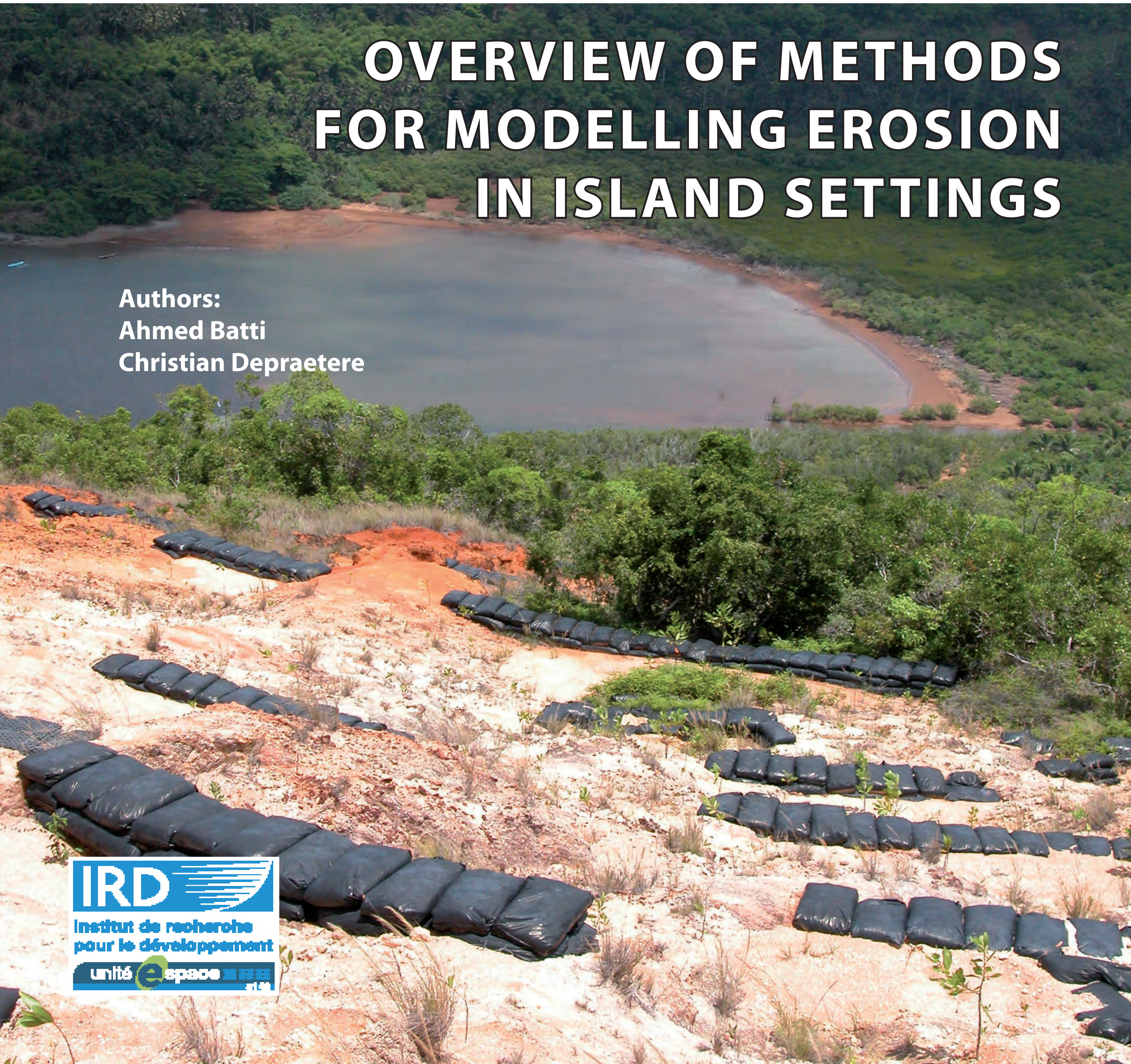
CRISP
Coral Reef InitiativeS for the Pacific
Initiatives Corail pour le Pacifique

