EVALUATION AND PREDICTABILITY OF TERRAIN SUSCEPTIBILITY TO HILLSLOPE EROSION AT THE REGIONAL SCALE USING DEM-DERIVED INDICES AND REMOTELY SENSED INFORMATION

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Soumis le 15 décembre 2006 ; révisé le 23 avril 2007 ; accepté le 12 juillet 2007- © *Revue Télédétection*, 2007, vol. 7, n° 1-2-3-4, p. 373-391

UTILISATION D'INDICES DÉRIVÉS D'UN MNA ET DE L'INFORMATION EXTRAITE DE L'IMAGERIE DE TÉLÉDÉTECTION POUR L'ÉVALUATION ET LA PRÉDICTION DU RISQUE D'ÉROSION HYDRIQUE À L'ÉCHELLE RÉGIONALE.

Résumé

La dégradation des milieux naturels et l'érosion du sol sont le résultat des interactions entre divers facteurs environnementaux, tels que la végétation, la topographie, le sol, la roche mère, les précipitations, le drainage et l'utilisation des terres. Dans le cas de l'érosion hydrique, la topographie exerce une influence majeure sur l'état et la dégradation du sol ainsi que l'importance de cette dégradation, parce que l'énergie du ruissellement et son intensité sont contrôlés par les attributs topographiques que sont le gradient de pente, la courbure de la pente et l'aire de drainage. Des combinaisons de ces attributs (indices hydrologiques) sont utilisées comme indicateurs des conditions de drainage, de l'agressivité de l'écoulement de surface et du potentiel d'érosion. Dans cette recherche, on examine l'utilisation conjointe de la télédétection et d'un modèle numérique d'altitude (MNA) pour évaluer la susceptibilité à l'érosion hydrique induite par les processus de pente en général et les phénomènes reliés au ruissellement en particulier. L'approche adoptée consiste à combiner les attributs géomorphométriques, dérivés du MNA, et l'information spectrale, extraite des images satellitaires, afin de définir un ensemble d'indicateurs, spectraux et topographiques, des processus de dégradation. Les résultats démontrent que l'utilisation combinée des attributs topographiques et des indices hydrologiques a permis d'obtenir une cartographie de la répartition des patrons régionaux du risque d'érosion hydrique. Cette approche a abouti à la segmentation du paysage en unités de risque en fonction de la lithologie, de la végétation et de la susceptibilité à l'érosion hydrique.

Mots clés : dégradation du sol ; susceptibilité à l'érosion ; indices hydrologiques ; déconvolution spectrale ; unités de réponse à l'érosion.

Abstract

Land degradation and soil erosion are the result of interactions between various watershed environmental factors such as vegetation, soil, topography, parent material, drainage, rainfall and land use. In the case of water erosion, topography controls the status and magnitude of soil erosion. Topographic attributes such as slope gradient, curvature, and upslope contributing area are critical to the assessment of overland flow intensity and energy. Moreover, some combinations of these factors (hydrologic indices) can be used as indicators of drainage status, overland flow aggressiveness, and erosion potential. The present paper investigates the use of digital elevation model (DEM) analysis and remote sensing techniques to characterize hillslope processes. The main objective is to evaluate the potential of

geomorphometric variables and remotely sensed information to assess ecosystem fragility and its susceptibility to water erosion. The methodology adopted uses an integrated approach that combines geomorphometric variables, derived from a DEM, and spectral information, provided by remote sensing images, in an attempt to define a set of indicators (spectral and topographic) of geomorphic processes and land degradation. The results demonstrate that the spatial distribution of regional patterns of water erosion risks can be reliably mapped by the combined use of geomorphometric attributes and hydrologic indices. Moreover, landscape-unit analysis shows that DEM variables combined with spectral information are very useful for the evaluation of land degradation. This approach allowed us to segment the landscape into different units according to lithology, vegetation characteristics, and susceptibility to water erosion.

Keywords: Land degradation ; erosion susceptibility ; hydrologic indices ; response unit ; spectral unmixing.

1. INTRODUCTION

During the last decades it has been widely agreed that the knowledge of the spatial distribution of key landscape variables is sufficient to capture important physical responses of watersheds. These are hydrologic units that correspond to an agglomeration of geographical units (sub-basins, terrain-based units) differentiated in terms of their ground conditions and their hydrological responses. They constitute physical-biological units that are vulnerable to various processes, whether natural or human-induced, that may result in serious damages of soil and vegetation resources. These damaging effects can be induced by various hazardous phenomena such as water erosion, landslides, forest fires, deforestation, mismanagement, and overexploitation of natural resources. When the vegetation cover is removed, soils have less protection against raindrop impact and runoff energy, thereby becoming susceptible to the loss of organic and mineral particles. So-called soil degradation limits vegetation growth and, therefore, favours land degradation and desertification processes. To address these problems, several models have been developed and various approaches have been proposed (Moore *et al*., 1993 ; Bishr and Radwan, 1995 ; Gessler *et al*., 1995 ; Hill *et al*., 1995 ; Lacaze *et al*., 1996 ; MEDALUS, 1995 ; Mitasova *et al*., 1996 ; Thornes *et al*., 1996). Previous research programs [e.g, DeMon (Desertification Monitoring) and MEDALUS (Mediterranean Desertification and Land Use)] have demonstrated that quantitative determination of vegetation conditions and soil development status constitute key indicators for the assessment of degradation processes and risks (Lacaze *et al*., 1996 ; Sommer *et al*., 1998). These have stated that the major issue is to identify indicators for land degradation-desertification that have general applicability and that can be observed with operational remote sensing systems. This is the objective with respect to the degradation of the permanent semi-natural vegetation and the erosional status of soils. Water erosion is an important source of soil deterioration that, together with the destruction of the vegetation cover, contributes to the increase of desertification in arid and semi-arid lands. Accordingly, regional degradation indicators can be produced from physically-based models integrating factors of climate, topography, soil, erosion processes, and vegetation cover.

Recent work has tended toward using geographic information system (GIS) approaches to model erosion-deposition risks for landscape-scale applications. They consist of:

- various modifications of the Universal Soil Loss Equation (USLE) (Flacke *et al*., 1990 ; Huang and Ferng, 1990) ;

- models based on the unit stream power theory (Moore and Wilson, 1992 ; Mitasova *et al*., 1996 ; Desmet and Govers, 1997 ; Mitasova *et al*., 1997) ;

- topographic methods for prediction and mapping of substance motion along land surface and in soil (Florinsky, 1995).

The common underlying hypothesis of these approaches is that both soil development and soil degradation occur in response to the way water moves through and over the landscape. Water migration and accumulation are in turn controlled by the topography (surface geometry) and the underlying parent materials (permeability). Therefore, land surface geometry can be used for predicting water motion and substance migration in the landscape (Moore *et al*., 1991 ; Dymond and Harmsworth, 1994 ; Gessler *et al*., 1995). Moreover, soil-landscape studies explore the relations between hillslope processes, topographic attributes, and soil development. They focus on the potential for correlating soil conditions with measurable and meaningful terrain and environmental attributes. The determination of the spatial distribution of soil attributes is relevant information for environmental modelling and management. It helps to define actions to mitigate soil degradation and to determine management practices for soil conservation.

To this end, identifying and mapping terrain units that are sensitive to soil degradation are important given their lithological properties, their vegetation cover characteristics, and their geomorphometric attributes. In this framework, soil scientists rely on their knowledge of soil-vegetation-relief-hydrology interactions and associations to derive soil types and soil-landscape features. With the development of geomatics technologies (GIS, remote sensing, global positioning systems), such an approach can be implemented through a combined analysis of digital elevation models and remotely sensed data.

The overall objective of this paper is to provide a summary of an integrated approach developed for predicting areas at risk of land degradation in a semi-arid Mediterranean environment and to report on the comparison of its results with field observations and cartographic documents. The methodology adopted is based on a combined analysis of spectrally-derived information and geomorphometric variables in an attempt to define regional indicators of geomorphic processes and land degradation. Terrain analysis of DEM data reinforces the interest of integrating spatial topographic attributes with composite topographic indices to characterize the hydrologic behaviour of terrain units and to understand its effects on landscape evolution. Topographic variables quantify the contextual nature of points and characterize the spatial variability of processes affecting the landscape. They are the major factors controlling the direction and the intensity of hillslope-hydrologic processes. The latter are responsible for landscape exposure to degradation risks by water erosion. This allows us to determine the ecosystem fragility and to evaluate its susceptibility to degradation and desertification processes. This paper presents and discusses results in connection with the following issues : 1) use of digital geomorphometric attributes for the characterization of hydrologic and hillslope processes, 2) contribution of remotely sensed data to derive some geo-ecological parameters of semi-arid ecosystems, and 3) assessment of potential erosion and terrain susceptibility to land degradation.

2. BACKGROUND

Land degradation processes result from complex interactions between agents of climate, hydrology, geology, soils, vegetation, relief, and human activities. While only a few of these parameters are directly measurable, remotely sensed data combined with DEM have been demonstrated to provide useful surrogate indicators of geomorphologic processes affecting the landscape (Pickup and Chewings, 1988 ; Hill, 1993a ; McDermid and Franklin, 1994 ; Pickup and Chewings, 1996). In fact, vegetation abundance can be measured with relative ease using remote sensing techniques and spatially distributed models for superficial hydrologic and erosion processes are heavily related to topographic indices. Given the close connection between vegetation cover, hydrologic behaviour, and erosional processes, a relationship should exist between topographic attributes and terrain susceptibility to water erosion and therefore land degradation risks. Accordingly, relief has been shown to play a central role in geomorphic activity in semiarid environments, namely through its influence on moisture availability, vegetation growth, soil development, and the erosion process (McDermid and Franklin, 1994; Pickup and Chewings, 1996). Therefore, we will examine the effects of topography on some environmental parameters that are relevant to understanding and conceptualising land degradation processes. We also propose a brief introduction to the linear mixture modelling used to infer information on vegetation and soil conditions.

