FOREST FIRES, EROSION AND RISK CARTOGRAPHY: EXAMPLES IN NORTHERN PORTUGAL

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ABSTRACT – Forest fires are responsible for important modifications in terms of hillslope dynamics, resulting often in increased erosion rates and, as a consequence of this, land loss. Higher rates of surface runoff, formation of gullies and *holes* or even soil de-structuration are some of the consequences of forest fires to the physical space. In this sense, the need to employ techniques to mitigate its effects is urgent. In this paper it is our intention to analyse some examples describing the consequences of forest fires in terms of hillslope dynamics in Northern Portugal and also the development of a methodology focussing on the analysis of gully risk by using Geographic Information Systems (GIS) software in a region where burned areas are considered high risk areas as far as the formation of this geomorphological process is concerned.
Keywords: Forest fires; Northern Portugal; I_{gully}; Geographical Information System (GIS).

RESUMO – *B.M. Martins & A. de S. Pedrosa - Incêndios florestais, erosão e risco cartográfico: exemplos no norte de Portugal.* Os incêndios florestais são responsáveis por importantes modificações ao nível da dinâmica das vertentes, traduzindo-se na maioria das vezes pelo aumento da acção erosiva e consequente perda de solo. O aumento da escorrência de superficial, o surgimento de ravinas, a existência de *buracos* ou mesmo a desestruturação do solo são algumas das consequências dos incêndios sobre o espaço físico. Neste sentido urge aplicarem-se técnicas para mitigar os seus efeitos. Na presente comunicação são analisados alguns exemplos de consequências dos incêndios ao nível da dinâmica de vertentes no Norte de Portugal e ainda o desenvolvimento de uma metodologia que procura analisar o risco de ravinas utilizando o Sistema de Informação Geográfico (SIG) e onde as áreas incendiadas recentemente são consideradas como área de risco no surgimento deste processo geomorfológico.
Palavras-chave: Incêndios; Norte de Portugal; $I_{ravinamento}$; Sistema Informação Geográfico (SIG).

INTRODUCTION

In any given ecosystem, energy, carbon anhydride, water and nutrients are absorbed and transported through a ramified network, in which hillslopes, soils, flora, fauna and man all maintain auto-stabilising and interdependent relationships. This balance may be disrupted as a response to variations of external controls. This disruption tends to be interrupted and the system returns to its natural state, or oscillates with regularity around it, when the pressure is removed. We call this process *resilience* (Holling, 1973). Excessive or unusual variations may, however, transform the system in such a way, or induce such violent fluctuations that it may reach a new balance. In simpler ecological terms, the name of the balance reached in an ecosystem through a long term evolution is *climax.* The systems returning to climax can be found in several *successional* stages, and the balance points reached after disruptions are called *disclimaxes* (Warren & Maizels, 1992).

The notion of resilience is intimately related to the idea of risk. Intense rain has minimal effects on the soils and plants of the systems reaching the climax phase, but they cause serious harm to the systems in a successional stage. If erosion destroys nutritive soils with a high water holding capacity, the return to climax, or reaching the climax phase, may be slow or even impossible. The occurrence of forest fires will be of particular importance to the disruption of the bio-geophysical balance of a hillslope and in triggering a whole set of erosive processes which, depending on the characteristics of the slopes, may lead to serious consequences at the level of soil loss.

In this paper it is our intention to analyse some examples describing the consequences of forest fires in terms of hillslope dynamics in Northern Portugal and also the development of a methodology focussing on the analysis of gully risk by using Geographic Information Systems (GIS) software in a region where burned areas are considered high risk areas as far as the formation of this geomorphological process is concerned.

THE EROSIVE PROCESSES IN BURNED AREAS

One of the most direct consequences of forest fires is the destruction of vegetation. In Northern Portugal in pine and eucalyptus forests, after a forest fire, the eucalyptuses generally recover faster contributing to the prominence of this species in some forest areas.

