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MODELING THE EROSION OF SHIELD VOLCANOES: THE TAHITI CASE

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ABSTRACT

We quantitatively model the erosion of the Tahiti Island by using the empirical model USLE and make *in fine* a qualitative comparison with a physical modeling of the erosion by using the Apero-Cidre computer code. The USLE model and its derivatives RUSLE1&2 take into account rill and sheet erosions, while the physical model Apero-Cidre uses transport and conservation equations for sediment and water flows. We find from the USLE model that the main driver for the erosion processes in Tahiti is the cover and management factor, albeit the terrain is very mountainous and covered at 95 % by tropical forests. Areas under erosion stresses are mainly located on croplands and inside the high valleys.

Keywords: erosion modeling, shield volcano, USLE, Apero-Cidre

I. INTRODUCTION

I-1. Presentation of the Tahiti Island

The Tahiti Island created around 1.4 Myear ago by an intraplate hotspot (Le Roy, 1994; Hildenbrand *et al.*, 2008), is divided into two geological units: the main island Tahiti-Nui to the Northwest (end of volcanism 200,000 years ago) and the subsidiary Tahiti-Iti to the Southeast (end of volcanism 380,000 years ago). It is now volcanically inactive and is deeply dissected by erosion (Hildenbrand *et al.*, *Ibid*). Tahiti Nui (Fig. 1) is around 30 km in diameter, and Tahiti Iti around 15 km. Both are connected through the isthmus of Taravao. The highest elevations are the Orohena Peak (2241 m) in Tahiti-Nui and the Roniu Peak (1332 m) in Tahiti-Iti. The two sub-islands are basaltic edifices, with an overwhelming presence of oxisols (down to tens of meters in some places). Slopes can be divided into three classes: 15° for the global slope of the shield volcanoes, 47° for the incision valleys and 2° for the seashore rim. Rainfalls range from 8,000 mm/year on the East side of Tahiti exposed to trade winds to 2,000 mm/year on the West side (Météo-France, 2004), the humid season of a year being the austral summer.

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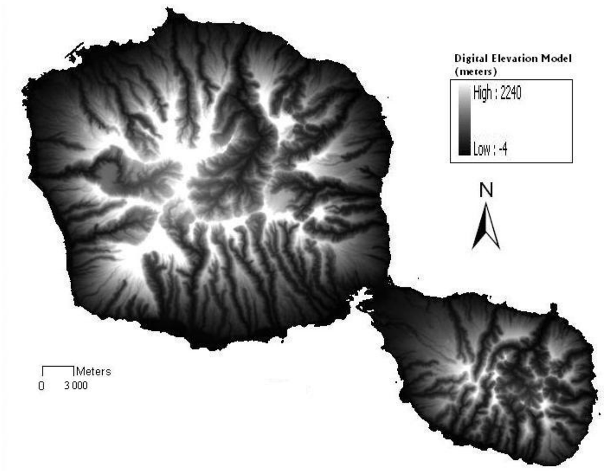

Fig. 1: Digital Elevation Model of the Tahiti Island.

I-2. Study Objectives

In this study, we model the erosion of the Tahiti Island, with as a main objective risk assessment (erodibility of terrains with rainfall, catastrophic runoffs). Erosion models help to predict basin sediment export and identify source areas that deliver most sediments, which are not necessarily most eroding areas (de Vente and Poesen, 2005). For this purpose, we firstly use an empirical approach with a preliminary comparison with a physical model. The empirical model is the well-known USLE model (and its derivatives RUSLE1&2) commonly used throughout the world to calculate average annual soil loss per unit land area resulting from rill and sheet erosion. Our physical model is derived from the 3D landscape evolution Apero-Cidre model.

II. EMPIRICAL MODELING

II-1. Universal Soil Loss Equation (USLE)

The USLE model (Wischmeier and Smith, 1978) was first developed for croplands, and was later extended to other land uses. The Revised USLE (RUSLE, Renard *et al.*, 1991) is an improved version of USLE designed to predict the long-term average annual soil loss from specific field slopes in specified land-use management systems. However it is land-use independent and applies to any land having exposed mineral soil and Hortonian overland flow (Foster *et al.*, 2003). USLE and RUSLE equation read

$$A = R * K * LS * C * P, \qquad (1)$$

where A is the soil loss, R is the rainfall-run off erosivity factor, K is the soil erodibility factor, L is the slope-length factor, S is the slope steepness factor, C is the cover-management factor and P is the supporting practice factor. We used a DEM resolution of 5 m to correctly describe the mountainous terrain of Tahiti.

