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Rainfall erosion risk mapping in volcanic soils of Santiago Island, Cape Verde Archipelago

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Abstract - Surface runoff and soil erosion are major threats to sustainable agriculture and mapping regional erosion risk is increasingly needed by local, national and international environment agencies. Because erosion results from the interaction of several parameters which vary in space and time, no simple model can take into account all relevant factors, particularly in cultivated areas where human influences are predominant. The aim of this work is to develop a methodology based firstly on Le Bissonnais's model and to apply it to evaluate the erosion risk on the Santiago Island in Cape Verde archipelago.

According to the model, the rainfall erosion map revealed that Santiago Island may be broadly divided into five major erosion risk zones. While bare soils and rain fed sectors are respectively in the severe to extremely severe erosion risk zone with 916 km², this is 91 % of Santiago's area. The coastal sector of Santiago is generally in the low erosion risk zone; the irrigation and forest sectors are in the very low erosion risk zone; the arbored sector is generally in the moderate erosion risk zone.

Keywords: Cape Verde, Santiago Island, Rainfall erosion risk, Tree model decision, GIS

Cartographie de risque d'érosion hydrique dans les sols volcaniques de l'île de Santiago–Archipel du Cap Vert

Résumé - Le ruissellement superficiel et l'érosion des sols représentent de sérieuses menaces pour l'agriculture durable. En effet, la cartographie du risque d'érosion au niveau régional devient alors un outil performant pour les agences nationales et internationales qui s'occupent de l'environnement. La complexité de l'érosion résulte du fait de l'interaction de plusieurs paramètres variant dans le temps et dans l'espace. De ce fait, il est difficile, avec un modèle simple, de prendre en considération tous les facteurs, particulièrement dans les zones cultivées où l'influence de l'homme prédomine. Ainsi, l'objectif de ce travail consiste à développer une méthode basée d'abord sur celle de Le Bissonnais *et al.* (2001, 2002) et ensuite de l'appliquer pour évaluer le risque d'érosion sur l'île de Santiago dans l'archipel du Cap Vert.

Selon le modèle développé, la carte de l'érosion hydrique montre que l'île de Santiago peut être divisée en cinq zones majeures de risque d'érosion. Les secteurs où on retrouve les terres nues et l'agriculture pluviale présentent un risque d'érosion compris entre sévère et extrêmement sévère ; ces secteurs occupent une superficie de 916 km², ce qui représente 91 % de l'île de Santiago. Par contre, la zone côtière présente un risque d'érosion faible. Les zones où on pratique l'agriculture irriguée et celles forestières présentent un risque d'érosion très faible. Enfin, les zones arborisées sont comprises dans un secteur où le risque est qualifié de modéré.

Mots clés : Cap Vert, île de Santiago, risque d'érosion hydrique, modèle arborescent de décision, SIG

INTRODUCTION

Soil erosion by rainfall is the major process of land degradation in Santiago region, which constitutes one of the keys of desertification and drought.

Surface runoff and soil erosion are major threats to sustainable agriculture and mapping regional erosion risk is increasingly needed by local, national and international environment agencies. Because erosion results from the interaction of several parameters which vary in space and time, no simple model can take into account all relevant factors, particularly in cultivated areas where human influences are predominant. The aim of this work is to develop a methodology based firstly on Le Bissonnais's model and to apply it to evaluate the erosion risk on the Santiago Island in Cape Verde archipelago.

Soil erosion occurs when intense rainfall either exceeds the capacity of the soil to absorb it, or a crust on the surface stops rainfall to infiltrate in the soil and generates overland flow runoff. When runoff is sufficiently powerful, it picks up soil and carries it downslope, cutting small channels, or rills, in the fields. Where soil is shallow, severe erosion leads to complete removal of the soil and exposure of bedrock. Where soil is deep, the rills can grow into gullies which are too deep to plough over, and break fields into inconvenient fragments.

Soil is also eroded from the areas between rills and gullies, removing the topsoil which has the best structure, and most of the organic matter and nutrients (Kirkby, 2001). Once runoff is initiated on a cultivated field, various forms of erosion are likely to occur, showing various combinations in space and time: sheet hillslope erosion, parallel linear erosion and gully erosion (Le Bissonnais *et al.*, 2001).

As suggested by these descriptions, erosion processes result from numerous interacting factors. Modelling is difficult because of the complexity of these interactions. Four main factors are generally considered: soil, topography, land cover and climate (Wischmeier and Smith, 1978; King and Le Bissonnais, 1992). Two main steps must be distinguished in the modelling of erosion processes and risks mapping: (i) selection of factors and

representative parameters for these factors, and (ii) choice of a model and mapping procedures, both steps being dependent on each other.

Baver (1965) and Oduro-Afriyie (1996) have indicated that soil erosion by water is due to the dispersive action and transporting power of water. It is affected by rainfall erosivity and the soil erodibility. Rainfall erosivity is mainly a function of rainfall characteristics; while soil erodibility is may a function of the physical properties and management of the soil.

In the context of Cape Verdean's island, the problem of rainfall erosion is very crucial; soils are in general badly protected by the vegetation, steep slopes and intensive rainfall. Many studies about soil degradation have been locally realized by Mannaert (1984, 1986), Colombani *et al.* (1984), Olivry (1989), Smolikowski *et al.* (1998), Prodap – FIDA (1997) and Sabino *et al.* (2000).

To protect the land from further degradation and make the mitigation measures effective, it is essential to know the spatial distribution of the areas susceptible to degradation and to assess hazard severity (Shrestha and al. 2004).

Techniques to evaluate land degradation range from simple methods for hazard assessment (Bergsma 1992, 1997; Kunwar *et al.*, 2002) to sophisticated models for estimating soil losses (Beasley, *et al.*, 1980; Nearing *et al.*, 1989; Lorup and Styczyn, 1996; Morgan *et al.*, 1998) and for simulation modelling and hazard prediction (Bocco *et al.*, 1990; Fabbri and Chung, 1999; Zick, 1999). Results from advanced modelling are often impressive but also difficult to interpret. A general problem for applying such models is data availability. Frequently, missing data have to be generated on the basis of assumptions, including pedotransfer functions. It is essential to devise a method for hazard zonation, which can be applied in a data-poor environment (Le Bissonnais *et al.* 2001).