2.1. Topographic effects on some environmental parameters and processes

Relief is one of the major factors that heavily influences landscape development. Topography exerts its control on soil properties (Moore *et al*., 1993), on microclimate and vegetation distribution (Frank and Isard, 1986 ; Peddle and Duguay, 1995), and on runoff and moisture availability (Moore *at al*., 1991 ; Pickup and Chewings, 1996 ; Wood, 1996). Current understanding of the principles of landscape evolution and physically-based field studies have emphasised the multivariate nature of geomorphic processes and their complex relationship with the topographic and lithologic contexts (Franklin *et al*., 1990).

2.1.1. Effect on vegetation cover

Climatic variables are critical factors that govern vegetation patterns in mountainous regions. The factors of precipitation, temperature, wind, snow distribution and insolation contribute to complex interactions among physical processes that control the moisture regime and, ultimately, vegetation growth and distribution (Peddle and Duguay, 1995). These climatic and microclimatic factors are controlled, in many respects, by topographic attributes such as elevation, slope, aspect, and curvature. Consequently, relief becomes an important controlling factor on the availability of soil moisture that affects the nature and distribution of vegetation in mountainous landscapes. In such environments, terrain slope controls flow velocity and drainage conditions; elevation determines the altitudinal zonation of vegetation and soils; while aspect controls flow directions, insolation, evaporation rates, and snow melting (Moore *et al*., 1993 ; Peddle and Duguay, 1995).

In semi-arid environments, vegetation growth is moisture limited and nutrient availability dependant. Soil moisture is a function of rainfall and evaporation but is also influenced by runoff, which is a function of topography and lithology. Soil type and nutrient availability are controlled by topographic factors and hydrologic processes that determine the spatial distribution of depositional and eroding areas in the landscape. In fact, accumulation zones are more suitable to vegetation growth than denudation zones (Pickup and Chewings, 1996). Therefore, relief affects vegetation growth and distribution through its influence on moisture availability and local microclimate and, ultimately, through its control over hydrologic and erosion processes. For instance, in south eastern Spain, where the study area is located, terrain aspect plays a major role in the distribution of natural and semi-natural vegetation cover. Topographic aspect controls terrain exposure to solar radiation and the duration of insolation: hillslopes facing south and southeast are more exposed

to solar radiation than those facing north and northwest. Consequently, dense vegetation covers are encountered on the slopes facing north and northwest while only shrubs and semi-arid vegetation grow on slopes facing south and southeast because of the high evapotranspiration rates.

2.1.2. Runoff and soil moisture

Water balance varies spatially over the landscape because of the variability of runoff and water flow in the saturated zones of soils, both of which are a function of local topographic attributes: terrain slope and curvature. Consequently, upslope areas shed quickly the surplus water, while downslope areas gain water from upslope and may not shed it quickly. The latter corresponds to the watershed regions with higher plant-available moisture levels, resulting in more herbage and, frequently, more woody vegetation cover (Pickup and Chewings, 1996). The key topographic parameters controlling overland and in-soil water flows are drainage area, local slope, horizontal curvature, and vertical curvature. However, some combinations among these factors can be used as approximate indicators of soil saturation and, therefore, subsequent surface flow importance. Indeed, Beven and Kirkby (1979) proposed the topographic index (combination of drainage area and slope) as an indicator of soil water distribution and saturation zone location in the watershed, assuming a uniform soil transmissivity. This combined topographic characteristic represents a theoretical estimation of flow accumulation and is connected with soil moisture content (Quinn *et al*., 1991), thickness of soil profile horizons, organic matter content of soils (Moore *et al*., 1993), and potential erosive power of overland flow (Moore *et al*., 1988).

2.2. Spectral mixture analysis of remotely sensed imagery

Image classification techniques, relying on Bayesian statistics, assume pixels to be pure and the areas they represent to be homogeneous and of unique landcover. This is often a false assumption, especially in arid and semiarid environments where the landscape fabric is characterized by both heterogeneity and discontinuous surface cover. In such areas, classification maps will often be a poor representation of reality (Settle and Drake, 1993) because of the imprecise geographical information. Spectral mixture modelling is an alternative approach for representing these environments and extracting information from their corresponding scenes. The objective is to model the pixel reflectance signature as a mixture of a few prototype spectra, called endmembers, through the decomposition of each ground resolution element into its constituent cover components (Hill, 1993a ; Williamson, 1994). The approach includes several assumptions (Adams *et al*., 1989 ; Hill, 1993a ; Settle and Drake, 1993): 1) within a pixel, the resulting spectrum is an additive mixture of the spectra of all cover components in the corresponding ground resolution element, which presupposes that there is no significant amount of multiple scattering between the different cover types; 2) all cover components have sufficient spectral contrast, allowing their separability, and 3) most of the spectral variations in remote sensing images are the result of mixtures of a limited number of surface materials (e.g, vegetation, soil, rock, shade).

Spectral mixture modelling presumes that, according to their proportion in the ground resolution element, the endmembers commonly mix at sub-pixel scale, producing mixed-pixel spectra. Thus, as a first approximation, the expected spectral value of a mixed pixel may be modelled as a linear combination of pure component spectra (endmembers) such that:

$$R_i = \sum_{j=1}^{n} F_j \, RE_{ij} + \varepsilon_i \qquad and \qquad \sum_{j=1}^{n} F_j = 1 \tag{1}$$

where:

R_i is the reflectance of the mixed pixel in band i,

RE_{ij} the reflectance of the endmember j in band I,

F_j denotes the fraction (abundance) of the pixel area covered by the endmember j,

ε_i is the residual error in band i.

These linear mixture equations will have a unique solution on condition that the number of endmembers is equal or less than the number of bands plus one. Endmembers could be selected in different ways by extracting spectral signatures from the image itself, convolving selected field spectral measurements to match the bandset of the sensor used, or selecting reference spectra from laboratory spectral libraries (Adams *et al*., 1989 ; Hill, 1993a).

As the unmixing procedure aims to retrieve the spectral contributions of the main cover components responsible for the spectral variability of the scene, it involves estimating the fractions F_j, given the observations R_i. This can be performed by inverting Eq. 1 using a least-squares regression with the following constraint: the sum of the fractions F_j must be

equal to one. The quality and suitability of the mixing model can be analyzed by computing the following average root-mean-squared (RMS) error:

$$RMSE = \sum_{k=1}^{m} \left(\sqrt{\left(\sum_{j=1}^{n} (R_{jk} - R'_{jk})^2 \right) \frac{1}{n}} \right) \frac{1}{m} \qquad (2)$$

where:

R_{jk} and R'_{jk} refer, respectively, to the modelled and the measured reflectances of a pixel,

m denotes the number of pixels within the image,

n the number of spectral bands.

The resulting RMS image provides an intrinsic means of quantifying the accuracy of the unmixing process and fitness of the mixing model. It measures how much of the spectral variability of the scene has been explained (modelled) by the retained endmembers. This modelling adequacy analysis can be reinforced through a careful examination of the wavelength dependent band residuals that are calculated by subtracting the modelled reflectance in each spectral band from the sensor measured reflectance (Hill, 1997). These intrinsic controls provide important diagnostics for handling uncertainties for the spectral unmixing and its optimisation.