COMPONENT 1A - Project 1A4
Integrated Coastal Management - GERSA Project
Spatial Approach - Remote Sensing

June 2007

Methodological analysis



OVERVIEW OF METHODS FOR MODELLING EROSION IN ISLAND SETTINGS

Authors:
Ahmed Batti
Christian Depraetere

IRD
Institut de recherche pour le développement
unité espace

CRISP

Coral Reef InitiativeS for the Pacific
Initiatives Corail pour le Pacifique

SPREP/PROE

The CRISP programme is implemented as part of the policy developped by the Secretariat of the Pacific Regional Environment Programme for a contribution to conservation and sustainable development of coral reefs in the Pacific

The Initiative for the Protection and Management of Coral Reefs in the Pacific (CRISP), sponsored by France and prepared by the French Development Agency (AFD) as part of an inter-ministerial project from 2002 onwards, aims to develop a vision for the future of these unique eco-systems and the communities that depend on them and to introduce strategies and projects to conserve their biodiversity, while developing the economic and environmental services that they provide both locally and globally. Also, it is designed as a factor for integration between developed countries (Australia, New Zealand, Japan, USA), French overseas territories and Pacific Island developing countries.

The CRISP Programme comprises three major components, which are:

Component 1A: Integrated Coastal Management and watershed management
- 1A1: Marine biodiversity conservation planning
- 1A2: Marine Protected Areas
- 1A3: Institutional strengthening and networking
- 1A4: Integrated coastal reef zone and watershed management

Component 2: Development of Coral Ecosystems
- 2A: Knowledge, monitoring and management of coral reef ecosytems
- 2B: Reef rehabilitation
- 2C: Development of active marine substances
- 2D: Development of regional data base (ReefBase Pacific)

Component 3: Programme Coordination and Development
- 3A: Capitalisation, value-adding and extension of CRISP Programme activities
- 3B: Coordination, promotion and development of CRISP Programme

CRISP Coordinating Unit (CCU)
Programme manager: **Eric CLUA**
SPC - PO Box D5
98848 Noumea Cedex
New Caledonia
Tel.: (687) 26 54 71
E-mail: ericc@spc.int
www.crisponline.net

Project 1A4 (GERSA)

Integrated coastal reef zone and watershed management

The purpose of GERSA is to foster the emergence of an integrated cross-cutting approach based on public policy tools and monitoring methodology and local-scale stakeholder dynamics. Ultimately, the goal is to have a scientific foundation and indicators suited to Pacific Island settings so as to set up country sustainable development observatory networks as part of the introduction of MPAs. GERSA is then a cross-cutting project relating also to project 1A2 (MPAs).

The project 1A4 is composed of 4 working packages:

- ■ *WP 1 - SPATIAL APPROACH*
- ■ *WP 2 - TERRITORIALITY AND SOCIO-ECONOMIC VALUES*
- ■ *WP 3 - ENVIRONMENTAL INFORMATION SYSTEMS AND MODELISATION*
- ■ *WP 4 - DYNAMICS AND MODELISATION OF WATERSHED*

Head of project: **Gilbert DAVID**
Contact: **Jean-Brice Herrenschmidt**
IRD - Unité ESPACE
101, Promenade Roger LARROQUE
BP A5
98848 Noumea Cedex
New Caledonia
Tel./Fax: (687) 26 08 27
E-mail: herren@noumea.ird.nc

This CRISP project is funded by the following agencies:

afd Agence Française de Développement
FFEM
Conservation International

Overview of methods for modelling erosion in island settings

Table of contents

Overview of methods for modelling erosion in island settings

In this report, we will provide a synopsis of several studies dealing with soil erosion on high islands with tropical climates. Our work is not intended to be comprehensive in this regard. At the most, we will refer to some recent studies on examples in the South Pacific and Indian Oceans so as to provide a framework for the efforts to be carried out as part of CRISP. We will mainly concentrate on the work of Dumas (2004) and Luneau (2006) in New Caledonia; Atherton et al. (2005) in Fiji; Batti (2005) on Reunion Island; and finally, the work that Wahlstrom et al., (1999) carried out in Hawaii. Finally, we will resituate this work within the wider context of Henensal's research (1986) on erosion processes. Our goal is to try to include more physical parameters in the definition of the environmental factors that control erosion processes, with erosion considered here as the entire three-part weathering/transport/sedimentation cycle[1]. We feel that this approach and definition are prerequisites for one of the GERSA/CRISP project's expected outcomes, i.e. estimating the amount of soil rivers deposit into lagoons.