On the other hand, forest fires are also responsible for the de-structuration of soils as a result of the high temperatures reached during the fires. The duration and intensity will be responsible for that de-structuration or, in cases where the intensity and duration fosters it, hydrophobia. In this way, the knowledge in terms of the intensity and duration of a fire will allow conducting an analysis in terms of the capacity of resilience of the physical space and in particular of the soils. As a consequence of forest fires in pine plantations, the roots may burn leading the formation of "holes" in the soils which may measure up to 0.5 meters deep (Pedrosa, 1989). In granite areas, the *holes* will be responsible for the increasing infiltration levels in these sectors contributing to an accentuated discontinuity of the basic surface of erosion (Figure 1).

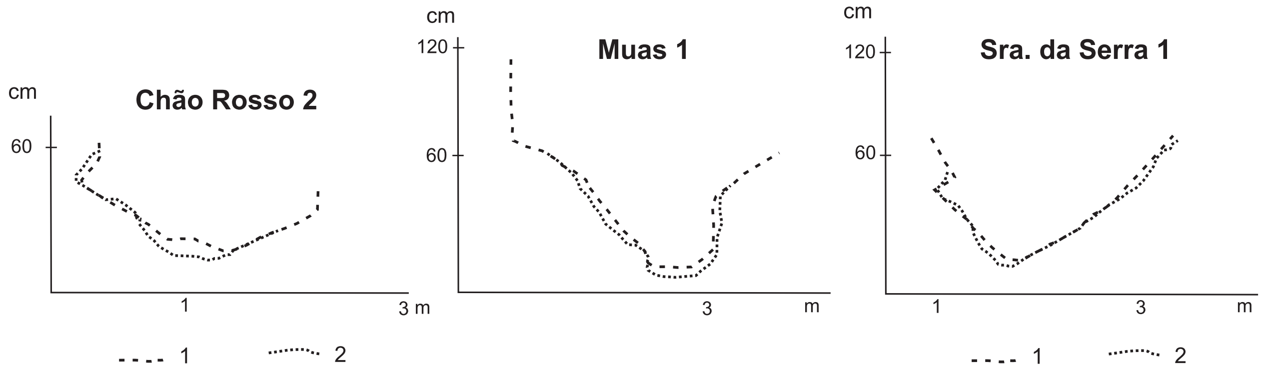

FIGURE 1. Longitudinal profile and evolution of gullies studied in Serra do Marão (Pedrosa, 1993). Line nr. 1 represents the starting stage and line nr. 2 its evolution.

The destruction of the vegetation will be also responsible for the increase in temperature variation and a decrease in humidity at the level of the soil. Along a day, during periods of greater radiation, the absence of vegetation stops acting as shield, reaching temperatures much higher at the level of soil as it would in case there was some vegetation. The losses of water are much higher and the water holding capacity very incipient. On the other hand, the losses of energy through irradiation during the night are also more accentuated. This fact will be responsible for phenomena of thermoclasty in areas with higher variations.

A phenomenon particularly important for land loss in recently burned areas is gullying. The formation of gullies associated with hilly terrains, stony soils or other manifestations, are indicators and serious signs of desertification in agricultural lands, grazing grounds and, in particular, in forest areas.

The productive loss of a soil may occur in either of two ways: (i) the slow loss of nutrients. The assessment methods include the accurate measurement of the availability of nutrients and the appearance or disappearance of certain vegetation species, indicators of the fertility of a soil (Warren & Maizels, 1992); (ii) the loss of the soil surface layer due to erosion. There are several methods to assess the level of erosion. **Class 1** *(slightly eroded)* – The surface is slightly shrunk and the top layer of the soil became thinner in some sectors. Soil management has not been affected by erosion; **Class 2** *(moderately eroded)* – Surface gullying is possible; gullies remain year after year, the surface layer is destroyed between 25-75%; **Class 3** *(severely eroded)* – Over 75% of the surface layer of the soil has been removed, gullies are deep and part of the subsoil has disappeared; **Class 4** *(excessively eroded)* – The soil is covered with a complicated network of deep and surface gullies, its restoration is very difficult (US Agriculture Dep., 1951). Another classification: **Level (a)** – *Minimal*, rare areas affected; **Level (b)** – *Moderate*, frequently small areas and occasionally great areas with moderate susceptibility to erosion; **Level (c)** – *Severe*, frequently great areas reveal great susceptibility to erosion with water lamination with shrinkage and gullies (Condon et al., 1969).