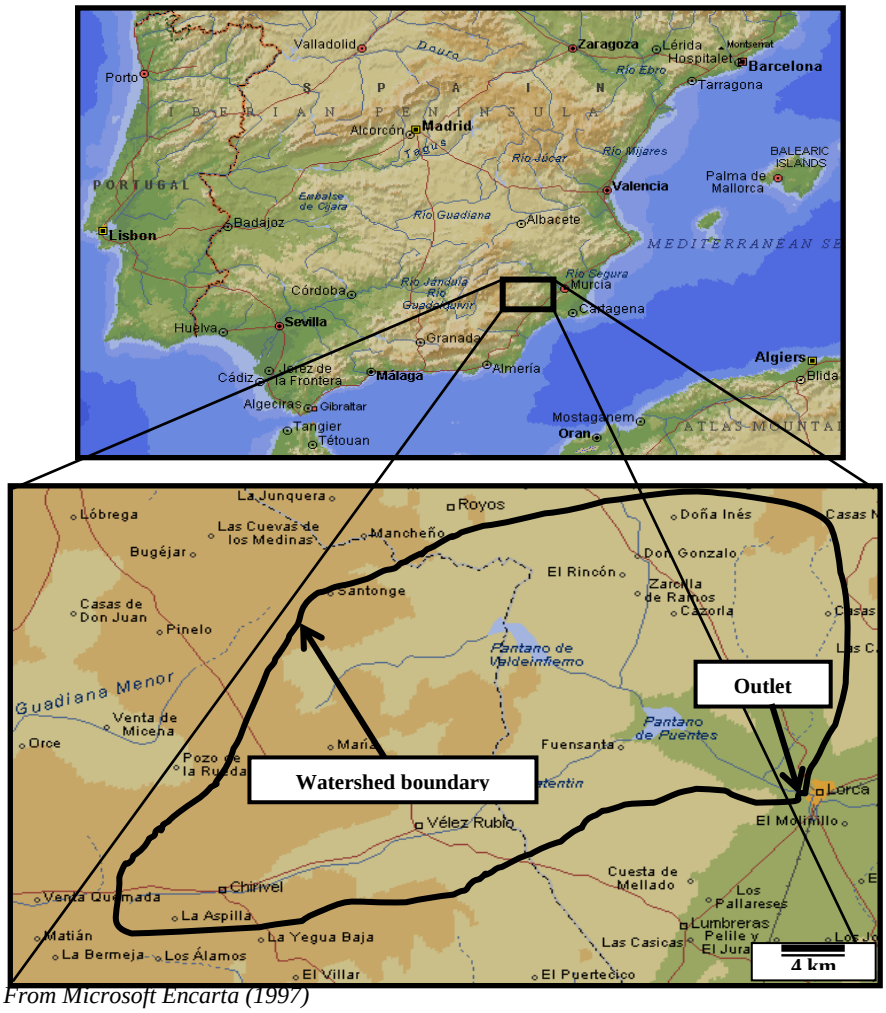
3. STUDY AREA AND DATA SOURCES

3.1. Geographical setting

The Guadalentin River basin, located in southeastern Spain, presents typical characteristics of Mediterranean landscapes vulnerable to land degradation processes and desertification risks (figure 1). It is one of the MEDALUS (Mediterranean Desertification And Land Use) sites chosen for continued intensive monitoring of land degradation and desertification in the Mediterranean region (MEDALUS, 1995). It has a semiarid climate with precipitation ranging between 260 and 400 mm, a mean temperature of 17 °C, and altitudes ranging between 260 and 2 036 m. These climatic conditions exert a strong influence on the vegetation cover, which is low and of various types, and control land-use types that are divided into semi-natural dispersed forests, shrubland, abandoned agricultural land, and agricultural land with various types of crops such as cereals and fruits. The natural vegetation of this region has been substantially modified during several thousand years of human activity, such that almost all remaining permanent vegetation represents degraded forms of mixed Mediterranean forest. Moreover, its growth conditions are constrained by the coincidence of high temperatures and a severe shortage of water in summer months (Hill *et al*., 1995). These forests are rather vulnerable to further destruction, mainly by the environmental impact resulting from interactions between drastic climatic characteristics and human interventions.

Geologically, the basin is located in the eastern sector of the Cordilleras Beticas, which are part of the western segment of the European Alpine Belt (Melia *et al.*, 1993). It is divided into two structural domains, the external and internal zones, differentiated by their paleogeographic and tectono-metamorphic evolution. Overlying these units, a filling material of the post-nappe basins developed after the upper Miocene. The external zone consists of sedimentary units dominated by carbonates and marls. It includes many lithological units including gypsum, clay, marls, limestones, dolomites among others. Exposed bedrock covers about 75 % of the river basin. The internal zone, which covers the southern part of the study area, consists of schists including different lithological units dominated by silicate and carbonate materials, namely quartzites, conglomerates, phyllites, limestones, and dolomites. The Quaternary deposits are made up of clays, sands, conglomerates, and calcareous crusts of small extent (Melia *et al.,*1993).

The two structural domains constitute two physiographic regions : the Palaeozoic sector in the south and the Meso-Cenozoic sector in the north. The limit between them is the geological boundary between Palaeozoic and post-Palaeozoic geological units. It coincides with a geological fault oriented SW-NE along the Chirivel-Corneras River (figure 1). As soil is derived from the underlying parent rock and landforms are defined by the lithology of geological materials, the boundary delineates the demarcation between two primary geobotanical zones that are different in respect to the following characteristics : geology, geomorphology, relief, vegetation types, soils, and hydrologic behaviour.



From Microsoft Encarta (1997)

Figure 1 : Geographical location of the study area. *Localisation de la zone d'étude*

3.2. Data

Three types of data were collected for this research: spectral data (including field reflectance spectra of natural materials and satellite optical imagery), a digital elevation model (DEM), and cartographic material (including geological and topographic maps).

Spectroradiometric field measurements were performed in June 1994 by the EGEO (Environment and Geoinformation) team at the JRC (Joint Research Centre) as part of the MEDALUS project. These were collected to provide spectral endmembers for the spectral mixture analysis and to construct a library of reference spectra representing the major surface components of the Guadalentin River basin, namely different soil conditions (developed, degraded, etc.), varied rock types (carbonates, marls, schists, etc.), and various vegetation states (green, dry, grey wood, etc.). The reflectances were measured with a GER-IRIS spectroradiometer of the EGEO Unit. Designed for bi-directional reflectance measurements, the instrument measures 900 wavelength channels between 400 nm and 2 500 nm, with bandwidths of 1.5 nm in the visible and near infrared (VIS-NIR) and 4.8 nm in the short-wave infrared (SWIR).

Field spectral data were used for modelling and interpretation of remote sensing imagery that consists of two cloud-free Landsat Thematic Mapper (TM) images acquired July 1st, 1989, and July 25, 1992, with the following solar illumination conditions: 63° elevation and 115° azimuth, and 59° elevation and 118° azimuth, respectively. They were purchased as "system processed" products from the Earthnet Program Office (EPO) of the European Space Agency (ESA). As atmospheric conditions were unknown at the time of image acquisitions, the "dark-object" approach developed by Kaufman and Sendra (1988) was used to correct atmospheric effects on image radiometry.

In order to perform the rectification of geometric distortions and the radiometric correction of topographically induced effects on the images, a DEM was generated by stereocorrelation of SPOT HRV panchromatic stereopairs (pixel size 10 m by 10 m). It served to compute geomorphometric attributes (slope, aspect, curvature, upslope contributing area) and hydrologic indices (water power index and topographic index). These variables were used first to perform the combination of elevation data with satellite images in an integrated atmospheric and topographic correction approach,

and second to integrate spectral data and geomorphometric attributes in an attempt to define and identify units of susceptibility to water erosion.

4. METHODOLOGY

The methodology adopted in this research involved five major stages : 1) processing of DEM data to derive digital geomorphometric attributes and hydrologic indices, 2) landscape evaluation in terms of hydrologic and geomorphometric analysis, 3) pre-processing steps including orthorectification and radiometric corrections of satellite images, 4) spectral mixture analysis of the original images, and 5) integration of spectral information and DEM-derived indices to identify areas susceptible to water erosion.

4.1. Topographic attributes and hydrologic indices

The digital geomorphometric attributes were computed from the DEM as local topographic characteristics represented by slope α, vertical curvature *kv*, and horizontal curvature *kh*. They were determined as functions of the following partial derivatives of altitude values *z* with respect to the Cartesian plan coordinates x and y (Zevenbergen and Thorne, 1987 ; Florinsky, 1998):

$$\frac{\partial^2 z}{\partial x^2};\ \frac{\partial^2 z}{\partial y^2};\ \frac{\partial^2 z}{\partial x \partial y};\ \frac{\partial z}{\partial x}\ and\ \ \frac{\partial z}{\partial y} \qquad (3)$$

Curvatures are related to land surface concavity and convexity. They control the relative acceleration or deceleration of overland flow (vertical curvature) and its relative convergence or divergence (horizontal curvature). Concerning the hydrologic indices, they include secondary topographic attributes involving the combination of the slope and the specific catchment area A_s (watershed area discharging to the point in question, also called upslope drainage area). The computation of A_s over a square-gridded DEM was performed through the use of the multiple-flow algorithm developed by Desmet and Govers (1997). It divides the flow out of a cell between several receiving cells by taking into account the parameters of slope and aspect and then considering parallel, convergent, and divergent flows.

Then, for a particular cell within the DEM, the compound topographic index (*CTI)* and water power index (*WPI)* are given by the relations below (Moore *et al*., 1993 ; Dymond and Harmsworth, 1994):

$$CTI = ln(A_s / tan(\alpha)) \qquad (4)$$

$$WPI = ln(A_s * tan(\alpha)) \qquad (5)$$

These are related to the processes of water motion and substance migration. *CTI* characterizes drainage conditions and potential soil moisture, while *WPI* underlines areas susceptible to water erosion. They contribute to determine the topographic potential for erosion and runoff power of a landscape, especially *WPI,* which is a measure of the potential erosive power of overland flow.

4.2. Spectral characterisation of land units

The spectral decomposition of the original image was performed by linear spectral mixture modelling in order to discriminate ground cover proportions at a sub-pixel level. The model is constrained to ensure that the fraction of any endmember lies between 0 and 1, and the sum of fractions for each pixel is equal to 1 (Adams *et al*., 1989 ; Smith *et al*., 1990). Thus, we used reference spectra selected from field measurements and a “shade” endmember accounting for shadows and variations in lighting. For this purpose, we defined a reference “shade” as the reflectance of an ideal black surface (Radeloff and Mehl, 1997). As shading and shadowing caused by the topography was modelled and removed through the combined atmospheric and topographic correction, the “shade” represents the shadow effects of the vegetation cover.

The results of the spectral unmixing consist in the following outputs: 1) an abundance image (fraction image) for each endmember giving the relative proportion of a surface component at every pixel, 2) a root-mean-square (RMS) image

providing a measure of how much the spectral variability within the scene was modelled by the selected endmembers, and 3) six images representing the wavelength-dependent residuals in the six TM channels involved in the unmixing procedure. Band residuals indicate image regions where the model, using a particular group of endmembers, is deficient, thus leading to discard and/or add new endmember(s) to improve the mixture modelling. The error distribution analysis is based on the RMS image, which was reclassified into the following error ranges: 0-0.5 %, 0.51-1.5 %, 1.51-5 %, and > 5 %. We note that in more than 95 % of the study area, the resulting error is less than 1.5 %. In 18 % of the area, endmembers were mapped with an error of ≤ 0.5 %. The error magnitude is close to the signal/noise specification of Landsat TM, values of which are 0.6 % in the visible and 1.7 % in the infrared (Hill, 1993b).

