values for both R^2 and NSE in calibration and validation, it is deemed as SATEEC ver. 2.1 allows the estimation considering more detailed precipitation characteristics.



(a) Calibration (1999–2004)



(b) Validation (2005-2008)

Fig. 23. Calibration and Validation of SATEEC ver. 2.1

4. References

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Part 3

Other Applications in Engineering/Geoscience

Internal Erosion Due to Water Flow Through Earth Dams and Earth Structures

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1. Introduction

This chapter describes the earth erosion caused by the water flow and seepage that occurs through earth dams, earth embankments and some other structures constructed with earth, such as canal systems, dikes, reservoirs and levees. The erosion in levees on river banks and in levees constructed to protect urban areas exposed to flooding is also discussed. It first describes the mechanism of the soil erosion and the importance of such phenomenon, particularly the damages and consequences that such erosion might produce when it becomes out of control. For instance, one of the main causes of earth dam failures all over the world is the so called piping event, which occurs due to the constant migration of soil particles towards free exits or into coarse openings; this event might occur through the earth embankment or its foundation soil. Another cause of constant earth structure failures is due to uncontrolled saturation and seepage forces. In this context, phenomena known as rapid filling and rapid drawdown, which occur in earth structures subjected to sudden changes of water level (increments or decrements) that modify flow conditions inside a soil mass are assessed. Examples of both failures are given in this chapter.

Each one of the main factors that affect the occurrence of the earth erosion phenomenon is described with detail. Among these factors are: a) the erodibility of the soil; b) the water velocity inside the soil mass; c) geometry of the earth structure. Other important factors discussed here are the homogeneity or anisotropy of the earth structure and its foundation soil, the soil graduation and degree of compaction of the materials used during the construction process; the hydraulic conductivity of such materials, the upstream water energy head, as well as the hydraulic gradient. The importance and the way that each of these factors affect the earth erosion are presented. The calculation of the seepage forces and their effects in slope stability are also described.

The main graphical and numerical methods used for the analysis of the erosion problem considering steady-state and transient flow conditions are discussed. The advantages and shortcomings of each one are emphasized.

Description of the existing procedures for preventing damages due to soil erosion is given in this chapter. Some remediation methods for solving hydraulic problems related to piping or internal erosion, such as impermeable flexible walls, impermeable blankets, grouting procedures and drainage blankets are also presented. A short section with some recommendations to protect river banks from the erosive attack of water (such as rockfill, *bolsacreto* or *colchacreto* system –concrete bags–, breakwaters, sheet pile walls, etc.) is also included. The construction of graduation filters to prevent piping and movement of erodible soils is also presented. Special emphasis is given in the actual filter design criterion that is recommended by the US Army Corps of Engineers (2000), U.S. Bureau of Reclamation (2000) and the U.S. Soil Conservation Service (1994). Together with these recommendations, those given for earth dams design by A. Casagrande (1968) for avoiding piping and internal erosion in earth dams are given.

Several devices that have been developed to assess how resistant earth materials are to water flow are presented. Additionally, the main recommended laboratory and field tests to analyze soil dispersion or erosion are discussed. A description of laboratory tests to verify the best suitable material to use as a filter and protect a dam core against piping or internal erosion is also given.

Two practical examples related to drainage failures caused by piping and by uncontrolled saturation and seepage forces are presented to illustrate the content of this chapter. In particular, analyses to assess how transient flow caused by rapid filling and drawdown affects soil erosion in typical levees constructed to protect urban areas exposed to flooding are performed by numerical modeling based on finite element method (FEM).

Finally, several recommendations for preventing or solving problems related to soil erosion are presented, together with the main conclusions of this chapter.

2. Soil erosion mechanism in earth structures

Erosion in earth structures due to water flow occurs when the erosion resistant forces are less than the seepage forces that tend to produce it, in such a way that the soil particles are removed and carried with the water flow. The resistant forces depend on the cohesion, the interlocking effect, the weight of the soil particles and the kind of protection they have downstream, if any. Since the seepage through an earth structure is not uniform, the erosion phenomenon increases where there exists a concentration of seepage and water velocity; in places where this concentration emerges at the downstream side, the erosive forces on the soil particles might become very significant. This accentuates the subsequent concentration of seepage and erosive forces there.

This erosion process might occur at any crack that exists in the earth structure, due to differential settlements, seismic movements, tension stresses, or holes caused by dry roots or gnawing animals (rabbits, rats, etcetera). The existence of cracks is also due to shrinkage drying or swelling due to saturation. Favorable internal erosion conditions also exist in contacts between soils and rigid walls, concrete structures, interface with bedrock foundation, etcetera. Areas where ark effect is present are also very susceptible to internal erosion. In all the previous cases, if the vertical effective stresses are reduced by the effect of the water flow, then the existing crack might propagate in such a way that it will create the hydraulic fracture phenomenon.

The erosion starts at any point where the seepage water discharges and works toward the reservoir, gradually enlarging the seepage channel. Depending of the stage of this process, the occurred damage might be classified as a simple “incident”, an accident, or a complete failure.

The first engineers that analyzed this problem were Blight (1910) and Lane (1935), as cited in Casagrande (1968), who defined the susceptibility to soil erosion through a percolation factor *C*, in terms of the horizontal and vertical paths of the water flow, the type of soil and the water head between the upstream and downstream water levels of a hydraulic structure. Figure 1 illustrates the definition of the percolation factor and Table 1 gives the minimum values of *C* recommended by these engineers to avoid soil erosion. Unfortunately, this criterion did not work well for all cases and its use is not recommended (Flores-Berrones, 2000).

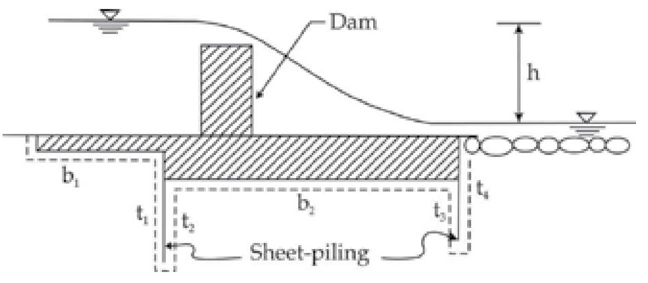


Fig. 1. Dam example given by Blight (1910) to define the percolation factor C_B (Casagrande, 1968)

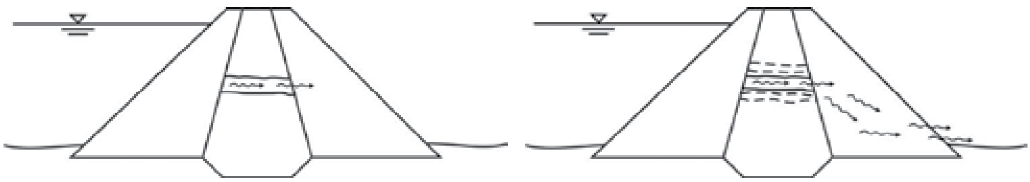
Material	$C_B = \dfrac{\sum b + \sum t}{h}$ (Blight criteria)	$C_L = \dfrac{\sum t + \frac{1}{3}\sum b}{h}$ (Lane criteria)
Fine sand and silt	18	8.5
Coarse sand	12	6.0
Gravel and sand	9	3.0
Boulders, gravel and sand	4	2.5

Table 1. Minimum values of percolation factors to avoid piping, according to Blight and Lane criteria (Casagrande, 1968)

In 1967 Sherard et al. published a table which gives a rough empirical relationship between piping resistance in earth dam embankments and soil types. Such table indicates that soils with the greatest piping resistance are the well compacted high plasticity clays, the intermediate are the well graded coarse sand and sand gravel mixtures, and the least piping resistance are the uniform fine cohesionless sands.

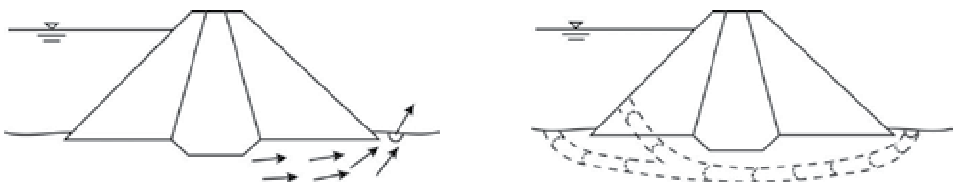
The soil erosion in earth structures, particularly in earth dams and levees, might occur through the embankment, the foundation or from the embankment to foundation (Figs. 2a, 2b and 2c). This kind of erosion has the following phases: a) initiation and continuation of erosion, b) progression to form a pipe, and c) formation of a breach (Fell et al., 2003). The initiation of the soil erosion usually starts at the exit point of the seepage, and retrogressive erosion results in the formation of a "*pipe*". In fact, this is the reason why this erosion phenomenon is also called *piping* (see Fig. 2c). The removal of a small portion of the earth embankment or foundation by erosive action at any point, particularly at the exit part of the downstream slope, accentuates the subsequent concentration of seepage and erosive forces in that zone.

This effect, due to concentrated water leaks, varies somehow from what is called *suffusion* or internal instability, which implies the internal movement of soil particles due to the adjustment of internally unstable soils; this is the case of gap graded or very broadly graded soils, such as coarse sands and gravels with small quantities of fine soils.



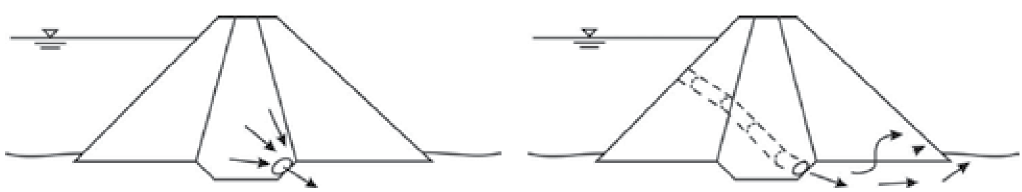
INITIATION →	CONTINUATION →	PROGRESSION →	BREACH/FAILURE
Concentrated leak forms and erosion initiates along walls of crack	Continuation of erosion	Enlargement of concentrated leak	Breach mechanism forms

Fig. 2a. Piping in the embankment initiated by concentrated leak (After Fell et al., 2003)



INITIATION →	CONTINUATION →	PROGRESSION →	BREACH/FAILURE
Leakage exits from the foundation and backward erosion initiations	Continuation of erosion	Backward erosion in progresses to form a pipe	Breach mechanism forms

Fig. 2b. Piping in the foundation initiated by backward erosion (After Fell et al., 2003)



INITIATION →	CONTINUATION →	PROGRESSION →	BREACH/FAILURE
Leakage exits from the foundation and backward erosion initiations	Continuation of erosion	Backward erosion in progresses to form a pipe	Breach mechanism forms

Fig. 2c. Piping from embankment to foundation initiated by backward erosion (After Fell et al., 2003)

The soil erosion problems also might occur in river banks. In tropical regions the intense rainfalls originate large and quick variations of the water surface of rivers. Problems related to rapid filling and drawdown conditions due to these oscillations of river water level and also to the seepage forces generated by rain infiltration at the crown of the levees protecting the margins of rivers are observed. Instability problems in river banks commonly begin with erosion, which in some parts (depending on the type of soil) causes *piping* and might result in landslides as shown in Figure 3 (Auvinet & Lopez-Acosta, 2010).

Fig. 3. Evidences of instability in river banks caused by erosion (Auvinet & Lopez-Acosta, 2010)

3. Factors affecting the earth erosion phenomenon

Main factors affecting the erosion phenomenon are: a) the erodibility of the soil; b) the water velocity inside the soil mass or the water velocity on a river; c) geometry of the earth structure through its size and shape.

Erodibility can be defined as the relationship between the velocity of the water flowing over the soil and the corresponding erosion rate experienced by the soil. This definition of erodibility presents some problems because water velocity is a vector quantity which varies everywhere in the flow and is theoretically zero at the soil-water interface. It is preferable to quantify the action of the water on soil by using the shear stress applied by the water on the soil at the water-soil interface. Thus, erodibility of a soil can be defined by the relationship between the erosion rate $\dot{Z}$ and the shear stress τ at the soil-water interface (Briaud, 2008):

$$\dot{Z} = f(\tau) \tag{1}$$

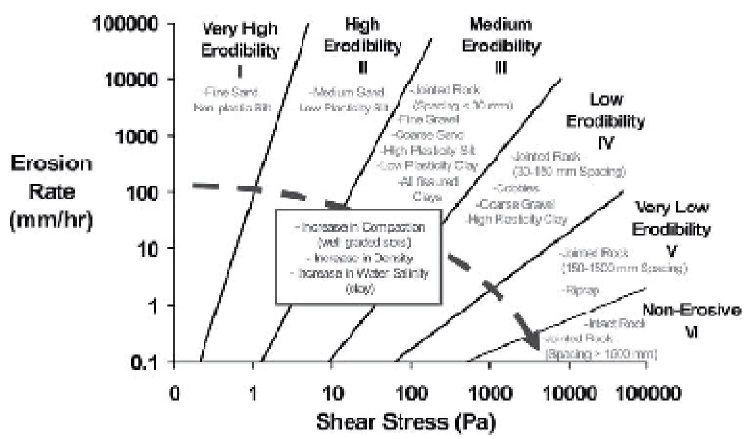


Fig. 4. Proposed erosion categories for soils and rocks based on shear stress (Briaud, 2008)

As explained later in section 7.1, this erosion function can be obtained by using a laboratory device called the erosion function apparatus –EFA– (Briaud et al., 2001). Recently, based on erosion testing experience, *erosion categories* have been proposed in terms of water velocity or shear stress. Erodibility as a function of water velocity is less representative and leads to more uncertainties than using shear stress, as mentioned above. Then, Figure 4 shows these proposed erosion categories for soils and rocks based on shear stress (Briaud, 2008). According to this figure, it seems that grain size controls coarse grained soil erosion and plasticity seems to have a significant influence on fine grain soil erosion.
Additionally, some of the most important properties influencing erodibility of soils are listed in Table 2.