The aim of this study is to identify areas of current erosion risk in Santiago Island, the largest island of Cape Verde Archipelago. To realize this research, we have combined four environments factors: land use, soil crustability, slope and precipitation in a decision tree model adapted from that of Le Bissonnais *et al.* (2002). The erosion factors will be combined with Geographic Information System (GIS) to identify areas of current erosion risk in Santiago Island.

METHOD AND MATERIALS STUDIED

Area description

The Cape Verde Islands (Fig. 1), geographic coordinates 16° 00' N and 24° 00' W, are located in the mid-Atlantic Ocean some 620 kilometers off the west coast of African continent and mainland (Dakar, Senegal). The archipelago consists of 10 islands and 5 islets,

conventionally classified in two groups, the “Barlavento” or windward group islands of Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and the “Sotavento” or leeward group islands groups of Maio, Santiago, Boa Vista, Fogo, and Brava. Some geographers (Reclus, 1887) and vegetation ecologists (Wollaston, 1867; Chevalier, 1935) refer to the Cape Verde Islands as an integral part of “Macaronesia”.

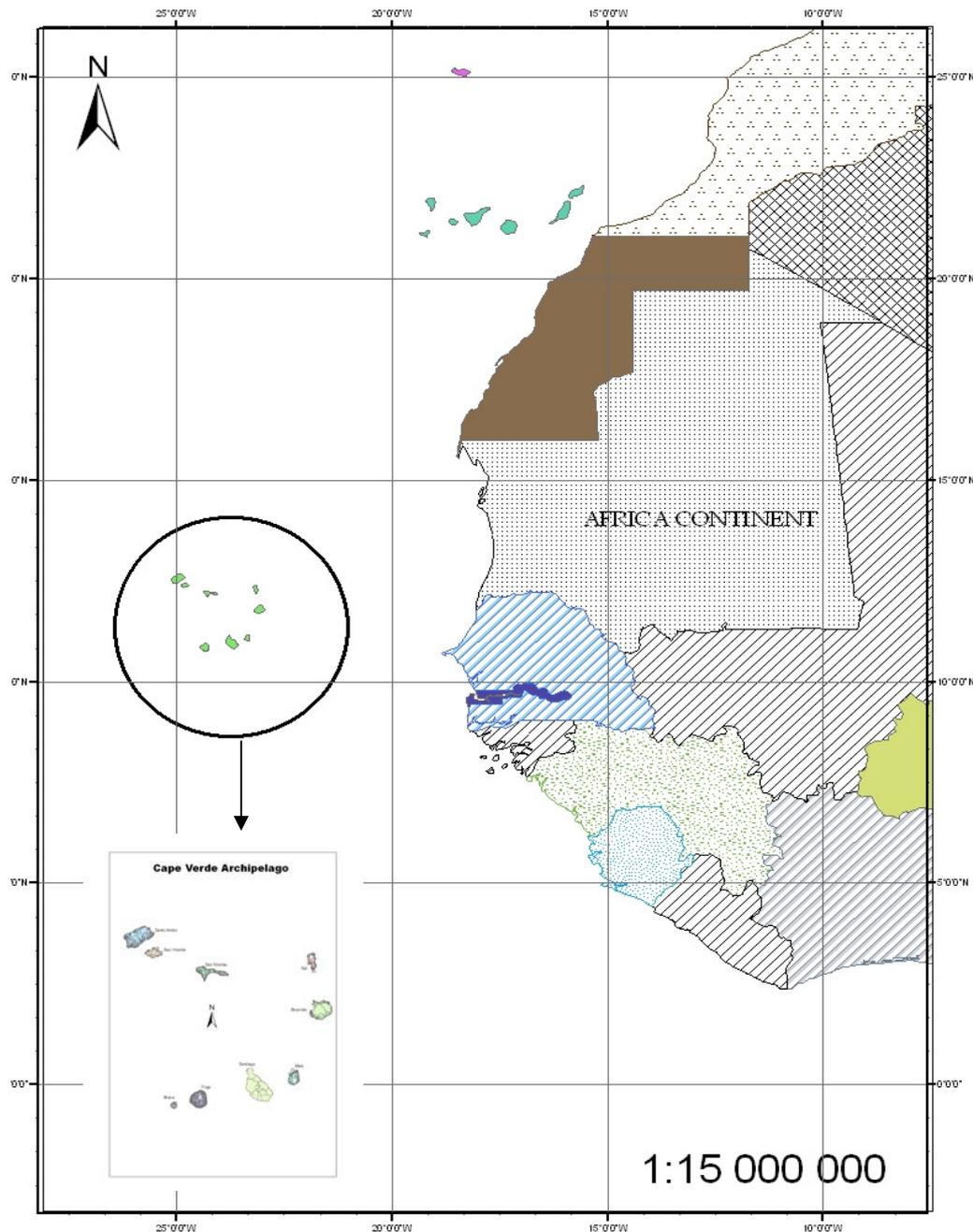


Fig. 1. Geographic location of Cape Verde Archipelago
Fig.1. Localisation géographique de l'Archipel du Cap Vert

The whole Cape Verde Archipelago has two distinct seasons associated with the movement of the Inter-tropical Convergence Zone (ITCZ). From November to June occurs the dry season dominated by the maritime northern trades, north-easterly or easterly harmatan and by some incursions of upper polar troughs that only directly benefit mountain areas with rains of weak intensity. During the rainy season, moisture-bearing south-westerly winds of South Atlantic origin, towards perturbations along the ITCZ, or cloud clusters expelled from north to the ITCZ provide the rains from which the entire area depends. 90% of all the annual precipitations occur from July to October. These rains present a high temporal and spatial variability (Ferreira, 1987).

Santiago Island, has an area of 998 km² occupied by 208 000 people including the Capital "Praia". The island is located between 14°50' and 15°20' N latitude, 23°20' and 23°50' W longitude, with a maximum elevation of 1394 m (Pico) (Fig. 2). According to Bebianno (1932), 97% of the Island is constituted by basaltic rocks and pyroclastic products, the other 3% is constituted by phonolitic and tephrite.