4.3. Contribution of topographic information: Geomorphometric homogeneous units

Many physical processes operating in the landscape are dependent on terrain geometry. Topography is the major factor that controls water flow directions and substance motion both over the terrain-surface and within the soil by gravity. It therefore significantly affects the processes of runoff and erosion, which are the most important causes of land erosion. Hydrologists and geomorphologists have long recognized the importance of studying the effects of topography and landforms on hydrologic and sedimentary processes. Consequently, the use of DEM for the description of surface geometry offers the opportunity to automatically characterize, within certain limits, these hillslope processes. In Mediterranean regions, erosional and runoff events are sporadic and intense, their effects difficult to predict, and their impact difficult to foresee (Thornes *et al*., 1996). For these reasons, we propose a simplified approach to characterise erosion potential and runoff power through the combined analysis of topographic attributes and DEM-derived hydrologic indices.

4.4. Unit concept and notion of risk

The notion of terrain unit is an important aspect for various disciplines that attempt to model interactions and interrelations between the processes and components of a landscape. Spatial modelling often faces the problem of defining elementary dynamic units having similar behaviour in terms of response to a particular process under study. The concept itself and its defining criteria depend, to some extent on the interests and the aims of the research. In the context of landscape ecology, these units should be geographical units differentiated from their adjacent in terms of physical, biological, and hydrological conditions. The thorny problem arises from the complex relationships between different environmental components that respond, with different sensitivities and intensities, to external events. Therefore, the definition of a landscape (terrain, environmental, hydrologic, etc.) unit is an issue open to considerable debate, especially when questions involving scale and data type and source are considered. In accordance with our objective of mapping environmentally sensitive areas, the landscape unit definition will focus on the criteria of vulnerability and sensitivity of soil and vegetation to hydrologic and geomorphic processes. Therefore, in the context of this research, homogeneous response units are based on the spatial homogeneity of the following components : 1) physiographic characteristics together with related hydrologic processes, 2) soil and parent material vulnerability, and 3) vegetation cover density as a protective factor for soils.

Consequently, from the remote sensing point of view, a landscape unit is a portion of an image having a uniform pattern generated through constant arrangements of image components (Deroin *et al*., 1990). Based on this concept, we used abundance fractions resulting from spectral unmixing analysis to determine the spatial distribution of homogeneous landscape units according to their lithological nature of parent material, soil development, and vegetation cover density. The same approach was implemented to infer the spatial distribution of potential hydrologic response units by considering only DEM-derived indices and attributes.

The above definition is a static approach that belongs to the domain of observation and survey. It describes soil conditions and vegetation status (partial ecosystem condition) as observed at the time of data acquisition. Therefore, it represents surface conditions at a given time. However, to study and understand ecosystem behaviour and functioning, a need exists to model ecosystem evolution under potential external disturbances, such as natural events and human activities. For this purpose, predictive modelling will help in discerning the ecosystem response to changing extraneous conditions. This leads to introducing the notion of risk, which belongs to the “theoretical” domain of modelling and simulations. Risk evaluation consists in, first, modelling the response of the environment, or a part of it, to changes in external factors and phenomena; and, second, predicting the evolution of its status under given external conditions. In the context of land degradation, the objective is to evaluate the degradation status of a given terrain unit subject to known processes.

Because the nature of the data used in this study is not appropriate for statistical and probabilistic processing, the term *susceptibility* is preferred to the word *risk*. Consequently, mapping terrain susceptibility to land degradation is based on the following considerations :

- sensitivity of lithological units to erosion by water (erodibility) ;
- role of vegetation cover density in protecting soils and substrate materials against rain erosivity ;
- aggressiveness of hydrologic processes evaluated in terms of relief energy and potential runoff.

5. RESULTS

5.1. Curvature analysis

Horizontal and vertical curvatures, *Kh* and *Kv*, are topographic attributes that describe terrain geometry in terms of concavity and convexity. They enable the evaluation of topographic effects on land surface flow direction and its intensity. Areas where both *Kh* and *Kv* are positive are subject to denudation and substance removal, while areas with negative *Kh* and *Kv* are zones where accumulation and deposition will take place. When *Kh* and *Kv* have opposite signs, the corresponding areas are assumed to be transit zones (Florinsky, 1995). The Guadalentin DEM was used to infer these topographic variables and, therefore, to map watershed areas at risk of denudation (erosion), transit (sediments transport), and accumulation (sediment deposition). Results are illustrated in figure 2 where we note that denudation (blue) affects hillslopes and transit (yellow) occurs along thalwegs and streams, while accumulation (orange) takes place in floodplains and pediments. These distinctive zones of the landscape represent homogeneous response units to water overland flow and, therefore, to its potential erosive power and transport capacity.

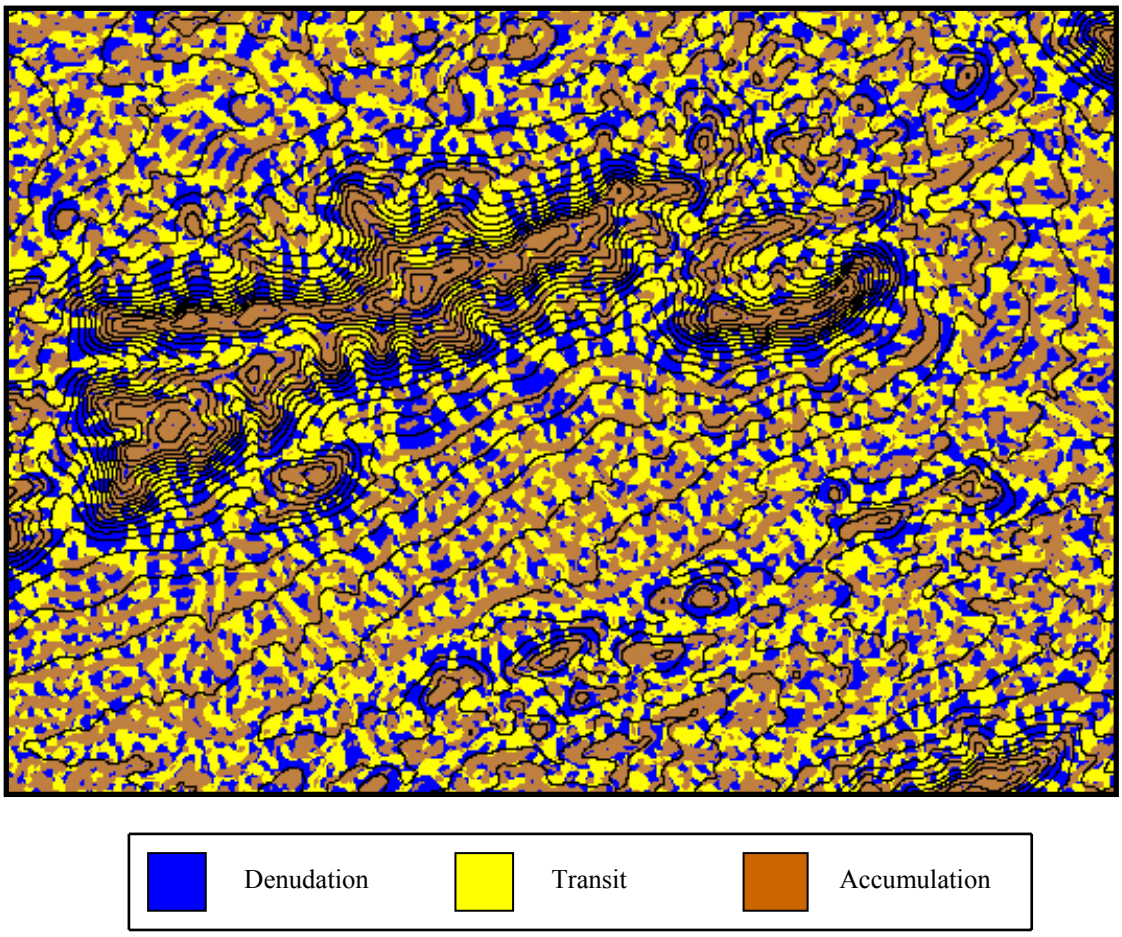


Figure 2 : Image of erosion potential with superposition of topographic contours (interval of 20 m), for a sub-area (south-west) of the Guadalentin basin, representing potential areas of denudation (blue), transit (yellow), and accumulation (brown). It is obtained by classification and analysis of vertical and horizontal curvatures. Image of approximately 22 km by15 km. *Image du potentiel d'érosion, avec superposition des courbes de niveau (intervalles de 20 m), d'un secteur dans le sud-ouest du bassin de la Guadalentin, représentant les zones potentielles de prélèvement (bleu), de transit (jaune) et de sédimentation (marron). Elle est obtenue au moyen de la classification et de l'analyse des courbures verticale et horizontale. Image d'environ 22 km par 15 km.*

This approach has the advantage of helping to understand and predict water and substance motion in the landscape. Consequently, it offers the possibility of controlling the motion of those materials causing soil salinization in accumulation zones and to assess risks of soil erosion over denudation areas (Florinsky, 1995). However, based on the data used in this study, the approach presents certain limitations, two of which are summarised below:

- thalwegs with steep slopes (figure 2) are identified as transit zones; this is not consistent with the theoretically expected effect of runoff in such areas ; in fact, thalwegs and streams with steeper slopes should be determined

as areas at risk of heavy erosion, owing to flow concentration (sufficient volume of runoff) and presence of sediments in water ;

- the approach does not allow identification of more than three groups of hydrologic response units.