Soil water content	Soil dispersion ratio
Soil unit weight	Soil cation exchange cap
Soil plasticity index	Soil sodium absorption rat
Soil undrained shear stress	Soil pH
Soil void ratio	Soil temperature
Soil swell	Water temperature
Soil mean grain size	Water salinity
Soil percent passing #200	Water pH
Soil clay minerals	

Table 2. Soil properties influencing erodibility (Briaud, 2008)

On the other hand, the velocity of the water flow through the soil mass depends on the hydraulic conductivity of the soil and the hydraulic gradient. According to several experimental tests, the water flow through fine soils is considered to be *laminar* (water particles move parallel each other), and such flow follows the Darcy's law, giving the following expression:

$$V = ki \tag{2}$$

Where V = discharge velocity, k = hydraulic conductivity and i = hydraulic gradient.
The hydraulic conductivity of the soil is determined through laboratory or field tests; for clean sands and gravel mixtures the hydraulic conductivity varies from 10^{-1} to 10^{-3} cm/sec, whereas for very fine sands to homogeneous clays the k value varies from 10^{-4} to 10^{-9} cm/sec (Lambe, 1951). The hydraulic gradient is given by the difference of the water head h_1 at the entrance and the water head h_2 at the exit of a soil section, where there exist a water flow, divided by the length L of the flow path. Using the information provided by Figure 5, the hydraulic gradient is given by the following expression:

$$i = (h_1 - h_2)/L = \Delta h/L \tag{3}$$

As it can be observed in Eq. (3), the hydraulic gradient is dimensionless. Later in this chapter, we demonstrate the existence of a hydraulic gradient that makes the effective stresses among soil particles become zero, in such a way that the friction resistance forces against erosion become nullified. The smallest hydraulic gradient that nullifies such stresses is called *critical* and its value usually ranges between 1 ±0.20.
Some other factors affecting the internal soil erosion or piping in soils are: a) the degree of compaction of the soil layers on the earth structure; b) the homogeneity and quality control

on the construction of the earth structure; for instance, if the permeability of the soil layers varies from one another, there might exist a mayor seepage concentration on those layers of higher permeability; c) the type of preventive measures in the downstream side of an earth structure, such as graded filters designed to prevent displacement of the fine particles; d) the compaction control along the installation of pipeline conduits; along such installations, many initial leaks and piping effects have been reported in the literature (Flores-Berrones et al., 2011); e) existence of hydraulic fracture in certain zones of an earth structure, where the water pore pressure becomes larger than the minor principal stresses (Peck, 1976); f) as it was already mentioned, the high plasticity soils, such as clays of high plasticity, are less vulnerable to erosion than cohesionless soils.

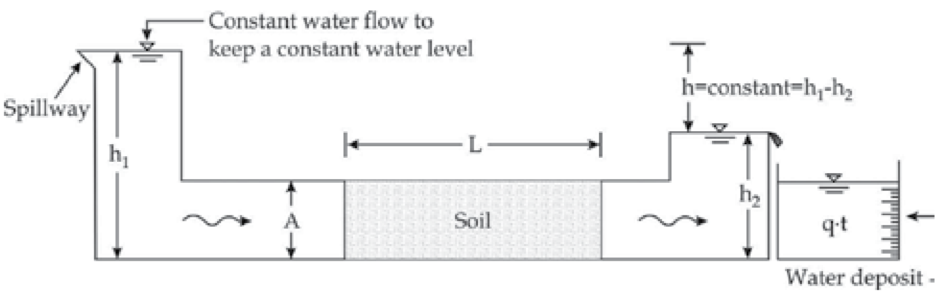


Fig. 5. Constant water head permeameter

4. Analysis of seepage forces and their effect in slope stability

There are several practical cases where it is necessary to consider the forces produced by the water flow for the slope stability analysis of an earth structure. In the case of earth dams and levees, the water flow conditions that might occur and have to be consider for slope stability analysis are the following: a) transient flow that occurs during the first filling or a rapid drawdown conditions; b) constant flow which occurs sometimes after the reservoir is operating under regular water flow conditions; c) anisotropic water flow when the horizontal permeability is different than the vertical one. These three conditions might be more complicated when seismic forces have to be considered.

The water flow effects on the stability of an earth structure are the following: a) internal soil erosion o piping by removing and transporting soil particles, starting a duct that might increase rapidly, producing a complete failure; b) water pressure increase that will decrease the effective stresses and therefore decrease in the shear strength of the soil; c) increment on the water flow forces due to gravity might significantly decrease the safety factor and produce a slope failure.

Using either the graphical or numerical analysis, as it is explained later in this chapter, it is possible to obtain the hydraulic gradient at any point of the flow region.

For the most common practical cases that exist in earth dams and levees, Flores Berrones et al. (2003) have demonstrated that the water flow analysis can be reduced to a two dimensional system, so equation (4) is the one that must be considered for steady-state conditions:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \tag{4}$$

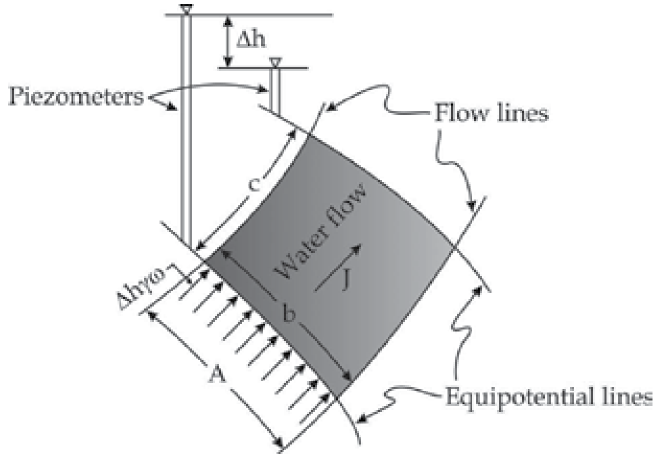


Fig. 6. Water flow forces over a soil element from the flow net (Flores et al., 2003)

This expression is the so-called Laplace's equation, which can be solved by different methods. The most common technique is the graphical solution to such equation, which is represented by two families of curves that intersect at right angles to form a pattern of square figures known as a *flow net*. In hydromechanics one set of these lines is called the *streamlines* or *flow lines*, and the other *equipotentials*. The flow net is constructed by setting first the boundary flow and equipotential conditions, and later on some additional flow lines are drawn in such a way that there will be, between each pair of flow lines, the same amount of water volume Δq. The equipotential lines are constructed in such a way that there exist equal head losses, Δh, between adjacent equipotential lines. Most flow nets are composed of curves that form curvilinear squares. A detail description to construct a flow net for any particular problem is given by Cedergren (1989) and Flores-Berrones (2000). From a flow net it is possible to obtain the total volume of water per unit of length at any part of the flow region, and also the water pressure, hydraulic gradient and flow velocity at any point of the studied domain.

On the other hand, the force over a soil element of a flow net, produced by a water flow, is analyzed in Figure 6. It can be observed in such figure that the force J per unit of length over the soil element is given by:

$$J = \Delta h\ \gamma_w A\ (1) = \Delta h \gamma_w A \tag{5}$$

Where A is the cross-sectional area of the soil element, and γ_w is the volumetric unit weight of water. The seepage force per unit of volume is:

$$j = \frac{\Delta h \gamma_w A}{cA} = \frac{\Delta h}{c}\gamma_w = i\gamma_w \tag{6}$$

Where i is the hydraulic gradient.

For regions in which there exists a uniform water flow, with a constant hydraulic gradient, the seepage force is given by:

$$J = i\ \gamma_w V \tag{7}$$

Where V is the soil volume through which the water flow is taking place. If the hydraulic gradient is not constant but is a point function, the seepage force is the vector sum of all the forces applied in the volume of each element; for this case such seepage force is given by:

$$J = \int_V i dV \tag{8}$$

To illustrate the effect of the seepage force on soil erosion and slope stability, in Figure 7a are given the total, neutral and effective stress distribution of a saturated soil sample, where there is not a flow, whereas Figure 7b shows those stresses under the existence of an upward water flow. In the last figure (Fig. 7b), it can be observed the decrease of the effective stresses as a function of the water head h. It is important to notice that such stresses are nullified when:

$$h = D\gamma_m' / \gamma_w \tag{9}$$

Where γ_m' is the submerged weight of soil, and γ_w is the unit weight of water. Since for most soils $\gamma_m' \approx \gamma_w$, the effective stresses become null when $h/D = 1$. As it was mentioned before, this case is known as critical hydraulic gradient, and when it takes place, the resistance friction forces of the soil particles against erosion also become zero. Under such conditions, the probability of soil erosion, particularly for fine cohesionless soils, is very high.

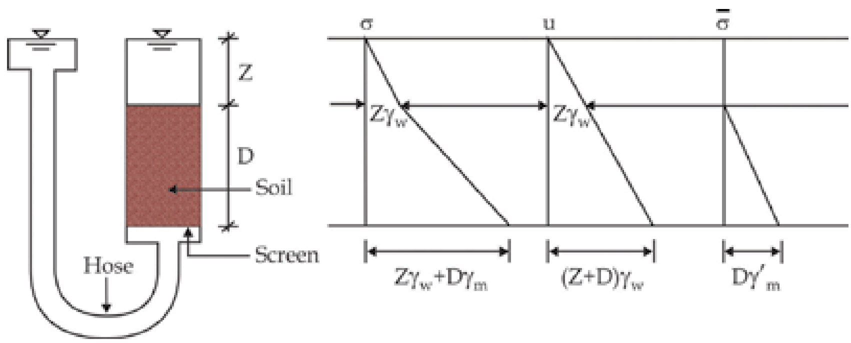


Fig. 7a. Total (σ), neutral (u) and effective ($\bar{\sigma}$) stress distribution in a soil sample without any water flow (Flores et al., 2003)

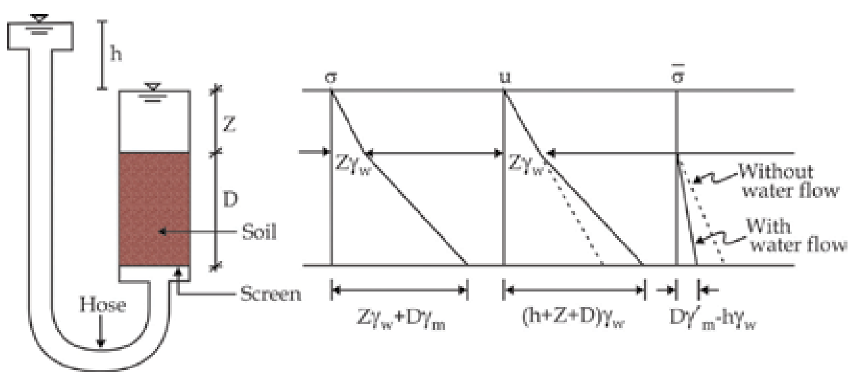


Fig. 7b. Total (σ), neutral (u), and effective ($\bar{\sigma}$) stress distribution in a soil sample with an upward water flow (Flores et al., 2003)

As it has been demonstrated by some authors (Cedergren, 1989; Flores-Berrones et al., 2003), seepage forces might decrease (or increase in some particular cases) the factor of safety on the stability of earth dams and levees.

5. Graphical and numerical methods for analyzing the erosion problem

Solving soil erosion problems involves the calculation of hydraulic gradients, seepage forces, water or pore pressure, flow velocities, flow rates, among other variables. The assessment of such properties is carried out by solving partial differential equations. For steady-state conditions, water flow is calculated by Laplace's equation (see eq. 4, applicable to homogeneous and isotropic soils). For transient flow conditions in a homogeneous and isotropic soil domain the following partial differential equation is used:

$$div\left[kgrad\left(h\right)\right]+c\frac{\partial h}{\partial t}=Q \tag{10}$$

Where k is hydraulic conductivity of soil, h is hydraulic potential (also named hydraulic head), c is specific capacity of soil, t is elapsed time and Q is a discharge quantity corresponding to a possible source within the medium.

The above equations (eqs. 4 and 11) combine Darcy's law and continuity of flow. They can easily be generalized to the case of heterogeneous and anisotropic soils (Auvinet & Lopez-Acosta, 2010; Lam et al., 1987). In the case of partially saturated soils, specific capacity depends on porosity and degree of saturation. Deformability of soil skeleton is commonly ignored. At the same time, degree of saturation and permeability depend on local pressure (Van Genuchten, 1980).

The resolution of the above equations can be performed in an exact or an approximate form, by analytical or numerical techniques (Alberro, 2006; Cedergren, 1989; Lopez-Acosta et al., 2010; among others). Thus, the methods that can be used for evaluating steady and transient state flow conditions include:

- Analytical solution of partial differential equations (Alberro, 2006).
- Approximate graphical method simply named *flow nets* for steady conditions, or *transient flow nets* for transient conditions (Cedergren, 1989; Flores-Berrones, 2000).
- Numerical techniques such as *finite element method* (e.g. *Plaxflow*, Delft University of Technology, 2007), or *finite differences* (e.g. *Flac3D*, ITASCA Consulting Group Inc., 2009).