After the formation, land restoration is often expensive and usually requires technical assistance (Garduño, 1992). One way to control gullies is the mapping of areas, which given its characteristics are more or less prone to degradation and land loss due to gullying.

Gullies are essentially related with the existence of alteration mantles in areas in which the rockground is constituted by granitoid rocks (Picture 1) or in slopes regularized by slope deposits (Picture 2).

In serra do Marão (Northern Portugal) there were analyzed some gullies which developed immediately after a fire. They were analyzed in terms of their morphological development and erosion capacity.

Generally speaking, compared with initial transversal profile, the gullies under study showed a retreat in a discontinuous process. The periods of retreat were essentially due to two phenomena: (i) accumulation of material resulting from the parts located immediately above and (ii) soil lifting and subsequent movement due to *pipkrakes,* caused by frost and which becomes clear in shady hillslopes where the action of this process can be more intensively felt.

The value of mobilized material proves the importance of gullying as an erosion process. The results obtained vary between 6,37 kg/m^2/year and 49,97 kg/m^2/year. The measurements revealed periods of greater mobilization contrasting with others when the mobilization of material was incipient. Although runoff is the process responsible for the formation of gullies, this is not always the only one intervening in its evolution. In fact there is no correlation between the amount of eroded material and the total of rainfall.

In some periods of the analysis, small amounts of rainfall corresponded to high values of mobilized material. The contrary is also true. It can thus be conclude that the characteristics of rainfall are related with the intensity and duration as well as the season of the year. The first summer and autumn rainfall revealed particularly important in the formation and evolution of the gullies, as it is generally intense and prolonged, following very warm and dry periods.

PICTURE 1. Gullying in a slope regularised by slope deposits – Serra do Alvão (Northern Portugal).

PICTURE 2. Detail of the material deposited on the slope after the formation of the gullie .

THE GULLY INDEX (I_{GULLY}) AND FORREST FIRES

There are several methods to assess soil erosion levels, but a common characteristic is that in every scale gullying coincides with advanced levels of erosion. After the formation, land restoration is often expensive and usually requires technical assistance (Garduño, 1992). The formation of gullies is related with the disruption of the ecological balance of a hillslope, as a response to an environmental change, naturally induced or as a consequence of changes in land use and vegetal coverage. The definition of areas more or less prone to gullies must necessarily take into account natural and land use and occupation factors.

The use of Geographic Information System (GIS) allowed the definition of areas more likely to experience gullying, allowing in this way to map the areas more susceptible to this process. With the objective of assessing gully prone areas it was defined a gully index. One of the advantages of estimating this index is to combine different parameters and to rank the areas according to the index resulting in a standardization of the values. On the other hand, this index does not automatically exclude an area with a low parameter involved in the estimation of the index. Geomorphological risk cartography and in particularly gully risk maps, faces however some problems, namely as far as the work scale is concerned. This influences not only the selection of data but even the choice of the method of information treatment. For this paper and taking into consideration the type of digital information available and the compelling need of conducting thorough field work, intended at adjusting the model to reality, it was opted for the 1:25.000 scale. Other difficult concerns the "weight" attributed to each class and parameter of the model. Finally, it is necessary to isolate the influence of each one of the elements, which may be difficult in a complex system, but this will make sure that all factors interact as a whole and not isolated.