II-1-1. Rainfall erosivity Factor R

R is the rainfall and runoff factor (MegaJoule mm / (ha hour yr)). Because of the lack of long-term rainfall intensity data in Tahiti, we applied the formula developed by Roose (1977) in

West Africa as

$$R = 0.8675 * PA, \quad (2)$$

where PA is the average annual rainfall in millimeters instead of the complete formula of Renard and Freimund (1994) that takes into account storm erosivity. The value of the R factor (Fig. 2) ranges between 1322 on the West side and 7000 on the East side of Tahiti-Nui.

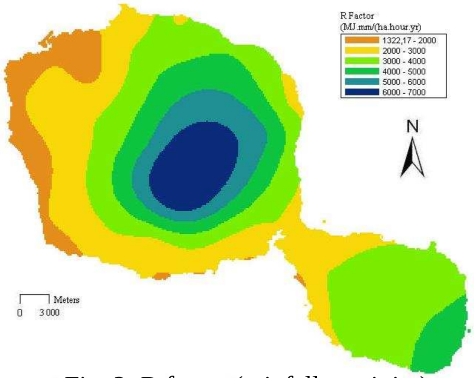

Fig. 2: R factor (rainfall erosivity)

II-1-2. Soil erodibility Factor K

The K factor represents the soil erodibility (ton ha hour / (ha MegaJoule mm)). It is an empirical measure, as it is affected by intrinsic soil properties such as soil texture, organic matter, structure and permeability of the soil profile. It must be evaluated independently of the effects of the other factors, because a soil with a relatively low erodibility may show signs of serious erosion when this erosion occurs on long or steep slopes or in localities with numerous high-intensity rainstorms. On the other hand, a soil with a high erodibility may show little evidence of actual erosion under gentle rainfall when this erosion occurs on short and gentle slopes (Wischmeier and Smith, 1978.) Jamet (1987) classified the soil of Tahiti into four families (Fig. 3): Oxisols (80%); Histosols / Fluventic Europepts along the rivers and the seashore; Inceptisols and Entisols on some plateaus and high valleys. The oxisols in French Polynesia exhibit large variations both in nature and mineral composition, have a good infiltration capacity but weak retention capacity, with a large proportion of organic matter. They cover the relicts of the gentle slopes of the volcanic cones. The K value (Fig. 4) is between 0 (Urban Area) and 0.0059 (Oxisols), the principal value being 0.003. In some high plateaus, the soil contains a high level of unstructured organic matter with high water retention capacity. We choose a value of K of 0.001 for this type of soil, because the organic matter in the soil reduces erodibility (Galetovic *et al.*, 1998).

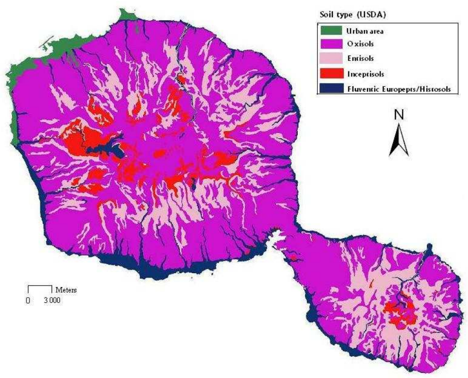

Fig. 3: Soil type

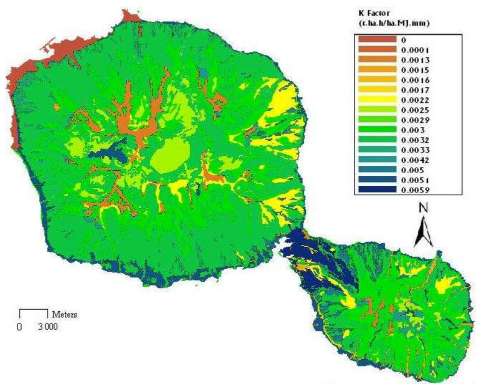

Fig. 4: K factor (soil erodibility) derived from soil type

II-1-3. Cover management Factor C

The C factor represents the cover and management factor. It integrates the effect of cropping and management practices in agricultural management, and the effect of ground, tree and grass covers on reducing soil loss in non-agricultural situations.