Erosion process in Santiago Island

The Cape Verde Islands suffer from soil degradation, improper land use, high slopes and intensive rainfalls. Cape Verde's steep watersheds, torrential rains, rapid water runoff and strong winds cause extensive soil erosion. The inhabitants add to the problem by removing natural vegetation for fuel, construction, agricultural extension and intensive livestock feeding. One of the biggest environment problems is soil erosion.

Soil erosion has been of much concern especially to countries like Cape Verde whose 45 % of population lives in rural zone and their principal activity depend on agriculture and particularly rain fed and cattle breeding. UNEP/FAO/UNESCO/OMM, (1977) and FAO/UNEP (1984) put 100% of the Cape Verdean territory susceptible to rainfall erosion. Population growth, with its attendant increase in demand for land and agriculture products, is likely to increase the problem.

Since 1976 (one year after Cape Verde's Independence), construction to modify slopes and stream gradients has included earth or stone-walled terraces, contour ditches to slow water runoff and check-dams for streams. Since 1976,

with the help of international organisations, emergency steps have been taken to re-store the vegetal cover of denuded soil surfaces, to increase underground water supply and to control the river flooding (Ferreira, 1987). At present, there are no available works that allow an evaluation of erosion risk at the national or island scale.

According to the results of Smolowsky *et al.* (1998), soil erosion can vary from 45 to 1097 t.km⁻².yr⁻¹ in Godim (watershed of Ribeira Seca in the center of Santiago in semi-arid zone). Researches doing by Mannaerts (1993), in the central southern part of Santiago (arid zone), have shown that soil loss erosion varies from 0.2 to 60 t.km⁻².yr⁻¹. In comparison with others results like in Mahgreb (North Africa) obtained by Probst and Amiotte-Suchet (1992), soil erosion vary from 420-500 t.km⁻².yr⁻¹. And on São Miguel volcanic island in Azores archipelago, Louvat and Allègre (1998) calculated mechanical erosion rates of 170-500 t.km⁻².yr⁻¹. The results of erosion rates for Santiago of Smolowsky *et al.* (1998) are high compared to those of the world's largest rivers (Pinet and Souriau, 1988): 200 t.km⁻².yr⁻¹ for Amazon and Mississippi, 25 for Congo and Ob, 35 for Nile, Yenisei, Niger and Murray, and 50 for Parana and Lawrence. Only Chinese and Indian rivers, for which upstream levels are of a mountainous type, have higher or comparable total erosion rates: 370 t.km⁻².yr⁻¹ for Yangtze, 290 for Mekong, 540 for Indus, 1230 for Ganges-Brahmaputra and 1410 for Huanghe (partly because of human activities, Milliman *et al.*, 1987).

Modelling erosion risk

In this paper, a procedure for mapping rainfall erosion risk is described, which follows a four-steps approach: (1) detection and selection of main factors, (2) statistical analysis of meteorological data and digitising of thematic maps (land use map, soil map), (3) development of a decision tree model and (4) applying decision trees with Geographical Information System (GIS).

Two main steps must be distinguished in the modelling of erosion processes and risk mapping: (i) identification of factors and representative parameters for these factors, and (ii) choice of a model and mapping procedures, both steps being dependent on each other.

