ABSTRACT

The high islands of the Pacific are characterised by short and steeply-sloping watersheds, where erosive events can generate large terrigenous material run-off loads that threaten the adjacent reefs. To assess the sediment deposition it is necessary to characterize the erosion process on the watersheds and to highlight the areas most affected. This article aims to describe the implementation of the Universal Soil Loss Equation (USLE) for the mapping and quantification of the potential soil erosion in these countries. The USLE model, commonly used to calculate average annual soil loss per unit land area resulting from sheet and rill erosion, can be written as \[ A = R \times E \times L \times S \times C \times P \]. A is the soil loss, R is the rainfall-runoff 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. The spatialization of this model is implemented using the data processing and mapping functionalities of a Geographical Information System (GIS) from input data which included a digital elevation model, a soil map, a land cover map and precipitation data. In this paper, the methodology developed for each parameter and the results on New-Caledonia site will be presented.

Keywords: Erosion, Universal Soil Loss Equation (USLE), Integrated Coastal Zone Management (IZCM), Geographical Information System (GIS), New Caledonia

INTRODUCTION

Soil erosion is a serious global problem that threatens sustainable agriculture but also ecosystems. Among these, coral reefs are increasingly subject to significant damage caused by terrigenous pollution from watersheds. The situation for the Pacific islands that comprise nearly 25% of coral structures of the world must be taken in account. The high islands of this region particularly in the Melanesian zone, are subject to steep slopes, high intensity storms and natural pedologic process set the stage for high natural erosion rates. In addition, human pressures with the increasing population and activities on the watersheds and the coastal zone accelerate the erosion processes. Natural erosion rates are high in tropical landscapes on a worldwide basis (Nelson, 1987). Streams in tropical areas have up to 15 times the natural sediment loads as comparable streams in temperate areas (Simonett, 1968). Within the South Pacific Region, particularly on the high islands, soil erosion is a marked feature of the landscape. After each storm, rivers change colour and much material is carried away towards...
the sea (Eyles, 1987), bringing very abundant sedimentary contributions that induce changes in the profile and degrade coastal reefs fringing (Dumas, 2004). 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.

Many models for soil erosion loss estimation have been developed (Nearing et al., 1989, Bathurst and O. Connell, 1992, Arnorld and Williams, 1995, Adinarayana et al., 1999, Neistch et al., 2002, Shen et al., 2003). However most of these models often apply to geographically limited areas and require many complex field measurements which are not available in the Pacific countries. These types of models are thus unsuitable in the undeveloped countries like most Pacific island countries where financial supports in research are limited. For these reasons we chose to apply the Universal Soil Loss Equation (USLE), a deliberately simplistic model. USLE, one of the most widely use throughout the world, is an empirical quantitative model designed for the evaluation of the annual soil loss rates on a long-term basis. With this model, one of the specific objectives is to create risks maps, identified, located and prioritized the watersheds most pollutant. This type of document could be useful particularly for decisionmakers. It’s one of the objective of the GERSA project (a French acronym for « Watershed and Coastal Reef Zones Integrated Management: from Satellite to Stakeholders ») implemented in the South Pacific region particularly on the west coast of New Caledonia, on the North western coast of Viti Levu (in Fiji), in Moreea and Tahiti in French Polynesia and in the island of Efate in Vanuatu (Dumas and Fossey, 2009). 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. The project is led 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). This communication presents some results about the application of the USLE equation on the North western coast of New Caledonia.

