Mapping Potential Soil Erosion in the Pacific Islands
A case study of Efate Island (Vanuatu)

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ABSTRACT
Soil erosion is a serious problem in Pacific Islands mainly due to the cyclonic tropical weather, bush fires and the development of the human activities (mining activity, farming sugarcane, agricultural practices). This article aims to describe the implementation of the Universal Soil Loss Equation (USLE) for the mapping and quantification of the potential soil erosion. The USLE model (and its derivatives RUSLE) is commonly used throughout the world to calculate average annual soil loss per unit land area resulting from sheet and rill erosion (t/ha/year). The USLE equation can be written as A=R*E*L*S*C*P where A is the soil loss, R is the rainfall-run off erosivity factor, E is a soil erodibility factor, L is a slope-length factor, S is a slope steepness factor, C is a cover-management factor and P is a supporting practice factor. These five major factors involved in the USLE were derived using a Geographic Information System (GIS). This work is being implemented in Efate Island in Vanuatu.

Keywords
Erosion, Universal Soil Loss Equation (USLE), Geographical Information System (GIS), Vanuatu.

1. INTRODUCTION
This communication outlines some results of the GERSA project (a French acronym for « Watershed and Coastal Reef Zones Integrated Management: from Satellite to Stakeholders »). This program aims at creating tools designed to better understand the interactions between watersheds and coastal reef zones in order to optimize coastal zones and protected marine areas management. GERSA, implemented by the French Institute for Development (IRD) and the University of New-Caledonia, is the watershed component of the CRISP program (Coral Reefs Initiatives for the Pacific).

The Pacific islands that comprise nearly 25% of coral structures are increasingly subject to significant damage, the result of the increased local population and development activities on the coastal zone. Controlling pollution that could degrade these fragile ecosystems need to be able to assess the natural and human pressures developing upstream of this environment but directly affecting it. The management of coral reefs should be done through an integrated management of the coastal zone, taking into account the impacts of pollutants in watersheds. In the high islands subject to a tropical climate aggressive, sediment inputs are significant and a major cause of degradation of fringing reefs. In addition all the human activities chain that depend on natural resources regularly suffer the effects or the consequences of these phenomena. To assess the sediment deposition into the lagoon, it is necessary to characterize the erosion process on the watersheds and to highlight the areas most affected by erosion.

So, one of the specific objectives of the GERSA project is to create risks maps on the watersheds, particularly for decisionmakers. Various approaches based on the modelling of the transfer processes of the sediment or pollutants exist, however they often apply to geographically limited areas (SWAT: Soil and Water Assessment Tool; [1]; [7]; [3]). These models differ in complexity, processes considered, and data required for model calibration and model use. Moreover, these modelling types require many field measurements for their calibration which are not available in the Pacific countries and are thus unsuitable. So we chose to apply the Universal Soil Loss Equation (USLE), an empirical quantitative model designed for the evaluation of the annual soil loss rates on a long-term basis [14]. All of the major factors involved in this model were derived from spatial input data using a Geographical Information System (GIS) framework from input data which included a Digital Elevation Model (DEM), a soil map, a land cover map (by remote sensing classification) and precipitation data.

2. STUDY AERA
In the case of the GERSA project the USLE model was tested on a pilot site, on the west coast of New Caledonia [4]. Then, we applied these methods to three other sites in the Pacific: the North western coast of Viti Levu (in Fiji), Moreea and Tahiti in French Polynesia and the island of Efate in Vanuatu. In the case of this paper, the methodology developed for each parameter and the results on Efate site will be presented.

Vanuatu is an island nation located in the South Pacific Ocean. The archipelago, which is of volcanic origin, is located from 1,750 kilometers east of northern Australia, 500 kilometers north-east of New Caledonia, and south of the Solomon Islands, near New Guinea. Located at 16.69° S and 168.36° E in the Pacific Ocean, Efate is the main island of Vanuatu. It is the most populous (approx. 55,000 inhabitants) and in terms of land area Efate is Vanuatu's third largest island (900 km²). Most inhabitants live in Port Vila, the national capital. Its highest mountain is Mount McDonald with a height of 647 m. The climate of the island of Efate is characterized by colder season from May to October with low rainfall and a hot season from November to April with rainfall higher. Average temperatures annual of 24.5° with maxima and minima, respectively, of 26.7° and 22.5° corresponding to two distinct seasons, and average annual rainfall are in the range of 2034 mm. About geology, Efate presents a
3. METHODS

3.1 The USLE model

The Universal Soil Loss Equation (USLE) is a mathematical model used to describe soil erosion processes [14]. The USLE or one of its derivatives (RUSLE; [11]) are the most widely used models for prediction of water erosion hazards and planning of soil conservation measures.