For the definition of the I_{gully} 3 parameters were used:

Climate Parameter

Climate Parameter results from the sum of í values obtained from the average annual rainfall (Pmm), from the number of days with more than 10 mm of rainfall. This element is particularly important to assess the impact of convective rainfall in the summer months, characterized by high levels of precipitation, playing a decisive role in the formation of grooves, in which gullies will later evolve. Together with R≥10, the element MDR intends to introduce this factor in the production of a final risk map. (R≥10) and the maximum daily records (MDR), calculated using the formula:

$$I_{climate} = (\Sigma\ \nu_{Pmm} + \nu_{R\geq10} + \nu_{MDR}) / 3$$

The ν values obtained from the annual average rainfall (Pmm), number of days with precipitation above 10 mm (R≥10) and maximum daily records (MDR) calculated using the formulae:

$$\nu_{Pmm} = Pmm/500;\ \nu_{R\geq10} = R\geq10/15 \text{ and } \nu_{MDR} = MPD/40$$

Geomorphological Parameter

Geomorphological parameter is calculated from the elements: slope, type of soil, AGUT (maximum amount of water available for evapotranspiration) and rockground as it is described by the formula:

$$I_{gully} = \frac{\nu_{slope}\,(\nu_{type\ of\ soil} + \nu_{AGUT} + \nu_{geology})}{3}$$

The topography, namely the hillslopes, conditions the relationship between surface runoff and infiltration, determining the conditions of potential and kinetic energy of a slope. This fact influences not only the formation of gullies, but also land use and occupation and the relationship between accumulation and denudation of material on the slopes. The formation of gullies increases in the direct proportion of the slope angle and decreases as it becomes near the vertical (Strahler, 1979). The selection of relevant information to the production of a digital elevation model (DEM) using a triangulated irregular network (TIN model).

The type of soils may assume four values, according to the permeability, valuing soils with higher surface runoff rates over soils with higher infiltrations rates:

- Type A soils (high permeability) – Low runoff potential and high infiltration rates, even when the soils are completely moist. This type includes especially deep, well-drained sands.
- Type B soils (moderate permeability) – Moderately low runoff potential and moderate infiltration rates when completely moist. This type consists of moderately deep soils with moderately fine to coarse textures, moderately well-drained.
- Type C soils (low permeability) – Moderately high runoff potential and slow intensity rates when completely moist. It includes soils with an impermeable layer near the surface with moderately fine texture.
- Type D soils (very low permeability) – High runoff potential and very slow infiltration rates when completely moist. It includes clays with high swelling potential, soil with permanently high water tables, soils with clay layer at or near the surface and shallow soils over nearly impervious parent material.

The AGUT element (maximum amount available for evapotranspiration) is an important variable in gully analysis, since it defines soil depth. The deeper the soils are, the higher the water holding capacity will be (Figure 2). Shallow soils lose a great proportion of water through evaporation and during intense, prolonged rainfall episodes, they may become saturated and lose water through runoff.

The AGUT variable is quantitative and depends upon two factors: (i) n_u index (in which n_u designates

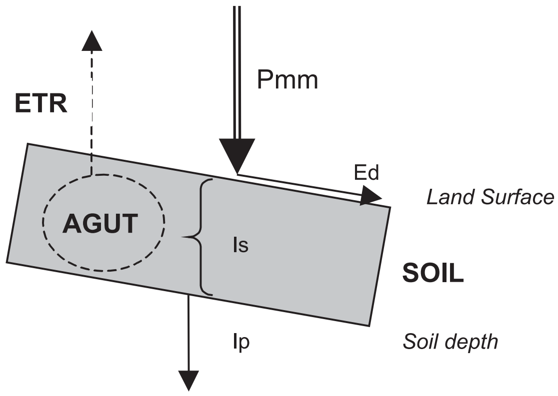

FIGURE 2. Soil and topography as factors promoting infiltration (*adapt*. Oliveira et al., 1997).

usable capacity): $n_u = s_r - w_p$; and (ii) r_p index (defining the approximate depth of the plant roots) (Table 1). The variable AGUT has been used several times in studies estimating aquifer recharge, currently there are being conducted several studies in LNEC-DH-GIAS, which allow assessing n_u index using basic cartographic information (Vermeulen et al., 1993; Oliveira et al., 1997; Zakharova et al., 2002).

$$AGUT = r_p \text{ X } (s_r - W_p)$$

When there is no evapotranspiration, the soil water content is minimal which corresponds to the specific soil water holding capacity (s_r). In case there is evapotranspiration, the soil water content may drop to a minimum value given by the wilting point (w_p). The maximum depth until evapotranspiration may occur is the depth reached by the roots of the plants (Figure 3 and 4).