STUDY AREA

New Caledonia is a French territory located in the subregion of Melanesia in the southwest Pacific, at 1200 kilometers at east of Australia. The population was estimated in 2009 to be 245 000. It comprises a main island (“Grande Terre”), the Loyalty Islands, and several smaller islands. Approximately half the size of Taiwan, it has a land area of 18 575 square kilometers. The “Grande Terre”, with 450 kilometers in length and 50 to 70 kilometers wide, is the largest and the only mountainous island (16 300 square kilometers). From North to South a mountain range, the “Central Chain”, runs the length of the island, with five peaks over 1500 meters. New Caledonia lieing astride the Tropic of Capricorn, between 19° and 23° south latitude, has a tropical climate. 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. In the main island many areas are made up of deeply weathered geological materials as very erodible limonite layers (laterites: highly vulnerable to erosion when stripped). These soils are therefore the first target of erosion in a cyclonic regime of precipitations. Particularly, the effect of runoff increases when degradations of protective plant cover appear after bush fires or nickel openpit mining. All of these factors constitute catalysts to the erosion process. Runoff mobilized soils particles from high terranes pass quickly through creeks and rivers, stay in the cultural plain when inundations occur and stop their way in the closed lagoon after just fewer 20 to 30 kilometers since soil removal. Then coral reef and lagoon life is disrupting by sporadic episodes of hypersedimentation. All
human activities chain that depend on natural resources are regularly affected by soil erosion and consequences of this phenomenon. It’s also important to note that UNESCO listed New Caledonia Barrier Reef on the World Heritage List under the name The Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems on July 2008.

The study area is located in the north of New Caledonia on west coast. This region includes the communes of Koné, Pouembout and Voh in the North Province (Fig. 1) and 23 watersheds, covering an area of 1 350 square kilometres. The study area presents a dichotomy between a coastal plain and a mountain zone and hills covering three quarters of the region. In terms of pressures that exists in New Caledonia, this region is representative with natural pressures due to the amount and the intensity of rainfall and the steepness of slopes and with human pressures to bushfires, agriculture, land-clearing by fire and mining activities. Indeed, there are several old mines (closed before 1975) in this area, not revegetated, that are still contributing to soil losses, as well as a new mining project on the Koniambo Mountain which will be the largest nickel mines in the world.

![Fig. 1: Location, digital elevation model and map of the study area (communes of Koné, Pouembout and Voh)](image)

**MATERIALS AND METHODS**

The Universal Soil Loss Equation, later revised as the RUSLE (Renard et al., 1997), was developed by Wischmeier and Smith (1978). It’s a mathematical and an empirical model used to describe soil erosion processes and based on many factors such as soil, topography, climate, land cover and human activities. The USLE predicts potential erosion and is widely used in the world. Potential erosion, representing by soil losses, has units of weight per unit area per year (t/ha/yr). This equation is the product of six factors:

$$A = R \times K \times L \times S \times C \times P$$

Where A is the average soil loss due to water erosion (t/ha/yr), R the rainfall-runoff erosivity factor; K the soil erodibility factor, L, the slope length, S the slope steepness, C the land cover management factor and P the soil conservation practice factor. This model is 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 purpose, its use has been extended to watershed with other land uses.

**Rainfall-runoff Erosivity: R-factor**

The R factor is the climatic factor determining the erosive force of rainfall on the ground. The R-factor is usually measured as the product (EI) of total storm energy (E) and the maximum 30-min intensity (I30) for all storms over a long time (Brown and Foster, 1987). The EI parameter quantifies the effects of raindrop impact and reflects the amount and rate of runoff likely to be associated with the rain (Wischmeier and Smith, 1978). R was calculated from these equations:

\[ R = E \times I_{30} \]  

where R is in MJ.mm ha\(^{-1}\) h\(^{-1}\) and (E) is the kinetic energy of rain in MJha\(^{-1}\) and (I30) is the maximum 30 minute intensity in mm h\(^{-1}\).

The calculation of E was made from the equation derived by Brown and Foster (1987) who found that the kinetic energy of the rain was an exponential function of the intensity of the rain:

\[ E = 0.29 \times (1 - 0.72e(-0.05 \times I)) \]  

where I is the rainfall intensity in mm h\(^{-1}\)

It is then possible to calculate R for a year:

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

where R is in MJ.mm ha\(^{-1}\) h\(^{-1}\) yr\(^{-1}\), N is number of years, K is number of rainy events, E is total storm kinetic energy in MJ.mm ha\(^{-1}\) h\(^{-1}\), and I30 is the maximum 30 minutes intensity of rain in mm h\(^{-1}\).