The USLE is an empirical equation derived from more than 10,000 plot-years of data collected on natural runoff plots and an estimated equivalent of 2,000 plot-years of data from rainfall simulators. Numerical values for each of the six factors of the equation were derived from analyses of the assembled research data and from National Weather Service precipitation records in USA. USLE only predicts the amount of soil loss that results from sheet or rill erosion on a single slope and does not account for additional soil losses that might occur from gully, wind or tillage erosion. Although originally developed for agricultural purposes, its use has been extended to watersheds with other land uses.

The USLE/RUSLE estimates long-term average annual soil loss using a factor-based approach with rainfall, soil, topography and land cover and management as inputs. It calculates mean annual soil loss (A in tons/ha/year) as a product of six factors:

\[ A = R \cdot K \cdot L \cdot S \cdot C \cdot P \]

Factor R, rainfall and runoff erosivity, based on long-term average rainfall conditions. R is in MJ.mm/(ha.h.yr);

Factor K, soil erodibility, based on soil texture, organic-matter content, permeability, and other factors inherent to soil type. K is in t/h/(MJ.mm);

Factors L and S, slope length and slope steepness, based on length and steepness of slope, regardless of land use;

Factor C, cover management, based on surface residue, surface roughness, and canopy cover;

Factor P, support practice, based on installation of practices that slow runoff and thus reduce soil movement.

Since all factors in the USLE have a spatial distribution (table 1), a GIS based evaluation of the different factors is possible by overlaying the layers and multiplying them on a grid basis.

### Table 1: Data used for the GIS layers

<table>
<thead>
<tr>
<th>Data</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>Monthly averages</td>
</tr>
<tr>
<td>Topography (VANRIS GIS data base)</td>
<td>20 m</td>
</tr>
<tr>
<td>Soil map (paper) digitized</td>
<td>1 /100 000</td>
</tr>
<tr>
<td>Vegetation map (paper) digitized</td>
<td>1/250 000</td>
</tr>
<tr>
<td>Land cover map (Spot 3 image)</td>
<td>20 m</td>
</tr>
</tbody>
</table>

3.2 Rainfall and runoff factor: R

The rainfall and runoff factor (R) represents two characteristics of a storm determining 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 minutes intensity [2]. R was computed as:

\[ R = \frac{1}{N} \sum_{i} (E \times I_{30}) \]

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 minutes intensity of rain in mm/h.

As there are no possibilities for obtaining precise climatic data on the study area, Roose’s approximation (1975) was used to compute R with the equation:

\[ R = 0.5 \times P \times 1.73 \]

with P, the average annual rainfall

To make the map of average annual rainfall, we used data from 16 weather stations (over a period of 10 years from 1984 to 1994). To these, in order to obtain a consistent interpolation of the spatial distribution of rainfall, were added "ghost" stations spread across the study area. The rainfall of these stations has been allocated to the normal estimation procedure based on kriging interpolation method (maximum value: 4188 mm/yr and maximum value: 1195), the rainfall factor layer was generated over the whole Efate island.

The R factor values vary with altitude, namely MJ.mm 1034/ha.h.an around the city of Port Vila, for the lowest value, with the coast, which presents values slightly higher in 3623 MJ.mm/ha.h.year at its peak, Mount McDonald.

3.3 Slope length and slope steepness factor: LS

Topography is the richest source of data about erosion process. The topographic factors are based on the slope length (L) and the slope steepness (S). The longer the slope length the greater the amount of cumulative runoff. Also the steeper the slope of the land the higher the velocities of the runoff which contribute to erosion [6]. LS factor was derived from Wischmeier and Smith (1978):