In general, exact and analytical solutions are laborious when geometric, hydraulic and boundary conditions become complex. Approximate solutions are usually used. Nowadays, numerical methods are preferred with increasing frequency due to their easy adaptation and automation to widely varying conditions, and in general because of their capability for solving complex problems. Numerical methods have been applied by different authors (Auvinet & Lopez-Acosta, 2010; Freeze 1971; Huang & Jia, 2009; Lam & Fredlund 1984; Lam et al., 1987; Ng & Shi, 1998; among others). The present chapter focuses on the finite element method (FEM), using the *Plaxflow* algorithm (Delft University of Technology, 2007), a specialized computer program which is applied to solve steady and transient flow problems by means of the approximate solution of Laplace's equation and equation 11. This algorithm utilizes the previously mentioned Van Genuchten model to represent flow in unsaturated soils and allows carrying out steady-state analyses following the methodology indicated in

Figure 8a; and transient flow analyses in two different ways: 1) *Step-wise conditions* and, 2) *Time-dependent conditions* as illustrated in Figure 8b. The *Plaxflow* algorithm provides hydraulic potential field, flow velocity field, pore pressure, degree of saturation field, among others, as exposed below.

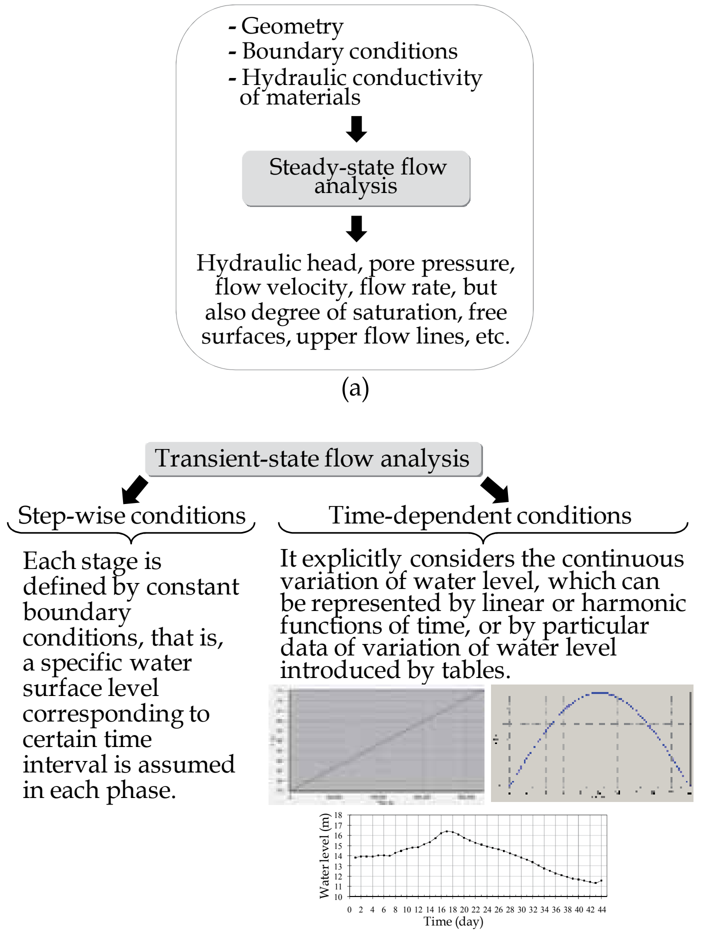


Fig. 8. Types of flow analyses performed with *Plaxflow* algorithm (Lopez-Acosta & Auvinet, 2010)

6. Procedures and practical recommendations for preventing damages due to soil erosion

The design of an earth dam or a levee is based on analytical studies of the site of construction and on personal experience of the individual designer. At a given site, it is possible to design a variety of earth dams which would be both, economical and safe. The final design depends on the quantities, types and location of the soil available for constructing the embankment, as well as the size and shape of the valley and the nature of the foundation. Sherard et al. (1967) present several typical designs of earth and earth-rock dams that have been constructed in the USA. Such dams vary from homogeneous earth dams (constructed on rock or impervious stratum) to dams with embankments constructed with different graduation materials and founded on either impervious or pervious soil stratums.

As it was mentioned before, internal erosion might occur through the embankment or through the dam foundation. To prevent earth erosion through the embankment, several measures might be taken. The following recommendations should be considered:

a. Obtain the best selection of the available construction materials.
b. Control the homogeneity of the materials during the construction process.
c. Use transition zones between the coarse and fine materials.
d. Use properly designed filters and drains for all earth facilities exposed to the damaging actions of water in their foundations or around the impervious core.

Properly designed filters should satisfy the following characteristics:

a. The filter should intercept water flowing through cracks or openings in protected soil and block the movement of eroding soil particles into it. Therefore, there must be a relationship between the size of the particles of the protected soil and the openings of the filter.
b. Filters should have enough permeability to avoid high seepage gradients or water pressures; this hydraulic condition means that the filter should act as a good drain.
c. Filter grain particles should not have migration or suffusion due to the water flow action. This means that the filters should be designed to keep its internal structure always stable.

In relation to the drain design, Cedergren (1989) recommends that "designers should analyze every component of a drainage system (filters, conducting layers, collectors, outlets, and so on) to ensure that the entire system will have the necessary capacity and will function as intended". On the other hand, the criteria for the filter design was first established by Karl Terzaghi (1929) and later on modified by several authors (Sherard & Dunnigan, 1989; Wan et al., 2002) and several institutions (ICOLD, 1994; USACE, 2000; USBR, 2000; US Soil Conservation Service, 1994; among several others). Applications of these criteria to a case history and its implications are reported by Flores-Berrones et al. (2011). Sometimes it is necessary to use multi-layer filter systems, in which the characteristics for each layer should satisfy the selected design criteria for those materials surrounding the one under analysis.

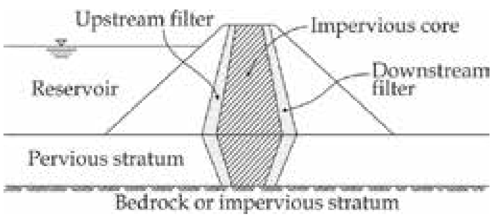
For preventing soil erosion or piping through a pervious foundation of an earth structure, the following measures might be taken:

a. Continuation of the impervious zone of the embankment up to an impervious soil stratum or bedrock (Fig. 9a).
b. Construction of a grout curtain or a steel sheet piling or a concrete cutoff wall, below the impervious core (Fig. 9b).
c. Impervious upstream blanket, in order to decrease the exit hydraulic gradient (Fig. 9c).
d. Combination of recommendations 1), 2) and 3) referred above. Sherard et al. (1967) present several examples of earth and earth-rock dams that have been constructed around the world, in which it is possible to observe alternative design solutions.

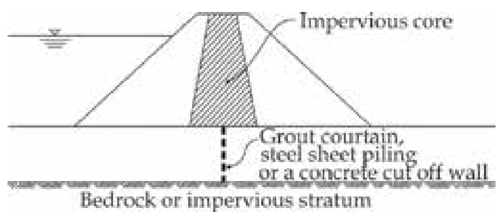
Cedergren (1989) recommends the use of high standards for all facets of design and construction, use relatively wide impervious cores and other features that hold seepage quantities and hydraulic gradients to the lowest practical levels, and provide well designed and constructed filters and drains wherever needed. It is also recommended special precaution when designing filters to protect gap-graded soils, and to avoid severe segregation during the construction stage of any filter.

To protect the upstream faces of earth dams, levees, and in any other situations in which erodible soils must be protected from rain currents and wave action, a layer of rock should be placed. One or more filter layers should be placed between the rock slope protection layer and the soil material that forms the earth embankment. Each transition filter layer must also satisfy the filter criteria in such a way that internal erosion or piping effect does not occur. For multi layer filters, the US Corp of Engineers (2000) and the US Bureau of Reclamation (USBR, 2000) recommend that grading curves of such filters should be more or less parallel between each other, in order to avoid segregation or clogging.

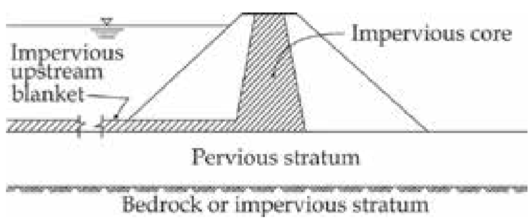
When filter fabrics are used, the protective filter is only the thickness of the fabric, which may be as little as 1mm. It is therefore very important that no holes, tears or gaps be allowed to form in the fabric. In this case, the openings between the filaments of a fabric should not be so large that significant loss of soil can occur. If the D_{85} of a soil is larger than the near maximum opening size of the fabric, little soil should be able to move through the mesh of the fabric (Cedergren, 1989).



(a) Extension of the impervious core to bedrock or impervious stratum



(b) Impervious curtain through the pervious foundation



(c) Construction of an impervious upstream blanket

Fig. 9. Measures for preventing soil erosion or piping through a pervious foundation of an earth structure

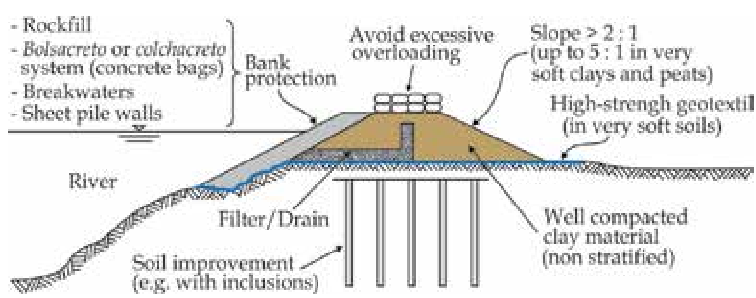


Fig. 10. Recommendations to protect levees on river banks (Auvinet et al., 2008)

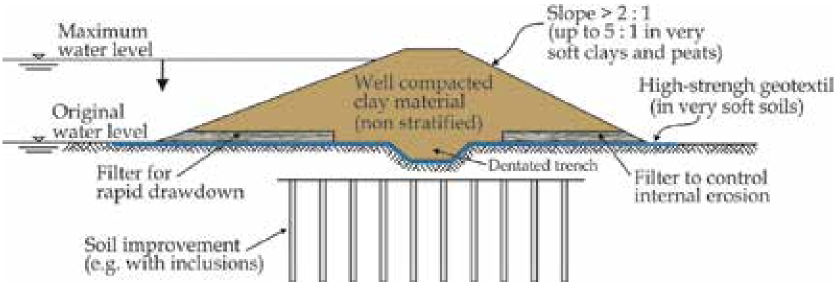


Fig. 11. Recommendations to protect levees in urban areas exposed to flooding (Auvinet et al., 2008)

In addition, Figures 10 and 11 illustrate respectively some practical recommendations that should be taken into account for the protection of levees on the river banks, and levees that are built in order to protect urban areas exposed to flooding (Auvinet et al., 2008).

7. Laboratory and field tests for analyzing erodible and special soils such as dispersive

7.1 Analysis of the soil erodibility

Several devices have been developed to evaluate how resistant earth materials are to water flow. Some of them are the *rotating cylinder* to measure the erosion properties of stiff soils (e.g. Chapuis & Gatien, 1986); the *jet test* to evaluate the erodibility of surface soils (e.g. Hanson 1991), and the *hole erosion test* to measure the erosion properties of stiff soils (e.g. Wan and Fell 2004). Another popular device developed in the early 1990s to measure the erosion function is the called *Erosion Function Apparatus* –EFA– (Briaud et al., 2001). The EFA test (Fig. 12) consists of eroding a soil sample by pushing it out of a thin wall steel tube and recording the erosion rate for a given velocity of the water flowing over it. Several velocities are used and the erosion function is defined through the results of this test (Briaud et al., 2001).

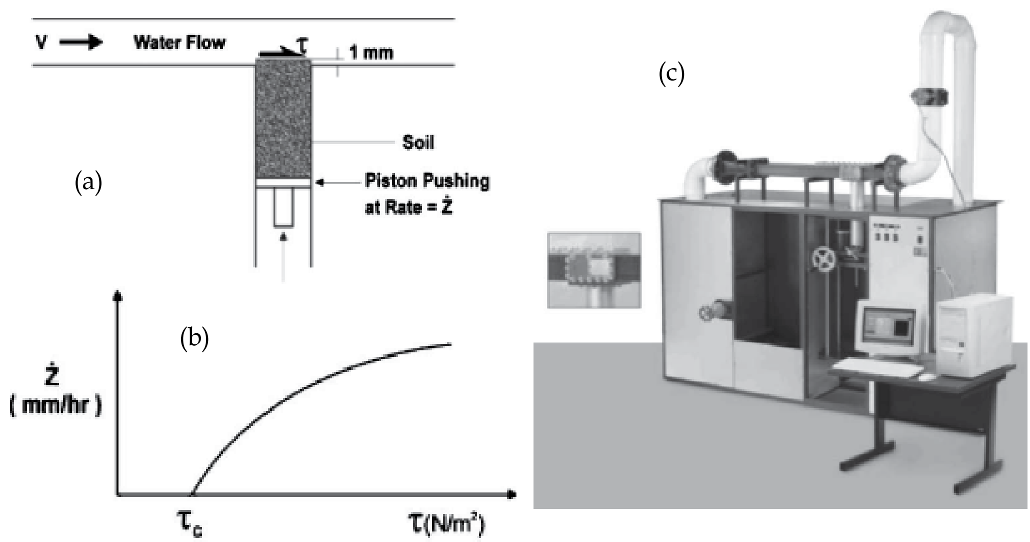


Fig. 12. Erosion Function Apparatus –EFA– (Briaud et al., 2001)

7.2 Identification of dispersive soils

Additionally, as it was mentioned before, soil erosion is likely to occur in certain types of soils. Among those are certain types of clay which erode by a process called dispersion or deflocculation, that occurs when the clay mass is in contact with water. If water is flowing, individual clay particles are detached and carried away through erosion channels or *pipes* that can form rapidly. As it is established by Cedergren (1989), one of the problems related with dispersive clay action, is that the deflocculation process starts as soon as there is a significant flow of water, as it can occur through poorly compacted or cracked layer in an impervious core, or along inadequate bonded contacts with rock foundations, abutments, or outlet conduits extending across the impervious core.