The approach is based on the analysis of convergence/divergence mechanisms and acceleration/deceleration processes. Because it considers only two surface descriptors, concave and convex, the method remains qualitative and does not measure the magnitude of concavity/convexity that largely controls the increase/decrease of overland flow power (by determining runoff volume). For instance, a curvature with low concavity (*Kh* or *Kv* negative) and a curvature with a low convexity (*Kh* or *Kv* positive) represent two similar surface shapes. Using this approach, these surfaces are determined as two distinct hydrologic response units rather than units having almost identical hydrologic behaviour. Moreover, the approach does not consider key topographic parameters having a major influence on surface runoff and its power: slope and upslope contributing area per unit length of contour (A_s). In fact, for a given slope, the method assumes runoff effects to be the same for different points regardless of the upslope watershed area discharging to those points. This is not in agreement with the hydrologic mechanisms of water concentration and flow discharge.

5.2. Incorporation of hydrologic indices

With the purpose of defining terrain units with similar hydrologic behaviour, we used topographic attributes that quantify the contextual nature of points and characterize the spatial variability of hydrologic processes occurring in the landscape, namely horizontal and vertical curvatures, topographic index *CTI,* and water power index *WPI*.

An automatic classification of these attributes leads to 14 classes that were regrouped into five homogeneous units of dynamic response to hydrologic processes (table 1). The regrouping was performed on the basis of the average characteristics of the topographic attributes, especially *WPI*, *Kh*, and *Kv*. They were qualified in terms of surface flow aggressiveness: very low, slight, moderate, severe, and very severe, as shown in table 1 and figure 3.

Table 1: Erosion severity levels determined by cluster analysis of geomorphometric attributes and hydrologic indices. Classes were obtained through an unsupervised clustering involving the following parameters: vertical and horizontal curvatures, water power index, and topographic index. *Niveaux de sévérité de l'érosion obtenus par regroupement des attributs géomorphométriques et des indices hydrologiques. Les classes ont été générées au moyen d'une classification non dirigée des paramètres suivants : courbures verticale et horizontale, indice d'énergie d'eau et indice topographique.*

Class	Water power index	Topographic index	Vertical curvature	Horizontal curvature	Overland flow aggressiveness
2	2.74	5.36	- 0.14	0.30	Very low
1	1.46	5.67	- 0.11	0.24	Very low
3	0.66	7.01	- 0.06	0.12	Very low
5	2.22	7.48	0.00	0.02	Slight
6	2.94	6.84	0.02	0.01	Slight
4	3.04	5.87	0.01	0.07	Slight
7	3.22	9.04	0.01	0.00	Moderate
10	3.12	8.84	0.02	- 0.04	Moderate
9	3.93	8.09	0.05	- 0.08	Severe
13	3.76	10.67	0.04	- 0.09	Severe
12	4.88	9.75	0.05	- 0.11	Severe
8	4.90	7.02	0.09	- 0.12	Severe
14	6.43	10.37	0.08	- 0.17	Very severe
11	5.58	8.59	0.10	- 0.18	Very severe

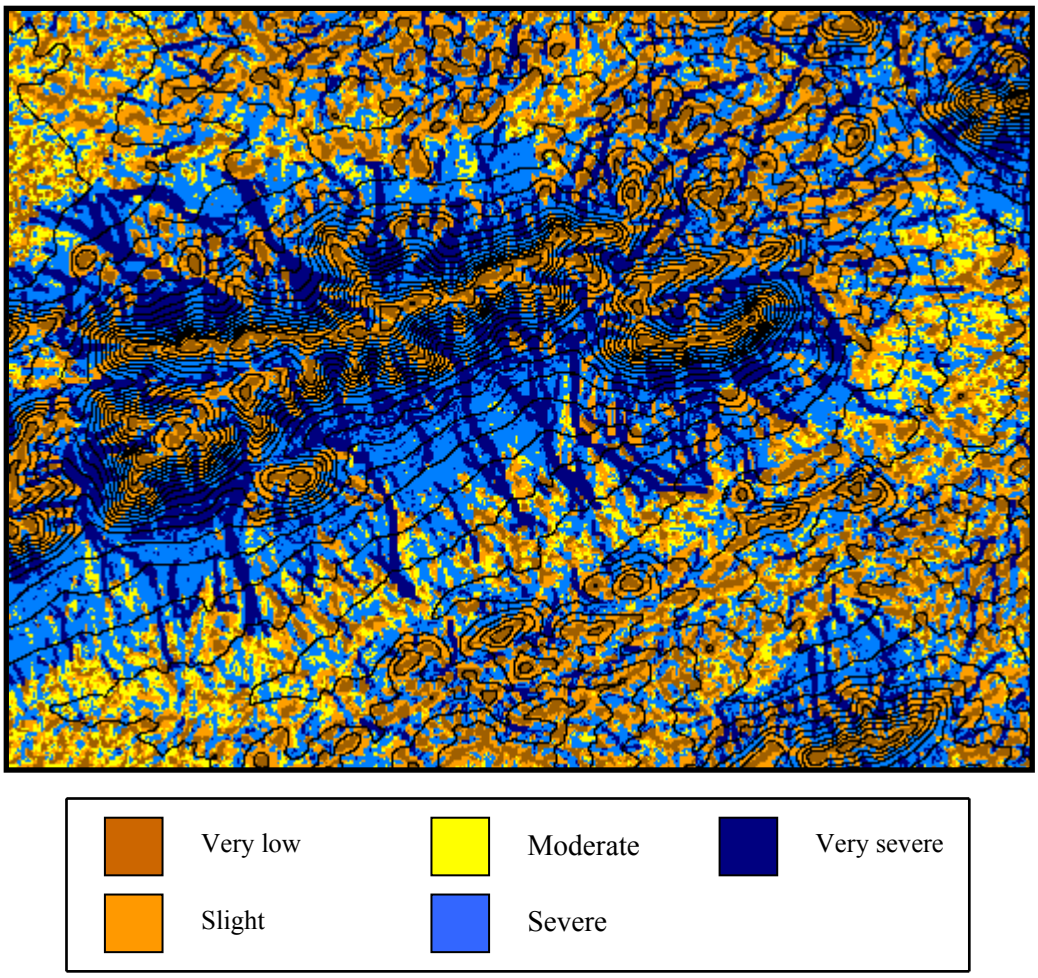


Figure 3 : Image of erosion potential with superposition of topographic contours, for a sub-area of the Guadalentin basin, representing the flow aggressiveness (erosion potential) obtained by classification of topographic attributes and hydrologic indices. Image of approximately 22 km by15 km. *Image du potentiel d'érosion, avec superposition des courbes de niveau (intervalles de 20 m), d'un secteur au sud-ouest du bassin de la Guadalentin, représentant l'agressivité du ruissellement (potentiel d'érosion) obtenue au moyen de la classification des attributs topographiques et des indices hydrologiques. Image d'environ 22 km par 15 km.*

Figure 3 illustrates the spatial distribution of areas with similar potential for erosion over a sub-area of the Guadalentin River basin. High levels of erosional aggressivity are encountered in the valleys and over areas with steeper slopes, as underscored by the topographic contours. The valleys are zones of flow concentration (accumulation) receiving the contribution of large upslope drainage areas. Conversely, low runoff aggressiveness is connected with areas of low slopes and small drainage areas located in the piedmont and in higher mountainous zones. In fact, high slope gradient values generate high levels of relief energy, while large upslope contributing areas generate a large volume of runoff and, therefore, their combination results in increasing overflow aggressiveness.

A preliminary evaluation of the interpretative capacity of this approach is carried out by applying a sensitivity analysis to change the parameters used in the regrouping procedure. We resumed the classification operations with different combinations of topographic attributes. Three scenarios were analyzed:

A. Curvatures (*Kh*, *Kv*) + topographic index *CTI* + water power index *WPI* (figure 3) ;

B. Curvatures (*Kh*, *Kv*) + water power index *WPI* ;

C. Curvatures (*Kh*, *Kv*) + topographic index *CTI*.

Similar maps were generated for the three scenarios as shown in figure 4. The prediction using scenario C is not satisfactory (figure 4B) because it resulted in lower values of runoff aggressiveness in the thalwegs with steep slopes. This is not in agreement with the expected effect of flow concentration and water volume increase. On the other hand, when the topographic index *CTI* is discarded, the predicted hydrologic behaviour (figure 4A) is similar to the one

generated by scenario A (figure 3). Therefore, the key attributes to describe runoff aggressiveness are topographic curvatures, *Kh* and *Kv*, and the water power index *WPI*. Nevertheless, the use of *CTI* helped to enhance the differences within aggressiveness units defined by scenario ii, namely by allowing to distinguish between the following sensitivity levels: high and very high; low and very low (figure 3). Eliminating the factor *CTI* results in decreasing the number of classes (units) determined by the automated clustering: it identified only 11 units for scenario B (table 2) instead of the 14 units generated for scenario A (table 1).

