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Developing erosion models for integrated coastal zone management: A case study of The New Caledonia west coast

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A B S T R A C T

The tropical climate and human pressures (mining industry, forest fires) cause significant sediment inputs into the New Caledonia lagoon and are a major cause of degradation of the fringing reefs. The erosion process is spatially characterized on the west coast of New Caledonia to assess potential sediment inputs in the marine area. This paper describes the methodologies that are used to map soil sensitivity to erosion using remote sensing and a geographic information system tool. A cognitive approach, multi-criteria evaluation model and Universal Soil Loss Equation are implemented. This article compares the relevance of each model in order to spatialize and quantify potential erosion at catchment basin scale. These types of studies provide valuable results for focusing on areas subject to erosion and serve as a decision-making tool for the minimization of lagoon vulnerability to the natural and human dynamics on the level of the catchment basins.

1. Introduction

The mechanical erosion of soils is a natural feature of the high tropical islands which are subjected to extremely heavy rainfall. Moreover, any human action leading in particular to the destruction of the plant cover and to the stripping of the soil highlights the inherent instability of the natural system. In New Caledonia, the major causes of this erosion are inappropriate agricultural practices, urbanisation of slopes, construction of various infrastructure (roads and water-management systems), but above all mining. Indeed, the country is the fifth largest nickel producer in the world (with about a quarter of global resources). The nickel ores are exploited in open pit mines and the unstabilized waste rocks are carried away by the rivers down to the lagoon. These huge sediment inputs cause severe degradation and changes in the littoral system:

- elevation of watercourse beds contributing to repeated floods affecting fertile agricultural land;
- burial of bank vegetation and destruction of the aquatic fauna;
- modification of the fluvial and littoral morphologies;
- aesthetical pollution of the near-shore waters resulting in red sea water;
- hyper-sedimentation of the bays. Deposits are responsible for the stress of corals by increasing the water turbidity which causes a decrease in the light required by coralline life.

Thus, erosion is the most significant cause of the degradation of lagoon ecosystems and fringing reefs in New Caledonia, in particular during cyclonic floods. The evaluation of this type of terrigenous input which is likely to be transferred to the lagoon, is absolutely essential for an Integrated Coastal Zone Management (ICZM). Such a study has never been conducted before in New Caledonia at the scale of several catchment basins (Dumas, 2004). Various approaches based on the modelling of transfer processes of the sediment or pollutants exist, but they often apply to geographically restricted areas (SWAT: Soil and Water Assessment Tool: Arnold and Williams, 1995; Neistch et al., 2002; SHE: *Système Hydrologique Européen*: Abbott et al., 1986; Bathurst and O'Connell, 1992). Moreover, these models require many field measurements for their calibration that are not available in New Caledonia and are thus unsuitable.

This article aims to describe the implementation of two models for the spatialization and quantification of potential erosion. The first model is based on a cognitive multi-criteria approach. The second is based on the Universal Soil Loss Equation (USLE), an empirical quantitative model designed for the evaluation of annual soil loss rates on a long-term basis. All of the major factors involved in these models were derived from spatial input data using a Geographical Information System (GIS) framework. Finally, we

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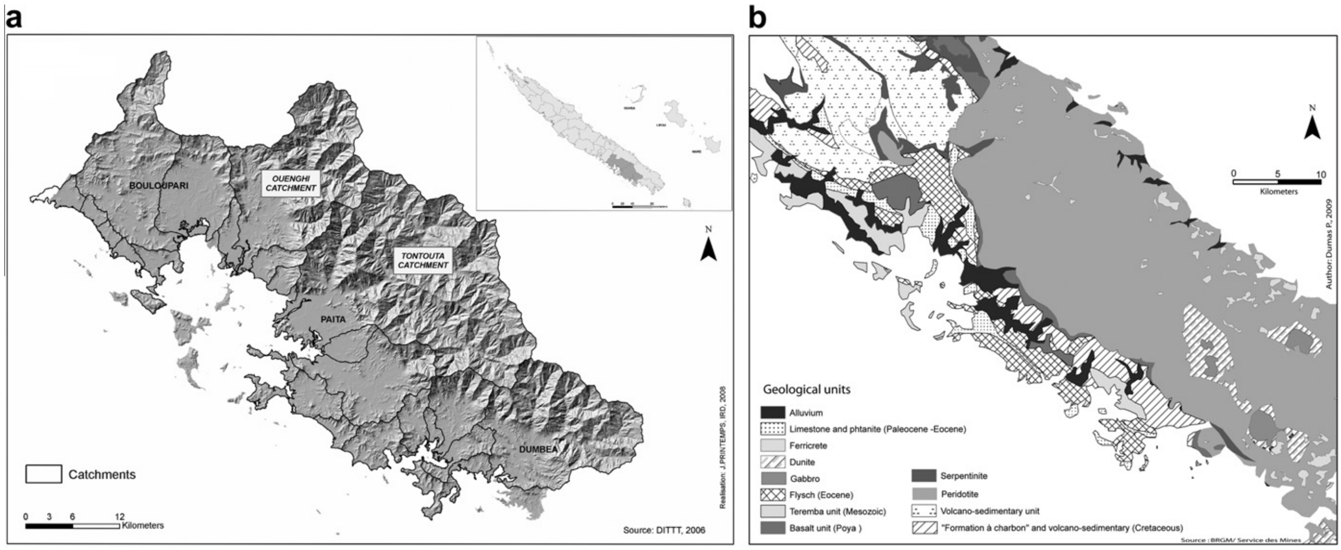

Fig. 1. Location, digital elevation model and simplified geological map of the study area. The study area in New Caledonia covers the whole of part of three communes (Bouloupari, Païta and Dumbéa) in the southern province.

compare the results from these two approaches in order to assess their relevance (cross validation).

2. Study area

New Caledonia, an overseas territory of France, is located in Melanesia in the southwest Pacific Ocean (21°30′S–165°30′E), approximately 1200 km east of Australia and 1500 km northwest of New Zealand. This territory comprises a main island the "Grande Terre", the Loyalty Islands, and several smaller islands. The "Grande Terre" is by far the largest of the islands, and the only mountainous island. It has an area of 16,360 Km^2 and is elongated northwest–southeast, 450 km in length and 50–70 km wide. From North to South a mountain range, the Central Chain, runs the length of the island, with five peaks over 1500 m. In the South and along the west Coast the very large occurrence of ultramafic rocks is the dominant feature of the folded arc of "Grande Terre". These rocks make large and high massifs then named "massifs miniers". With a variety of shapes and vegetation, these mountains are areas of bush and red soils in ultramafic massifs, primeval rain forest on heights and along creeks, savanna with niaoulis (*Melaluca quinquenervia*) in its driest parts. The East Coast has steep slopes towards the sea. This coast is exposed to the trade winds and has high mountains. Consequently it gets a much higher rainfalls and has a lush vegetation contrasting with the dry savanna of the west coast.

New Caledonia has a tropical climate, and rainfall is highly seasonal[1]. On the main island, rainfall varies a lot according to elevation and wind exposure. It rains mostly in the mountains on the East Coast and in the South. Rainfall averages are 1000–2000 mm yearly at low elevations on eastern "Grande Terre", and 3000–4000 mm at high elevations on the main island. The western side of the big island lies in the rain shadow of the central mountains, and rainfall averages are significantly lower. During the warm season (mid-November to mid-April), frequent tropical depressions and cyclones produce heavy rainfall which is the main driving factor for soil erosion.

