Predicting Potential Soil Loss in Pacific Islands: Example in Tahiti Iti – French Polynesia

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Abstract: Soil erosion by water has become a serious problem in Pacific Islands mainly due to the tropical natural conditions and to the progressive and continuous human pressure (agricultural practices, bush fires, mining activity…). In the current study, an effort to predict potential annual soil loss has been conducted in Tahiti Iti island in French Polynesia. For the prediction, the Revised Universal Soil Loss Equation (RUSLE) has been applied in a Geographical Information System framework. RUSLE-factor maps were made. The R-factor was determined from the average annual rainfall data. The K-factor was estimated using soil map available and granulometric analysis of samples of soils. The LS-factor was calculated from a 5 meters digital elevation model. The C-factor was calculated using remote sensing techniques and particularly supervised classification methods based on SPOT 5 satellite images. The P-factor in absence of data was set to 1. The mean annual soil loss predicted by the model is 2.4 t/ha/yr. The results show that some 85% of the region of interest has a potential erosion rate of less than 5 t/ha/yr but an extended part of the area is undergoing severe erosion with a potential soil loss up to 50 t/ha/yr, demanding the attention of local land managers.

Keywords: Soil erosion, Revised Universal Soil Loss Equation (RUSLE), Geographic Information System (GIS), Integrated Coastal Zone Management (ICZM), Tahiti

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Soil erosion and related degradation of land resources are significant environmental and socio-economic problems in a large number of countries throughout the world (Millward and Mersey, 1999; Hoyos, 2005). Soil erosion occurs naturally and its importance to humanity depends on a host of factors, including the nature of soil, climate, topography and land cover but most importantly the nature of human activities. Soil loss is particularly associated with farming practices that do not conserve soil in situ, for example ploughing against the contours, rapid ground cover removal, overgrazing and deforestation - these are entirely natural and indeed needed for many semiarid and Mediterranean systems. Also important can be mining activities, construction and urbanization that does not consider hydrological conditions.

Source: Pascal Dumas

Figure 1: Tourism is an important source in income in Tahiti

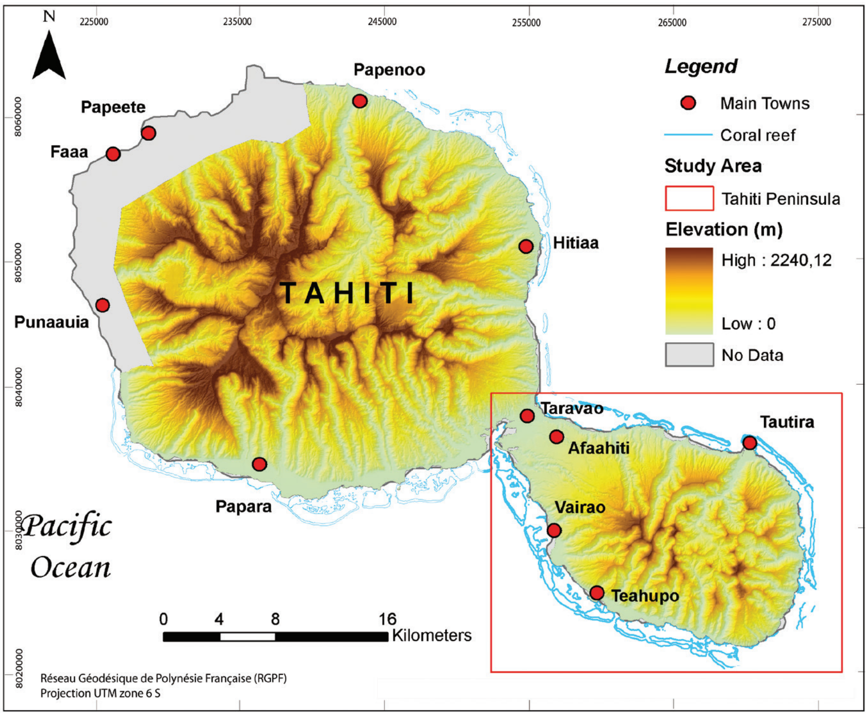


Figure 2: Tahiti consists of two high islands formed by young volcanic mountains

Source: DEM, 5 m resolution, dydrology data, Service d' Aménagement de de l'Urbanisme

In the South Pacific region, the high tropical islands are most vulnerable to soil loss and land degradation. They have steep slopes, tropical storms and cyclones with extremely heavy rainfall and high natural erosion rates due to rapid soil weathering. Moreover, most of the islands in this part of the world have an important and fast growing population and therefore a strong pressure on natural resources. The vast majority of rural Oceanian peoples practice subsistence farming and artisanal fisheries. Excessive soil erosion threatens sustainable agricultural production by decreasing the fertility of agricultural soils with a loss of soil rich nutrients. Streams in tropical areas have up to 15 times the natural sediment load compared to those in temperate areas (Simonett, 1968). But water quality is affected by increased sedimentation in rivers with large volumes of terrigenous runoff.