As far as the geological parameter is concerned, it is taken into account the lithological characteristics, in particular in the relationship between direct runoff (Ed) and infiltration (Is). Birot (1949) described the essential properties of the schists as opposed to the properties of the granites. Schists, of fine texture and of difficult chemical transformation, promote surface runoff. Granites are more vulnerable to chemical transformation, due to their granular texture. Their mineralogical composition is characterised by the existence of vulnerable elements to weathering with more resistant elements, originating alteration mantles.

TABLE 1. Approximate depth of plant roots (r_p) according to land use and occupation *adapt.* Oliveira et al (1997) and Vermeulen (1993; 1994).

Land Use (Code)	R_p (mm)
Continuous urban fabric	0
Discontinuous urban fabric, industrial, commercial and general equipments sites, road and railroad networks and associated areas, harbour areas, airports.	200
Stone pits, sand extraction sites, open pit mines, industrial discharge areas, dumps, shipyards	250
Urban Green Spaces	1000
Sport and leisure areas, farm use areas outside the irrigation perimeters, irrigated parameters	500
Rice Fields	600
Vineyards, vineyard + orchard, vineyard + olive yard	1300
Orchards, orchard + vineyard, orchard + olive yard	1500
Olive yards, olive yard + vineyard, olive yard + orchard	1300
Grazing grounds	800
Annual harvest associated to permanent crops, complex parcel cultural systems	1000
Land covered mainly by farm fields with important natural spaces	1200
Agro-forest areas, non-coniferous, cork tree, holm tree, cork tree and holm oak, chestnut tree, oak-tree, eucalyptus, resinous trees, wild-pine tree, stone pine, mixed forests	2750
Poor grazing grounds, tracks	800
Swamps and moors	500
Sclerophyte Vegetation	600
Degraded Green Spaces	1500
Beaches, dunes, sands and soils without vegetal cover, bare rock, sub-desert treeless plains, recently burned areas, peat moss and marshes	250
Slat pits, water courses, lakes, lagoons and coastal cordons and estuary	0

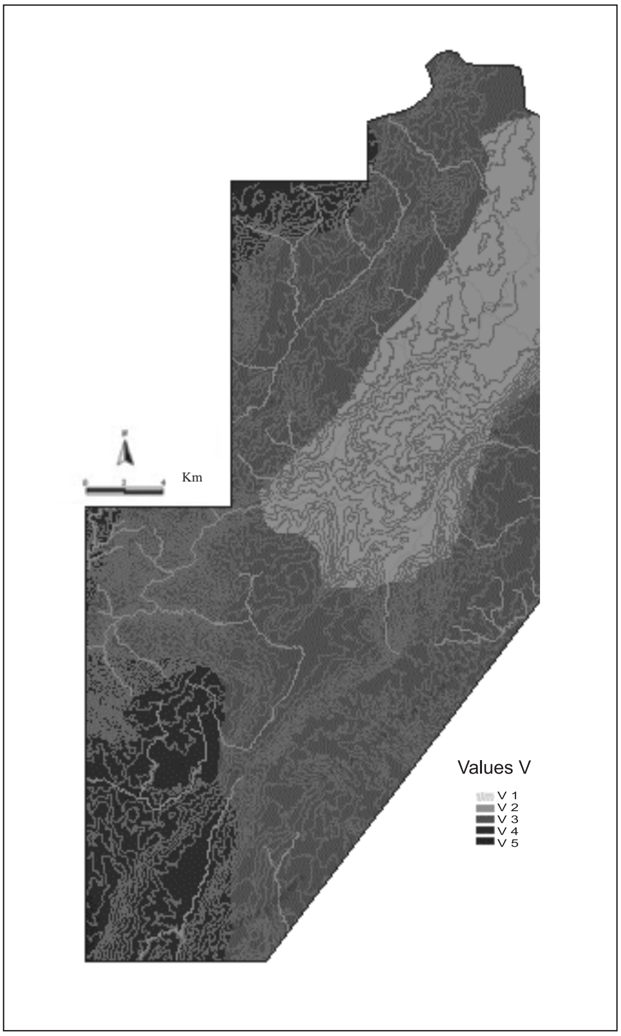

FIGURE 3. $I_{climate}$ index for the study area. The use of the command *Union* of *Geoprocessing Wizard* tool allow successively joining data from different layers.