The study area, located on the west coast, is made of 26 catchment basins, covering an area of 1750 Km^2 (Fig. 1a). This vast region presents a dichotomy between a large coastal plain and a mountain zone and hills covering half the region. The plain is covered by an extensive grass and dry niaoulis savanna over low hills and flat areas. Savanna is used for permanent pasture but bush fires occur nearly every year in this vegetation. On the east side of the study area, large areas of ultramafic rocks ("massifs miniers") add to the landscapes originality. They correspond to mountainous areas with vivid red lateritic soils covered by an endemic vegetation bush and forests of unique plants species. In terms of geology (Fig. 1b), ultramafic rocks (formed by peridotite as harzburgite, dunite and a thick bed of serpentinite occurs at the massifs bottom) are capped by a weathering mantle (5–50 m thick) including very erodible limonite layers (laterites: highly vulnerable to erosion when stripped) and a hard iron crust. Rainfall varies a lot according to elevation. Rainfall averages are about 500–2000 mm at low elevations on small islands in Saint-Vincent Bay, on coastal plain and in valleys, and 3000–3500 mm at high elevations along the mountain areas.

The choice of this study area can be explained regarding factors of natural erosion processes and the impact of human pressures. In fact, this region is representative in terms of pressures that exists in New Caledonia. On one hand, natural pressure exists due to the amount and the intensity of rainfall and the steepness of slopes while, on the other hand, human pressure exists due to bushfires, agriculture, land-clearing by fire and mining activities. There are several old mines (closed before 1975) in this area, not revegetated, that are still contributing to soil losses, as well as several mining operations on Mount Tontouta.

All of these factors contribute to the erosion process. At the scale of a watershed exploited by the mining activity, data have been collected, notably on the watershed of the Ouenghi River (245 km^2). This study showed that during the last 28 years, the total of the solid inputs resulting from natural erosion and mining exploitation is estimated at one million cubic meters, that is, a progression of the delta of 300–400 m in the lagoon on a 3 km front, burying the coralline reefs under the sediments over 100 ha (Danloux, 1987; Danloux and Laganier, 1991). Another study has shown that more than forty rivers and indirectly downstream estuaries are affected to varying degrees by mining activity (Bird et al., 1984).

[1] Two dry seasons : the main dry season (September to November) and the small one (April-May). Two rainy seasons: the main one (December-March) and the small one (June-August).

3. Methodology

The objective of the two developed models is to spatialize the intensity of the erosion hazard from the perspective of a potential transport of solid particles in the catchment basins. The aim is to assess the volume of terrigenous inputs that may be transferred to the lagoon and could, therefore, disturb the coralline ecosystems or littoral dynamics.

The first method is based on a cognitive approach and a multi-criteria evaluation model. It is a qualitative method; some of the factors taken into account are expressed in terms of an intensity level as defined by expert opinion (Maurizot and Delfau, 1995; Le Bissonnais et al., 2002).

The second method is based on the Universal Soil Loss Equation model. In this empirical model, values of the factors are calculated on the basis which ones (Wischmeier and Smith, 1978).

The spatialization of these two approaches is implemented using the data processing and mapping functionalities of a Geographical Information System (GIS).

3.1. Cognitive multi-criteria approach

An initial mapping of the erosion hazard was carried out on the study area on the basis of a cognitive approach (Dumas, 2004). The sensitivity of soils to erosion which emerges from this first study takes into account the cross-referencing of three factors (slope steepness, erodibility of the superficial geological formations and protection of the vegetation cover). The cartographic results are presented in terms of four sensitivity levels (zero, low, medium and high), qualitatively defined in the view of experts. In this article we describe the use of a method which is more sophisticated from the perspective of the number of factors taken into account, their representation and their modes of cross-referencing but still based on a cognitive model (Luneau and Dumas, 2006).

3.1.1. Making the layers

Seven factors are selected to characterize the erosion process. The values for some of these factors were qualitatively reclassified on the basis of an indicator prioritizing their contribution to the erosion. The following information schemes are mapped using a GIS:

1. The slope steepness is certainly one of the most significant parameter by virtue of its gravity action and its impact on the transport of sediment (Dumas, 2004). The slope affects the overall rate of movement downslope. This variable is calculated from the values of a digital elevation model (DEM) with a 30 m resolution (Fig. 2a).
2. *The measured horizontal curve*: This is the measure of the separation of the contour lines (Fig. 2b). The planiform curvature influences convergence and divergence of flow. Positive values indicate convex areas which facilitate the dispersion of the