Moreover, downstream of the watershed, the degradation of lagoon biodiversity and fringing reefs during cyclonic floods, due to sediment transfer, can be serious (Fabricius, 2005; Jones and Berkelmans, 2014). For the Pacific islands that comprise nearly 25% of the world's coral structures, biodiversity and landscape preservation are important concerns for tourism. The effect of soil erosion on agricultural land is also a concern, although the region's inhabitants have a fine array of traditional farming techniques that avoid its worst effects.

An attempt to assess the erosion hazard and quantity of sedimentary material carried toward Pacific island lagoons will aid in planning for high level of soil erosion, especially where Integrated Coastal Zone Management (ICZM) is being applied. In this article the aim is to map the erosion process on Tahiti Island in French Polynesia, and to highlight the watersheds that are most affected. An empirical soil loss model for Tahiti Island is developed and presented.

Geography of Tahiti Island

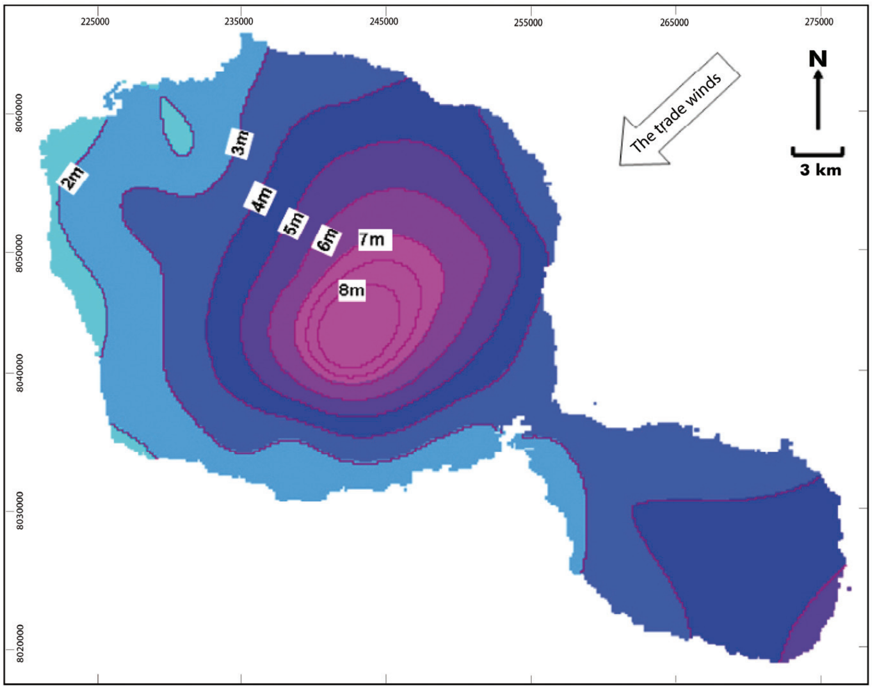
Tahiti island, located in the archipelago of the Society Islands in the central Southern Pacific Ocean, is part of an overseas collectivity of the French Republic. This highest and largest island in French Polynesia (covering an area of 1045 km^2) was formed from volcanic activity (around 1.4 Myear ago). Tahiti consists of two round portions centred on volcanic mountains: the bigger, northwestern part Tahiti Nui (around 30 km in diameter) and the smaller, southeastern part Tahiti Iti (around 15 km) (Figure 2).