The practical relevance of dispersive clays in dam engineering, started about 60 years ago after realizing that it was the main cause of piping failure of several small earth dams and levees. Most of the earth embankment failures caused by dispersive soils occur during the first filling. If there are no well designed and constructed filters upstream and downstream of the core embankment that has these clays, the probability of an internal erosion failure will be very high. This probability might increase when preexisting surface erosion caused by rainfall contributes to the formation of superficial channels that become connected to tunnels originated by internal erosion. As this type of soil is not possible to identify through the conventional index tests, it was necessary to develop certain laboratory and field procedures for its identification.

Whereas the susceptibility to erosion in cohesionless soils, such as fine sands and silts, is due to high values of water flow velocity, hydraulic gradients and seepage forces, normal clays are usually erosion resistant, except for water velocity higher than 1 m/sec. Nevertheless, for dispersive clays the erosion phenomena occur due to causes that are different to those associated with granular soils. Such causes are due to the following characteristics:

a. **Physic-chemical characteristics.** The erosion resistance property that normal clays have, due to the electrochemical attraction between clay particles, is reduced to a minimum in dispersive clays, due to their physic-chemical characteristics. Therefore, under a low water flow the dispersive clay particles tend to separate and taken away easily by the water current. The rate of erosion of these clay particles might be higher than the one that takes place in fine sands and silts. There are several factors that affect the dispersive action of these clays, among which are their chemistry and mineralogy, as well as the kind of salts that exist in the pore water and the circulated water. The principal difference between dispersive clays and ordinary erosion-resistant clays appear to be the nature of the cations in the pore water of the clay mass. Dispersive clays have a preponderance of sodium, whereas ordinary clays have a preponderance of calcium, potassium, and magnesium cations in the pore water (Knodel, 1988).
b. **Physical characterization.** Dispersive clays are not related to any specific geological origin, but they have been founded under alluvial environment, in lakes and in flood plain deposits. They are very important in hydraulic structures, such as earth dams, levees and channels, since many of them are constructed over such soils. In some cases marine deposits have the same pore water salts as dispersive clays, and the residual soils from such deposits are also dispersive.
c. **Mechanical characterization.** The external erosion or piping, caused by a water flow is very obvious and it occurs in granular or cohesionless soils. As it has been said, in this case it starts at the discharge end of a leak, at the downstream side of an earth

embankment, where there exists a high hydraulic gradient; such phenomenon progresses upstream, forming a kind of pipe until it reaches the water source. With dispersive clays, however, the internal erosion is due to a deflocculation process and it might start at the upstream side where there is the water source; the tunnel-shape passage or pipe, that is formed, is propagated toward the downstream side. If such dispersive soils exist in areas where there are already some cracks, or not well compacted zones as those presented along conduits, such cracks might increase and propagate very rapidly causing a dam failure.

7.2.1 Field and laboratory test for dispersive soils

During the field investigation to construct an earth dam, particularly when looking for the materials that might be used to construct the embankments, it is very important to identify the existence of dispersive soils. This identification should be done first through one of the special field tests that exist for this purpose. Although the results of such tests must be verified through laboratory tests, field tests might give a good preliminary evaluation of the dispersivity of the soils under investigation. Knodel (1988) presents a good description of the most common laboratory and field tests that are used in the engineering practice to identify the dispersivity of soils. Among them are the following: a) for field: *crumb test*, *water drop test*, *dissolved sodium test*, and *turbidity test*; b) for laboratory: *crumb test*, *the double hydrometer test*, *pinhole test* and *chemical test*.

7.2.2 Design considerations when constructing with dispersive clays

For any earth construction it is necessary to investigate, by using one or more of those methods mentioned above, the existence of dispersive soils; this investigation can be carried out through soil samples obtained in open wells during the soil exploration phase. Once the construction materials have been identified, a decision to use or refuse them has to be taken. Sometimes dispersive soils might be used in earth structures if they are mixed with lime or if well designed filters and drains are installed. If for economical reason it is decided to use dispersive clays, the following conditions have to be taken into account:

a. Arching. This problem might occur in zones around conduits through the embankment, near concrete structures, and at the foundation interface. In order to avoid negative effects, special control of compaction and moisture content during construction should be taken.
b. Cracking due to differential settlements caused by soil consolidation, stress concentration, two or three dimensional effects, etcetera, should be avoided.
c. Soil improvement of the dispersive clay, by adding hydrated lime or non dispersive clay of medium to high plasticity. Special care should be taken in compacting soil adjacent to rigid structures such as conduits.
d. Construction control. Special standards and specifications should be used when dispersive soils are involved in the construction of earth structures, particularly those related to soil density and compaction procedures. For instance, there should not be moisture concentration while adding water to obtain the specified water content during layers' compaction. Special monitoring consideration to dams with cores containing dispersive soils, should be giving during the first filling, in order to prevent any piping or internal erosion effect. Observation instruments are particularly recommended to periodically measure water pressures, water leaks and water levels at different zones of the embankment.

8. Practical examples to illustrate the analysis of earth erosion problem caused by rapid filling and drawdown conditions in embankments

8.1 General settings

The wet slope of an earth dam, lake or river banks and channel slopes are frequently subjected to sudden changes of water level (increments or decrements), which modify flow conditions inside the soil mass. Flow velocities, hydraulic gradients and seepage forces might, in extreme conditions, cause soil erosion problems ranging from slight to severe, such as piping or even the total failure of the structure. These phenomena, known as *rapid filling* and *rapid drawdown*, are complex problems in which the magnitude and rate of filling or drawdown, hydraulic conductivity and porosity of materials constituting the earth structure, geometry of slope and initial boundary conditions of flow are involved (Auvinet & Lopez-Acosta, 2010). By using the *Plaxflow* algorithm (Delft University of Technology, 2007), analyses to assess how these two phenomena affect soil erosion in earth structures are carried out through a numerical modeling based on finite element method (FEM) (Auvinet & Lopez-Acosta, 2010; Lopez-Acosta et al., 2010).

8.2 Analysis considering only rapid drawdown phenomenon

In this practical example, the effect of rapid drawdown phenomenon on erosion problems in a typical embankment is analyzed (Auvinet & Lopez-Acosta, 2010). Simplified geometry of the studied domain and boundary conditions considered in this analysis are shown in Figure 13. Rate of drawdown was established at 1.1m/day. Thus, a total dewatering of 5.5m in 5 days was assumed in this analysis. In the same way, it was accepted that embankment is constituted by a homogeneous and isotropic material with hydraulic conductivity $k=1\times10^{-5}$ m/s and porosity n = 0.3 (void ratio e = 0.43).

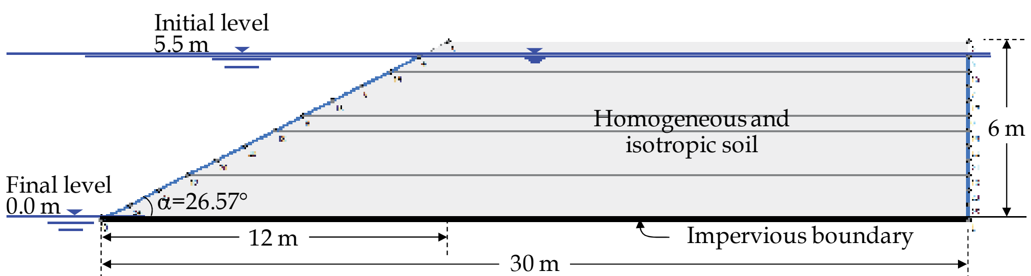


Fig. 13. Simplified geometry and boundary conditions of the studied embankment (Auvinet & Lopez-Acosta, 2010)

From results of analyses (Auvinet & Lopez-Acosta, 2010), Figure 14 shows, for a typical time interval during drawdown (t=4 d), the free surface line which separates unsaturated material (upper part) from saturated material. Variation of this free surface, called *desaturation line* (for drawdown), obtained at different time intervals during rapid drawdown is illustrated in Figure15. Other authors prefer to call it *phreatic line* (Huang & Jia, 2009; Lam & Fredlund 1984; Lam et al., 1987). It must be underlined that this free surface line is not rigorously a flow line since velocity vectors cross it (see Figs. 16a and b). In the same way, results from analysis demonstrate that during drawdown, when water surface descends, large velocities are generated at the contact between the level of water and the slope (which are proportional to hydraulic gradients, and consequently to seepage forces in that zone); these velocities can facilitate local “piping” of material of these regions and jeopardize slope stability. The existence of this maximum flow velocity close to the slope and under the level of water can be observed in Figures 16a and 16b (Auvinet & Lopez-Acosta, 2010).

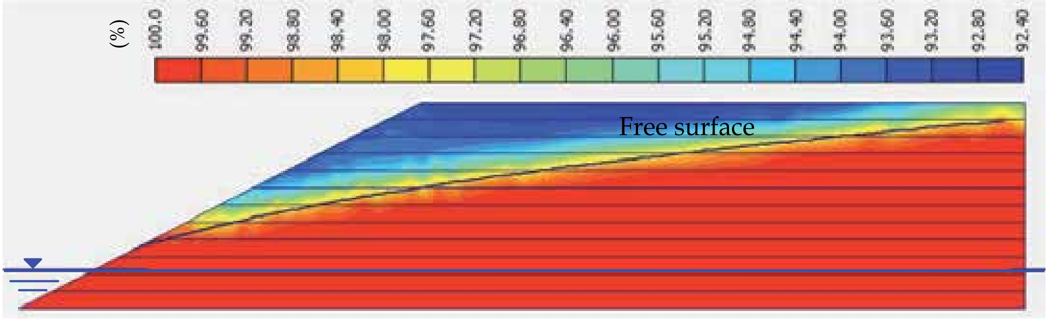


Fig. 14. Variation of degree of saturation for t = 4 d (345200 s) (Auvinet & Lopez-Acosta, 2010)

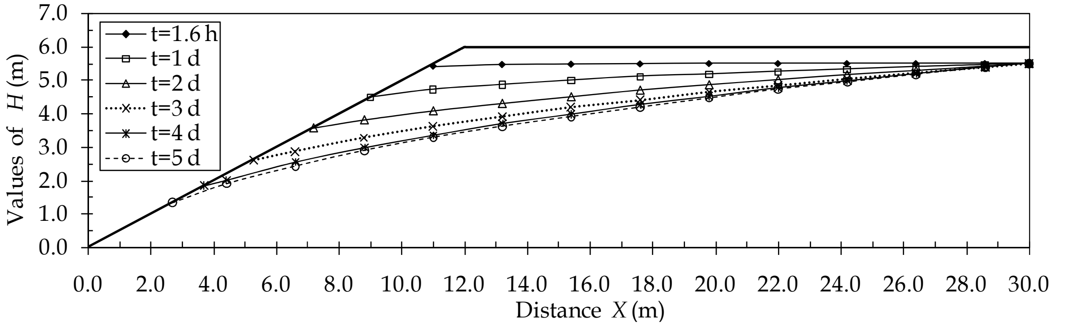


Fig. 15. Variation of *desaturation line* at different time intervals during rapid drawdown (Auvinet & Lopez-Acosta, 2010)

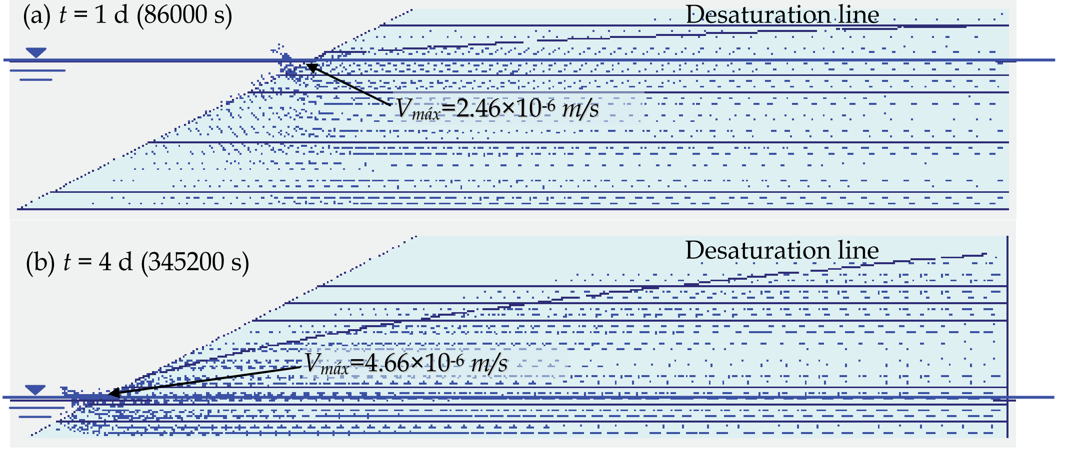


Fig. 16. Velocity vectors (magnitude) for two different time intervals during rapid drawdown (Auvinet & Lopez-Acosta, 2010)

Figure 17 shows the maximum exit hydraulic gradient (i_{max}=0.499) reached at the toe of slope at the end of the rapid drawdown (t=5 d). Additionally, Figure 18 illustrates how the free surface line and velocity vectors change due to the placement of a horizontal drain inside the embankment (Lezama, 2010). The most conspicuous difference can be observed in the reduction of hydraulic gradient at the toe of slope at the end of rapid drawdown (t=5 d), from i_{max}=0.499 to i_{max}=0.25. This demonstrates the usefulness of placing drains in order to reduce soil erosion problems in earth structures.