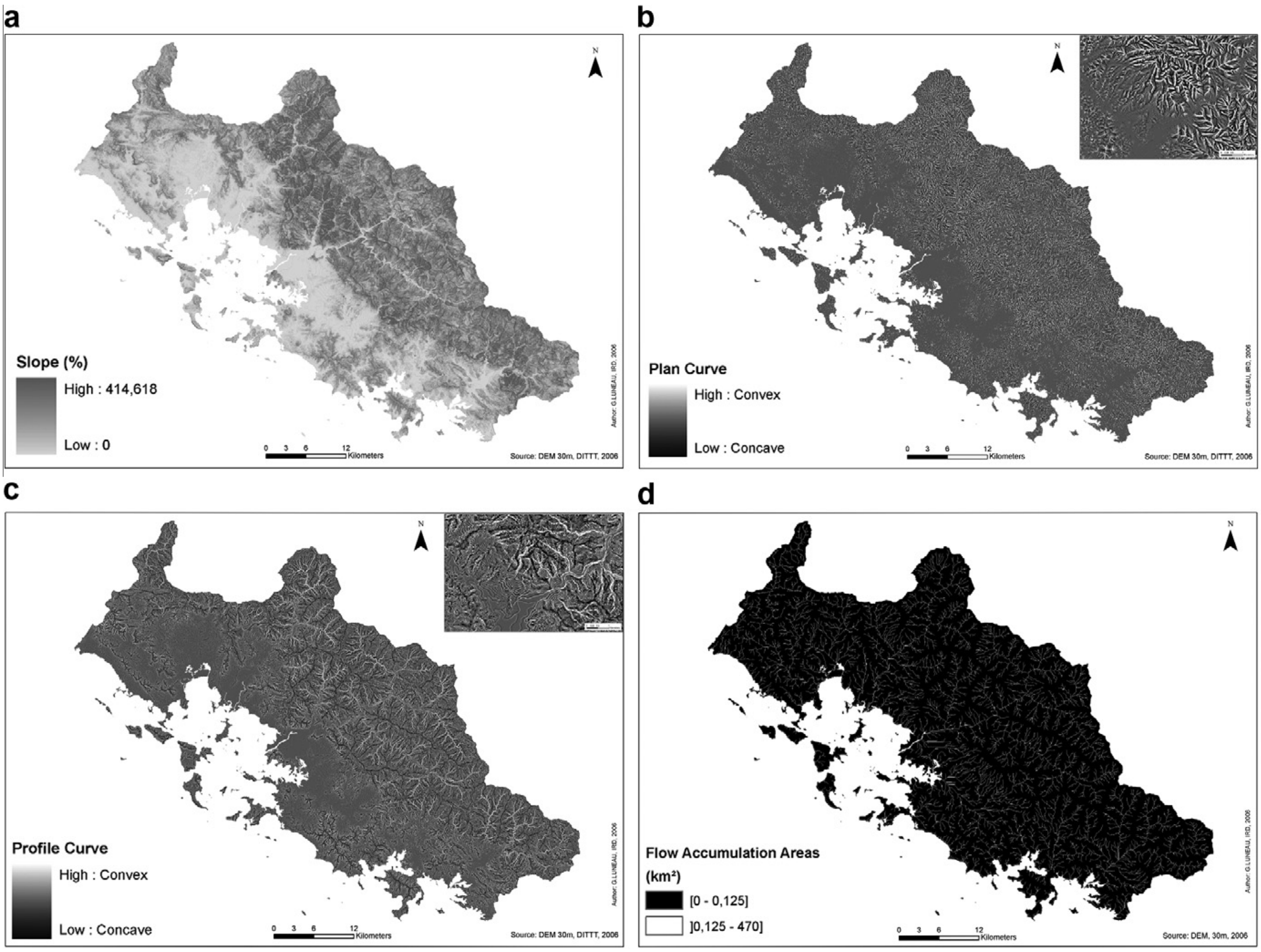

Fig. 2. The first four factors taken into account in the multi-criteria approach: slope steepness, horizontal curves, profile curve, and flow accumulation areas.

runoff, while negative values indicate the presence of entrenched valleys which facilitate the erosion process (Maurizot and Delfau, 1995).

3. *The profile curve*: Physical characteristic of a drainage basin, this is the curve measured in a vertical section systematically reoriented towards of the direction of the altitude gradient (direction followed by the fluids). The profile curvature affects the acceleration and deceleration of flow and, therefore, influences erosion and deposition. Negative values indicate a slope which decreases along the profile and, thus, a concave surface facilitating the erosion process (Fig. 2c).
4. *Cumulative drained surfaces are also calculated from the DEM*: This calculation reveals for each pixel the upstream area covered by the water flowing into this pixel. The larger is the drained surfaces, the higher is the quantity of water that flows on the soil in the pixel, increasing the risk of detaching particles. This risk of erosion increases in a linear way according to the size of the cumulated drained surfaces. However, we may consider that a hydrographic network definitely plays a role in the erosion process, starting from a drained area of 1125 km^2 (Wotling, 2000). This minimum threshold indicates that below this value, water drainage is not considered as sufficient to contribute significantly to the soil erosion process (Fig. 2d).
5. The nature of soils is a major parameter in the erosion process as the removal of particles depends directly on their physical properties. As pedologic data were not available at that time, only one parameter was calculated: the erodibility index, which was defined from the map of superficial geological formations with a scale of 1/50,000. Based on this map, which differentiates over 90 geological classes, a resequencing of 1 (little erodible geological formations) to 10 (highly erodible) is carried out. The attribution of this index takes several components into account (hardness, friability etc.). It is carried out "in the view of experts" that is, on the advice of experts knowing the area very well (Maurizot and Delfau, 1995) (Fig. 3a).
6. The land use is a determining factor in the soil protection, in particular through the type of vegetation present and its rate of cover. The land use layer is implemented on the basis of the results of supervised classifications of satellite data Landsat 7 and Spot 3 (Fig. 3b). Based on these data, the classes of land/soil use are prioritized in accordance with the protection they provide against erosion. These classes range from 1 (dense forest, very high soil protection) to 10 (bare soil, very vulnerable to erosion). In view of the fact that bare soils are far more subjected to erosion than all other classes, we undertake recoding process to emphasize this difference: the bare soils of the mangroves are re-coded as 14 and the other bare soils as 15.

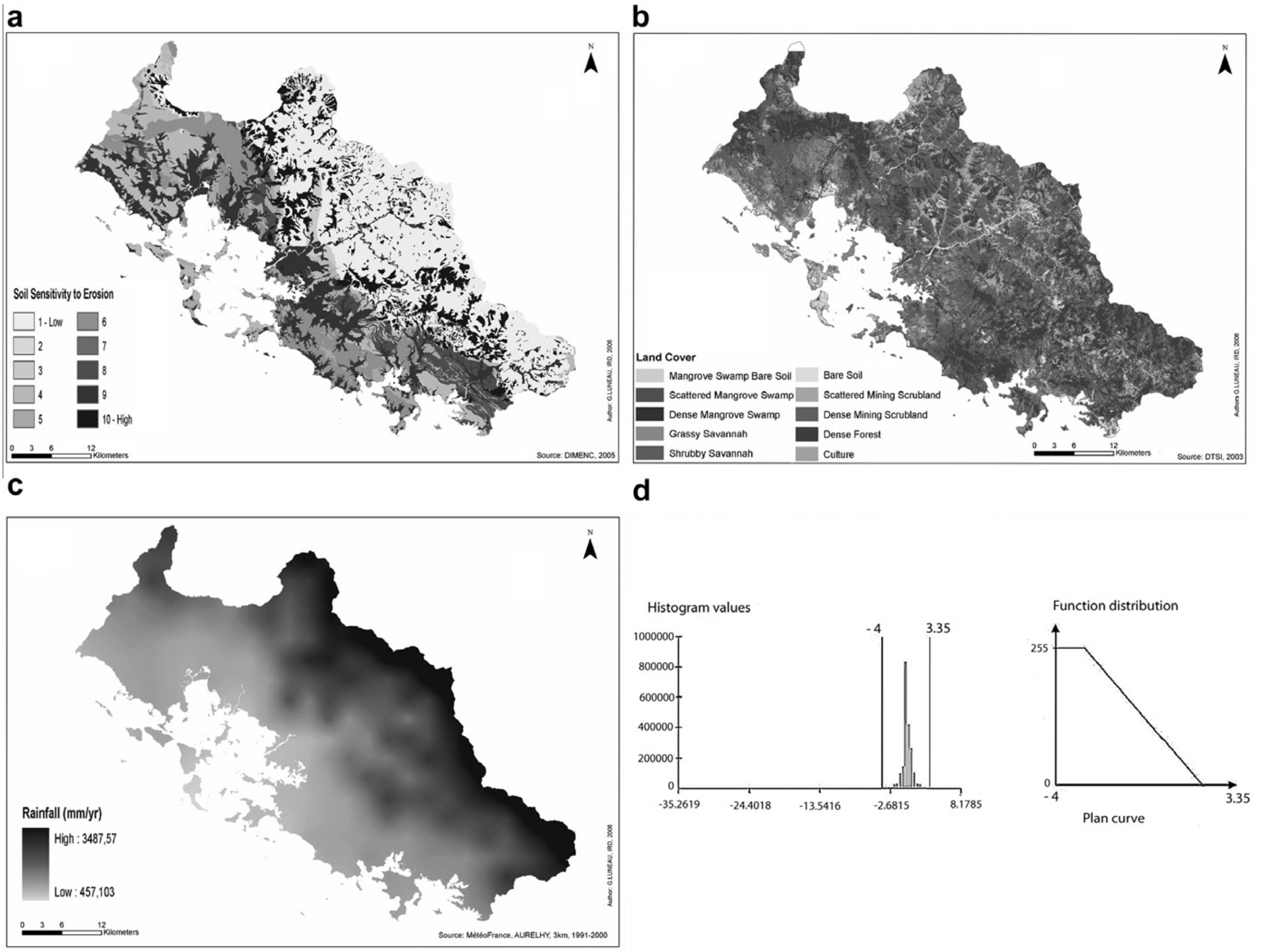

Fig. 3. The three others factors taken into account in the multi-criteria approach: erodibility of the geological materials, land-use and mean annual rainfall (1991–2000). The (d) illustrates the standardisation of the horizontal curves factor.