These two parts are connected by a short isthmus named after the small town of Taravao. The island is surrounded by modern discontinuous fringing reefs grading into a chain of barrier reefs, commonly interrupted and locally enclosing a narrow lagoon. The island is volcanically inactive and is deeply dissected by erosion (Hildenbrand et al., 2008). The spatial distribution of the rainfall depends mostly on the topography and most particularly with exposure to prevailing winds: from 8 000 mm/year on the east coast hit by Tahiti trade winds, to 2 000 mm/year on the west coast (Figure 2). The two sub-islands are basaltic edifices, which over the millennia have eroded to form mainly laterite soils. Four main forms of terrain topography are identified: the coastal plain has a slope of less than 2°, the plateaus and riverbeds with a slope of between 2° and 15°, the planezes between 15° and 47° and the incised valleys have more than 47° slope (Ye et al., 2010). In 2012, the population was 184 000 inhabitants making it the most populous island of French Polynesia (68.5% of its total population) focus in majority on Tahiti Nui. With 20 000 inhabitants, the population density of Tahiti peninsula is 80 inhabitants / km². However, this population is concentrated exclusively near the coast and in the region of Taravaro, where density reaches 350 inhabitants/km² leaving the central part of the island uninhabited.

Erosion modeling: material and methods

In order to spatialise and quantify the erosion hazard on the Tahiti Iti Peninsula, we choose an approach based on modeling. The Revised Universal Soil Loss Equation was used, (RUSLE, Renard et al., 1997), an empirically based model founded on the Universal Soil Loss Equation, USLE (Wischmeier and Smith 1978). These mathematical models are the most widely used through the world for prediction of water erosion hazards and for the planning of soil conservation measures. RUSLE predicts only 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. It estimates long-term average annual soil loss rate using a factor-based approach with rainfall, soil, topography and land cover and management as inputs. These five major factors are used in USLE/RUSLE for computing the expected average annual erosion through the following equation:

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



Source: from Ye., et al 2010.

Figure 3: The spatial distribution of the annual rainfall (Ye et al. 2010). The East coast, subject to the trade winds, receives more rainfall than the West coast. The rains are more abundant during the warm season (October to April).

Where A is the computed spatial average potential soil loss and temporal average soil loss per unit area (t/ha/yr), R the rainfall-runoff erosivity factor [MJ mm/(ha h year-1)], K the soil erodibility factor [t ha h/(ha MJ mm)], L the slope length factor, S the slope steepness factor, C the cover management factor, and P the conservation support practice factor. The RUSLE was applied in a Geographical Information System (GIS) environment, where every factor was calculated and spatialized as a raster/grid. Raster models are cell-based representations of map features, which offer analytical capabilities for continuous data and allow fast processing of map layer overlay operations (Fernandez et al., 2003). In this case, a pixel value of each grid square is equal to a level of sensitivity to erosion for the factor in question.

Rainfall erosivity factor (R)

This factor, by definition, is the sum of individual storm erosivity value, EI30, for a year averaged over long time period (> 20 years) where E is the total storm kinetic energy and I30 is the maximum 30 min rainfall intensity. Because of the lack of available data from weather stations in French Polynesia, the World Climate database, developed by Hijmans et al. (2005) was used. WorldClim is a set of very high resolution interpolated climate surfaces for global land areas. These data available for 1950-2000, expressed in monthly average on a 1km scale, has been corrected in GIS environment to match the spatial resolution of the digital elevation model and compiled to obtain results in the year for use in RUSLE. With these data it was not possible to compute longterm rainfall intensity data in study area, so we applied the simplified formula developed by Roose (1975):

$$R = 0.5 * P * 1.73$$

With P is the average annual rainfall, 1.73 the index conversion between US unit and metric unit, and 0.5 an index of climatic aggressiveness that expresses the relationship between an index of average annual rainfall and the height of the average annual rainfall. The spatial distribution of the factor R obtained follows the variations of the rainfall and topography (Figure 7a). It ranges from 1.478 to 2.465 MJ.mm/ha.h.yr in Tahiti Peninsula.

Soil erodibility factor (K)

The soil erodibility factor (K) represents both susceptibility of soil to erosion and the rate of runoff. This factor reflects the resistance of soil to erosion caused by the force of precipitation. 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. If this information is known, the soil erodibility factor K can be approximated from an equation (Wischmeier and Smith 1978), which estimates erodibility as:

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

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.