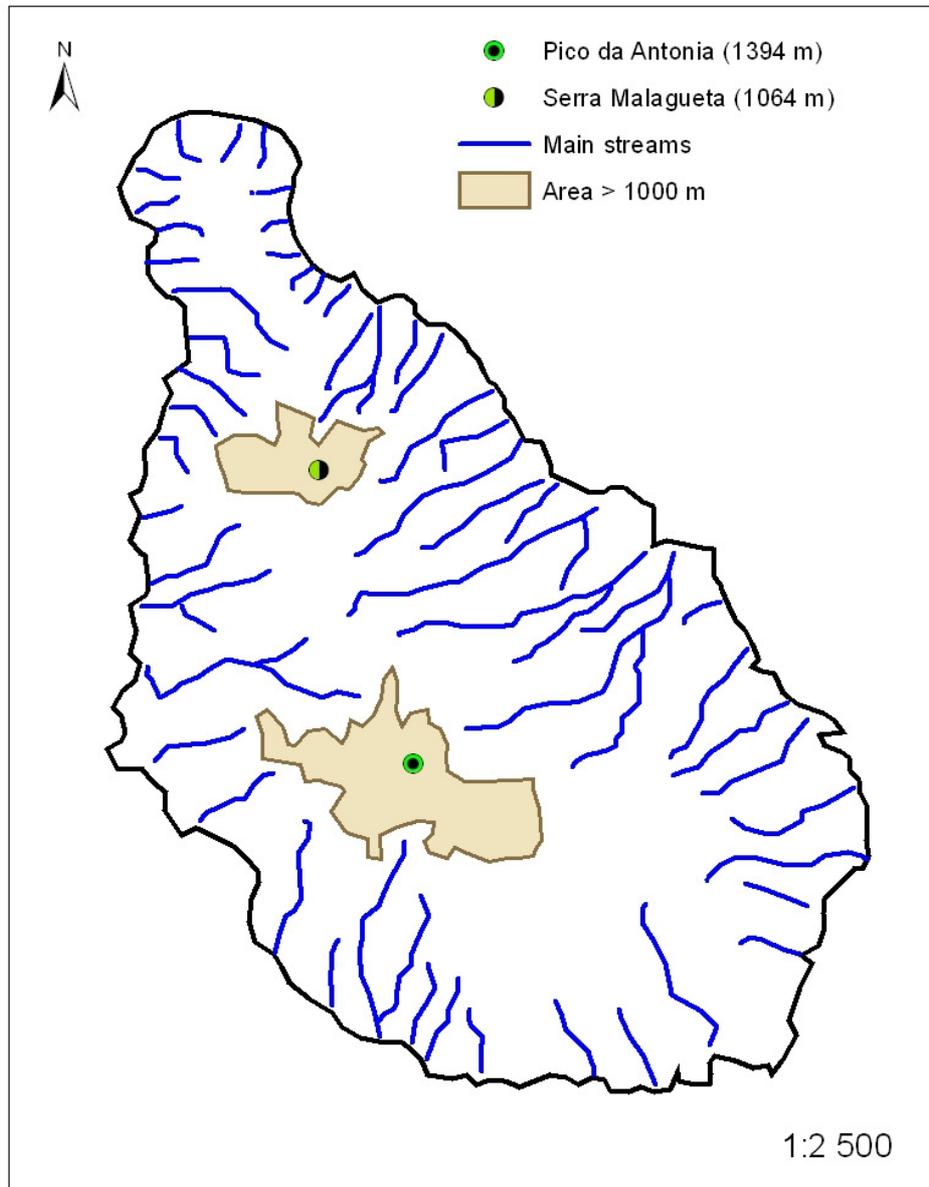


Fig. 2. Santiago island

Fig. 2. Île de Santiago

During, this study we have developed a decision tree model (Fig. 3) with four different factors:

- 1- Land use (with 5 parameters: irrigated, forest, rain fed, arbored and bare soil areas)
- 2- Crust on surface (was got with 2 parameters: soil texture and organic matter content)
- 3- Slope.
- 4- Rainfall (1950-2001, with 10 local meteorology stations).

In compliance with the method, land use and soil properties were determined digitising respectively two thematic maps: land use map

and soil map (Xavier, 1970). Digital Elevation Model (DEM) of Santiago (INIDA & CIRAD-CA, 1991) was treated with Idrisi software, slopes values were calculated at each pixel.

Basic soil properties like soil texture and organic matter content, which are important as of erosion, were analysed and combined to determine the formation of the crust on surface soil. Santiago's Island soils were classified in five categories according to the susceptibility of crusting: very low, low, moderate, high and very high.

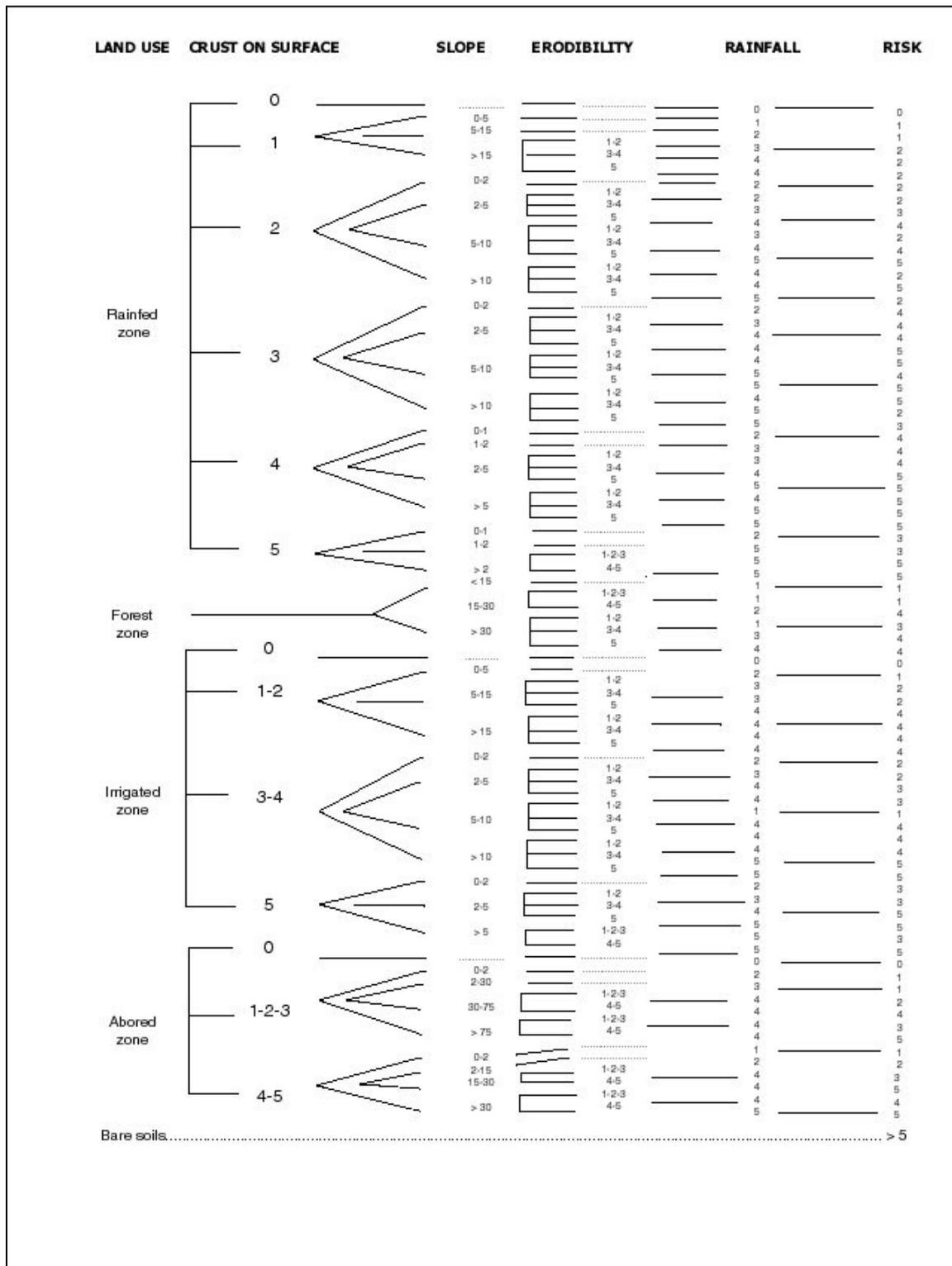


Fig. 3. Decision tree model

Fig. 3. Modèle arborescent de décision

The methodology used was influenced by the research's results obtained by Le Bissonais *et al.* (2002) to map the rainfall erosion risk in

France. This research explores the rainfall, soil, slope and land use components of the contemporary physical erosion problems in the

island of Santiago. Soil erosion by rainfall is the major process of land degradation in Santiago region, which constitutes one of the keys of desertification (UNEP, 1994).