About the climate of the study area, New Caledonia lying astride the Tropic of Capricorn, between 19° and 23° south latitude, has a tropical climate. Rainfall is highly seasonal, brought by trade winds that usually come from the east and varies a lot according to elevation. Rainfall averages about 2 000 millimeters at low elevations on eastern “Grande Terre”, and 2 000-4 000 millimeters at high elevations on the Grande Terre. The western side of the Grande Terre lies in the rain shadow of the central mountains, and rainfall averages 1 200 millimeters per year. In the study area, rainfall varies from 500 mm/year near the sea to almost 2 000 mm/year in the “Central Range”.

For the computing of R factor, we use the data of 8 weather stations from Meteo France (National Meteorological Service) spread across the study area (Table 1, Fig. 2). However, these data are not insufficient for making a precise interpolation in the spatial distribution of the R factor. In this case, the option taken was to seek a relationship between the R factor and altitude of stations that would extrapolate to the area. Indeed, it is not unusual that there is a gradient of precipitation in relation to altitude. Thus, from a straight linear correlation (R = 3.5205 x Z + 3661), 12 others “ghost stations” were computed to obtain a more precise interpolation. From the results of this calculation, a rainfall factor layer was then generated in the GIS (ArcGIS) (Fig. 3) over the whole study area by using a spline interpolation on a 10 meters resolution Digital Elevation Model (DEM).
The R values range from 1743 to 4747 MJ.mm ha\(^{-1}\)h\(^{-1}\)yr\(^{-1}\). We can observe a variation of the R factor with a spatial distribution depending on the topography. Near the coasts, the R values are lowest (< 2500 MJ.mm ha\(^{-1}\)h\(^{-1}\)yr\(^{-1}\)), while the highest mountain ranges have high values (> 4500 MJ.mm ha\(^{-1}\)h\(^{-1}\)yr\(^{-1}\)).

**Soil erodibility: K-factor**

The soil erodibility factor (K) represents the susceptibility of a soil type to erosion. The K-factor reflects the ease with which the soil is detached by splash during rainfall and/or by surface flow, and therefore shows the change in the soil per unit of applied external force of energy. This factor is related to the integrated effect of rainfall, runoff, and infiltration and accounts for the influence of soil properties on soil loss during storm events on sloping areas. This factor is determined using inherent soil properties (Parysow et al., 2003). 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:

\[
K = 2.1 \times M^{1.14} \times 10^{-6} (12 - MO) + 0.0325 \times (b - 2) + 0.025 \times (c - 3) \text{ where } M = (\% \text{silt} + \% \text{fine sand}) (100- \% \text{clay}), \text{ MO is the percent organic matter content, } b \text{ is soil structure code, and } c \text{ is the soil permeability rating.}
\]

For computing the K factor, two soil maps, one at 1/200 000 scale (Podwojewski et Beaudou, 1987) available on all New Caledonia territory and the other at 1/50 000 scale available only on the study area (Denis et Mercky, 1982) were used. There are 22 different soils on the area.
(Fig. 4), but not all soils have information about structure analysis. Thus, clusters were operated with similar soil classes. At the end, the study area was divided into 5 major soil classes (Table 2).

Table 2: K-factors for the study area

<table>
<thead>
<tr>
<th>Soil</th>
<th>USDA class</th>
<th>K factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altered ferritic and ferrallitic soils</td>
<td>Sandy loam</td>
<td>0.013</td>
</tr>
<tr>
<td>Tropical eutrophic brown soils, hypermagnesic, on ultrabasic rocks</td>
<td>Clay</td>
<td>0.022</td>
</tr>
<tr>
<td>Desaturated fersiallitic soils</td>
<td>Loam</td>
<td>0.03</td>
</tr>
<tr>
<td>Little developed soils of alluvial contribution, modal with variable texture</td>
<td>Sandy loam</td>
<td>0.013</td>
</tr>
<tr>
<td>Tropical eutrophic brown soils, little developed and modal on basalts</td>
<td>Clay</td>
<td>0.022</td>
</tr>
</tbody>
</table>

The percentages of clay, silt, sand and organic matter were determinate for each major soil type, and using the USDA texture triangle (Brown, 2003), the texture of each major soil type was defined. To obtain the K factor for soil we use the chart correlating the textures and the standard K-factor (Stone and Hillborn, 2002).