In this study, soil erodibility was estimated with the help of the soil map provided by Jamet (1990) from IRD (Institute of Research and Development) at a scale of 1:40 000. This soil map has been digitalized and 13 major soil types were identified (tropical eutrophic brown soils, ferralitic soils…). A field campaign took samples of soils for each type of soil across Tahiti Iti. A granulometric analysis of these samples using the gravimetric method, and organic matter determination using the loss on ignition method was conducted for each soil type, allowing us to determine the percentage of sand, silt, clay, and organic matter content. From these values and using the texture triangle of the United States Department of Agriculture (Figure 3), the soil texture of each type soil was identified (Brown, 2003). Most of soils in the region of interest (mainly covered by ferralitic soils) have relative proportions of sand, silt and clay similar (with a percentage of sand superior to 80%). They are thus characterized by the same texture, which explains the low spatial variability of this factor (Figure 4b). Then the table of correspondence between the standard textures and the K factor (Table 1) was used (Stone and Hilborn, 2000). In the study area the values of the K factor range from 0.0026 to 0.0171 t.ha.h/ha.MJ.mm.

Slope-length (L) and slope steepness (S) factors

The L and S factors in the model represent the effect of topography on erosion. It has been demonstrated that increases in slope length and slope steepness can produce higher overland flow velocities and correspondingly higher erosion (Haan et al., 1994). Slope length is defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases to a point where deposition begins, or runoff becomes focussed into a defined channel (Foster and Wischmeier, 1974). The common equation used for calculating LS is an empirical equation provided by the USDA Agriculture 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 □ is the slope length in meters; □ is the angle of slope in degrees; and m is a constant dependent on the value of the slope gradient: 0.5 if the slope angle is greater than 2.86°, 0.4 on slopes of 1.72 to 2.85°, 0.3 on slopes of 0.57 to 1.72°, and 0.2 on slopes less than 0.57°.

A limitation of using at regional scales the USLE/RUSLE soil-erosion models has been the difficulty in obtaining an LS factor grid suitable for use in GIS applications. Different models and methods have been tried to solve this problem (Hickey, 2000). Thus, the algorithms adopted in the current work to estimate the LS factor were the raster grid cumulation and maximum downhill slope methods, which were developed by Van Remortel et al. (2001). A digital elevation model (DEM) at 5 meters spatial resolution from the Urban Planning and Development Service of French Polynesia, and an AML (Arc Macro Language) program under ArcInfo software based on the equation of Renard et al. (1997), were used for the calculation of the LS factor. As a result, each 5 m cell of the grid surface of each one of the study area was assigned an LS value (Figure 4d). The topographic factor ranges from 0 in the flat zones to 116 at the many steep slopes in the central watersheds of Tahiti Peninsula, with an average value of 12.8. Most of the values of the LS factor are under 5, and are the flatter plains and coasts. High values (superior to 20) are important in this part of Tahiti, representing 22% of the total area.

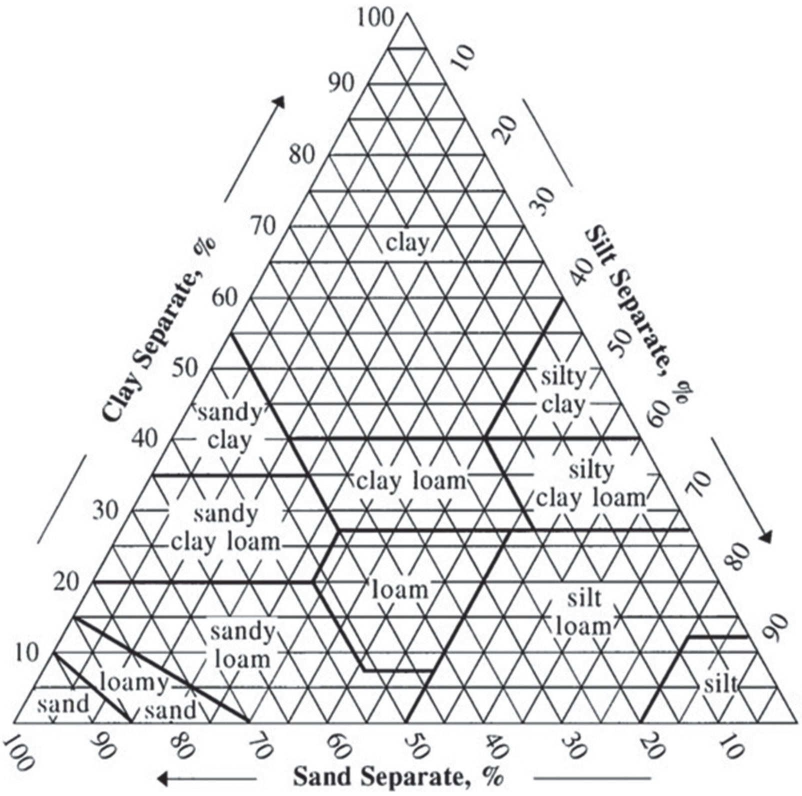


Figure 4: Texture triangle of the United States Department of Agriculture

Source: United States Department of Agriculture (USDA)