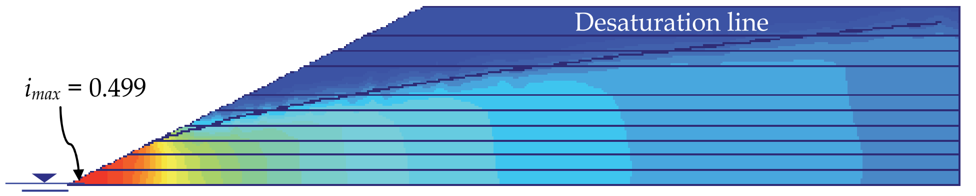


Fig. 17. Hydraulic gradients (magnitude) at the end of rapid drawdown (t=5 d) (Lezama, 2010)

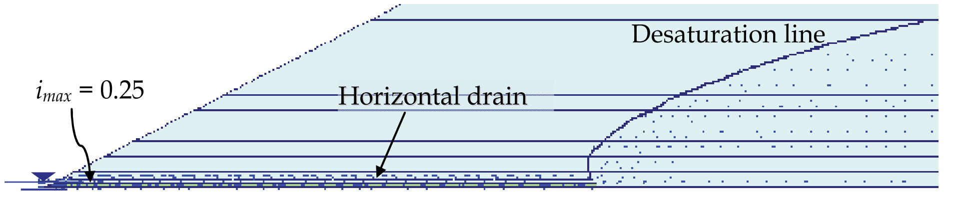


Fig. 18. Changing in velocity vectors and reduction of hydraulic gradient (magnitude) at the end of rapid drawdown (t=5 d) due to the placement of a horizontal drain into the levee (Lezama, 2010)

8.3 Analysis considering both rapid filling and drawdown phenomena

This example focuses on studying the effects on soil erosion due to transient flow within a levee as water level of a river increases and decreases because of the rain cycles in a tropical region. Simplified geometry of studied domain including foundation soil of the levee is illustrated in Figure 19. Properties of materials are specified in Table 3 (Lopez-Acosta et al., 2010).

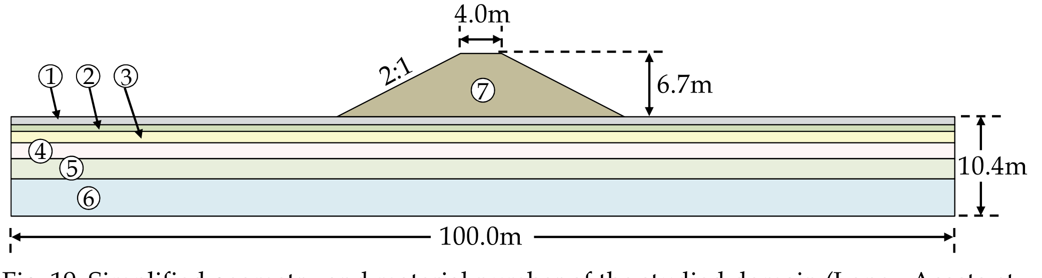


Fig. 19. Simplified geometry and material number of the studied domain (Lopez-Acosta et al., 2010)

N°	Material	Hydraulic conductivity, *k*	Void ratio, *e*
1	Clay sand (SC)	0.0864 m/d ($1{\times}10^{-6}$ m/s)	0.43
2	Sandy clay of low plasticity (CL)	0.0864 m/d ($1{\times}10^{-6}$ m/s)	0.50
3	Organic sandy-clay silt of high plasticity (OH)	0.00864 m/d ($1{\times}10^{-7}$ m/s)	0.90
4	Clay sand (SC)	0.0864 m/d ($1{\times}10^{-6}$ m/s)	0.43
5	Silty sand (SM)	0.0864 m/d ($1{\times}10^{-6}$ m/s)	0.43
6	Organic clay of high plasticity (OH)	0.00864 m/d ($1{\times}10^{-7}$ m/s)	0.90
7	Clay levee	0.00864 m/d ($1{\times}10^{-7}$ m/s)	0.70

Table 3. Properties of material layers (Lopez-Acosta et al., 2010)

Boundary conditions assumed for analyses were as follows:

- For *filling*: water surface ascends from initial level of 13.7m up to maximum level of 16.4m, in a period of 17 days (variation is illustrated in Figure 20).
- For *drawdown:* water surface descends from maximum level of 16.4m up to final level of 11.3m, in a period of 27 days (variation is shown in Figure 20).

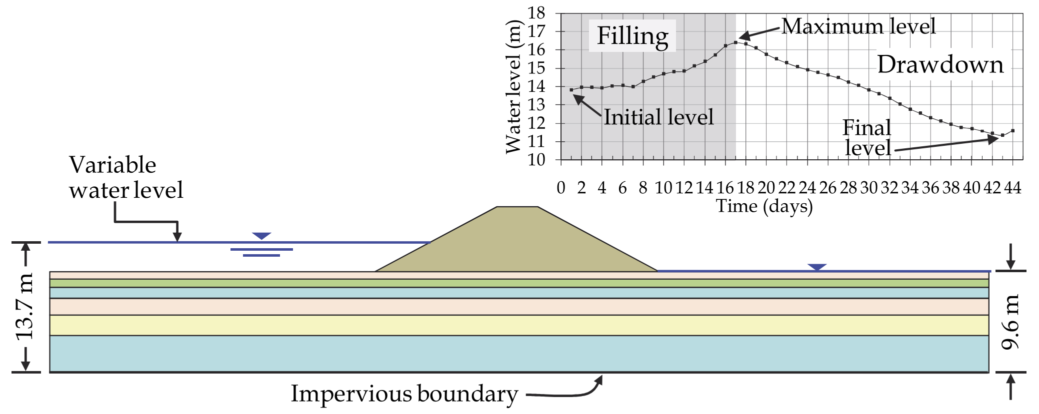


Fig. 20. Boundary conditions assumed for analyses (Lopez-Acosta et al., 2010)

From results of analyses (Lopez-Acosta et al., 2010), it is interesting to note that during transient flow certain regions of higher hydraulic gradients and flow velocities are generated, as appreciated in Figures 21 and 22, respectively. Predominantly, the highest values of hydraulic gradients and velocities take place at the toe of downstream slope of levee. Specifically, the gradient values of those areas greater than the so-called critical gradient (>1) could facilitate *global piping* through the body of levee or through the foundation soil (Figure 21). These above mentioned highest values occur when maximum level of water surface is achieved (day 17 of filling). Additionally, it can be observed that during rapid filling velocity vectors are directed towards downstream (Figure 22a) and during rapid drawdown the direction of some of these vectors changes towards upstream (Figure 22b). Particularly, during rapid drawdown it can be observed that velocities and gradients generated near the upstream slope, as water level descends, are not negligible; in extreme conditions they could facilitate *local erosion* of material in those zones (Lopez-Acosta et al., 2010).

In the same way, from Figures 21 and 22, it can also be observed that in general the highest values of flow velocity occur in the more pervious materials of the studied domain; in contrast, the highest values of hydraulic gradient arise in the less pervious materials of this domain. This is a suggestion that instability problems of levees could not be solved by constructing them with more impervious material, but rather building them with more or less pervious material or even placing drains in strategic areas of the body of levees (Lopez-Acosta et al., 2010). Some authors have indeed concluded that soils with a low hydraulic conductivity, such as clayey and silty soils, are more prone to slope failure than more pervious materials such as granular soils (Pradel & Raad, 1993).
Based on previous results, it can be said that in the case of slope stability analysis, it should be considered on the one hand, the susceptibility to erosion of the material used for constructing the levee; but on the other one, the analysis must also consider measures to decrease the hydraulic gradients and seepage forces generated within the soil mass.
Quite recently, some types of analyses based on probabilistic methods have been suggested for the study of levees in general. Hubel et al. (2010) presented a practical approach to assess combined levee erosion, seepage forces, and slope stability failure modes; they developed response curves for landside and waterside slope stability, as well as landside seepage failure modes for various hydrostatic water loads. In a similar context, the Army Corps of Engineers (Lee & Wibowo, 2007, as cited in Hubel et al., 2010) used the limit state approach for estimating the probability of levee erosion that might induce a breaching failure.

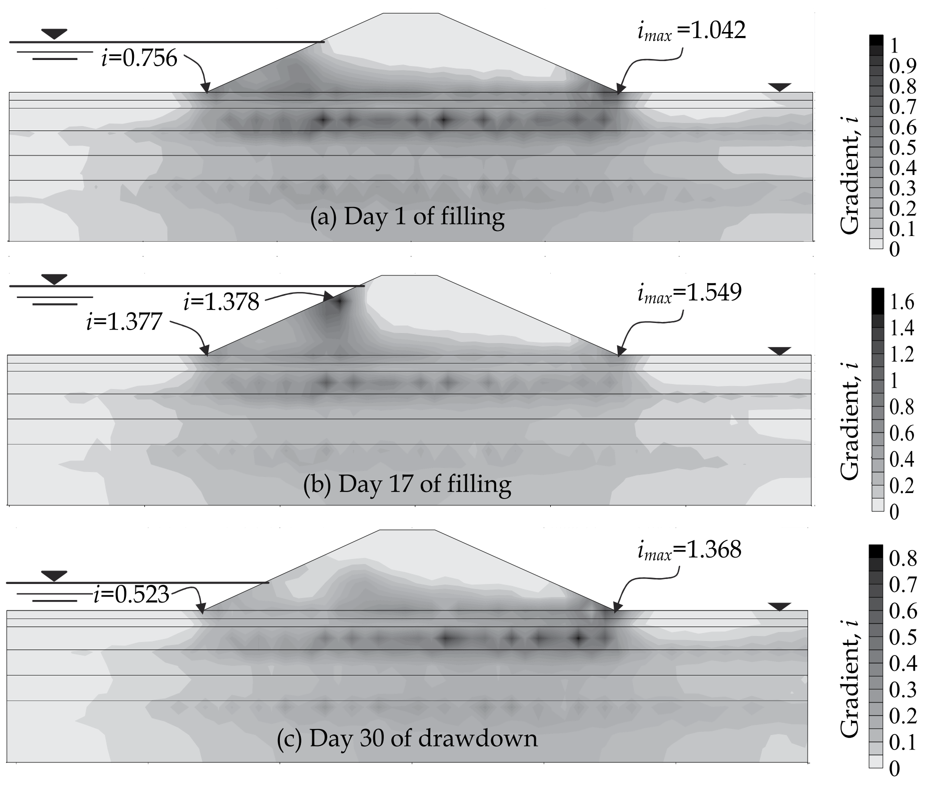


Fig. 21. Hydraulic gradients (magnitude) for three different times during rapid filling and drawdown (Lopez-Acosta et al., 2010)

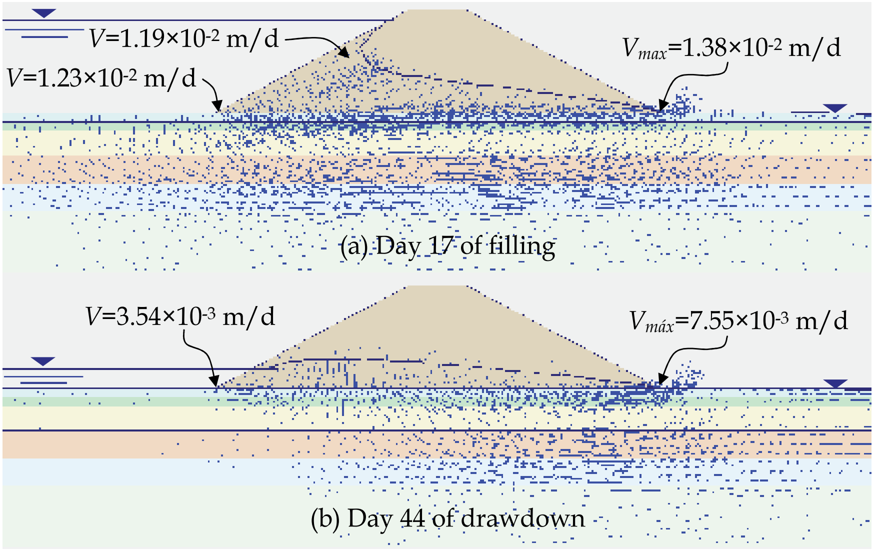


Fig. 22. Velocity vectors (magnitude) for two different time intervals during rapid filling and drawdown (exaggerated scale) (Lopez-Acosta et al., 2010)

9. Conclusions and recommendations

The main conclusions and recommendations derived from this chapter are the following:

- If internal erosion caused by water flow or seepage through earth dams, levees, and other earth structures that contain water is not detected in time and if corrective actions are not taken to stop or control such erosion, the consequences may be a complete failure of that structure.
- The process of soil erosion might occur through the mass of the earth structure or through its foundation. The initiation of this process usually starts at the exit point of the seepage and retrogressive erosion results in the formation of a "pipe".
- The main factors that affect the erosion phenomenon are: a) the erodibility of the soil; b) the water velocity inside the soil mass; c) geometry of the earth structure. The erodibility of the soil depends on several factors, such as water content, plasticity index, undrained shear strength, mean grain size, percent passing #200, soil clay minerals, soil dispersion ratio, water salinity, soil pH and water pH, among other factors.
- The seepage forces that affect the erosion problem are related to the hydraulic gradient that exists in the soil mass. This gradient might be computed and analyzed through the graphical flow net method or through one of the numerical methods that exist in the literature.
- Several procedures and practical recommendations were presented for preventing damages due to soil erosion. Among those are: a) Obtain the best selection of available construction materials; b) Control the homogeneity of the materials during the construction process; c) Use transition zones between the coarse and fine materials; d) Use properly designed filters and drains for all earth facilities exposed to damaging actions of water in their foundations or around the impervious core.
- The erodibility of soils might be analyzed through laboratory and field tests. Some of the most common of these tests were mentioned in this chapter, particularly the ones related to the identification of dispersive soils.