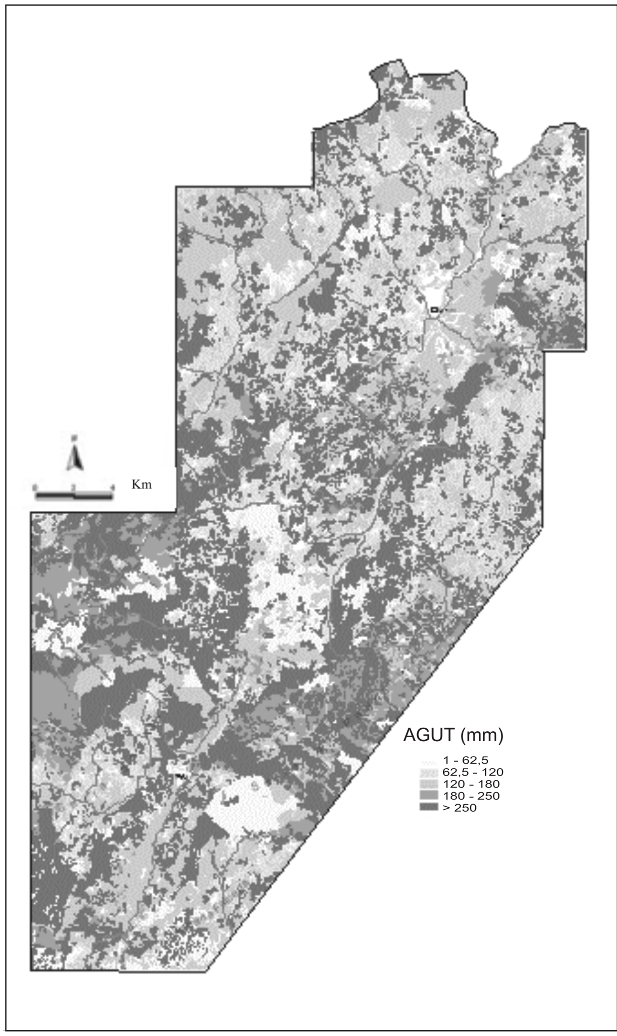

FIGURE 4. AGUT Amount measured in mm for the study area.

The alteration mantles result from the desegregation of granitoid rocks, of coarse texture and are highly permeable. On the other hand, they are the cause and consequence of the alteration, nourishing themselves, especially in smooth areas (Table 2).

Land Use and Vegetal Coverage Parameter

Value 1 comprises two units of land occupation: agricultural lands and forest areas. Agricultural lands are located preferably in depressions, corresponding to alluvia plains, and in mountain peaks, in smooth areas (< 5º). With regard to forest areas, they correspond to forests with a cover between 30-50% or above 50% with a good soil protection level.

Value 2 includes two areas of land use and occupation, forests between 10-30% of poor, herbaceous brush cover and occupation. In these areas the soil protection level is lower, resulting from a deteriorating bio-geoecological balance. However, the existence of herbaceous vegetation serves as protection shield to the opening of grooves. Infiltration rates exceed surface runoff.

Value 3 corresponds to forest areas with a cover inferior to 10% or degraded forests with exposed soils. The susceptibility to gullying is high due to both soil exposure and old gullies. This class includes also all the agricultural areas without any type of soil protection by herbaceous or brush vegetation, such as vineyards,

TABLE 2. The different elements and respective í values used to calculate $I_{geomorphological}$ index.