Cover management factor (C)

According to Benkobi et al. (1994), the vegetation cover factor together with slope length and steepness factors is most sensitive to soil erosion. C factor represent the effects of cropping and management practices on soil erosion rates in agricultural lands and the effects vegetation canopy and ground covers on reducing the soil loss in forested regions (Renard et al., 1997). As the vegetation cover increases, the soil loss decreases. Usually, the vegetation cover C factor is based on empirical equations with measurements of many variables related to ground and aerial coverage collected in sample plots (Wischmeier and Smith 1978). This method only provides point values for limited locations. The C factor values at non-sampled locations are estimated through spatial interpolation techniques. But, to compute C factor for the scale of large watersheds, it is


Figure 5: Pineapple fields near Taravao


Figure 6: Deforestation on steep slopes

Source: Pascal Dumas

Soil texture	K factor (t.ha.h/ha.MJ.mm)
Sand	0,0026
Loamy sand	0,0053
Coarse sandy loam	0,0092
Fine sand	0,0105
Loamy fine sand	0,0145
Sandy clay	0,0158
Sandy loam	0,0171
Fine sandy loam	0,0237
Sandy clay loam	0,0263
Clay	0,0289
Silty clay	0,0342
Clay loam	0,0395
Loam	0,0395
Organic	0,0395
Silty clay loam	0,0421
Silt loam	0,05

Source: Stone and Hilborn, 2000.

Table 1: K factor for different soil texture in US units

very difficult or impossible to measure every plot to obtain C-factor values. The interpolation results based on the C factor point values could be poor due to the limited number of sample plots in complex environments (Wang et al., 2002). Therefore, remotely sensed data have been used to estimate the C factor distribution based on land-cover classification results (Millward and Mersey, 1999; Lu et al., 2004), assuming that the same land covers have the same C factor values. In our case, we used remote sensing techniques and particularly supervised classification methods based on SPOT 5 satellite images taken with a 5 m resolution for obtain a land cover map of the area of interest. Unfortunately, a part of the image is covered by clouds and their shadows. Three main types of vegetation were mapped in the peninsula: crops, mainly in the plateau of Taravao or near urban areas along the coast and low slopes, savannah on low hills, and forest, the main type of vegetation, particularly in the mountain zones. For each type of vegetation and land use, a C factor value was adopted based on some research papers. Cover factor ranged from 0.003 to 1. Bare lands, bare soils (construction sites), representing the greatest sensitivity to erosion, have the highest coefficient (1) while the areas covered by mixed forest, limiting erosion, have a low coefficient (0.007) (Ma, 2001). About C value over urban areas (residential and built-up land and not totally covered by buildings and roads) mainly localized on the coast, previous papers in the literature have proposed a value between 0.0001 and 0.38 (Rosewell, 1993; Jabbar and Chen, 2005). For Tahiti, we retain a C value of 0.003 (Zaluski et al., 2003) as the typical housing style is the small creole cottage surrounded by gardens (Ye et al., 2010). For crops areas mainly include banana and pineapples crops, C factor is 0.3 (Roose, 1975) and 0.04 for savannah. With this method we obtain a GIS layer for factor C (Figure 7c).

Soil conservation practice factor (P)

The erosion management practice, of P value, is also one factor that governs the soil erosion rate. The P value ranges from 0-1 depending on the soil management activities employed and anti-erosion measure in place. Cropping in alternating strips or terracing, agroforestry integration on bench terraces, mounding and ridging are the most effective practices for soil conservation (Juo and Franzluebbers, 2003). Because of a lack of information on anti-erosion practices at the scale of Tahiti peninsula (no spatial data and no map), we choose to adopt P = 1 over the area of interest. It's also important to consider that agricultural practices are mainly localized in Taravao region and on the coast around the small villages (the central part of the island and the south are not inhabited). So the P factor is not need to be taken in account in a large part of the study area. This factor will not impact the final product but soils loss will be slightly overvalued in relation to reality.