7. Rain is also one of the main erosion factors. Soil erosion occurs when the rain water that cannot infiltrate into the soils and flows away carrying soil particles (Le Bissonnais et al., 2002). A spatialization through interpolation (kriging method) is carried out on the basis of the data on rainfall provided by Météo France (mean annual rainfall for 1991–2000 period: Fig. 3c).

3.1.2. Multi-criteria evaluation

Once all information layers have been processed, the multi-criteria evaluation procedure is initiated. The first operation required is the standardization of each selected factor. In fact, in order to cross the different layers of a model, they must be defined on the same scale ranging from 0 (low erosion risk) to 255 (high erosion risk). For each factor, values should be distributed on this scale, according to its nature and role in the erosive process. Only the example of the horizontal curve is discussed here.

The calculation of the horizontal curve indicates the concavity of an area through a negative value, convexity through a positive value and a flat surface through a zero value. The function used is therefore of a decreasing linear type because erosion decreases progressively as the curve value increases. Threshold values are defined so as to perform the standardization in a value interval ranging from -4 to +3.35. Indeed, the analysis of the value histogram demonstrates the concentration of values in this interval (Fig. 3d).

The second step consists in organising the factors into a hierarchy of their implication in the erosion processes. This was carried out empirically with a good knowledge of the factors coming into play. By the means of a pair-wise comparison matrix (Saaty matrix), weights were attributed to each pair of factors based on a bibliographical study and expert advice (Maurizot and Delfau, 1995). The Saaty matrix enabled the calculation of the following weights (Table 1).

Finally, the last step in our methodology involves the cross-referencing of all our weighted factors. So we apply a Weighted Linear Combination (WLC) which has the following algorithm: $E = \sum Pi \cdot Si$ with: E = Evaluation, Pi = weight of factor i, Si = value of factor i standardized.

This technique simply consists in multiplying each standardized factor by its weight and then adding them. The total is divided by the number of factors.

The result of the multi-criteria evaluation is a gradation map of the "hydric erosion" of the soil. This hazard is reflected by a continuous variable ranging from 52 (low hazard) to 202 (high hazard).

3.2. Universal soil loss equation (USLE)

The universal soil loss equation USLE (Wischmeier and Smith, 1978), later revised as the RUSLE (Renard et al., 1997), is the most widely used model for the prediction of water erosion hazards and planning of soil conservation measures. The USLE was statistically derived from a large database generated from plot experiments in the United States of America. It estimates the long-term average annual soil loss rate using a factor-based approach with rainfall, soil, topography, land cover and management practice as inputs.

Table 1
Weights for each layer of the model.

Layers	Weight
Slopes	0.2644
Rainfall	0.2644
Profile bends	0.0486
Horizontal bends	0.0486
Flow accumulation	0.1152
Geology	0.1152
Land Cover	0.1152
Roads	0.0284

It calculates mean annual soil loss (A in tons/ha/year) as a product of five factors:

$$A = R \times K \times (LS) \times C \times P$$

where: A is soil loss in tons/ha/yr, R is rainfall and runoff erosivity factor in MJ m/(ha h yr), K is soil erodibility in t h/(MJ mm), LS is slope length and slope steepness, C is cover management, and P is support practice.

Since all factors in the USLE have a spatial distribution, it is possible to carry out a GIS-based evaluation of the different factors by overlaying the layers and multiplying them on a grid basis (Printemps, 2007; Printemps et al., 2007).

3.2.1. Rainfall and runoff factor: R

The rainfall and runoff factor (R) represents two characteristics of a storm that determine its erosivity: amount of rainfall and peak intensity sustained over an extended period. Research showed that soil losses are directly proportional to the total storm energy (E) times the maximum 30-min intensity (Wischmeier and Smith, 1978; Brown and Foster, 1987). R is computed as (Eq. (1)):

$$R = \frac{1}{N}\sum_{i=1}^{k}(E \times I_{30}) \tag{1}$$

where: R is in MJ mm/(ha h yr), N is number of years, k is number of rainy events, E is total storm energy in MJ mm/(ha h), and I_{30} is the maximum 30 min intensity of rain in mm/h.

As there are no possibilities for obtaining precise data on the study area, Roose's approximation (1975, 1977a and b) was used to spatialize R with the Eq. (2):

$$R = 1.73 \times P \times 0.5 \tag{2}$$

with P, the average annual rainfall

About this substitution method, Morrison (1998) reported that the use of $R = P$ (mm/yr) $\times$ 0.5 in Fiji gave reasonable values. So, the spatialization of precipitation (P), produced by Météo–France according to the Aurelhy model, was used and integrated in Roose's approximation to get the R factor (Fig. 4a). The R values range from 396 to 3017 MJ mm/(ha h yr), which is compatible with other estimations in the literature. For example, R = 8098 in Haïti for an average of precipitations around 1900 mm/yr (Delusca, 1998).

3.2.2. Slope length and slope steepness factor: LS

The length and slope steepness factor (LS) represents the effect of topography on erosion, as increases in slope length and slope steepness produce higher overland flow velocities and therefore stronger erosion (Haan et al., 1994).LS is derived from Eq. (3) Wischmeier and Smith (1978):

$$LS = \left(\frac{\lambda}{22.13}\right)^m \times (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \tag{3}$$

Where: λ is the slope length in meters, θ is the slope angle in degrees, and m is a slope angle contingent variable ranging from 0.01 to 0.56 (McCool et al., 1987).λ and θ were calculated using a 30 m resolution DEM and an AML script under ArcInfo developed by Van Remortel et al. (2004). LS values vary from 0 to 126, with an average of 9.47 (Fig. 4b). These values are compatible with previous studies, for example 0–88 in Morocco for slopes between 0% and 60% (Sadiki et al., 2004), 0–102 in Haiti for slopes between 0% and 60% (Delusca, 1998).