To derive the C factor we used remote sensing techniques and particularly supervised classification methods based on a SPOT 5 satellite image taken in May 30, 2002 with a 10 m resolution (Fig. 5). Unfortunately, 20 % of this image is covered by clouds and mountain shadows. So we supposed that these parts are occupied by forests (C value of 0.001). The crop is principally located in the Taravao plateau or near urban areas, with a C value of 0.35 (Roose, 1977). The bush/grass colonizes the low valleys with a C value of 0.01 (Roose, *Ibid*). The C value over urban zones is difficult to determine. However, the urban zone is not totally covered by buildings and routes. Previous papers in the literature retain a C value between 0.0001 and 0.38 (Jabbar and Chen, 2005; Rosewell, 1993). The main urbanized zone in Tahiti is the seashore rim, extending inward the island year after year. We detected bare soil (with a C value of 1) in some high valley constructed sites. As the typical housing style in Tahiti is the small creole cottage surrounded by gardens, we choose a C value of 0.003 (Zaluski *et al.*, 2003) as a principal value for the urbanized zone. We detected bare soil along the Papenoo river, with therefore also a C value of 1. Results of this section are summarized in Fig. 6.

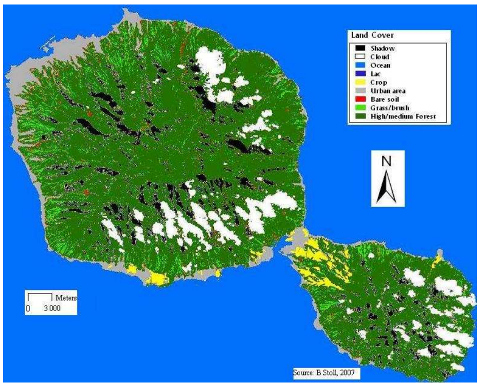

Fig. 5: Land cover derived from SPOT 5 data

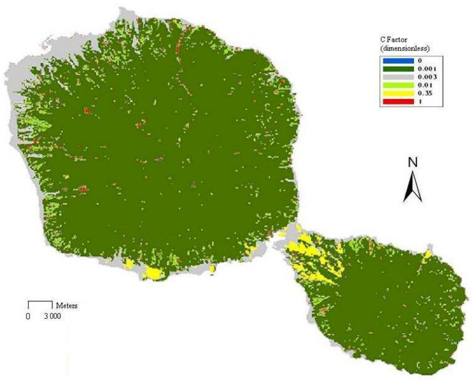

Fig. 6: C cover management factor derived by us from land cover. (The Papeeno river is showing up in the upper part of Tahiti-Nui)

II-1-4. Support Practice Factor (P)

The P factor represents the support practice factor. It is the ratio of soil loss with a specific support practice with respect to the corresponding loss with up-and-down-slope culture: contour tillage, strip-cropping on the contour, terrace systems etc…. The normalized value of P is between 0 and 1. Because of the lack of any information in Tahiti, we choose a value of 1, therefore with no impact on the potential erosion estimates.

II-1-5. Slope Length-Steep Factor (LS)

The LS factor represents the length and the steepness of land slopes which substantially affect the rate of soil erosion by water. The LS value as originally defined by Wischmeier and Smith (1978) is 1 for a field of 22.13 meters length and of 9 % slope. The slope length is defined as the horizontal distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins, or the runoff water enters a well-defined channel that may be part of a drainage network or a constructed channel.

Later, Moore and Wilson (1992) developed an estimation of the LS factor for RUSLE from the physical notion of sediment transport capacity as

$$LS = L * S = (As/22.13)^{m} * (\sin\beta / 0.0896)^{n}, \qquad (3)$$

where As is the upslope contributing area with the exponent *m* in the range 0.4 - 0.6 and β is the slope angle with the exponent *n* in the range 1.2 – 1.3. The As term characterizes the effect of convergence and divergence of terrain on soil erosion. The RUSLE method provides a lower estimation of the LS factor for longer slope-lengths and steeper slope-angles than the original USLE equation. Desmet and Govers (1996) considered that the L value must be computed by taking artificial catchments bound by woodlands or grasslands which cut off the water flow. But this contradicts the conservation law of water flow, and is probably invalid for high-slopes so we used naturally bounded catchments.