Potential soil loss in Tahiti Iti

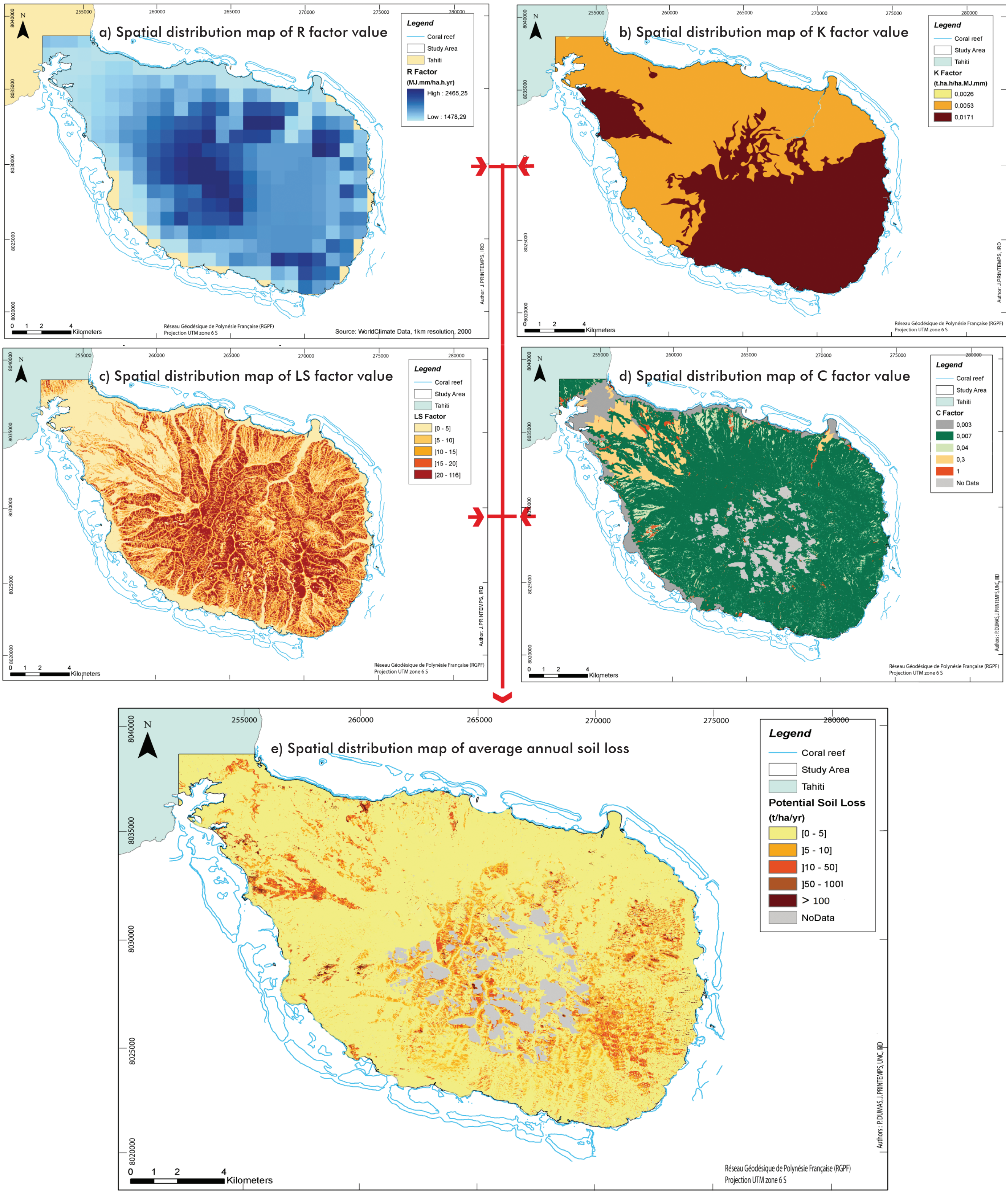
All the individual GIS layers, created for each factor in the RUSLE are combined by cell-grid modeling (the size of pixels is 5m x 5m). The result is a spatial distribution of erosion, where each pixel represents a quantity of potential soil loss (Figure 4e). On Tahiti Peninsula, the values obtained range between 0 and 3,126 t/ha/yr, with an average of 2.4 t/ha/yr corresponding to 0.16 mm of soil loss for 1m² in one year. Some 85% of the region of interest has a potential erosion rate of less than 5 t/ha/yr and this corresponds to areas covered by dense vegetation, in forested and the flatter parts of the catchment. Only 0.8% of the area has a potential soil loss superior to 50 t/ha/yr and this largely has bare soils (including construction sites) or at areas where crops are grown on steep slopes. Thus, the croplands located in the Taravao region represent one of the areas most impacted by erosion risk in Tahiti-Iti.