Slope	Value (v)	Type of Soil	Value (v)	AGUT (mm)	Value (v)	Geology	Value (v)
1-8	5	A	6	1-62.5	1	RG	2
8-16	4	B	4	62.5-120	2	RM	4
16-24	3	C	2	120-180	3	RS	1
24-32	2	D	1	180-250	4		
>32	1			>250	5		

RG – Granitoid Rocks; M – Metasediments; RS – Sedimentary Rocks

with vegetal cover inferior to 10%, or orchards and olive yards. In agricultural areas, especially in smooth areas, there are important cases of gullying, made easy or induced by human action, in a Mediterranean climate. Intense, concentrated rainfall is followed by periods of dry, warm weather. In extensive farming areas there are also important modifications at the level of soil surface and its cover. In the first case, soil stirring is mainly related with ploughing, the second is related with the growth stages of crops, since there are moments after the plantation when the soil is completely exposed, contrasting with a later stage when it may be protected. In grazing grounds, gullying is frequent and is often related to the action of some animals, such as goats, which contribute to soil sealing through trampling, compacting the soil, or through the destruction of vegetation. Gully risks in areas with the value 3 depend highly upon the slopes of these areas.

Value 4 includes areas of disruption of the bio-geophysical balance, such as recently burned areas. Soil protection and infiltration capacity are scarce or even null. Forest fires take place especially in the summer months and destroy great part of the vegetation. Soils are without any type of vegetation cover, and are not even structured by the action of the roots. The first summer and autumn rainfall is generally intense and concentrated, following very warm and dry periods and it will be responsible for the formation of gullies accompanied by important land loss. Some studies (Rebelo et al., 1986; Pedrosa, 1993) link the post-summer period with the first rainfall and the formation of gullies, related with the temperature variation at the level of soil (especially in the SE oriented hillslopes) or in some hillslopes, related more specifically with forest fires, absence of vegetation or wind exposure.

Reforestation is also extremely important, as it is responsible also for new erosion problems and gullying. The preparation of soils and the deficient adaptation of the species increase slope vulnerability. The disruption of the geo-ecological balance resulting from the action of fires on the slopes is possible to be observed in the study area, due to the gullying and the existence of tors, the latter resulting from meteorisation of granite and subsequent detachment of alterites. These form especially in granitoid rocks, more resistant to mechanical erosion and susceptible to chemical transformations. In that regard, it should pointed out the alkaline granites, coarse to moderate biotites, in opposition to the basic granular rocks, in which the more intense decomposition is more superficial.

Finally, value 5 corresponds to stone pits and open pit mines. The existence of this type of land use increases the area of bare land and therefore accelerates erosion and gullying. The existence of mobilised material will determine the formation of gullies.

The channels surrounding the mines become obstructed with sediments, turning generally dustier and less resilient. Cinder stacks surrounding it may lead to mass movements or generate a great amount of incohesive material susceptible to be gullied. Its control is complicated since the plantation and natural fixation of the more frequent species, as a strategy of soil protection, may reveal difficult. These areas should be object of conservation works so as to mitigate the erosive processes, especially gullies, such as (i) to avoid soils to be perturbed by cars, (ii) plan the areas turned bare by the mines and/or accumulation of waste by harvesting aerodynamically wrinkled surfaces, (iii) treatment of harmful waste, bearing them or diluting them.

A very similar process takes place in stone pits and landfill sites, which besides problems related with gullies, also originate rockfalls, solifluction flows such as mudflows with more or less impact on the territory.