According to Renard *et al.* (1997) the slope lengths estimated from contour maps are usually too large because most maps do not have sufficient resolution to indicate all the concentrated flow areas that end RUSLE slope lengths. So they defined L as

$$L = (\lambda/22.13)^{m}, \qquad (4)$$

where λ is the slope length, not the upslope contributing area. Thus soil loss increases more rapidly with slope steepness than it does with slope length, so they evaluated the S factor as

$$S = 10.8 \sin\beta + 0.03 \text{ for slopes} < 9\%, \qquad (5)$$

$$S = 16.8 \sin\beta - 0.5 \quad \text{for slopes} \geq 9\%, \qquad (6)$$

There are two concurrent methods for calculating the LS value in the GIS software ArcGis: the method of Mitasova *et al.* (1998) and the method of Van Remortel *et al.* (2001). The Mitasova *et al.* method is based on the Moore and Wilson's equation (*Ibid*); Van Remortel *et al.* use the equation of Renard *et al.* (*Ibid*). Both results (Fig. 7 and 8) broadly agree but we found almost the same artefacts (unphysical large value) over the zones where the rill network is vertical or horizontal.

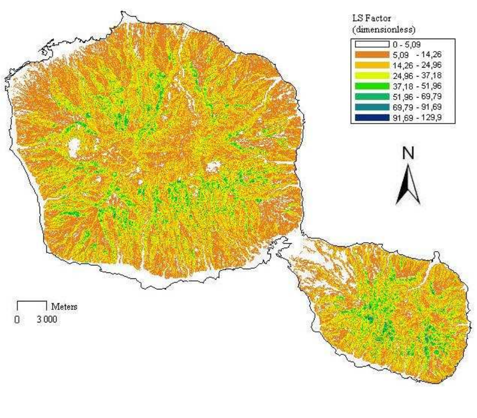

Fig. 7: Length-Slope factor by the Moore and Wilson's method (divergence or convergence of water flow)

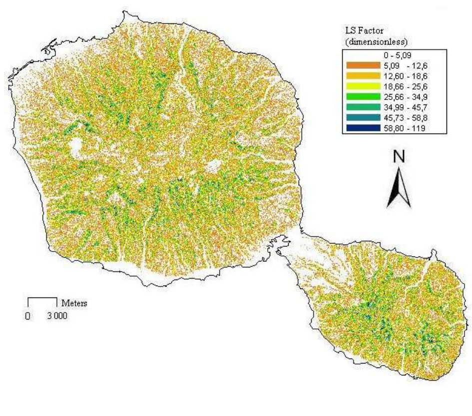

Fig. 8: Length-Slope factor by the Renard *et al.* method (see text)

II – 2. Potential erosion (soil loss)

The maps of potential yearly soil loss (Fig. 9) derived from the USLE-RUSLE equation can be divided into 4 zones: zone 1 is relative to a soil loss under 0.5 ton/ha/yr, and occupies 70 % of Tahiti; zone 2 is relative to soil loss quantity between 0.5 – 1 ton/ha/yr, and it is located on the South-East side of Tahiti-Nui / Tahiti-Iti towards the trade winds; zone 3 is relative to a soil loss quantity between 15 - 75 ton/ha/yr, located in croplands; zone 4 is globally located in the West side of Tahiti-Nui, and we could see in this zone the effect of bush/grass cover and of urbanization (3 – 15 ton/ha/yr). In some very limited places (construction sites), we have bare soil with a loss of more than 75 ton/ha/yr.