Erosion factors - To study and understand the soil erosion rainfall in Santiago Island it is fundamental to consider the next factors: land use, crust on surface, slope and rainfall.

Land use - The map of land use was directed in 1981 by Republica de Cabo Verde & SCETAGRI (1981). The initial classification included 18 classes. Land use types have been reclassified into 5 classes (table 1), each one corresponding to a specific behaviour towards soil erosion. The 5 classes are described as follows:

1. rain fed zone. In Santiago Island the land use is particularly dominated by rain fed activities essentially constituted by maize and beans.
2. forest zone showing low erosion sensitivity except in cases of steep slopes ; The vegetal cover protects soil decreasing kinetic energy of drops rain consequently, reduces the flash effect and runoff (Lafren *et al.*, 1985; Renard *et al.*, 1997; Milward *et al.*, 2001), who are an erosion origin. The vegetal cover generates also a mechanical action by plants root. Moreover, it brings organic matter that considerably ameliorates the soil structure and soil cohesion (Stevenson, 1985). Organic matter improves the land's stability structural in that case, mitigates crust formation and ameliorates the soil resistance to detachment (Le Bissonnais and *al.* 2000).
3. irrigated zone showing also a low erosion sensitivity
4. arbored zone
5. bare soils

Crust on surface - The map of soils was realized by Xavier (1970) with six classes: entisols: ushortent, xerothent and xeropsament (30, 8%) with ustifluent and tropofluent (2, 6%), aridisols (7, 9%), molisols (8, 4%), inceptisols (10, 8%), vertisols (2, 9%) and alfisols (1, 5%).

Three parameters were elaborated to determinate the soil crustibility based on soil texture and soil organic matter content. We have determinate 5 crusting area classes: very low, low, moderate, high and very high.

Not all soil has the same erodibility face to the erosivity of rainfall. The soil erodibility

depends on soil proprieties: chemical and physical (CTFT, 1979). According to Wu (1999), Marceau and *al.* (1999), Tessier and *al.* (1996), Hénin and *al.* (1969), this erodibility depends on: soil structure, permeability, texture and organic matter content. According to Wischmeier and *al.* (1969), sand fine and silt are the particles more susceptible to detachment and transport.

Slope - We used a gridded digital elevation model (DEM) of Santiago Island with a cell resolution of 50 x 50 m. The DEM determined the basic cell resolution for all other information layers. This cell size is a compromise between the requested accuracy and the amount of data to be managed. The average slope of each cell (in percentage) was calculated from the greatest elevation difference between it and its eight neighbours. Slopes were classified into 9 classes, the limits of which were defined according to field experience or values to be found in the literature: 0 - 1%; 1 - 2%; 2 - 5%; 5 - 10%; 10 - 15 %; 15 - 30 %; 30 - 40%; 40 - 75%; > 75%.

Rainfall - The altitude of Santiago island starts from the sea level and reaching to 1394 m. Santiago like the others islands of the arquipelago, is submitted to a sahelian climate arid and sub-arid (Ferreira, 1986). Annual rainfall in Santiago is about 200 mm. The rainfall average decreases gradually to summit from littoral.

In the Cape Verde Archipelago, the dryness has a rhythm that derives from the geographical position, in a cool oceanic region, dominated by the subtropical anticyclone. This position commands what we can consider as the permanent field of dryness that is clearly reflected in the staggering of natural and agricultural landscapes in the mountainous islands such as the case of Santiago. Santiago Island rainfall occurs between August and October (winter season) with a high variability inter annual and spatial. From November to June occurs the dry season. The major part of rainfall in Santiago is located in the mountains zone to the detriment of littorals zone.

Rain is the main factor for water erosion and its erosive effect is related to its amount and intensity. Moreover, during this study, we just took the mean monthly rainfall height to characterise erosivity for winter season (July to October). Basic climate data come from records of local meteorological stations collected by "Instituto Nacional de Meteorologia e

Geofísica” of Cape Verde. According to the multiple regression rainfall distribution is in general due to altitude and exposition slopes with a determination coefficients $R^2 = 98\%$. Idrisi software (GIS) is used to spatialize these data. The method takes into account the topographical environment (orientation) of the stations and their altitude. The resulting map is a grid data layer at 50 m resolution, with a monthly average rainfall total recorder for each pixel. These values are classified in 5 erosivity effect classes: 1 (very low); 2 (low); 3 (moderate); 4 (high) and 5 (very high).

Factor ranking and factor’s combination - The choice of a decision tree model requires ranking of each parameter. We gave priority to the factors which can be modified by human activities. The entry order was the following: land use, crusting, slope, soil erodibility. These factors were linked successively and five classes (very low, low, moderate, high and very high) have been defined from literature and experiences, giving the agro-pedo-geomorphological sensitivity to soil erosion for each pixel. This sensitivity to erosion is then combined with the climate erosivity to

determinate erosion risk and five erosion risk classes have been defined: 1 (very low); 2 (low); 3 (moderate); 4 (severe) and 5 (extremely severe).

Decision Tree Model (DTM) - A decision tree model was developed. The model combines parameters according to logical operations. A specific decision tree was built for each of the 5 land use classes corresponding to rain fed zone (cultivated land), forest zone, irrigated zone, arbored zone and naked zone (Fig. 4). About 200 combinations of parameters could be obtained in theory. However, this number is reduced to 82 different combinations by numerous amalgamations of cases for the different factors. Each combination of parameters is labelled by a code ranging from 1 to 5, indicating the relative soil erosion risk. The model obtained according to Santiago realities has been applied firstly to characterize the potential soil’s erodibility, combining crust on surface, land use and slopes. Secondly, the potential sensibility was combined with rainfall to relative the risk, increasing or decreasing in accordance with the elevation of rainfall.

Table 1. Areas of land use (after reclassification).

Tableau 1. Nomenclature de surfaces (après reclassification).