![Fig. 4: Soil map at 1/200 000 scale](image1)

![Fig. 5: Spatial distribution of K factor](image2)

With these results, the spatial distribution of the K factor was computed under a GIS at 10 meters resolution (Fig. 5). We can see that most of the study area has a K factor between 0.013 and 0.03 t.ha/ha.MJ.mm. On the areas of utramafic rocks (mining massifs), the K factor is relatively low. These, consisting of a hard iron crust, have a sensitivity to erosion low. Conversely, the Central Range has a sensitivity to erosion with a high K value. This is explained by the high percentage of sand in the fersiallitic soil who compose it, making them fragile. The coastal plain as a whole presents a medium to high sensitivity to erosion especially in the river system in the presence of alluvial material with a high K value.

**Slope length and steepness: LS-factor**

In the USLE model, the effect of topography on erosion is accounted for by the slope length (L) and the slope steepness (S). The L factor is defined as the distance from the source of runoff to the point where either deposition begins or runoff enters a well defined channel that may be part of a drainage network. S factor reflects the influence of slope steepness on erosion (Wischmeier and Smith, 1978). 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. But soil loss increases more rapidly with slope steepness
than it does with slope length (McCool et al., 1987). The common equation used for calculating LS factor provide by the USDA Agricultural Handbook (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 (McCool et al. 1987).

For computing the LS factor, after testing different methods as Mitasova et al.(1998), we choose to use an algorithm developed by Van Remortel et al. (2001), based on the equation of Renard et al. (1997). Using an AML (Arc Macro Language) script under ArcInfo and a Digital Elevation Model (DEM) at 10 meters resolution, \(\lambda\) and \(\theta\) were computed directly under the GIS software. The LS factor ranges from 0 to 104 with an average of 6.4 (Fig. 6). Half of the values are under 5 and correspond mostly to plain zones. The high values (superior to 20) correspond to the crests of the mountains, more sensible to erosion. But it represents only 7% of the area.

![Fig. 6: Spatial distribution of LS Factor](image)

**Cover management: C-factor**

The C-factor measures the effects of all interrelated cover and management variables (Renard et al., 1997). 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. By definition, C equals 1 under standard fallow conditions. As surface cover is added to the soil, the C factor value approaches zero. A C factor of 0.15 means that 15% of the amount of erosion will occur compared to continuous fallow conditions (Kesley and Johnson, 2003).

The C factor was derived using remote sensing techniques. Thus, the land cover layer was implemented from the results of the supervised classification method (produced by DTSI) based on a SPOT 3 satellite image taken in 1996 with a 20 meters resolution (Fig. 7). These data seem old but the land cover has not really changed these ten last years because the human pressure is low in this region. The plain is covered by an extensive grass and dry niaoulis savannah over low hills and flat areas. Large areas of ultramafic rocks correspond to mountainous areas with vivid red lateritic soils covered by an endemic vegetation bush and forests of unique plants species. Along the coastal zone mangroves are present. The determination of factor C depends on the coverage of the soil surface by vegetation. From
bibliographic data, we assign a coefficient C between 0 and 1 for each type of vegetation on the study area. (Table 3). The distribution of factor C is quite heterogeneous (Fig. 8). Bare soils most erodible, are mainly located on the coast and the mountains degraded by mining activity. The areas of dense vegetation located mainly in the hills of the “Central Chain are less susceptible to erosion.