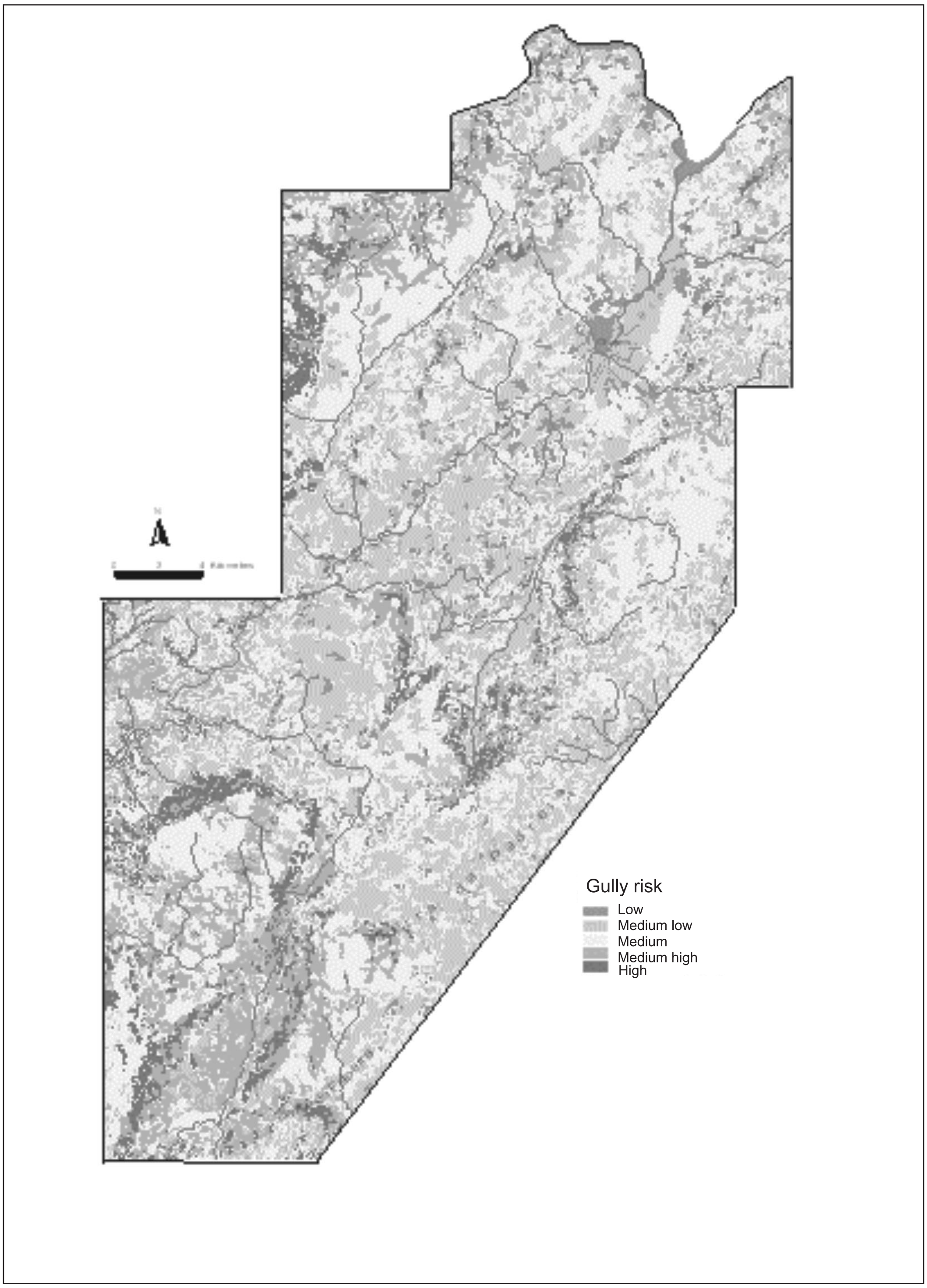

FIGURE 5. Gully risk map produced from the index $_{Igully}$

CONCLUSION

The occurrence of forest fires contributes very intensely to the disruption of the dynamic balance of the territory, contributing to the development of certain erosive processes, which generally harm the soils. One of the most effective processes in terms of land loss is gullying. Gullies, besides contributing to significant land loss, are very difficult and expensive to control.

Geographical Information System is a very important tool for the definition of highly susceptible areas to gullying. Gully risk prone areas should naturally be protected so as to mitigate the consequences of the processes.

The methods used in mapping require the development of a dynamic database as far as land use and vegetal coverage are concerned. Adjusting the models to reality should also be extremely thorough. Forest fires' impact on the hillslopes has been increasing in Portugal and in particular in Northern Portugal. Mapping burned areas and the inclusion of these areas in the models are fundamentally a demand and an essential element for land planning and management.

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