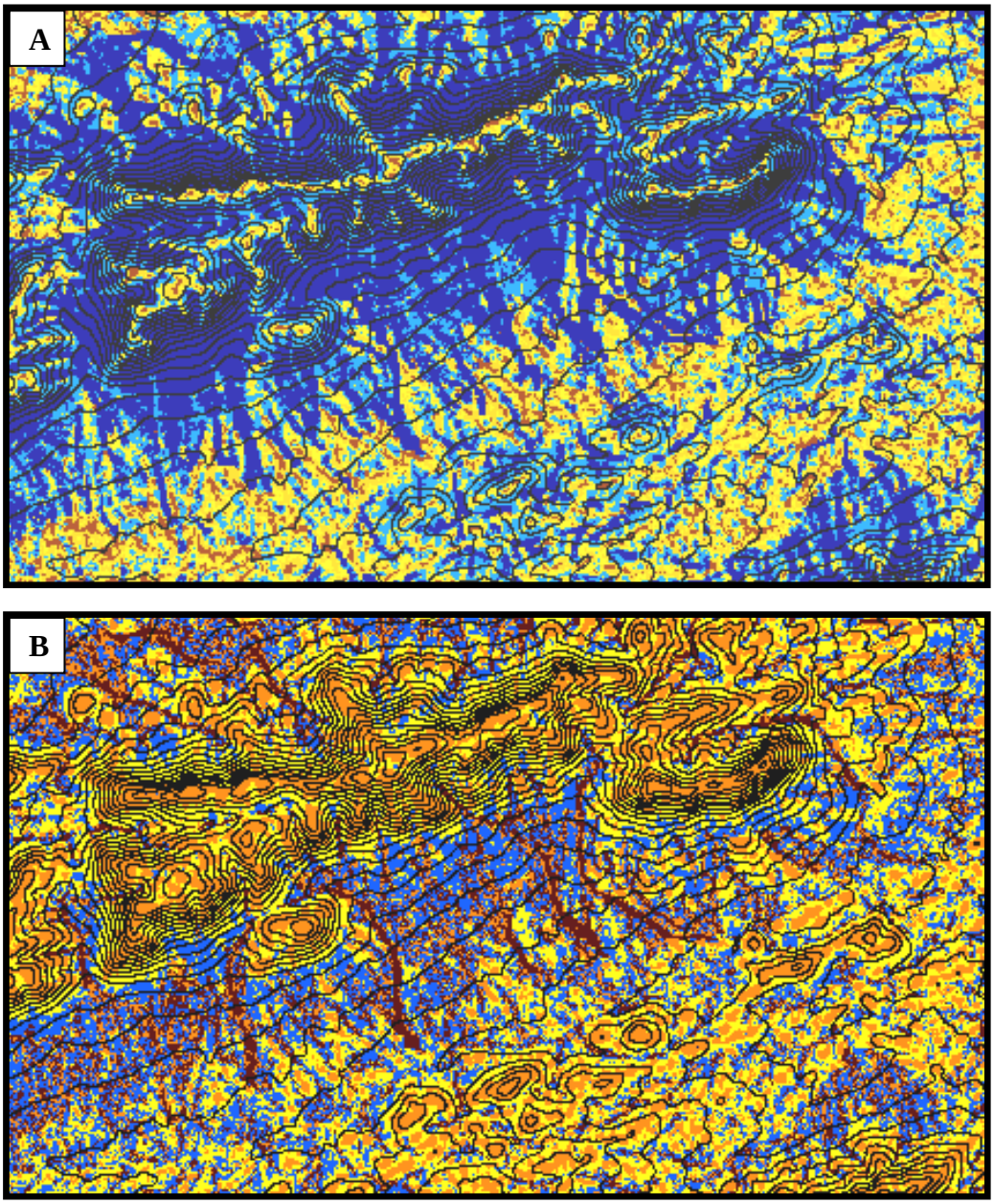


Figure 4 : Sensitivity of erosion capacity estimation to topographic attributes. A) Overland flow aggressiveness units obtained by classification involving curvatures (Kh and Kv) and water power index ; B) Overland flow aggressiveness units obtained by classification involving curvatures (Kh and Kv) and topographic index. Water erosion severity units are very low (brown), slight (orange), moderate (yellow), severe (pale blue), and very severe (dark blue). See figure 2 for scenario A. Images of approximately 22 km by15 km. *Sensibilité de l'estimation du pouvoir érosif relié aux attributs topographiques. A) Unités d'agressivité du ruissellement obtenues au moyen de la classification des courbures (Kh et Kv) et de l'indice d'énergie d'eau. B) Unités d'agressivité du ruissellement obtenues au moyen de la classification des courbures (Kh et Kv) et de l'indice topographique. Agressivité très faible (marron), faible (orange), moyenne (jaune), élevée (bleu pâle) et très élevée (bleu foncé). Voir la figure 2 pour le scénario A. Images d'environ 22 km par 15 km.*

Table 2 : Erosion severity levels determined by cluster analysis of geomorphometric attributes and hydrologic indices. Classes were obtained through an unsupervised clustering involving the following parameters: vertical and horizontal curvatures and water power index (Scenario B). *Niveaux de sévérité de l'érosion obtenus par regroupement des attributs géomorphométriques et des indices hydrologiques. Les classes ont été générées au moyen d'une classification non dirigée des paramètres suivants : courbures verticale et horizontale et indice d'énergie d'eau (scénario B).*

AutClass	Water power index	Vertical Curvature	Horizontal curvature	Overland flow aggressiveness
1	0.309	- 0.068	0.140	Very low
2	1.238	- 0.064	0.142	Very low
3	1.947	- 0.040	0.093	Slight
4	2.514	- 0.041	0.099	Slight
5	2.970	0.003	0.024	Moderate
6	3.403	0.009	0.010	Moderate
7	3.860	0.037	- 0.037	Severe
8	4.369	0.047	- 0.064	Severe
9	5.007	0.069	- 0.118	Very severe
10	5.811	0.079	- 0.158	Very severe
11	7.009	0.138	- 0.252	Very severe

5.3. Contribution of satellite images : Lithological units

Satellite images provide a good knowledge of the spatial distribution of land classes such as soils types, lithological units, and vegetation cover. Spectral mixture analysis was applied in the Guadalentin River basin using spectral characteristics of ground cover classes as derived from field measurements. It yielded abundance estimates of soils, different parent materials (marls, carbonates, gypsum, schists, phyllites), and vegetation. The generated fraction images were rescaled to emphasize the relative abundance of developed soils and parent rock material, allowing the automated mapping of soil conditions and erosion features.

Renormalized fraction images of soils and parent materials were used to define homogeneous units with a similar response to water erosion. First, the abundance estimates obtained by unsupervised clustering were analyzed to identify the major lithological units according to the relative proportions of parent rock types. Thus, in addition to developed soils, we distinguished the following parent lithology groups : gypsum, marls, carbonates, schists, and phyllites. Second, with respect to the vegetation cover density and the physiographic conditions, these lithological units were ranked on the basis of their relative sensitivity to water erosion (Haboudane *et al*., 2002). In fact, while relief and vegetation cover are important factors in determining runoff aggressiveness, chemical and physical properties of substrate materials control consolidation and erodability by water (Melia, 1995). This regrouping is also based on prior research on spectral approaches for the assessment of susceptibility to desertification in the Guadalentin basin (Younis and Melia, 1992 ; Haboudane *et al*., 1997).

5.4. Combined analysis : Susceptibility to water erosion

In order to characterise and evaluate soil degradation risks at the watershed scale, we carried out an integrated analysis of the geo-ecological parameters describing the studied ecosystem. It consisted in defining hydrologic response units through an integration of spectral information and geomorphometric attributes. The methodology was based on a systematic approach that enabled us to identify and weigh the homogeneous spatial entities according to the following

criteria : lithological nature, vegetation density, and hydrologic behaviour. The latter parameter was determined in terms of erosion potential.

The last step in the erosion risk analysis was to combine the DEM-derived units representing runoff aggressiveness with the spectrally-defined units describing lithologies susceptible to water erosion. The knowledge-based model that drives this integration investigates the cause-effect relationships between hillslope processes and both geomorphometric factors and physical indicators of land degradation related to vegetation and soil conditions. In this connection, DEM-derived units inform on topography prerequisites of flow intensity in terms of denudation and sediment transport, while lithological units underline terrain predisposition for erosion by water. Then, after establishing a hierarchy of components that contribute to or cause erosion, the above-mentioned units were assigned specific weight levels (table 3), depending on their importance in the degradation process (Haboudane, 1999). Scores in table 3 are assigned as an expression of soil sensitivity to degradation by water and as an appreciation of relief energy that determines flow intensity.

Table 3 : Assigning weights to lithological units and erosion potential units in order to determine terrain susceptibility level to water erosion. Each cell value is obtained by adding weights of corresponding lithological unit (column) and erosion severity unit (line). *Attribution d'un poids pondéré aux unités lithologiques et aux unités du pouvoir érosif de l'eau en vue de la détermination du niveau de susceptibilité à l'érosion. Dans chaque cellule, la valeur est obtenue au moyen de l'addition des poids correspondants des unités lithologiques (colonne) et de sévérité de l'érosion (ligne).*

		Overland flow aggressiveness				
Lithological units		Very low	Slight	Moderate	Severe	Very severe
	Weights	**1**	**2**	**5**	**8**	**10**
Soils	**8**	9	10	13	16	18
Gypsiferous marls	**10**	11	12	15	18	20
Marls	**7**	8	9	12	15	17
Phyllites	**5**	6	7	10	13	15
Schists	**4**	5	6	9	12	14
Limestones	**2**	3	4	7	10	12

Expert knowledge that allowed the definition and identification of erosion-sensitive areas was incorporated into the geographical information system. This is provided by information-based rules established on the basis of multi-disciplinary expertise and knowledge of the complex interactions between agents of vegetation, soil, geology, hydrology, and relief. The corresponding results are shown in figure 5.

The map of erosion risks illustrates the hydrologic behaviour differences between the two physiogeographic regions of the Guadalentin (figure 5). High and extreme risks are widespread in pediment areas of the post-Palaeozoic sector because of the dominance of long slope lengths; but they are of lesser extent in the Palaeozoic sector because of the presence of short slopes and moderate relief. This spatial pattern of potential severity of soil erosion is also largely controlled by the lithological nature of terrain units. In fact, in concert with topography, the geology exerts a strong influence on soil development, vegetation growth, and hydrologic behaviour. For instance, in the Paleozoic geobotanical sector, fractured schists favour water infiltration and enables soil development at depth inside the fractures. Moreover, abundant rock fragments in these areas slow down runoff and diminish risk of denudation and sediment transport.