- The applicability of the concepts presented in this chapter was illustrated through some examples related to the analysis of soil erosion problems caused by rapid filling and drawdown conditions in earth embankments.

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15

Lake Mladotice in the Western Czech Republic – Sediments as a Geoarchive for Flood Events and Pre- to Postcommunist Change in Land Use since 1872

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1. Introduction

Landscape changes are distinguished into those generated by natural processes and those caused or triggered by human activity (Barsch et al. 1993; Jansky & Urbanova 1994; Favis-Mortlock et al. 1997; Bork et al. 1998; Voelkel 2005; Bičik & Kabrda 2007; Bičik & Jeleček 2009). The geoarchives do not reveal which of these factors ultimately caused greater soil erosion. Improved dating techniques are necessary to increase the temporal resolution of the sediment records which have clearly increased the level of knowledge in recent years (e.g. Geyh 2005, Kadlec et al. 2009).

When examining sediment archives from recent times, we may have the opportunity to identify the factors controlling sediment formation in much more detail (e.g. Junge et al. 2005). This was the case with the natural "experimental setup" at Lake Mladotice (western Czech Republic), where it was possible to analyse a sediment archive dating back to 1872. Since the onset of lake sedimentation, rainfall and runoff have been recorded (in some cases continuously) at monitoring stations located in the surrounding area of the catchment area of the lake (Schulte 2007, Schulte et al. 2007).

Air photos from several decades document pre- and post-communist land use changes in the lake's drainage basin. Furthermore, records exist of fertiliser programmes affecting sediments and hydrochemism. Because of the change in land use, increased soil erosion and a rise in the sedimentation rate were expected. Against this background, our investigations into the lake sediments and the drainage area of Lake Mladotice aim to address the following questions:

1. To what extent has land use changed in the drainage basin of Lake Mladotice since 1872?
2. Has the magnitude or frequency of the rainfall runoff events changed since 1872?
3. To what extent is the sediment record a product of the rainfall runoff events or the change in land use in the drainage basin?

2. Lake evolution and drainage basin

During the final days of May 1872, an extensive area of southwestern and western Bohemia was affected by a massive incident of torrential rain, which according to historical reports lasted from noontime on 25 May until the morning of the following day. The Pilsen rain gauge recorded two thunderstorms on 25 May 1872, from which a total of 40 mm of precipitation was measured (Skrejšovsky 1872). However, a far greater sum of precipitation fell north of Pilsen, where no rain gauge was in operation at that time. Nevertheless, Karel Kořistka, a prominent cartographer, provided a detailed description of the meteorological situation (Kořistka 1872): "Observed in Mladotice, a standing empty vessel that was 9 inches or 237 mm tall was filled to the brim within one hour's time to the point that additional rain overflowed the vessel…".

This report of 237 mm of precipitation in one hour was for a long time considered to be unrealistic. Only with the measurement of torrential rain in southern Slovakia – i.e. in a similar Central European climate zone, recorded on 12 June 1957, when 225.5 mm of precipitation fell during 65 minutes at Skalka by Šturovo (southern Slovakia) – was the feasibility of these earlier data confirmed (see Štekl et al. 2001).

The extreme precipitation in May 1872 caused an extraordinarily destructive flood which devastated the catchment areas of the Střela and Blšanka Rivers as well as most of the Berounka River basin below Pilsen. On May 26, at 2 pm, the discharge of the Vltava in Prague was measured at 3300 m^3/s, which represents the fifth largest flood observed since 1825 (Brazdil et al. 2005).

As a consequence of earthworks for a railway track at the footslope and the extreme rainfall event, large masses of rock slumped down from the western slope of the Potvorovsky Hill (546 m asl) into the Mladoticky valley during the night from 27 to 28 May, damming the creek with a massive dike (Fig. 1). Bedrock and mass accumulation mainly consist of

Fig. 1. Dammed valley immediately after the landslide in May 1872; the lake is emerging in the background. Print from Geografie (Sbornik ČSZ) 28, Praha 1912. Photo by C. Purkyně.

Palaeozoic shale, sandstone and conglomerate, with some Proterozoic phyllite and spilite and Palaeozoic granite (Česky geologicky ustav 1996). The created lake is, up to the present day, the only example of such a genetic type of lake in the Bohemian Massif.

The preconditions for a landslide to occur on the slopes of the Potvorovsky Hill originated long before the catastrophic landslide of 1872. It is evident that there were multiple causes, and these should be viewed in the light of their mutual connections and not as isolated factors, owing to the fact that each of them contributed to a certain degree to disrupting the stability of the slope, as is discussed in detail by Jansky (1976, 1977).

Lake Mladotice still exists in the western Czech Republic about 30 km north of Pilsen. The receiving streams of the lake outflow are the Střela and Berounka Rivers; the latter drains into the Vltava River south of Prague. The erosion level of the lake is 413 m a.s.l.; its surface extends over 4.74 ha. The lake's drainage area is approx. 46.5 km², about 50% of which is being intensively farmed (Fig. 2). The lake's drainage basin – including the type of land use – is typical for a larger region of western Bohemia.

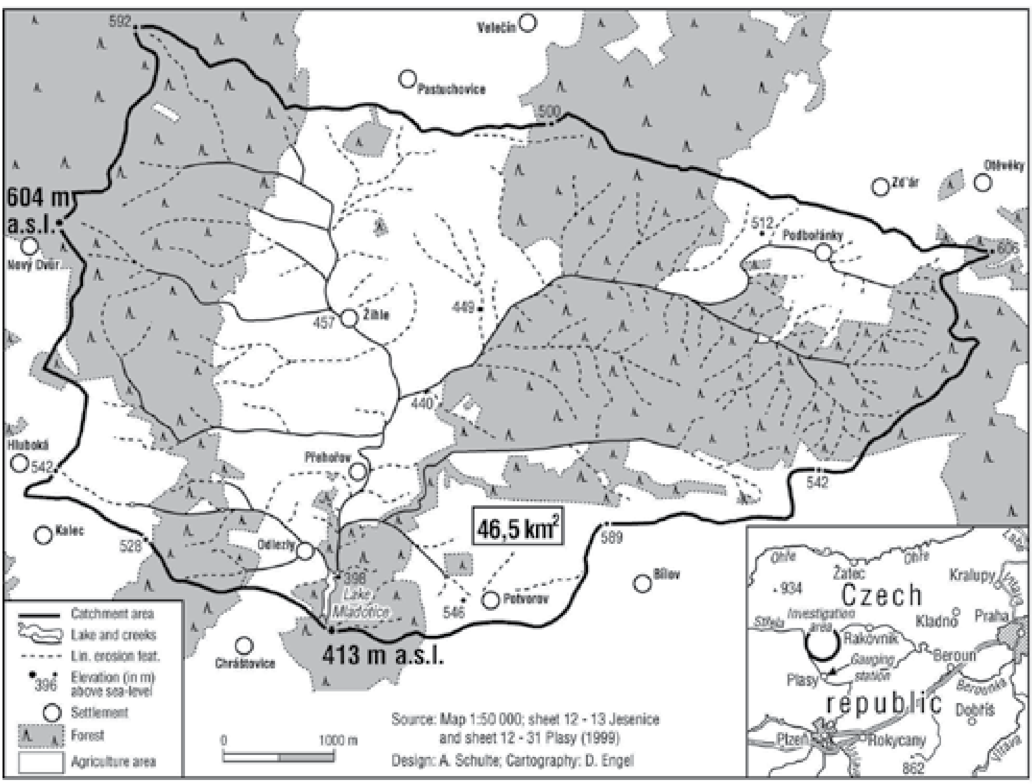

Fig. 2. Drainage basin of Lake Mladotice and location of the study area in the western Czech Republic.

3. Methods

Geodetic and bathymetric measurements of Lake Mladotice were conducted in 1972, 1990 and 2003 (Jansky 1976, 1977; Jansky & Urbanova 1994; Česak & Šobr 2005). By comparing the results of these measurements, it is possible to analyse the dynamics of the lake's sedimentation in the past and to attempt to predict the further development of the lake basin: in other words, to determine a period after which the lake will be entirely filled with sediment.

To reconstruct land use shifts, the Military Topographical Institute in Debrovska (western Bohemia) supplied air photos taken in 1938, 1952, 1975, 1987 and 1998. Up to now only 2-D interpretation has been possible, because of the lack of overlap. The air photographs document a considerable land use change with the introduction of collectivisation (see below). We anticipate that stereoscopic 3-D interpretation of the air photos will show the removal of field terraces that accompanied field enlargement and also contributed to increased erosion (Janský 1976, 1977; Jansky & Urbanova 1994).

Rainfall data were analysed from six stations recording data since 1881 to assess the influence of natural factors on erosion, transport and sedimentation rates in Lake Mladotice. The rain gauges at Kralovice, Plasy, Mladotice, Manetin, Liblin and Valecin are not located in the drainage basin of Lake Mladotice, but they are the closest stations in the surrounding area. These records do not seem to be homogeneous for all events at all stations and need to be examined carefully to identify the rainfall events relevant to flooding. Rainfall runoff analysis should therefore focus on major events which covered the whole area of the rainfall stations, including the drainage basin of Lake Mladotice.

Runoff data serve to indicate the dimensions of past flood events. The nearest runoff gauge is located on the Strela River (Plasy Station, 775 km^2, Fig. 2 small map), which also drains the Mladoticky creek. Daily records at this gauge date back to 1941. It is assumed that large floods recorded at the Strela River were also experienced at the Mladoticky creek and that sediments were deposited in the lake during these events.

To classify current sedimentation conditions and sediment properties, we measured the oxygen content, conductivity, temperature, visible depth and stream flow of the lake water in the summers of 2003 and 2004 in a depth grid across the lake.

Sediment echo sounding was used to measure sediment distribution along profiles in the lake basin in order to find suitable sites for core drilling. Unfortunately the sediments were extremely poor in reflection owing to the great number of cavities in the lake sediments, and thus results were unsatisfactory. The analysis of the sediment cores confirms the great number of cavities.

In spite of this setback, we obtained information about the distribution of the sediments by extracting 13 short cores, each about 1 m in length. Five long cores were drilled down to the bottom of the sediments. The reference core ML 18/03 was extracted from the deepest part of the lake, and core ML 14/03 was investigated for diatom analyses (Fig. 3).

Reference core ML 18/03, with a total length of 4 m, underwent analyses of water content, density, grain size distribution, total sulphur, total carbon, total phosphorus, clay mineral composition, the isotope content of ^{137}Cs, ^{241}Am and ^{210}Pb as well as thin sections from the entire length of the core. Sediment samples were taken and analysed in 10 cm sections. The upper part of the sediment core ML 14/03 was investigated for diatoms (0–160 cm core depth). As agrochemicals can indicate system changes, we analysed their input into the lake. Fractionated organic analyses were conducted on four samples using GC-MS technology.

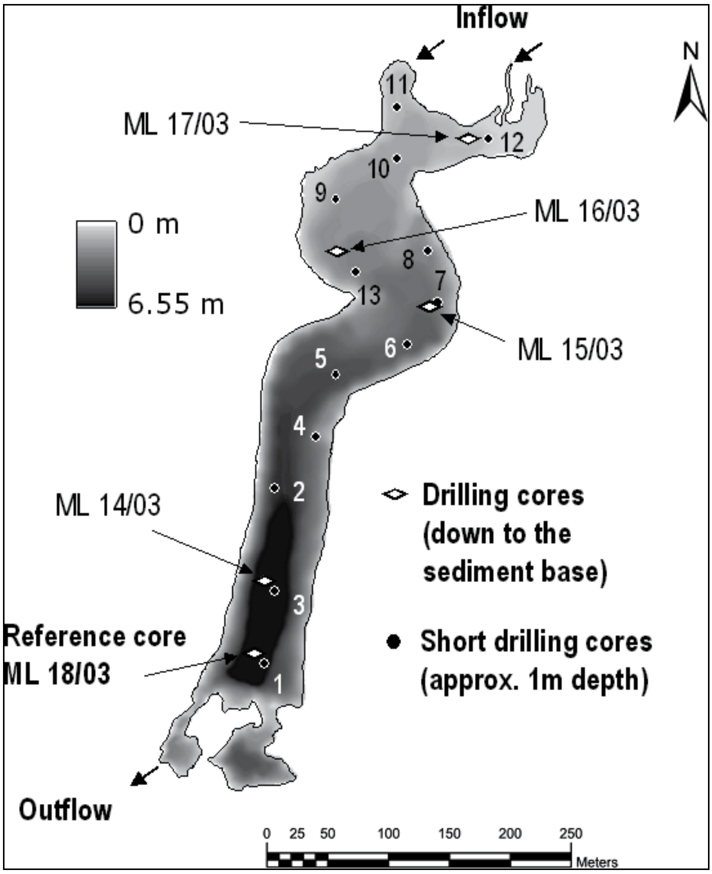

Fig. 3. Map of Lake Mladotice showing locations of short and long cores. Core ML 18/03 is located near the outflow with the maximum water depth.