Table 3: Land cover types and C-Factor

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>C Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.001</td>
</tr>
<tr>
<td>Savanna</td>
<td>0.04</td>
</tr>
<tr>
<td>Mining scrubland</td>
<td>0.25</td>
</tr>
<tr>
<td>Swamp</td>
<td>0.28</td>
</tr>
<tr>
<td>Brush</td>
<td>0.72</td>
</tr>
<tr>
<td>Bare land</td>
<td>1</td>
</tr>
</tbody>
</table>

Support practice P-factor

The P-factor is the ratio of soil loss with specific support practice to the corresponding loss with up and downslope tillage. These practices proportionally affect erosion by modifying the flow pattern, gradient, or direction of surface runoff and by reducing the amount and rate of runoff. The P values are between 0 and 1. Because of a lack of information on practices conservation tillage, we adopt P = 1 over the study area for not modify the final result.

RESULTS

All factors layers R, LS, K, and C, computed and spatialized previously by the use of GIS functions, are combined together to obtain a soil loss rate layer (Fig. 9). We obtain an average of 137 t/ha/yr of potential erosion in the study area. Three-quarters of the study area (64%) have an erosion rate under 200 t/ha/yr. These areas correspond primarily to the basin floodplains and flat areas of the “Central Chain” covered by forests. These regions are the least sensitive to erosion. The very high estimations of soil loss (more than 1000 t/ha/yr) are located in 6% of the study area and correspond primarily at the top hills of the “Central Chain”. The high values of soil loss are the result of the combination of steep slopes, high precipitation, altered soils and bare soils due to human activities, such as agriculture, land-clearing by fire and mining activities located on the most sensitive areas to erosion. A first
visual interpretation of the different factors shows that topography seems to be the dominant driver for explaining the variation in erosion rate. The results and particularly the high values seem to be overestimated. The LS values will be overweighted in this analysis. In fact, 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. The others reasons are probably the quality of the input data implemented in the model. 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. The estimation of soil loss is in the same order of magnitude as other studies: 200 to 400 t/ha/yr in Tahiti (Servant, 1974) or 200 to 500 t/ha/yr in the Burundi (Rishirumuhirwa, 1997). It’s also important to note that USLE model 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.

Fig. 9: Potential soil loss erosion in the study area. The high estimations of soil loss correspond primarily at the top hills of the “Central Chain”. They are the result of the combination of steep slopes, high precipitation, altered soils and bare soils due to human activities, such as mining activities.

CONCLUSION AND DISCUSSION

Soil erosion is a serious problem in New-Caledonia mainly due to the cyclonic tropical weather, bush fires and human activities such as openpit mining. Runoff on stripped soils causes degradations for anthropic laying out on high ultramafic terranes and pollution (mobilized soil particles) which modifies the coastal region and degrades the coral reefs by hypersedimentation processes. All the human activities chain that depend on natural resources regularly suffer the effects or the consequences of these phenomena. The situation, not for the same reasons and not in the same proportions, is similar in others high islands of the South Pacific such as Efate island in Vanuatu (Dumas and Fossey, 2009). These countries need to identify and rank erosion risk and define sensitivity maps, particularly for decisionmakers. In this case, the USLE model can be useful for processing the potential soil erosion mapping at a regional scale, implemented with some data not too complex and compatible with their
integration into a Geographical Information System (GIS), generally available in the Pacific countries as a digital elevation model, a soil map, precipitation data or satellite images. The use of GIS becomes an important and powerful tool for the implementation of this model. The USLE equation used lead a better understanding of spatial distribution of the erosion hazard. Moreover, a comparison with a multi-criteria method (expert approach) demonstrates that results obtained in term of spatial variation are similar (Dumas et al., 2009). But the values of soil loss from USLE should be considered as an order of magnitude and not as absolute values. In fact, USLE model is useful to identify risks areas and catchments that are more sensitive to erosion. This type of mapping should be relevant to classify the reef zone most affected by hypersedimentation hazard. Within the framework of Integrated Coastal Zone Management, the areas most affected by erosion will be classified as priority management areas so as to limit their impacts on the marine environment.

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