Land use	Area		
	Km ²	Ha	%
Irrigated crops	17.72	1772	1,8
Rain fed crops	353.24	35 324	35,5
Forest	7.83	783	0,8
Arbored	20.59	2059	2,0
Bare soils	598.62	59 862	59,9
Total	998	99800	100

OCCUPATION DES SOLS RECLASSEE

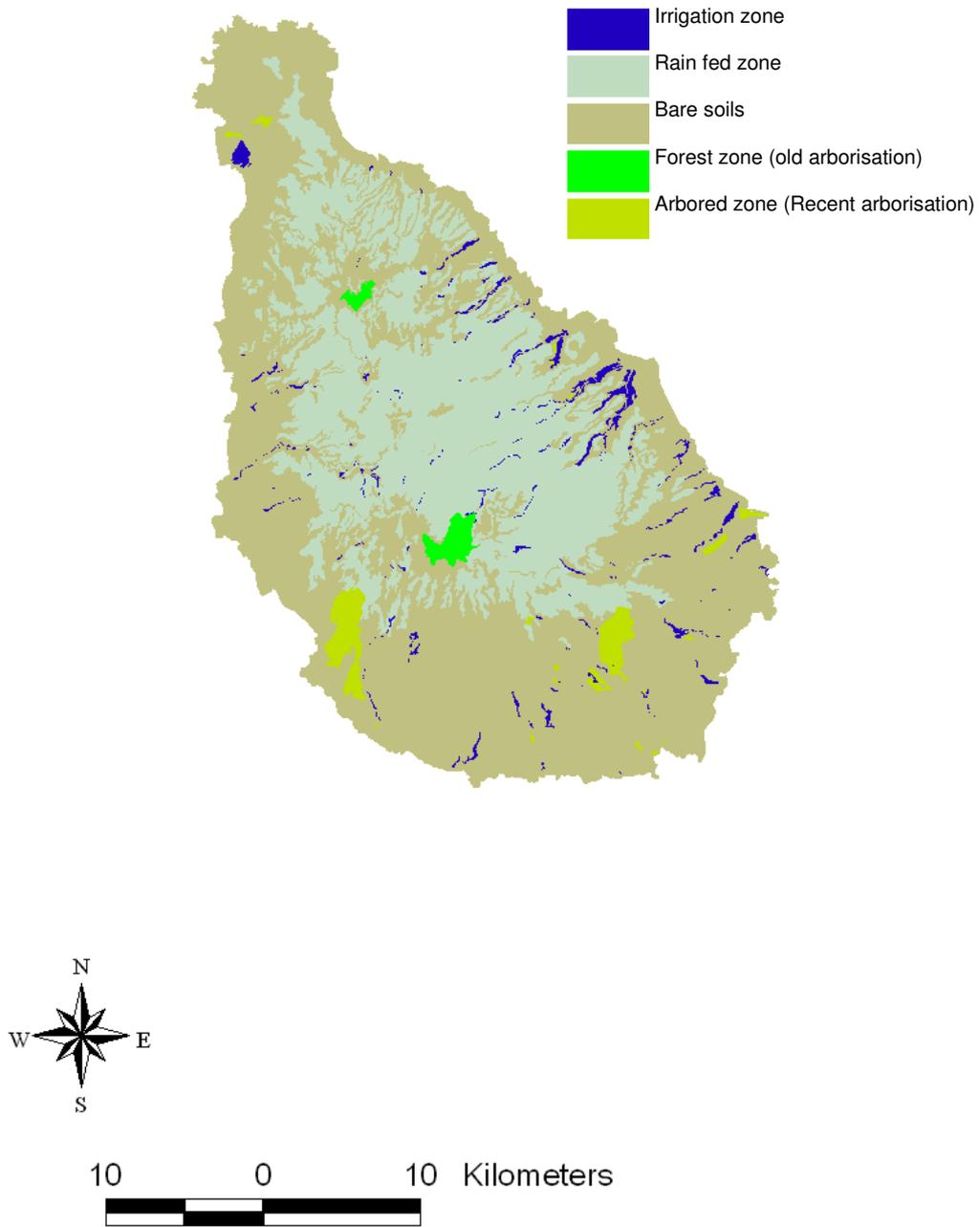


Fig. 4. Land use of Santiago.

Fig. 4. Occupation des terres de Santiago.

The production of crusting soil map shows that, Santiago soils are very sensitive to crusting. Crusting on surface soil was defined with three soil properties. According to the results (Fig. 5); crusting susceptibility affects only cultivated and bare soils, it has no effect or influence for grassland, irrigated areas and forest. Slope effect increases with crusting effect. Erodibility affects dangerously steep slopes. These results obtained show that more than the half (55%) of Santiago soils are a high to very high possibility to form a

crusting during winter season (table 2). The combination between crusting soil on surface, the high slopes: more than 50 % of Santiago's area present a slope included between 10-90 % (table 3) and land use do that soils are susceptible to erodibility (Fig. 6). According to the results, statistically 53 % of soils are in the high to extremely high erosivity, 44 % to very low at low and only 3 % has a moderate erosivity (table 4).