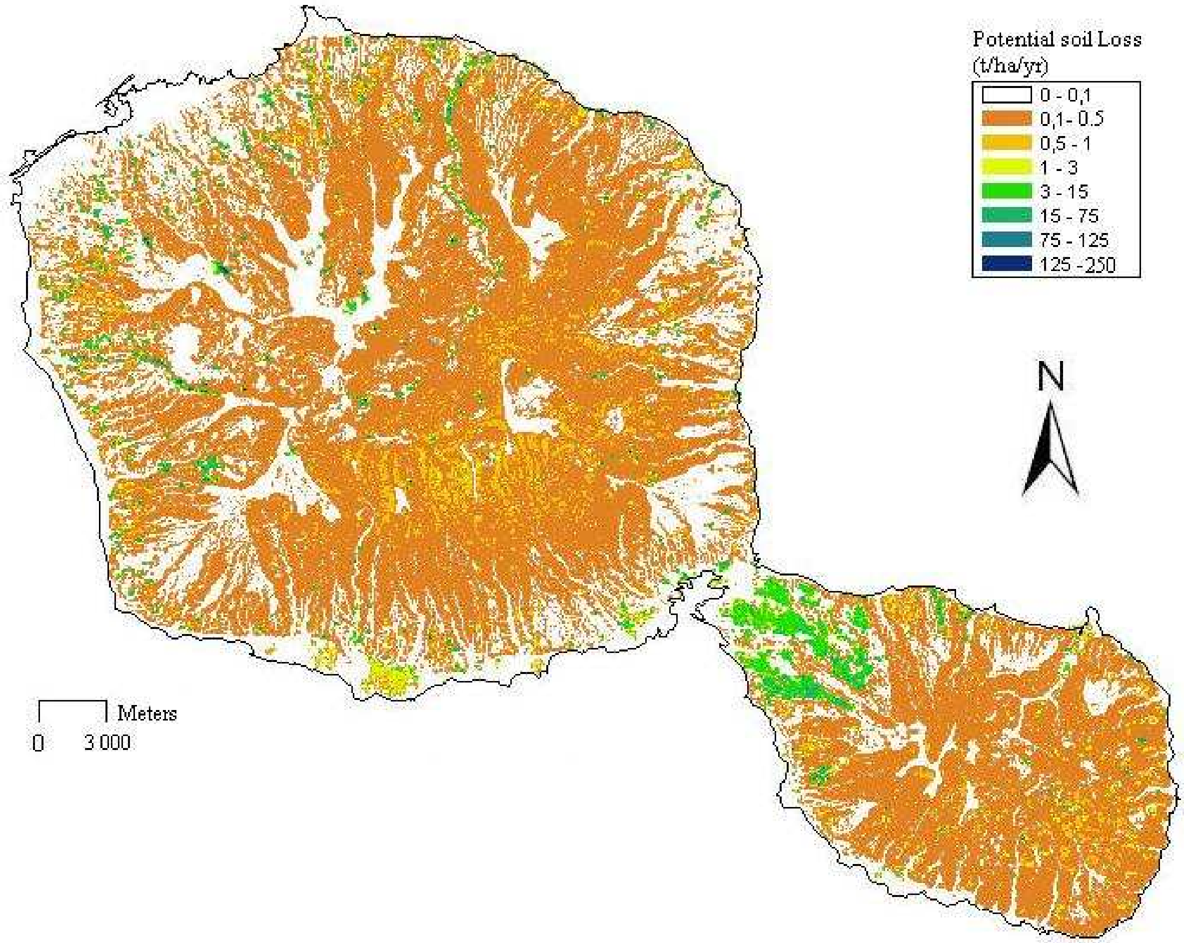

Fig. 9: Tahiti potential soil loss: the repartition of the potential soil loss is dominated by the vegetation and cover management factor C. Construction sites (bare soil) are often found in the West side of Tahiti-Nui, with an important potential soil loss (> 75 ton/ha/yr). The croplands, located in the Taravao plateau represent a second important potential soil loss (15-75 ton/ha/yr). Tahiti globally looses about 0.1 – 0.5 ton/ha/yr of soil, mainly with respect to soils under the forest cover. In some high plateaus, the potential soil loss is less than 0.1 ton/ha/yr, as the soils in these areas present a large content of organic matter.