3.2.3. Soil erodibility factor: K

The K factor is related to the integrated effects of rainfall, runoff, and infiltration on soil loss, accounting for the influences of soil properties on soil loss during storm events on upland areas

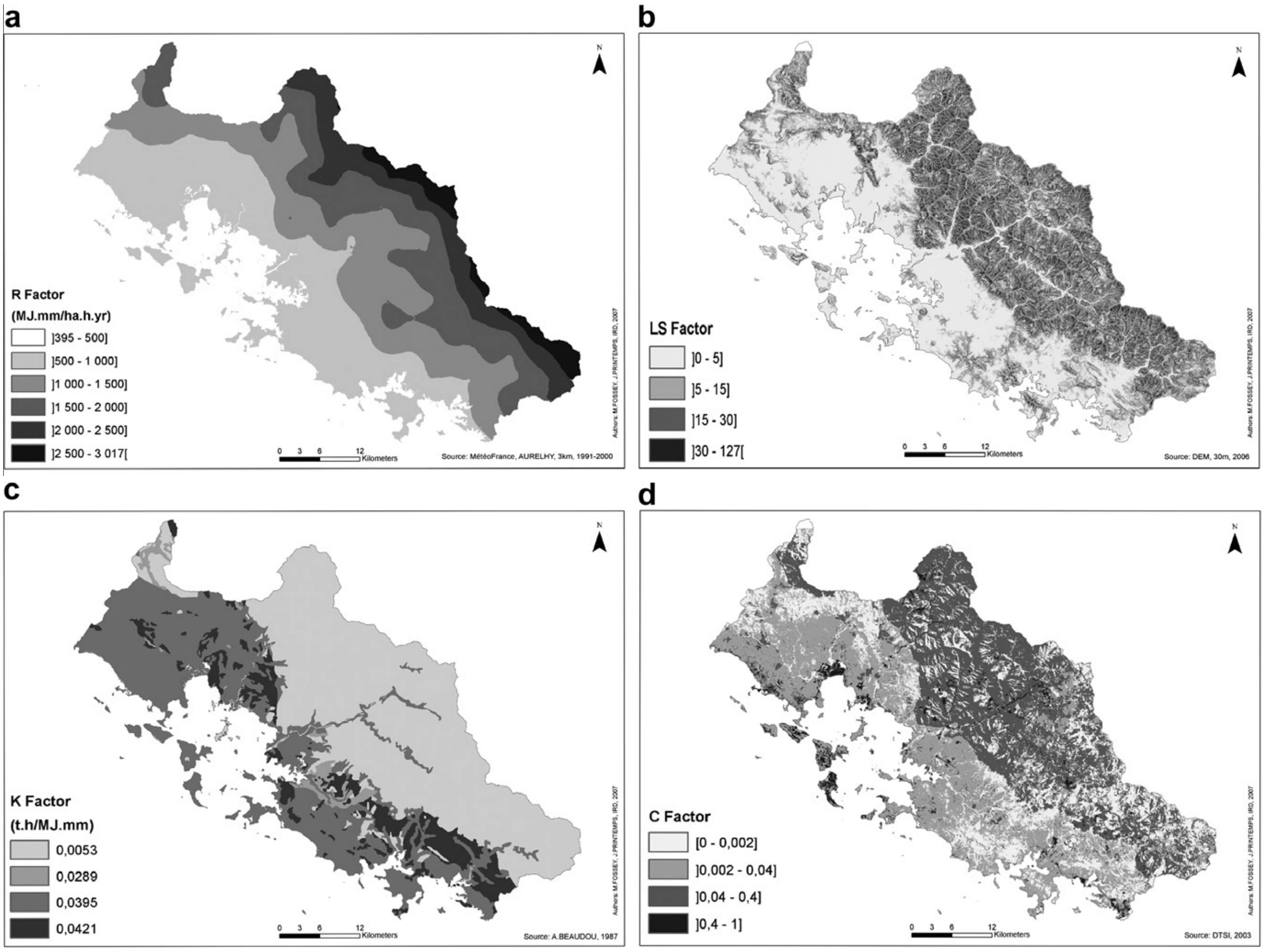

Fig. 4. Four factors are used for the application of Universal Soil Loss Equation: the rainfall and runoff factor (R), the length and slope steepness factor (LS), the soil erodibility factor (K) and the cover management factor (C).

(Renard et al., 1997). It is often estimated through experimental equations (e.g., Eq. (4)) or corresponding nomographs (Wischmeier and Smith, 1978).

$$K = 2.1 \times M^{1.14} \times 10^{-6}(12 - MO) + 0.0325 \times (b - 2) + 0.025 \times (c - 3) \quad (4)$$

Where: M = (%silt + %very fine sand)(100-%clay), MO is the percent organic matter content, b is soil structure code, and c is the soil permeability rating.

Table 2
K-factors for the study area.

Soil	Usda class	*K*
Altered ferritic and ferrallitic soils	Sandy loam	0.0053
Tropical eutrophic brown soils, hypermagnesic, on ultrabasic rocks	Clay	0.0289
Desaturated fersiallitic soils	Loam	0.0395
Little developed soils of alluvial contribution, modal with variable texture	Sandy loam	0.0421
Tropical eutrophic brown soils, little developed and modal on basalts	Clay	0.0395

The soil erodibility K (Table 2) was derived from a soil map of at 1/200,000 scale. The region is divided into five major soil classes. For each soil type samples were collected in the field across the study area. A granulometric analysis allowed determination of the texture as percentages of sand /silt/ clay and the percent organic matter content. The K value for each soil type was calculated, then each soil type was associated with a K value assuming that the same soil type has the same K value throughout the study area. They have K factors ranging from 0.0053 to 0.0421 (Fig. 4c). These values are compatible with other studies, for example K ranged from 0.004 to 0.15 in the Bouyaha catchment in Haiti (Durosier, 1990), and 0.026–0.052 on the Balan gully in Haiti (Delusca, 1998).

However, finding a suitable erodibility index for soils under tropical conditions has its limitations because the majority of existing erodibility indices has been developed for soils in temperate regions. There have been suggestions that the USLE K factor nomograph sometimes does not fit tropical soils (Vanelslande et al., 1987). This diversity can be explained by the wide differences in tropical soils. Another problem is the fact that K factor values are often quoted in relation to soil types that do not necessarily reflect erodibility. Morrison (1998), for instance, explains the limitations of the use of soil properties in assessing the erodibility and how the USLE erodibilty function can be influenced by the limitations in particle size analysis in irreversibly hardening soils, with short-range order minerals and high organic matter contents.

3.2.4. Cover management factor: C

The cover management factor (C) is a weighting index, taking into account the effect of land use on soil erosion (Renard et al., 1997). It is measured as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled land under continuous fallow conditions (Wischmeier and Smith, 1978). By definition, C equals 1 under standard fallow conditions. As vegetative cover approaches 100%, the C factor value approaches 0. In our study area, six vegetation types were defined from a 1996 thematic land cover map. Cover factor (Fig. 4d) ranged from 0.001 to 1 (Table 3).

3.2.5. Support practice factor: P

The support practice factor P represents the soil conservation operations or other measures that control the erosion, such as contour farming, terraces and strip cropping. Because no information was available on P for this study, a value of 1 was used. Under that condition, due to the definition of the USLE, as a multiplicative equation, support practice impact does not influence either the spatialization or the value of soil losses.

Table 3
Land cover types and *C*-Factor.

Vegetation type	*C*
Forest	0.001
Savannah	0.01
Mining scrubland	0.25
Swamp	0.28
Cultures	0.40
Brush	0.72
Bare land	1

4. Results

4.1. Cognitive multi-criteria approach

A significant spatial contrast between the distribution and intensity of the erosion hazard intensity can be observed on the map obtained (Fig. 5). Moreover, a strong dichotomy appears between the coastal plain and the mountain area and of course the intensity of the erosion hazard increases perceptibly in areas of high relief.