4. Results

4.1 Sediment filling in the lake basin and fluctuations of lake water level

Comparative analysis of bathymetric measurements from 1972 and 2003 yielded the following results (Jansky 2003). The maximum depth of the lake decreased from 7.7 m to 6.7 m (Fig. 4). The 7 m depth level disappeared entirely, and the area of all other depth levels decreased - the 6 m depth level to 61% of its initial area from 1972, the 5 m level to 43%, the 4 m level to 60%. The decline in the area of shallow water levels was somewhat less dramatic – the 3 m level decreased to 72% of its 1972 area, while the 2 m and 1 m levels decreased to 69% and 76%, respectively.

A decrease in the water level's surface area was measured, i.e. from an initial 5.85 ha (1972) to 4.73 ha (2003). This means a decrease of 1.12 ha in the lake's surface area, i.e. 19% of its initial area in 1972. The maximum water level fluctuation between 1972 and 2009 was recorded at around 55 cm. Moreover, the automatic limnigraph has measured a fluctuation of 26 cm in the last 12 months. After the bathymetric curves were elicited, the water volume of the lake basin was calculated. From an initial volume of 141,380 m^3 in 1972, it decreased by 37,471 m^3 to 103,910 m^3; the water volume of the lake decreased by 26.5%.

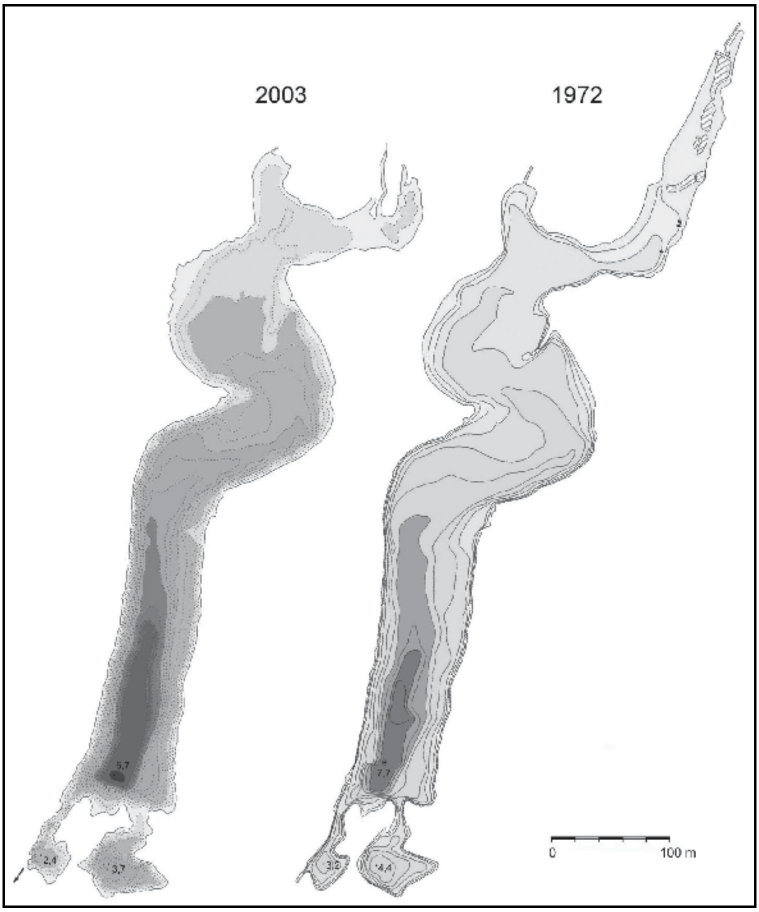

Fig. 4. The bathymetric maps of the Lake Mladotice from measurements in 1972 and 2003

4.2 Changes in land use and flood discharge

Landscape changes in the drainage basin of Lake Mladotice were reconstructed from air images. To visualise the land use changes, Fig. 5 displays as an example a field about 1 km² in size that is located northeast of Žihle (for orientation see Fig. 2). No changes are visible in the field patterns between 1938 and 1952. Collective farming had the greatest impact between 1952 and 1975, when fields were made much larger. A further increase in the size of some fields is visible in 1987. The photos taken in 1998 show that the size of the fields was reduced again after the political change in 1989. Bigger fields facilitate soil erosion due to longer slopes and increased surface runoff (see conclusions). Some quantitative data about land use changes were published in Schulte et al. (2006).

To clarify whether the system changes are due to natural or anthropogenic causes, we analysed the time series of discharge values at the Střela gauge at Plasy (775 km²) from 1941 until 2002 (2003 is the year of sediment coring). Plausibility and homogeneity checks of the discharge data revealed discontinuities and varying trends in the years 1956 and 1978, so further studies were made in three separate periods (1941-1956, 1957-1977 and 1978-2002). In these three periods, the annual flood peaks show a falling tendency, i.e. a lower peak over the years (Fig. 6). The number of floods above a threshold of 5.5 m³/s increased slightly from 4.1 flood events per year (1941-1956) to 5.0 (1957-1977) and 5.1 flood events per year between 1978 and 2002.

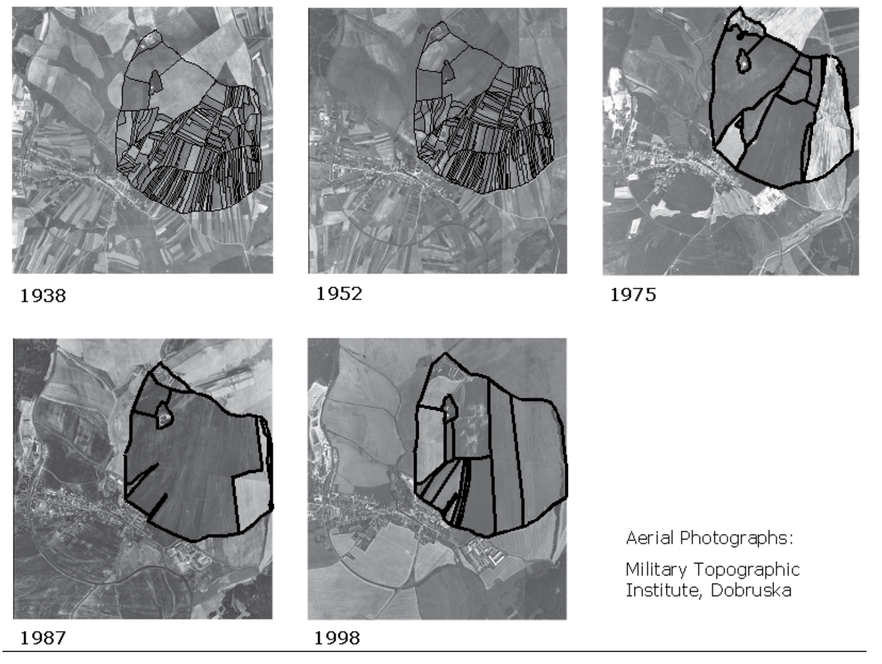

Fig. 5. Air images of a field about 1 km² in size, northeast of the town of Zihle in the basin of Lake Mladotice (see Fig. 2). Collective farming had the greatest impact between 1952 and 1975.

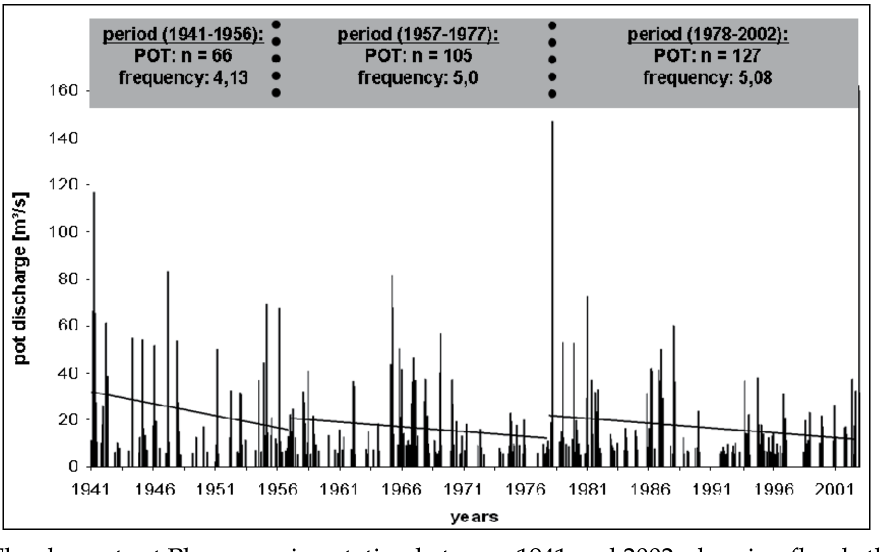

Fig. 6. Flood events at Plasy gauging station between 1941 and 2002, showing floods that exceed the threshold of 5.5 m³/s (pot = peaks over threshold).

Against the background of the contrary trends of magnitude and frequency of the time series of annual flood events, it does not seem possible to infer decreasing or increasing sedimentation in the lake. During the entire 1941-2002 period, only the 1978 flood is notable for having the highest peak discharge in the entire measuring period; accordingly, it has left a distinct event layer in the lake sediments (see below).

4.3 Stratigraphy and geochemistry of the lake sediments

The lake sediments of reference core ML 18/03 (location see Fig. 3) are largely muddy silts. The particle-size distribution indicates two noteworthy features: 1. Sand is found only in the lower sediment sequences. This is also the case in the other sediment cores and suggests that the sand was brought in by the Mladoticky creek. During the early decades there may have been some additional sediment input from the mass failure area, which was unvegetated during the first few years. 2. The particle-size median shows a distinct change in sedimentation at about 190 cm core depth. Below this depth, the sediment is coarser and the range fluctuates fairly widely; above it, the median remains constant at about 4 µm.

The sediment chemism of reference core ML 18/03 is shown in Fig. 7. Some of the contents of carbon (TC), phosphorus (TP) and sulphur (TS) double above a core depth of 190 cm. This system change is demonstrated even more clearly by the heavy metal levels. Pb, Cu, Ni and Zn rise sharply above 190 cm (Fig. 8). Other elements such as calcium (Ca) show an increase only in near-surface sediments above 60 cm, which correlates with the occurrence of calcite. Also TC, TP and TS show a marked increase near the surface. Owing to the phosphate content of the open water, the lake can nowadays be classified as eutrophic.

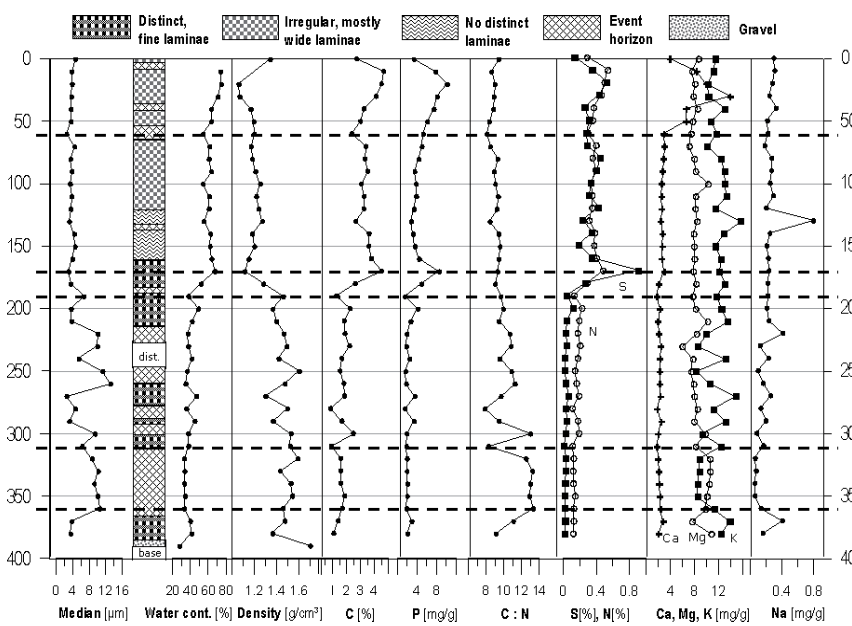

Fig. 7. Geochemistry of reference core ML 18/03 (median of grain size, C, S, N, C:N, Ca, Mg, K, Na, P). Changes in the element concentrations or the level are marked with dotted lines.

Sediment cores ML 14/03 and ML 16/03 (location see Fig. 3) show clear evidence of the system change. According to macroscopic and stratigraphic analyses of these cores, the system change occurred at different depths owing to the different thickness of the sediments. The sediment chemism of core ML 14/03 shows a distinct increase of TC and TS above a core depth of 200 cm (TS increases sixfold); core ML 16/03 shows the buildup of these elements at a core depth of 100 cm.