These results may be compared with other studies. On Tahiti Nui Island, erosion plots without vegetation cover reveal a soil loss above 35 tons per hectare only for 423 mm a month of rainfall during the wet season (Servant, 1974). On the west coast of the same island in areas subject to spreading urbanization, potential losses in excess of 75 t /ha /year were calculated (Ye et al., 2010). In the Pacific region, estimations using RUSLE from instrumented parcels are in the same order of magnitude, with for example in the Fiji Islands where Liedke, in 1989, found soil loss rate between 16.6 and 80 t/ha/yr near Lautoka and Morrison, in 1981, found soil loss rate around 36.7 t/ha/yr under sugar cane near Nadi.

Discussion and conclusion

This study has used a comprehensive methodology that integrates the RUSLE model and Geographic Information System techniques to determine the soil erosion vulnerability of many watersheds, on the island of Tahiti Iti in French Polynesia. The spatial pattern of annual soil erosion rate was obtained by integrating geo-environmental variables, including rainfall, erosivity, soil erodability, slope length and steepness and vegetation cover, in a raster based GIS method. The estimated soil losses are significant, but similar to other results of erosion rates found for mountainous tropical islands with steep slopes (Liedke 1984; Dumas and Fossey, 2009).

Nonetheless, the values for soil loss from RUSLE should be considered as an order of magnitude and not as absolute values. One of the limitations of USLE, originally developed for mild slopes in agricultural areas, can be its applicability in young mountain areas, and especially in areas with slopes higher than 40 % (Roose, 1996). In this case the runoff is a greater source of energy than rainfall, and additionally, soil creep and slumping is important on such slopes. Nevertheless, Liu



Source: Pascal Dumas

Figure 7: Implementation of RULSE model with GIS for predicting soil loss in Tahiti Iti

et al. (2000) showed the RUSLE model can be successfully applied on slopes up to 60 %. The quality of data sources implemented in the model may introduce uncertainties in soil erosion estimates. In the present study, the spatial scale of rainfall data sources or the soil maps are not really adequate, although the other factors are more precise. The methods of interpolation of these data only allow crosscutting the different layers of the model. It is necessary to have more detailed land use data, with an agricultural land use typology subdivided into specific crops.

However, in many situations, policy makers and land managers are more interested in the spatial distribution of soil erosion risk than in absolute values of soil loss. The model leads to better understanding of spatial distribution of the erosion hazard. Moreover, a comparison with a multi-criteria method (an expert approach) demonstrates that the results from an RUSLE model in term of spatial variation are similar (Dumas et al., 2010).

The map of soil loss obtained

constitutes a document which can be used as a decision tool for better land management planning and for sustainable agricultural practices (such as terraces on the steep slopes to reduce the slope lengths, which will slow down runoff velocities). It is also the first step to obtain an initial ranking of the watersheds most responsible for terrigenous sediment production. After taking into account the areas of deposition/delivery, this model could lead to the assessment of contributions in terms of terrigenous inputs in the hydrographic flow and identify watersheds which should be classified as priorities for land management efforts, in order to limit their impacts on the marine environment. Studies such as this have relevance for the framework of Integrated Coastal Zone Management for Pacific countries.

It's also important to note that the implementation of a model such as RUSLE is more suitable for the type of geographical environments found on Pacific islands, than others approaches based on the modelling of sediment transfer processes (as SWAT: Soil and Water Assessment Tool or WEPP: Water Erosion Prediction Project) designed for limited areas and that require complex data, and many field measurements for their calibration, not available in this region. A combination of remote sensing, GIS techniques and RUSLE provides the potential to estimate soil erosion loss and its spatial distribution at a scale that is feasible, with reasonable costs and better accuracy over larger spatial scales.

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