The signification of the slope-length factor L is far to be clear in the literature. Wischmeier (1966) indicated that the effect of L on annual runoff is usually insignificant. Moreover, Renard *et al.* (*Ibid*) and Galetovic *et al.* (1998) noted that if soil loss is entirely generated by interrill erosion, which is nearly always uniform along a hillslope, the L value will be 1 for all lengths (for rill erosion, the L value increases with length). We observed little or no impact on the potential soil erosion of Tahiti with a global value of 1 for L, except in downstream area where the rills concentrate.

III. PHYSICAL MODELING

All the physically based erosion models (e.g. the Carretier *et al.* Apero-Cidre model, 2009) are based on a conservation law of the form:

$$\frac{\partial h}{\partial t} = -div(\vec{q}_{diffusion} + \vec{q}_{non-diffusion}), \quad (7)$$

where h is the elevation (or soil depth), t is the time, *div* is the divergence operator and $\vec{q}_{diffusion}$ and $\vec{q}_{non-diffusion}$ are the total sediment discharges due respectively to short-range (tens of meters) phenomena like soil creep, bioturbation and rain-splash and to long-range phenomena like transport by rivers (tens or hundreds of kilometres). Alluvial transport by rivers can be typically one order of magnitude more efficient than diffusive transport.

Practical implementations of the physical models mainly differ in the way they handle non-diffusive processes. The Apero model that we used considers water flow as a steady state solution of the Saint-Venant's equation (Beven, 2002), taking also into account (with empirically determined parameters) soil production, bedrock incision and sediment transport laws. The notion of steady-state (time-independent) flow implies the use of an averaged (time-independent, or slowly time-varying) model of rain, i.e. averaged over the seasons.

One of the major differences with the empirical USLE family of models is that the physical models (and so Apero-Cidre) are able to compute net erosion as well as redeposition. USLE-like models are only able to determine "potential" erosion (i.e. maximum possible erosion). Under this restriction we could compare both approaches by writing

$$A = \rho \ S \ \frac{\partial h}{\partial t}, \quad (8)$$

where ρ is a given soil density (here we took 1.5) and S is a given "pixel" area. In this paper, we just made a rapid comparison between the Apero-Cidre and USLE models (Fig. 10 and 11), with the same *a priori* mean annual rainfall of 3,000 mm for both models. For computational reasons, we only considered the Tahiti-Nui part of Tahiti. In the Apero-Cidre model, the cover management factor C and soil erodibility factor K are not taken into account. In the USLE model, long range alluvial transport is not fully taken into account (L factor). This explains why the patterns of erosion differ in the detail. Nevertheless, they globally qualitatively match (particularly the central white areas relative to the high plateaus in the West side of Tahiti-Nui.)

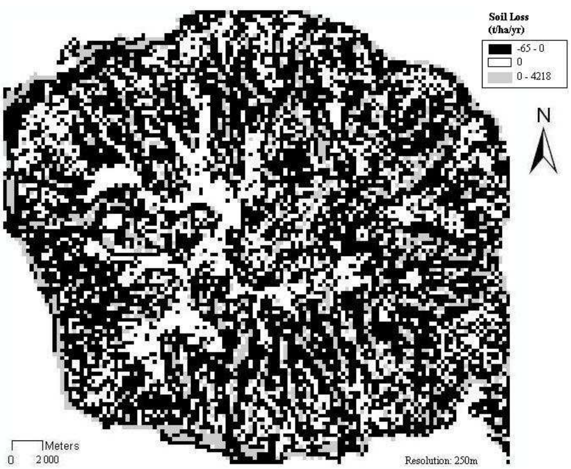

Fig. 10: Apero-Cidre results: Positive values represent redeposition, negative value abrasion (net erosion).

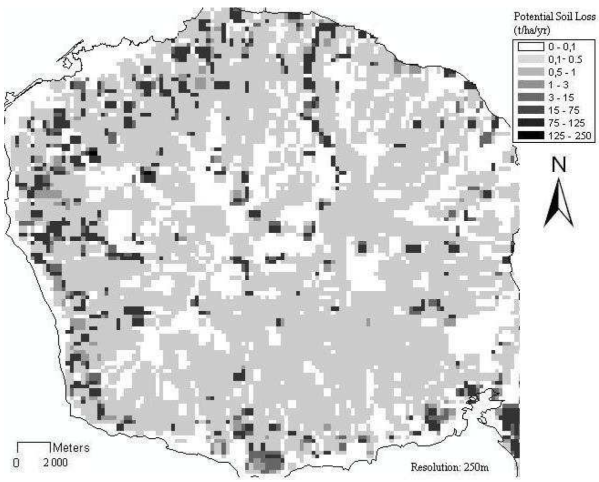

Fig. 11: Potential soil loss erosion (USLE)