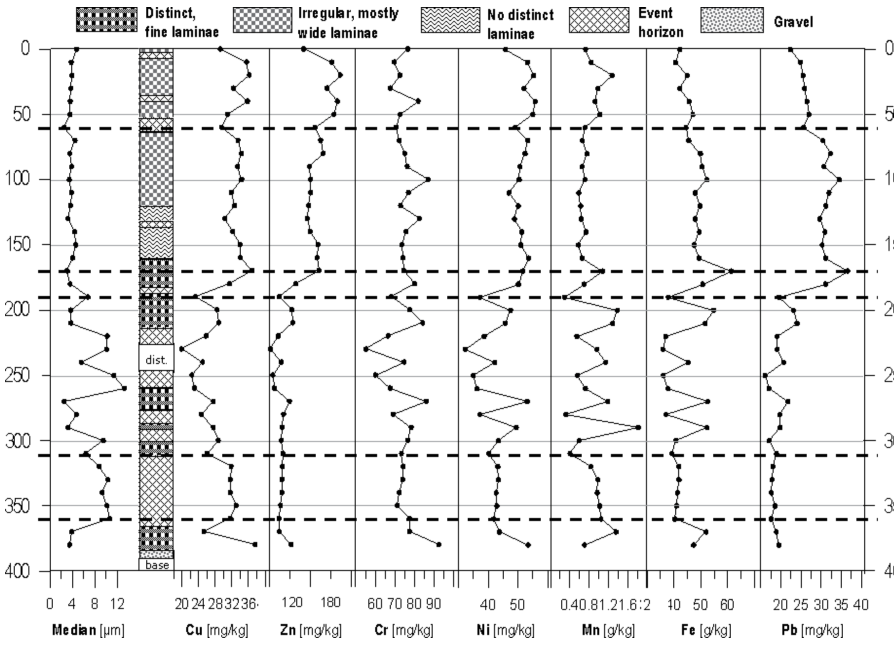

Fig. 8. Heavy metal contents in reference core ML 18/03 (median of grain size, Mn, Fe, Pb, Cu, Ni, Cr, Zn). Changes in the heavy metal concentrations or the level are marked with dotted lines.

4.4 Analyses of isotopes and diatoms

The absolute chronology of the sediments is also based on available isotope measurements of ^{137}Cs, ^{241}Am and ^{210}Pb (Fig. 9). The peak radiation of ^{137}Cs and ^{241}Am at a core depth of 100 cm is attributed to the 1963 maximum of bomb fallout which started in 1954. Americium clearly demonstrates bomb fallout because there was no emission of americium during the Chernobyl disaster. The peak at 40 cm core depth is assigned to the Chernobyl fallout in 1986.

Analyses of microfloral and faunal remains confirmed the system change between the upper and lower parts of the reference core (transition at 190 cm). However, a very high frequency of diatoms was found in the upper part of the core. Samples taken from core ML 14/03 from the sediment surface down to 166 cm core depth (location see Fig. 3), indicate that about 80-90 % of the individuals are planktonic and the remaining 10-20% are benthic diatoms. This uniform palaeolimnological stratification is interrupted by one distinct event at a depth of 66-76 cm, where the proportion of planktonic individuals drops to 15 % and the benthic forms increase to a peak of 85 %. This event indicates a high sediment inflow during a major flood. The analysis of the runoff data indicates that this big event relates to the extreme magnitude of the flood in 1978.

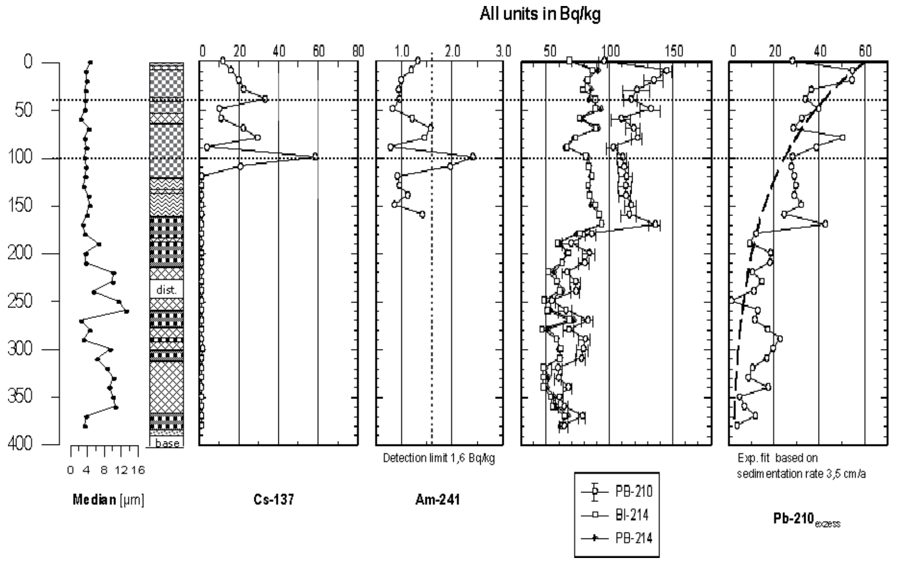

Fig. 9. Isotope contents in reference core ML 18/03 (^{137}CS, ^{241}Am, ^{210}Pb).

4.5 Agrochemical analyses

Agrochemical analyses of four samples in core ML 18/03 do not show the presence of pesticides such as DDT or any of its metabolites. Nor were any polychlorinated biphenyls (PCBs) found in the sediment samples. Fractionated qualitative and quantitative analyses reveal large quantities of polycyclic aromatic hydrocarbons (PAH). These compounds are evidently left over from incomplete combustion processes, and their presence in the sediment is due to atmogenic input into the sediments. The highest concentration is detected at a depth of 45 – 50 cm. The levels are comparable with concentrations in the sediments of other mountain lakes in central and southeastern Europe (Fernandez et al. 1999, Muri et al. 2003).

4.6 Thin sections, temporal resolution and sedimentation rates

Thin sections give an additional chronology, in some cases with an accuracy of one year. The new sediment data on geochemistry, isotopes, diatoms and thin sections especially of reference core ML 18/03 and partly of core ML 14/03 (diatoms) yield the following interpretation (see Fig. 10):

The 1872 landslide impounded the lake, and sedimentation began. Thin section analyses show that clastic sediments were deposited in annual layers above the base. In some cases the boundaries between the layers are blurred, resulting in erroneous ages for the lower part of the core. It was possible to count the layers up to 1883 with an error of ± 2 years. The average sedimentation rate was 1.8 cm/a.

This was followed by a 50 cm thick, homogeneous sequence of unbedded sediment. This sediment is interpreted as having been deposited during an event or a phase of events prior to 1890; the average sedimentation rate is about 9.1 cm per year. The material comes either from the still unvegetated mass failure area at the southern end of the lake (Fig. 3) or from flood input by the Mladoticky creek.

Up to 190 cm core depth, thick unbedded sequences alternate with annually bedded sediments. A layer count dated this depth to 1920. Partial blurring of the boundaries between the layers results in a possible error of ± 5 years. Owing to the alternation between event-dependent high sediment inputs and annual sediment layers, there are substantial variations in sedimentation rates between 6.7 and 1.8 cm/a.

Above 160 cm core depth, there is a clearly bedded diatom mud that can be dated relatively accurately by various sediment analyses. The start of bomb fallout in 1954 provides a time marker (120 cm core depth). The sedimentation rate between 1920 and 1954 was calculated at 2.1 cm/a. Maximum fallout at 100 cm core depth occurred in 1963 (sedimentation rate 2.2 cm/a). The next time marker is the flood of 1978, shown by a distinct event layer and a change in diatom composition. The sedimentation rate from 1963 to 1978 was calculated at 2.7 cm/a. Until the fallout from Chernobyl in 1986, the sedimentation rate fell only slightly to 2.5 cm/a. The rate is 2.4 cm/a between 1986 and the sediment surface (2003).

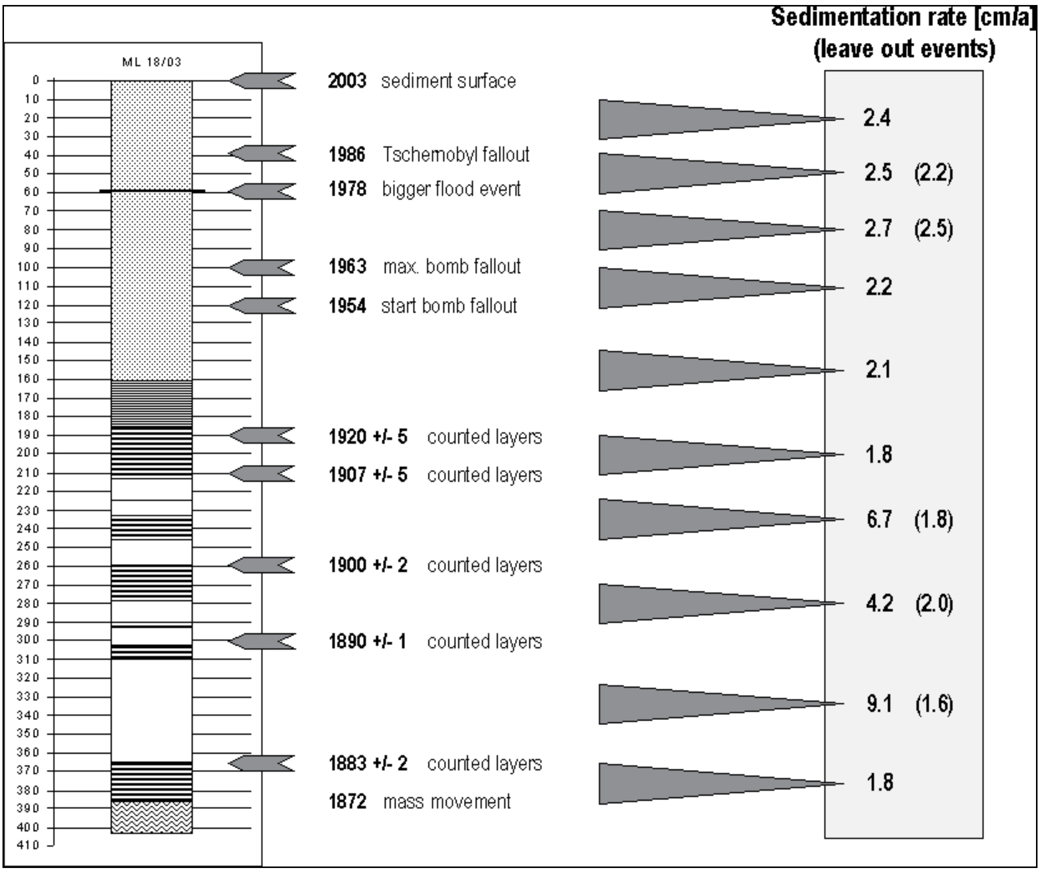

Fig. 10. Results of thin section analyses, temporal resolution and calculated sedimentation rates on the basis of the reference core ML 18/03.

5. Conclusions

Data obtained from various sediment analyses yield a high temporal resolution of the sediment stratigraphy. In 1920 the sedimentation rate was 2.1 cm/a; then came a slight rise, reaching 2.7 cm/a after 1963. Because this increase cannot be attributed to greater frequency or amplitude of big floods, we conclude that the switch to collective agriculture was responsible for the increase in sediment entering the lake. If we disregard the extraordinary event layers when calculating sedimentation rates, greater importance then attaches to the "change in land use" factor. The differences in sedimentation rates are smaller, but still remain (Fig. 10).

Collectivisation led to larger units of farmland. According to Janský (1976, 1977) and Janský & Urbanová (1994), the enlargement process was most active during the 1960s and 1970s and was accompanied by the removal of field terraces. In consequence, slopes became steeper and the fine colluvial material that had collected above the terraces over decades or centuries was easily remobilised. From then on, the bigger fields were worked by larger and heavier agricultural machinery, thus increasing soil compaction and erodibility. All three parameters (greater slope length, steeper slope angle, modified farming practices) intensify average soil erosion according to the Universal Soil Loss Equation (Wischmeier & Smith 1978). A substantial increase in sediment input and deposition might be expected, but did not occur to the anticipated extent.

These results may be interpreted in two ways. 1. The amount of soil erosion from the parts of the drainage basin used for agriculture corresponds to the sediment increase in the lake and the additional transport through the lake. 2. Soil erosion has increased much more than is indicated by the lake's sedimentation rates, because a (large) proportion of the sediments was deposited in colluvial, alluvial and lake inflow areas. If the latter is the case, such sinks are likely to provide relevant information.

In 31 years 37,471 m^3 of sediment accumulated in the lake basin. This represents a sedimentary deposit of 1,209 m^3 per year on average. If we consider the current volume of the lake basin of 103,910 m^3, this means that – under the existing dynamics of sedimentation - the lake would be entirely filled up within the next 86 years! In addition to the speed of sedimentation, the lake's drainage could also play a significant role in its future development. Over time, the outflowing creek will cut deeper and deeper into the lake's dam. During extreme floods, the drainage channel could be markedly deepened. This would mean the lowering of the water level and the quicker disappearance of the lake.

Processes of sedimentation in Lake Mladotice could be slowed by implementing thorough anti-erosion and soil protection measures throughout the entire catchment area draining to the lake along with changes in land use (with preference given to permanent grasslands and decreases in arable land).

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Soil erosion affects a large part of the Earth surface, and accelerated soil erosion is recognized as one of the main soil threats, compromising soil productive and protective functions. The land management in areas affected by soil erosion is a relevant issue for landscape and ecosystems preservation. In this book we collected a series of papers on erosion, not focusing on agronomic implications, but on a variety of other relevant aspects of the erosion phenomena. The book is divided into three sections: i) various implications of land management in arid and semiarid ecosystems, ii) erosion modeling and experimental studies; iii) other applications (e.g. geoscience, engineering). The book covers a wide range of erosion-related themes from a variety of points of view (assessment, modeling, mitigation, best practices etc.).

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