Soil deterioration is widely agreed to lead to the destruction of permanent semi-natural vegetation and vice versa. They are often connected because soil conditions are a reflection of the vegetation state and vegetation growth is tightly dependent on soil development. Thus, as soil erosion is an important factor that contributes to the potential increase of land degradation and desertification processes in Mediterranean regions, mapping erosion patterns and predicting areas at risk as shown in this paper allow precise identification of areas where intervention must be given a high priority. Such information is of great importance for environmental managers.

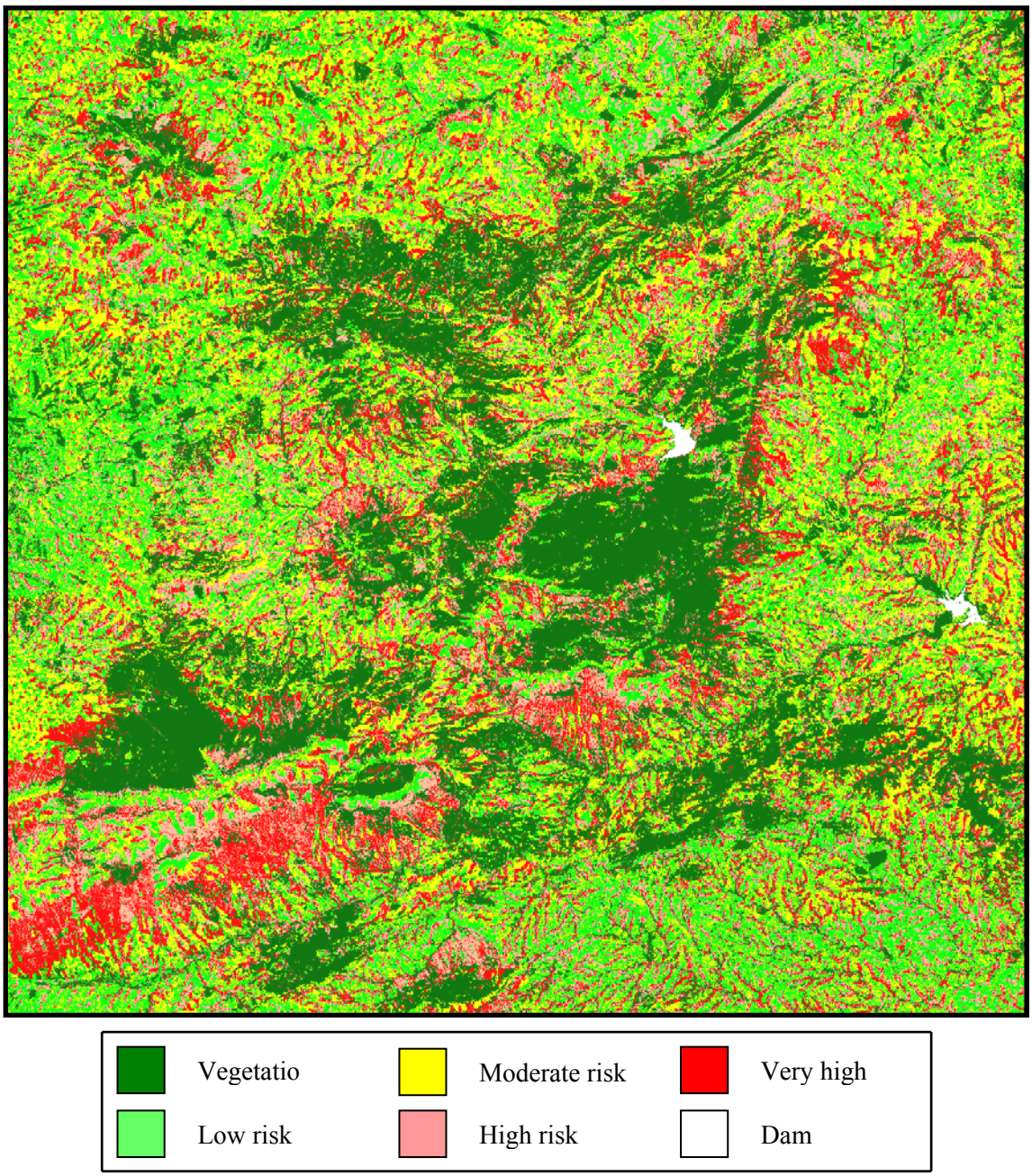


Figure 5 : Homogeneous units of susceptibility to land degradation by water expressed in terms of risks. Image produced by integration of erosion potential with lithological units. 45 km x 45 km image. *Unités homogènes de susceptibilité à la dégradation hydrique des sols, exprimées en termes du risque d'érosion. Image produite au moyen de l'intégration du potentiel érosif et des unités lithologiques. Image de 45 km par 45 km.*

6. DISCUSSION

The estimate of the different levels of sensitivity to water erosion can be assessed by comparing the final product (figure 5) to field observations. For this purpose, representative areas, showing evidence of sensitivity to water erosion, were identified inside the Guadalentin basin. This procedure relies on a qualitative visual comparison of the results shown in figure 5 with lithological maps and photographs collected during field studies. The objective here is to determine whether the predicted risks are in concordance with terrain unit features as reported in cartographic documents and field observations namely, erosion evidence and features, and anti-erosion management practices. These elements indicate that extreme hydrologic events have been observed in the past and that conservation/restoration planning has been implemented.

Figure 6 shows the geological units of the Palaeozoic district as shown in the geological map (figure 6A) and as a result of the spectral processing of Landsat TM images (figure 6B). It reveals a striking agreement between an existing

geological document (a compilation of various information on age, structure, lithology, petrography, and palaeontology of rock materials) and spectrally-based information regardless of the structure and fossils content of the outcropping materials. These are encouraging and satisfactory results in the sense that the spectral approach reproduced uniform geological patterns that are similar to those of the geological map taken as ground truth.

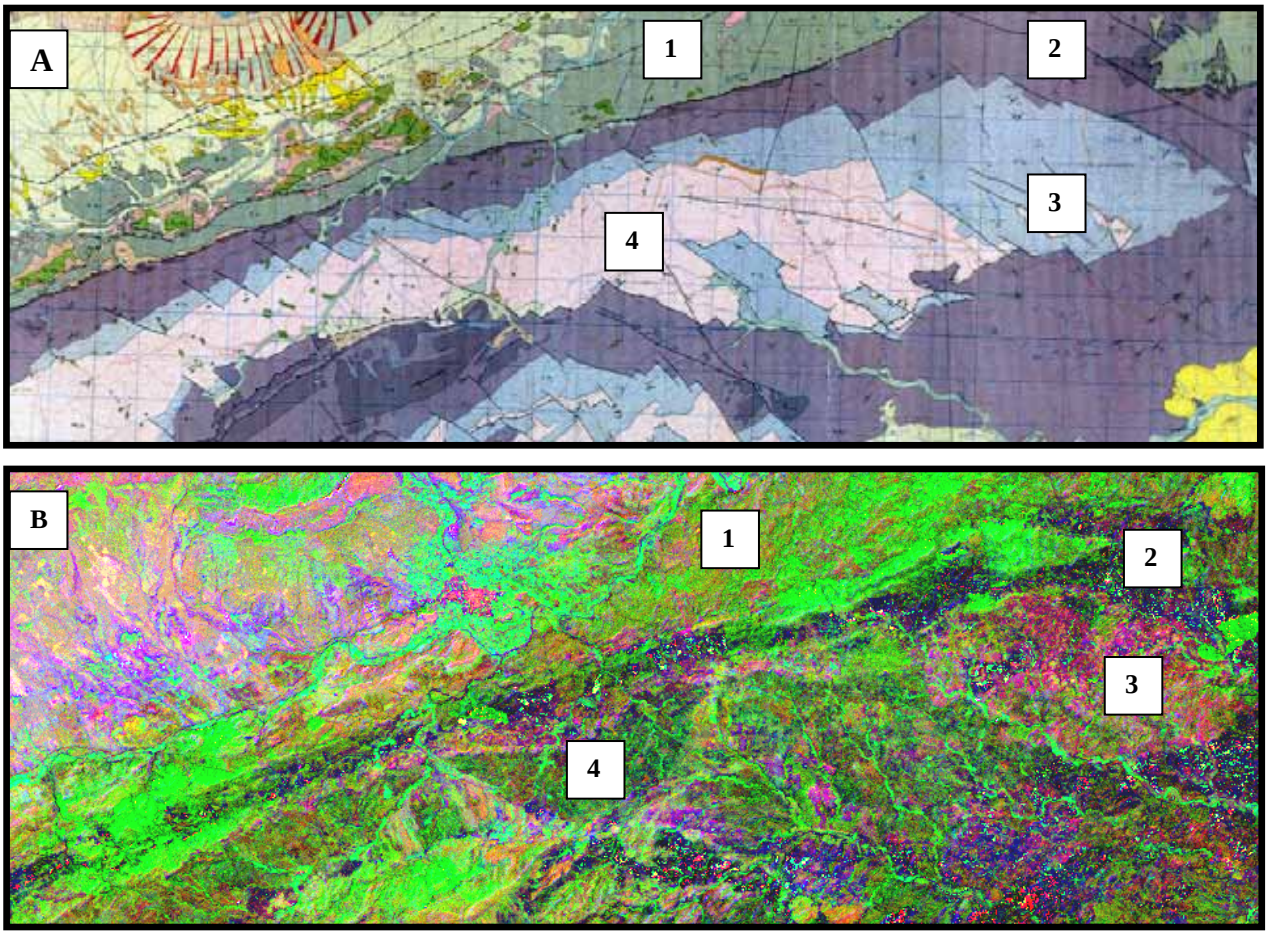


Figure 6 : Comparison between geological map (A) and lithological units obtained from remotely sensed data in the Paleozoic district (B). In addition to vegetation cover (green), four units are distinguished : 1) schists, 2) phyllites, 3) quartzites-phyllites, and 4) quartzites-schists. Images of approximately 30 km by 11 km. *Comparaison entre la carte géologique (A) et les unités lithologiques obtenues par télédétection sur le secteur paléozoïque (B). En plus du couvert végétal (vert), on distingue quatre unités : (1) schistes, (2) phyllites, (3) quartzites-phyllites et (4) quartzites-schistes. Images d'environ 30 km par 11 km.*