IV. DISCUSSION, CONCLUSION, AND FUTURE WORK

In this study, we used the USLE approach to model the potential erosion on Tahiti. The main advantage of USLE is its simple multiplicative expression. But USLE by essence cannot describe the erosion processes as a set of physical equations, as it is based on a multiplicative set of coefficients calibrated on test plots. Besides, Roose (1996) indicated that one of the limitations of USLE could be its applicability in young mountain areas, and especially in areas with slopes higher than 40 %, because there the runoff is a greater source of energy than rain and because soil creep is important in such slopes. Nevertheless, Kitahara *et al.* (2000) showed that USLE can be successfully applied to estimate surface erosion on long and steep mountainous forest slopes up to 50 %. In addition Liu *et al.* (2000) confirmed the applicability of USLE and RUSLE models on test plots for the slopes up to 60 %. For Tahiti, slopes could reach 155 % with a mean value of 61 % and with principal values in the 55 % to 87 % range, largely outside the expected nominal range for USLE. Nevertheless, we believe that our predictions are at least qualitatively correct, as they roughly match observed erosion patterns on the ground.

Our main result is that the repartition of the potential soil loss is dominated by the vegetation and cover management factor C. Important potential soil losses (> 75 ton/ha/yr) occur on construction sites (bare soil), often found in the West side of Tahiti-Nui. The croplands, located in the Taravao plateau represent another second important potential soil loss (15-75 ton/ha/yr). Tahiti globally looses about 0.1 – 0.5 ton/ha/yr of soil, mainly w.r.t. soils under the forest cover. In some high plateaus, the potential soil loss is less than 0.1 ton/ha/yr, as the soils in these areas present a large content of organic matter. Wotling and Bouvier (2002) estimated the erosion rates over three of the main watersheds in Tahiti from suspended sediments in river: 0.6 ton/ha/yr in a natural forested catchment, 1.4 ton/ha/yr in an urbanized catchment, 7 ton/ha/yr during preparatory urbanization earthworks before soil stabilisation. If they are correct, we therefore underestimate the soil loss over the urbanized and urbanizing zones (0 – 0.6 ton/ha/yr) probably because we are not able to separate them. We overestimate over the forest zone (0 - 1.4 ton/ha/yr,) probably because the classification of Wotling and Bouvier (*Ibid*) aggregates bush and tropical forest zones. Over tropical forest zones, our soil loss estimate is generally under 0.6 ton/ha/yr. Another point of concern is the R factor. Exceptional rainfalls in Tahiti initiate instantaneous sediment discharges at a rate superior to the mean annual sediment discharge, and the rain-gauge network is scarce especially over Tahiti-Iti (Wotling, 2000), so our current approach for estimating the R factor (Roose, 1977) is highly questionable.

In a future work, we will use a more detailed vegetation classification from high resolution satellite imagery, and we will also introduce the effect of the slope steepness (Roose, 1977), as the C factor dominates on the computation of the potential erosion. We will try to identify areas contaminated by the invasive species “Miconia calvescens” which is known to intensify soil erosion (Florence, 1987; Chan-Halbrendt *et al.*, 2007.) We will also determine the erosion rate by radionuclide methods (Navas *et al.*, 2008). In this frame, Fichez *et al.* (2005) report that the sedimentation rate at Papeete (Tahiti main city) is around 1-1.4 cm/yr through ^{210}Pb radionuclide dating, but we have to link this boreholes estimate to our USLE erosion rates. Finally, we plan to implement, in a physical model like the Apero-Cidre model, the equivalent of the C, K an P factors of USLE, as the physical equations of such models essentially consider the equivalent of the R and LS factors, to obtain erosion maps taking into account true erosion estimates (ablation/redeposition) and not only potential erosion estimates. In this frame, we will also need to discuss the sensitivity of erosion rates to climate variability.

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