Whereas the Central Chain in this region is mainly constituted by peridotite (as harzburgite and dunite and others, such as, altered peridotite as laterite and saprolite) and hilly areas at the base of this mountain range are often covered by colluvium and alluvium, these areas have the highest sensitivity to erosion. This can be explained (with the geological constitution) by the importance of rainfall and slopes in the cross-referencing of the factors. In fact, the surface cover of peridotite formation consists in a weathering lateritic mantle 5–50 m thick. The laterite, a loose material when not topped by a ferricrete, is highly vulnerable to erosion when stripped. Mining is possibly not the more significant cause of erosion considering the denuded surfaces (caused by fires, or natural erosion). In contrast, the coastal plain is less sensible to erosion processes.

These cartographic results provided by our multi-criteria approach appear to be generally relevant with the initial field surveys and visual analysis of aerial photographs of the study area. Indeed, a good correlation of the spatialization of the eroded areas can be observed between the field reality and the model. However, the detailed interpretation of the hazard variation remains difficult. Even if its intensity displays a value range of 52–202, its reading is

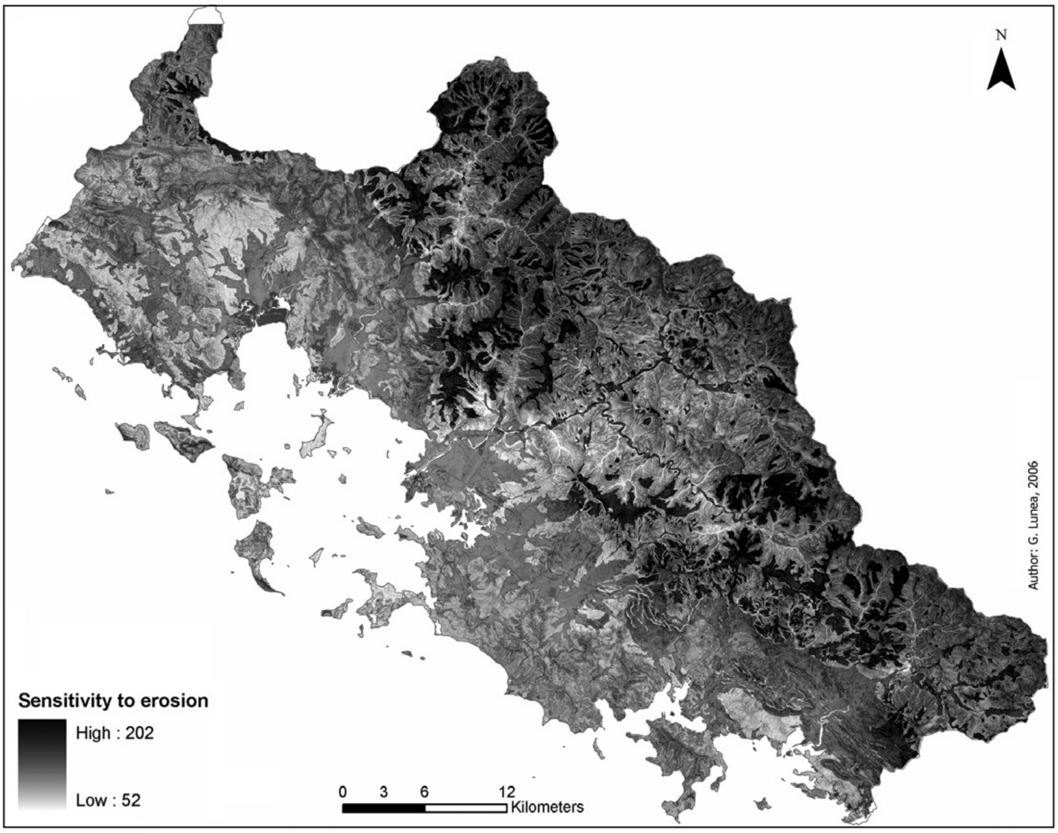

Fig. 5. Spatial distribution map of sensitivity to erosion by multi-criteria and weighted cross-referencing. This result highlights a high erosion hazard in denuded areas covered by laterite with steep slopes.

limited to a qualitative interpretation (low, medium, high). Thus, the quantification of the erosion phenomenon remains one of the main limits of this so-called "expert" approach.

One of the objectives of the study is the comparison of the two methods for the spatialization of the erosion hazard. It is therefore necessary to standardize the data produced by the results of the two models in a 0–1 range. The standardized histogram of the multi-criteria analysis is presented in Fig. 7a. Weak values are scarce due to the fact that the expert approach reckons that the entire study area is likely to be subjected to the erosion hazard, even in weak proportions. We can also observe that around 70% of the studied area is characterized by a mean sensitivity to erosion (values comprised in the [0.25, 0.50] interval). The distribution is clearly bimodal (typical of a coupling of measurements originating from two different environments).

4.2. Universal soil loss equation

Soil erosion loss is estimated by combining GIS layers. The *R*, *LS*, *K* and *C* factor layers are multiplied to create a soil loss rate layer (Fig. 6). The resulting erosion rate *A* ranges between 0 and 3300 t/ha/yr in the study area, with an average of 18 t/ha/yr.

Sixty-two percent of the study area has an erosion rate below 5 t/ha/yr. These areas are the least sensitive to erosion, and correspond primarily to basin floodplains and flat areas of the Central Chain covered by forests.

Eighteen percent of the study area is considered to have a medium to high erosion loss (more than 30 t/ha/yr). These areas are primarily in the Central Chain and result from the association of three factors:

- bare soils due to human activities, such as mining and bush fires (slash and burn practices),
- steep slopes,
- high precipitations and altered soils due to tropical climate (~2000 mm/yr).

These results are compatible with other estimations in the South Pacific Islands. For example in Fiji, Liedtke (1989) measured soil losses corresponding to 22–80 t/ha/yr on slopes of 5°–29°, in a sugarcane growing area north of Nadi. Always in Fiji, on a lowland floodplain of the Wainimala River, the sediment accretion rate over the last 45 years, measured by ^{137}Cs stratigraphy, is 3.2 cm year^{-1} (Terry et al., 2002). This measure exceeds rates reported from fluvial systems in other humid environments, and reflects both the frequency of tropical cyclone-induced floods and the high suspended sediment concentrations produced during these events. Using data for the sediment load in the Waimanu river, Glatthaar (1988) estimated that the average soil loss for the catchment was about 53 t/ha/yr. These values are particularly high given that the catchment is heavily forested. Further, Glatthaar stated that one important erosion feature is the instability of the steeper slopes (with important landslides during a major rainstorm). Clarke and Morrison (1987) made fields observations of soils losses of 90–300 t/ha/yr for areas where forest or indigenous grassland were converted to intensive sugarcane production in Fiji.The standardized histogram (Fig. 7b) shows that:

- Most of the values are low and range between [0; 0.1]. They are located on the coastal plain.
- The [0.1; 0.3] interval represents an average erosion: these values are few in number and located along relief areas.