Concerning the prediction of landscape susceptibility to water erosion, we have studied and compiled evidence gathered in different locations of the study area in order to state whether evaluated risks are in accordance with terrain indicators that favour land degradation and vice versa. One of these locations is a pediment zone located near a limestone mountain (figure 7). It is a pediment region, oriented south, with moderate slopes, developed soils, and dispersed vegetation, the growth of which is constrained by a severe shortage of water. On the map of susceptibility (figure 7B) the pediment zone is considered an area at very high risk of degradation (in red). This is in close agreement with the geological information (figure 7A) that identifies the pediment as underlain by Quaternary deposits dominated by clay materials which are very sensitive to erosion by water. These results are corroborated by terrain observations (figure 7C) showing the presence of erosion features: gullies, ravines, and crevasses. The latter is plausible evidence of overland flow aggressiveness, which is a principal agent of hillslope erosion.

Moreover, on the risk map (figure 7B) the transition zone between the pediment and the debris flow region (inselberg) is delineated by the presence of a vegetation cover strip (dark green). The vegetation cover follows an altitudinal zone that demarcates a drastic slope change from the inselberg (high gradient) to the downslope pediment (moderate gradient). Terrain observation (figure 7C) shows that it corresponds to a reforestation zone implemented as anti-erosion management aiming to protect downslope soils against water erosion. This targeted management is clear evidence that soil conservation managers and decision-makers have already identified the pediment as an area highly sensitive to degradation.

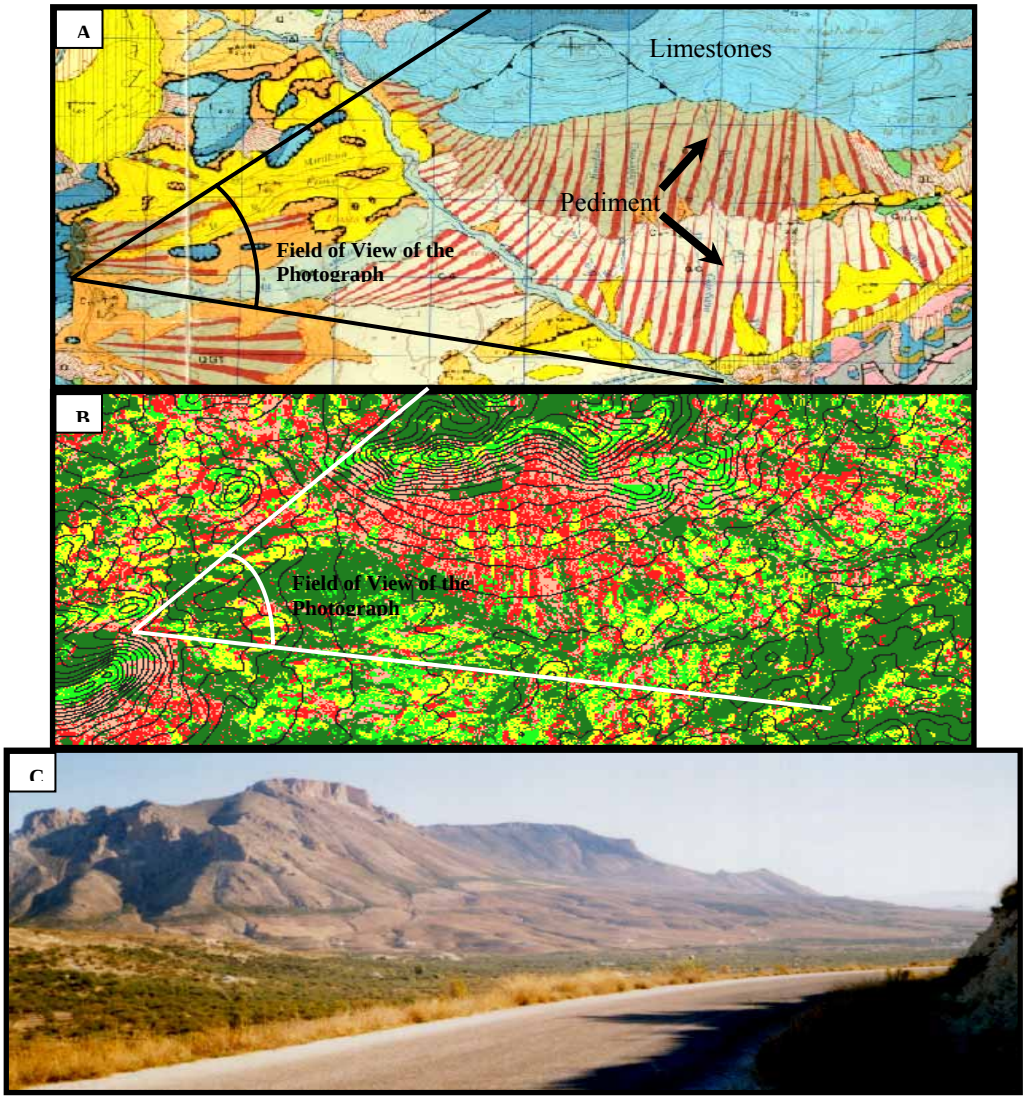


Figure 7 : Comparison between geological map (A), erosion risks map (B), and field photograph (C). In erosion risk map, vegetation is dark green while risk levels are slight (pale green), moderate (yellow), high (pale red), and very high (red). Risk map of approximately 15 km by 8 km. *Comparaison entre la carte géologique (A), la carte du risque d'érosion (B), et une photographie de terrain (C). Sur la carte du risque, la végétation est en vert foncé alors que les risques faible, modéré, élevé et très élevé sont représentés, respectivement, en vert pâle, jaune, rouge pâle et rouge. Carte du risque d'environ 15 km par 8 km.*

7. COMMENTS AND CONCLUSIONS

The integrated approach developed in this study allows the identification of the targeted problem areas for conservation planning and sustainable development of the watershed. It is a rule-based model that introduced a so-called multi-disciplinary expert's informed opinion to provide an extension to the traditional methods of assessing and predicting soil erosion risks. This should enable evaluation of different watershed management scenarios. Using remote sensing and geographical information systems, these methods provide a means of integrating information and knowledge from different sources (hydrology, geomorphology, pedology, ecology) in the decision-making process.

Our results suggest that spectral mixture analysis holds high potential in operational applications of satellite optical images. It is an appropriate approach for erosion risk assessment, which provides inventories of exiting soil degradation features and erosion damage. In fact, based upon physical surface properties (reflectances), the method derives information about vegetation and soil in terms of relative abundances. It presents the advantage of the high flexibility of editing, handling, and analyzing the resulting abundance images.

Concerning the contribution of DEM-derived variables, we demonstrated and discussed how useful their fusion with satellite-based information was in determining potential erosion risks. Their combined analysis provided the means to assess erosion potential and then to determine the spatial distribution of susceptibility to water erosion over the Guadalentin basin.

The proposed approach is limited because it concerns only present day processes with the existing human-influenced landcover. Paleogeographic landcover conditions are not considered in this work. It is probable that these conditions

played an important role in the landform development in this area in the past, even in the post glacial period before human influence on the vegetation cover.

Acknowledgements

This article is dedicated to the memory of Ferdinand Bonn who had the patience to direct the M.Sc. and Ph.D. research of the first author. From the beginning he was there to initiate him and remained until the end. He benefited from exemplary supervision where understanding, confidence, encouragement and involvement predominated. Since his arrival in Québec in 1992, he had the privilege of having Ferdinand as director, mentor, collaborator and friend. He was able to appreciate his humanist values: his goodness, kindness, sensitivity, generosity, his deep respect for cultural differences.

Cet article est dédié à la mémoire de Ferdinand Bonn qui a eu la patience de guider les travaux de recherche de l'auteur principal aussi bien au niveau de la maîtrise qu'au niveau du doctorat. Il était là du tout début pour l'initier et il est resté jusqu'à la toute fin pour le voir voler de ses propres ailes. Avec lui, il a bénéficié d'un encadrement exemplaire où régnaient compréhension, confiance, encouragement et engagement. Depuis son arrivée au Québec, en 1992, il a eu le privilège d'avoir Ferdinand comme encadrant, mentor, collaborateur et ami. Il a eu l'honneur d'apprécier ses valeurs humanistes : sa bonté, sa gentillesse, sa sensibilité, sa générosité, son profond respect des différences culturelles, son sens de partage et d'entraide.

The authors are very grateful for the financial support provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) (Driss Haboudane, No. 261897; Ferdinand Bonn, No. 6043; Alain Royer, No. 8643-04), the Fonds québécois de la recherche sur la nature et les technologies (FQRNT) (Driss Haboudane, NC-98062).

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