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

where

- \lambda is the slope length in meters,
- \theta is the slope angle in degrees, and
- m is a slope angle contingent variable ranging from 0.01 to 0.56 [8].
From a 20 meters resolution DEM created, we can obtain the slopes map which represents the first derivation from the elevation. The LS factor is the result of processing the DEM through the algorithm Van Remortel who had developed an AML (Arc Macro Language) script under ArcInfo [13]. This program begins with correcting the DEM in filling the low points. Indeed, the DEM has low points where water can not move virtually. These areas are often caused by inaccuracies in the DEM used. The treatment of these areas is necessary to allow the flow downstream. The second step is the creation of a raster of flow direction from each pixel to its neighbor with a lower altitude. This helps to calculate the slope length; first for a pixel and then, in aggregate for each pixel. The third step is the calculation of slopes in degrees for each cell. In function of the slope, the algorithm calculates the value of exposing $m$. Then, it proceeds to calculate S and L and finally, it determines the LS factor.

The values obtained for the LS factor on the study area range from 1 to 32 and the average is 4.3. Most values (93%) are between 1 and 10, and correspond to the plains. There is little difference, however, between coastal plains to low slopes and slopes of the mountains. Areas with steep slopes, corresponding to areas of high LS factor, remains very small minority on the island of Efate, with only 7% of values above 10.

### 3.4 Soil erodibility factor: K

The soil erodibility factor (K) represents the susceptibility of a soil type to erosion. A simpler method to predict K was presented by Wischmeier et al. (1971) which includes the particle size of the soil, organic matter content, soil structure and profile permeability. The soil erodibility factor K can be approximated from a monograph if this information is known. The USLE monograph estimates erodibility as:

$$K = 2.1 \times M^{1.4} \times 10^{-9}(12 - MO) + 0.0325 \times (b - 2) + 0.025 \times (c - 3)$$

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.

The soil erodibility factor layer was generated from a soil map of Efate at 1: 100 000 scale [10]. For each type of soil, samples were collected in the field across the study area. A granulometric analysis allowed to determine the texture as a percentage of sand/silt/clay and the percent organic matter content. Efate Island was divided into 6 major soil classes. They had K factors ranging from 0.01 to 0.037 (Table 2).

### Table 1: K-factors for the study area

<table>
<thead>
<tr>
<th>Soil</th>
<th>K factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td></td>
</tr>
<tr>
<td>Lithosol</td>
<td>0.01</td>
</tr>
<tr>
<td>Fersiallitic soils</td>
<td>0.013</td>
</tr>
<tr>
<td>Area of juxtaposition</td>
<td>0.024</td>
</tr>
<tr>
<td>Tropical eutrophic brown soils</td>
<td>0.031</td>
</tr>
<tr>
<td>Ferrallitic soils</td>
<td>0.037</td>
</tr>
</tbody>
</table>

### 3.5 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 of a lack of information on practices conservation tillage, we choose to adopt P = 1 over the study area. For this reason, it is considered invalid as anti-erosion and this factor will not impact the final product. The results of the calculation of losses in soil will be slightly overvalued in relation to reality.

### 4. RESULTS

The application of a modified model of equation of Wischmeier and Smith has been used to obtain data on soil loss by integrating the numerical values of environmental parameters such as rainfall erosivity, soil erodibility, vegetation cover and topography. All these factor were integrated into a geographical information system and soil loss is estimated by combining these GIS layers. The R, LS, K, and C factor layers are multiplied to create a soil loss rate layer. The values of the potential erosion on the site of Efate are between 0 and 1720 t/ha/year (between 0 and 163 mm/yr). The map of potential soil loss created show a heterogeneous distribution of erosion risk zones (figure 1). The areas most affected by the erosion risk are primarily located around coastal regions including the plains and low hills. In fact, these regions are the most populated. They concentrate the human activities that lead to a significant land clearing, as the food crops

### Cover management factor: C

The ground cover factor (C) provided by plants (and stones) has importance outweighs that of all other factors affecting erosion. Indeed, irrespective of the aggressiveness of the climate, slope, soil type, erosion will be low if the soil is covered in more than 90%. C factor 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 [14]. By definition, C equals 1 under standard fallow conditions. As vegetative cover approaches 100%, the C factor value approaches 0. The land cover layer was implemented on the basis of the results of the supervised classifications of satellite data SPOT 3 at 20 meters resolution and completed by the vegetation map (Atlas of Quantin [10] at 1/250 000 scale). 7 land cover types were defined. This land cover map shows the dominance of forests on this island and the location of areas anthropized along the coastal areas and low slopes, with the presence of crops. Coastal areas and plains are covered of savanna and coconut crops.