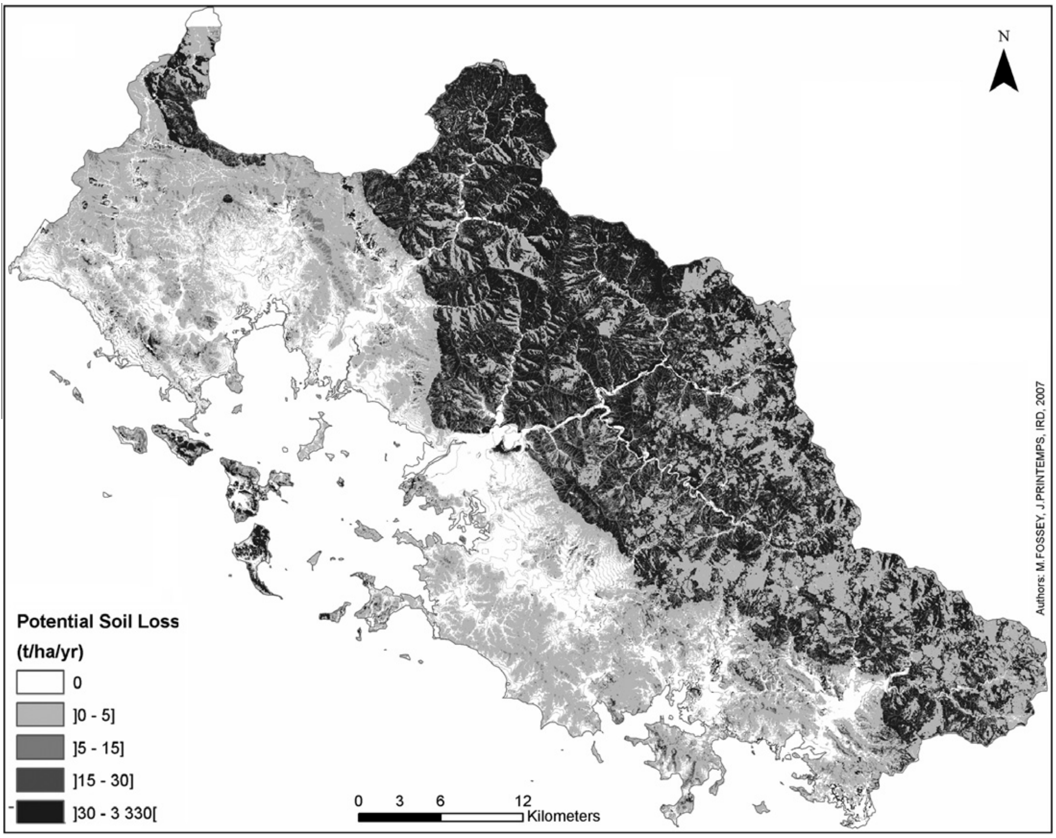

Fig. 6. Spatial distribution map of average annual potential soil loss with the Universal Soil Loss Equation. The average of soil losses is 18 t/ha/yr. At the difference of multi-criteria analysis, the dichotomy between the coastal plain and the ultramafic massifs is more characterised on this map.

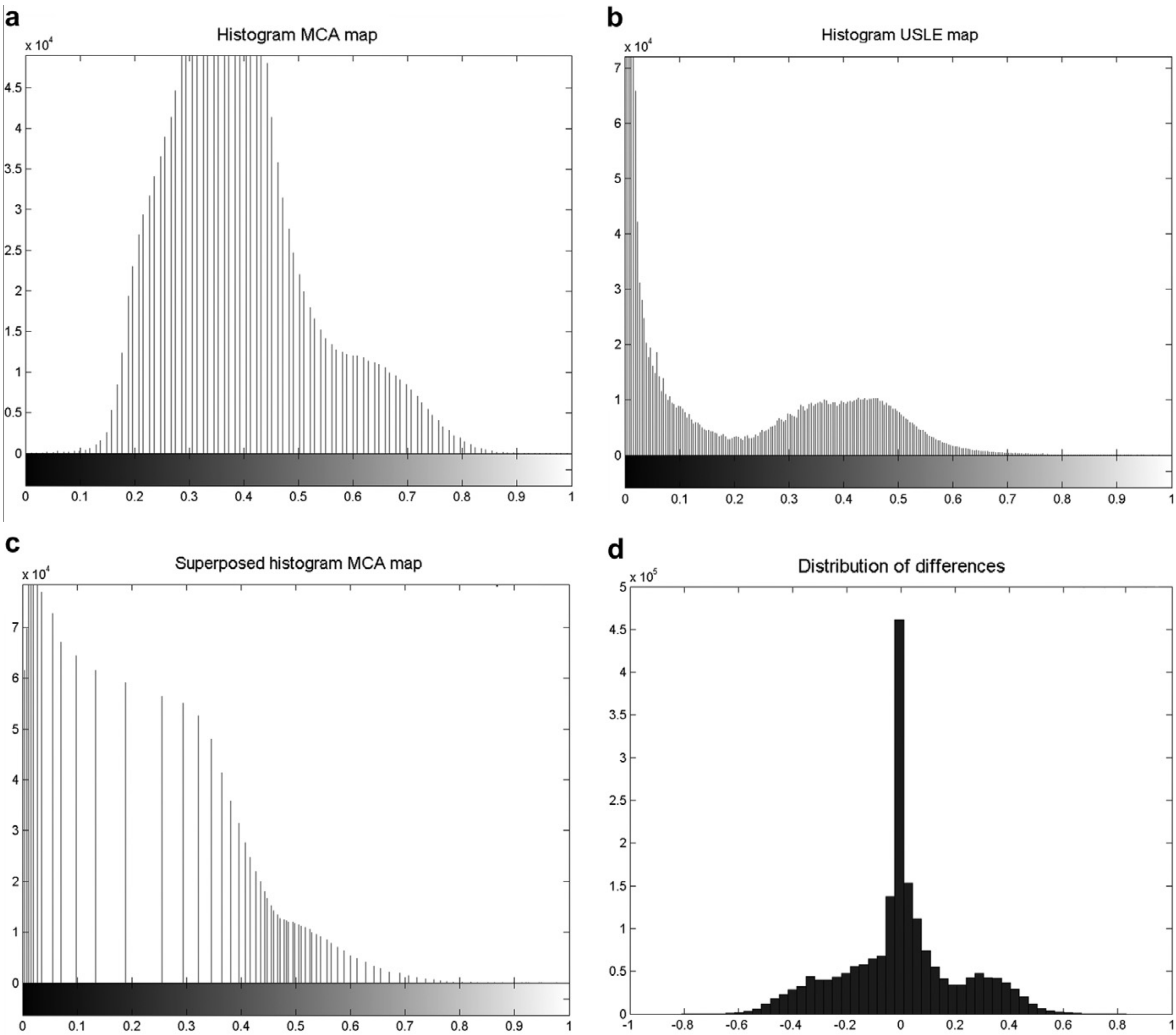

Fig. 7. Histogram of the sensitivity to erosion map (from multi-criteria analysis), histogram of the USLE map, superposed MCA histogram to USLE histogram, distribution of differences.

- A second peak can be observed in the [0.3; 0.5] interval which corresponds to strong erosion values mainly found in the mountain area.

In general, we observe a spatial distribution consistent with the erosion hazard in our study area.

5. Discussion

Based on the results we discuss here the relevance of the spatialization of the erosion hazard carried out by both methods. The aim is, first, to compare the two spatial distributions of the results based on the expert approach and those obtained using the USLE empirical approach. In order to carry out this comparison under the best possible conditions, we use a histogram equalization method. This method consists in enhancing the contrast by transforming the values so that the histogram of the output data (here the expert approach results) approximately matches a specified histogram (here the USLE results one). The ad hoc method (called "histeq") implemented in the software Matlab is used for this purpose (Fig. 7c).Having processed the data in this way, we can compute the dissimilarities denoted d, with$d = r_{\mathrm{USLE}} - r_{\mathrm{Multi\text{-}Criteria\ Approach}}$ and provide a representation of their distribution (Fig. 7d).