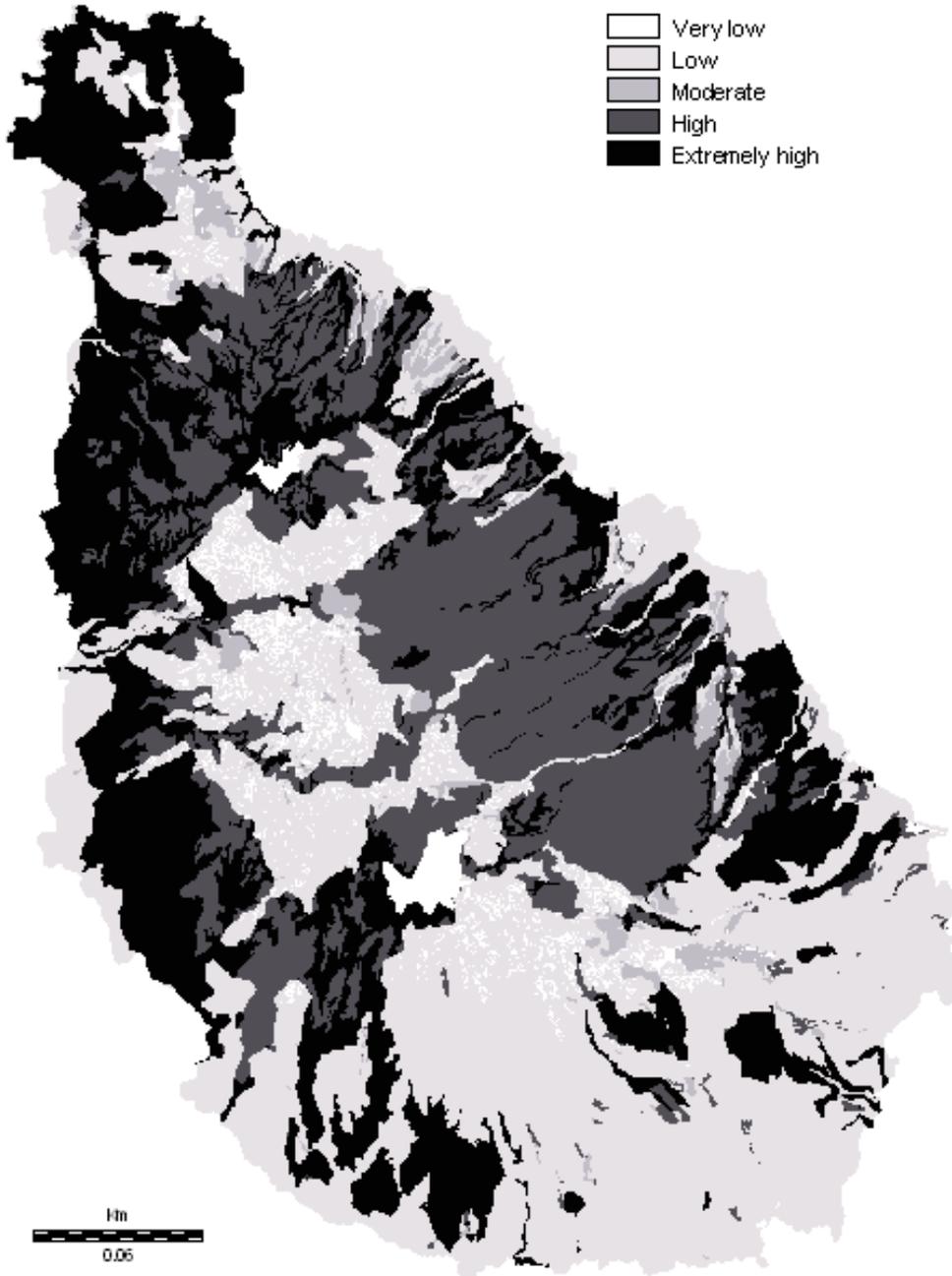


Fig. 5. Erodibility risk mapping.

Fig. 5. Carte de risque d'érodibilité.

Table 2. Crust on surface areas.

Tableau 2. Croûtes de surface

Index rating	Possibility to form a crust on surface	Area		
		km ²	Ha	%
1	Very low	289.42	28942	29
2	Low	69.86	6986	7
3	Moderate	89.82	8982	9
4	High	528.94	52894	53
5	Very high	19.96	1996	2
Total		998	99800	100

Table 3. Slope areas.

Tableau 3 Surfaces en pente.

Index rating	Slope (%)	Area		
		km ²	Ha	%
1	0 - 10	389.34	38934	39
2	10 - 15	179.64	17964	18
3	15 - 30	329.34	32934	33
4	30 - 90	9.98	998	1
Total		998	99800	100

Rainfall erosion risk mapping

The map of erosion risk (Fig. 7) reveals that Santiago may be broadly classified into five major erosion risk zones. The irrigation sectors are in the very low erosion risk zone; the coastal sector is generally in the low erosion risk zone; the forestry sector is generally in the moderate

erosion risk zone, while the rain fed sector is in the severe to extremely severe erosion risk zone with 826 km² about 91 % of Santiago's area. The table 5 shows a high correlation between land use and soil erosion. In Santiago Island 95% of the superficies are occupied by cultivated area with 35% and naked area with 60 %.