Cover factor ranged from 0.001 to 1 (Table 3). Bare lands, representing the greatest sensitivity to erosion, have the highest coefficient (1) while the areas covered by dense forest type, limiting the erosion process, have a low coefficient (0).

<table>
<thead>
<tr>
<th>Land cover type</th>
<th>C factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water and urban zones</td>
<td>0</td>
</tr>
<tr>
<td>Dense forest</td>
<td>0.001</td>
</tr>
<tr>
<td>Crops</td>
<td>0.01</td>
</tr>
<tr>
<td>Mangrove</td>
<td>0.04</td>
</tr>
<tr>
<td>Savanna</td>
<td>0.16</td>
</tr>
<tr>
<td>Bare land</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2: Land cover types and C-Factor
Figure 1: Potential soil loss map (Efate Island)

(yam, taro, sweet potatoes, cassava). Only the central part of
north-west of the island, although marked by steep slopes present
values of soil loss lower. This region has low erodible soils and is
covered by dense forest. For Efate the resulting erosion rate A has
an average of 8 t/ha/yr (0.75 mm/year). This mean can be regarded
as a low value in terms of observed or estimated values in Tahiti
(200 to 400 t/ha/year) [12], in New Caledonia (138 t/ha/year) [9],
[4] or in Fiji (16.6 to 80 t/ha/year) [5]. This result could be
explained by low slopes, reduced human activities and dense
vegetation that covers a large part of the island. In view of the
synthetic map of soil loss, it appears that whatever the slope,
fragile soils, high rainfall, a complete vegetation cover (regardless
of its architecture and botanical composition) if it reaches more
than 80% provides an excellent soil conservation. The influence
of C, and so of the vegetation cover, is really important. This
factor in this case study takes precedence over all other
parameters of the model.

5. CONCLUSION AND PERSPECTIVES
The study described above shows the first map of erosion from the
site of the island of Efate in Vanuatu, where environmental issues
are high. The use of GIS has enabled us to estimate the amount of
soil loss in the catchments of Efate Island. USLE gives the long-
term average soil loss resulting from sheet erosion processes.
However, soil loss from other types of erosion, gully erosion from
lavakas for example, need to be estimated. In fact, the results of
the USLE modified equation are underestimated for many
reasons. The quality of the input data implemented in the model,
is the first one. The spatial scale is not adapted as the soil map for
example or the typology of the land use map is not precise : it's
necessary to have more detailed land use data in which
agricultural land use could been subdivided into specific crops (C
factor). The extreme slopes throughout the mountain areas do not
correlate well with the USLE model, which was originally
developed for mild slopes in agricultural areas. In particular, the
LS values will be overweighted in this analysis. The error in
theses estimations can occur because the USLE is an empirical
equation that does not mathematically represent the physical
processes of soil erosion.

In fact, with this model, the spatial variation of soil loss can be
observed. The relative values are more important to take into
account than absolute values and are useful to identify risks areas.
These results also enable us to undertake an initial hierarchisation
of the most polluting catchments in terms of terrigenous sediment
production, which should be classified as priority management
areas so as to limit their impacts on the marine environment. Thus
these studies would appear to be relevant within the framework of
Integrated Coastal Zone Management. With the same aim, it
would also be conceivable to design soil loss scenarios based on
any change in land uses. A erosion control plan can be suggested.
For example, some land forming practices such as terraces on the
steep slopes to reduce the slope lengths (LS factors), which will
slow down the runoff velocities.

The undeveloped countries like most Pacific island countries
often haven’t financial supports for doing researches and making
programs for evaluating environmental degradation. For the
management of the coastal and coral reef zone, they have to take
into account the erosion process. Erosion is a good indicator to
measure the human activities pressure from the watersheds. For
this type of study, the USLE model presented is suitable for the
Pacific countries because it’s really difficult to have or to create
data for developing a complex erosion model at the regional scale.
In contrast the USLE model can be applied to large regions using
a geographical information system, can be implemented with
some data not too complex and compatible with their integration
into a GIS, generally available in these countries as a digital
elevation model, a soil map, precipitation data or satellite images. At last, this type of indicator can be made at a regional approach to have a overview or to compare situations between Pacific islands.

6. ACKNOWLEDGMENTS
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7. REFERENCES