It may be noted that the variable d has a Gaussian mixture density. The values within the [−0.1; 0.1] interval show that both methods mostly provide similar results. The other values emphasize the dissimilarities. The sources of differences remain to be assessed and, first of all, disparities and similarities must be spatially pinpointed.We have thus created two maps characterising close results:

1. values of dissimilarities within the [−0.3; 0.3] interval
2. values of dissimilarities within the [−0.1; 0.1] interval

The first map (Fig. 8a) shows a pronounced geographical dichotomy. On the one hand, the coastal plain is characterized by strong correspondences. Results of both methods in this area are

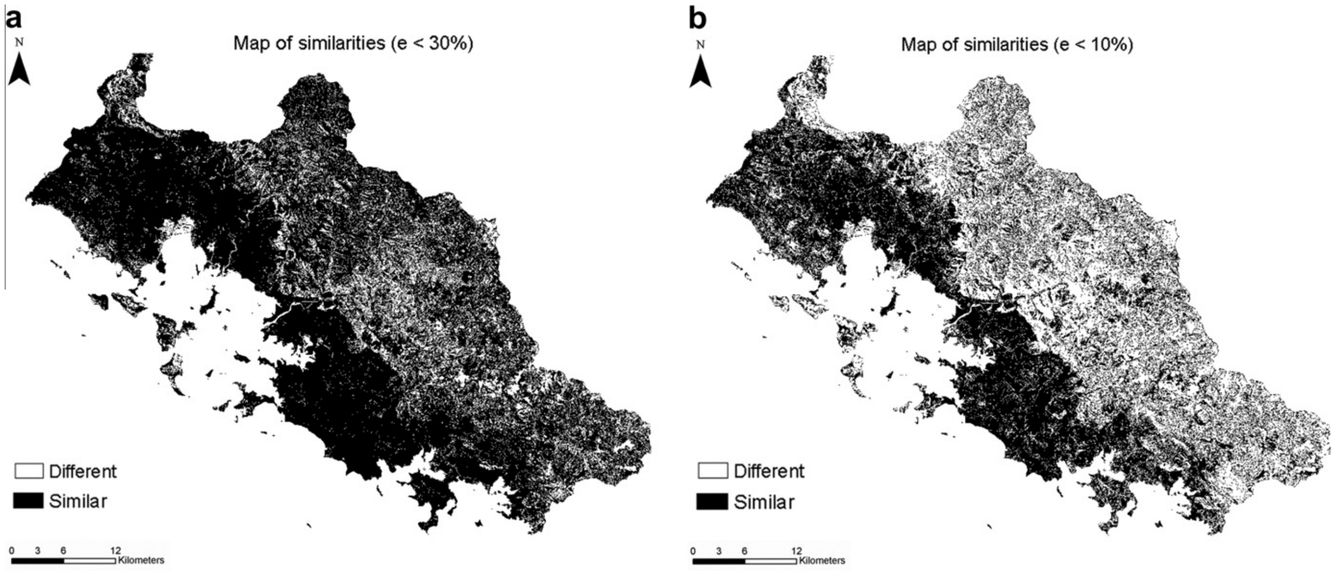

Fig. 8. Dissimilarities between [−0.3; 0.3] and dissimilarities between [−0.1; 0.1].

perceptibly similar. On the other hand, the situation is entirely different for the mountainous region where there are greater deviations in the results of the expert approach and the USLE approach.

This tendency is confirmed by its enhancement with the analysis of Fig. 8b. Similarities remain relatively high in the coastal area, whereas there are many more dissimilarities along the "Central Chain".

Computation of the spearman correlation coefficients between the variable *d* (dissimilarities) and the different model input (geology, slopes, rainfall...) indicates that a single parameter is significantly involved in the two approach disparity. The geology is correlated with a coefficient of −0.53 with a significant *p*-value when the other coefficients (absolute value) stand in a very low level (less than 0.1).

What emerges from this comparative analysis is that the spatialization of the erosion hazard with the multi-criteria (expert) approach and that of the USLE model are relatively close. In this regard, we can consider that both methods validate each other. However, the analysis reveals dissimilarities which are obvious in hilly regions. These deviations could be explained by the use of different parameters in each method. For example, the "nature of soil" parameter appears to explain some of the differences observed as the statistical analysis seems to confirm it. In the expert method, it is calculated from the superficial geological formations whereas the USLE method only takes pedology into account. Anyway, the study area presents a dramatic geological change between coastal plains and hills. This last one can be explained by steep slopes and also by the dominant role (high weight) of soil type or nature of the geological formations and their surface weathering, in these two models. In fact, the upper part of the hills are characterized by specific lateritic (limonite) surface layers (highly vulnerable to erosion when stripped) and targeted by nickel mining activities. Thereafter, this major geological factor should be considered more in these approaches in the modeling.

It would also be useful to reconsider the weighting proposed by the experts in the multi-criteria method. Indeed, the obtained hazard distribution appears rather too contrasted as compared with that of the USLE model. The values representing a mean sensitivity to erosion are over-represented, whereas the values representing a low and high sensitivity to erosion are under-represented.

6. Conclusion

The two methods used lead to a better understanding of the spatial distribution of the erosion hazard in catchments of the study area. Moreover, a comparison of the models demonstrates clearly that, in general, results obtained on this topic are similar. However, the multi-criteria method, which is considered as an expert model, provides a qualitative hazard level whereas the USLE model quantifies soil losses.

In any case, a relative comparison between sectors of the study area is more important than the absolute soil loss in any cell. These results also enable us to undertake an initial grading of the most polluting catchments in terms of terrigenous sediment production. As a matter of fact, without field data, an evaluation of solid transport by these methods allows an estimation of the over sedimentation in bays, in relation with human pressures, including past and present open mining. Thus such studies would appear to be relevant within the framework of Integrated Coastal Zone Management. Indeed, they enable us to identify risk areas, which should be classified as priority management areas so as to limit impacts on the marine environment. With the same aim, it would also be conceivable to design soil loss scenarii based on any change in land uses (e.g. opening of new mining sites or impacts of bush fires etc.).

These models constitute an initial step towards a more accurate estimation of the terrigenous discharge into the lagoon. Several actions are currently under development to this end. What is involved, on the one hand, is the operation of pilot sites for the collection of field measurements in both the terrestrial and marine environments so as to improve the calibration and validation of our models. On the other hand, we are working on improving the recognition of the surface runoff dynamics through the implementation and use of hydrological models for sediment transport. The objective is to estimate the sediment load in the marine environment from soil loss values at the catchment scale. This evaluation must also to take in account, that rate of sediment deposition in tropical South Pacific islands are some of the highest in the world as in Fiji (Terry et al., 2002) or at Samoa (Terry et al., 2005). This is explained by the high frequency of tropical cyclones in this region which can produce extreme rainfalls. Therefore, during cyclonic floods, the very high concentration of suspended sediments causes an increase in the degradation of lagoon ecosystems and fringing

reefs in New Caledonia, now inscribed on UNESCO's World Heritage List since 2008.

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