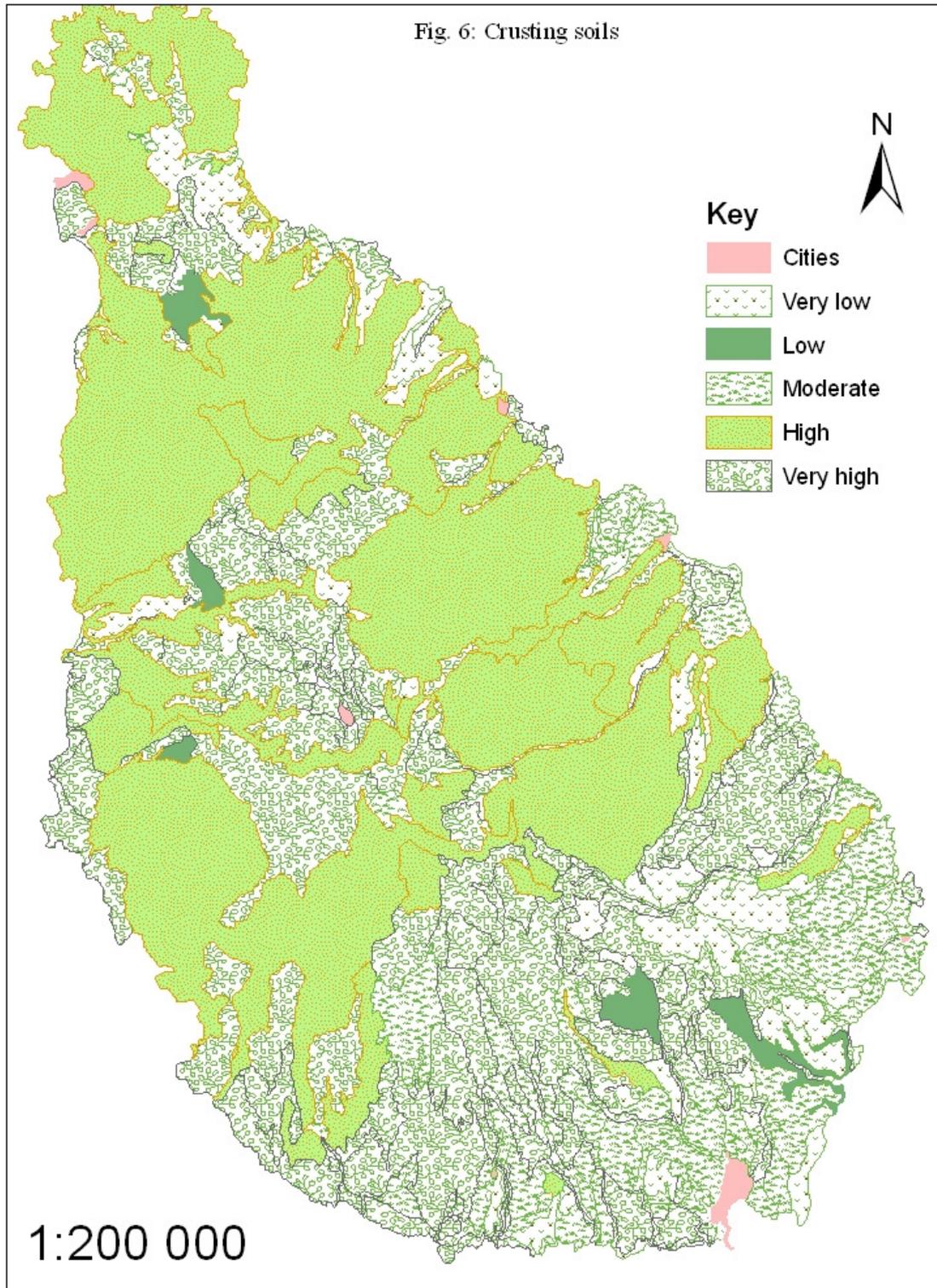


Fig. 6. Crust on surface

Fig. 6. Croûtes de surface.

Table 4. Erosivity areas

Tableau 4. Surfaces en pente.

Index rating	Erosivity	Area		
		Km ²	Ha	%
1	Very low	16.43	1643	1.64
2	Low	424.64	42464	42.5
3	Moderate	28.17	2817	2.86
4	High	229.32	22932	23
5	Extremely high	299.44	29944	30
Total		998	99800	100

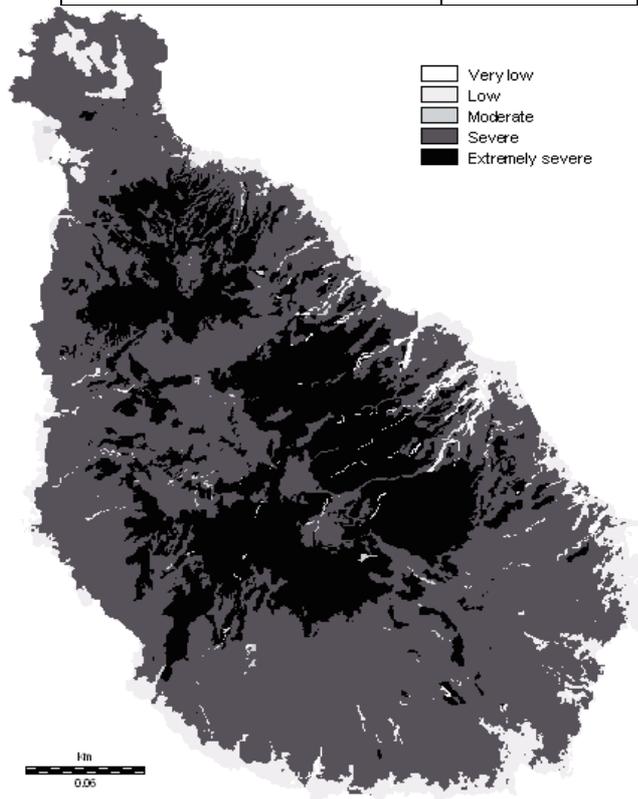


Fig. 7. Erosion risk mapping.

Fig. 7. Carte de risque d'érosion.

Table 5. Erosion risk areas.*Tableau 5. Risques d'érosion.*

Index rating	Description risk	Area			Land use
		km2	Ha	%	
1	Very low	0.21	21	0.02	Irrigation
2	Low	98.0	9800	8	coastal
3	Moderate	4.0	400	0.4	forestry
4	Severe	631.0	63100	63	rain fed
5	Extremely severe	285.0	28500	28	rain fed
TOTAL		998	99800	100	5 sectors

CONCLUSIONS

We propose ourselves to study the human and rainfall effects environment, mapping the risk of soils erosion by rainfall in Santiago Island.

Santiago is an agricultural island and a good part of the population live in rural areas and farming is the main source of income. More of 90 % of the land shows a high level degradation caused by farming activities only 10 % of the island has a moderate risk during rainfall period.

The choice of the methodology was influenced by the research's results obtained by Le Bissonnais *et al.* (2002). The model developed according to Santiago realities was been apply firstly to characterize the potential sensibility of soils, combining soil crusting, land use and slopes. Secondly, the potential sensibility was combined with precipitation data to relative the soils intrinsic sensibility, increasing or decreasing risk in accordance with the elevation of rainfall.

The modelling approach presented here is very simple and versatile: it can handle heterogeneous data resolution and quality; it does not require the use of parameters that are not available at national scale, such as the USLE model. This approach was also applied to a case study in the Middle Mountain region of Nepal (Shrestha *et al.* 2004).

However, errors and uncertainty associated to the results are much more dependent on the input data than on the model itself, because it is based on very simple and global assumptions accepted by all experts.

The map of erosion risk (Fig. 7) reveals that Santiago may be broadly divided into five major erosion risk zones and 91% of soils have high to very high risk, about 8 % with very low to slow and only a very small area with 0.4 % moderate risk.

This work could be improved and developed with respect to some guidelines: (i) to characterise the soil's erosivity, combine the intensity and the mean monthly rainfall height; (ii) simulations regarding the impact of climate changes or land cover modifications could be considered; (iii) update Santiago's land use and determinate the state actual of soil erosion.

It is hoped that the map will be useful for soil and water conservation planning in Santiago island and the model developed could then be used by local practitioners in soil management and protection for the others islands.

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