We will differentiate between so-called "expert opinion" cognitive approaches and those more physical approaches based on experimental data.

I – Cognitive approaches (Qualitative)

1. Dumas' work (2004)

The aim was to map the soil's susceptibility to erosion in the townships of Boulouparis, Dumbéa and Paita in New Caledonia.
The author described the manmade causes of erosion in New Caledonia, which are building infrastructures and, more importantly, open-pit mining. He considered that poor farming practices and the urbanisation of slopes had limited impact in New Caledonia.
The author mentioned the disappearance of the mangrove, which plays a well-known role in coastal sedimentation.
The goal was to determine morphodynamic hazard zones, i.e. to make a map of soil susceptibility to erosion at the local scale and then at a functional watershed scale so as to study the erosion process and evaluate its potential impact on coastal marine areas.
To do this, he chose a qualitative modelling process based on multi-criteria analysis combining the most representative erosion factors, i.e. slope, nature of the substrate and land cover. It is interesting to note that the climate factor was not included. In fact, Dumas (2004) considered that the probability of high intensity rainfall was equally distributed spatially throughout New Caledonia. In the New Caledonian climate, the periods of tropical storms, which cause the greatest erosion damage, are equal in all places. In this regard, he based himself on the work of Maurizot and Delfaut (1995), who claimed that the most abundant and hardest rains are linked to the passage of tropical storms, which due to their geographic impact and the depth of convection are little, if at all, affected by landforms, even mountainous. So, the author considered that rainfall aggressiveness is the same from the coast up through to the mountainous regions. This theory is interesting and should be studied more in depth.
The phenomenon of erosion is seen here from strictly the point of view of surfaces that give off solid particles (mobilisation), and not from the point of view of the transport of these particles in waterways and their deposit downstream (sedimentation). Based on an analogy with hydrology, what is involved is, then, a "production model" of sediment disconnected from the transfer function

---

[1] We will not deal with the issue of the alteration or, more precisely, weathering of rocks, which, strictly speaking, we should. This is basically because we have little information on the stages of alteration on tropical islands, particularly in volcanic areas.

(transport) which, in large watersheds, can be composed of several deposit and transport phases before reaching the coast.

In practice, the author integrated and crossed data in a GIS. Using these data, he extracted sensitivity indicators in line with their relative roles in erosion. Three factors were taken into consideration:

- Slope categorised in three classes: low, medium and high.
- Soil erodibility in three classes.
- Land cover, extracted by remote sensing analysis. This factor provided information on how well the ground was protected. However, there was no information on certain areas that were hidden by clouds in the satellite images.

Once the geographic database had been made, the author chose a lattice structure to which he applied a multi-criteria analysis based on qualitative parameters, which, by combining the different erosion factors, made it possible to differentiate four levels of soil susceptibility to erosion, i.e. low, average, high and very high.

A soil erosion susceptibility indicator at the watershed scale was devised using the weighted mean of the four susceptibility indicators for each watershed. This indicator is more relevant for impact studies on marine coastal areas near the mouths of rivers. This remark comes, undoubtedly, from the fact that, as noted previously, transport from the original erosion zone to the coast may occur in several stages, particularly if the downstream part of the watershed is in an alluvial zone that is fairly well fixed by vegetation with low-sloped shifting channels.

2. Spatial distribution of erosion hazards in New Caledonia, (Luneau 2006)

Luneau's work (2006) was a follow-up to the preceding study. In fact, this work was designed to make it possible to refine the cognitive model made by Dumas (2004).
The author defined a "water erosion" hazard as the combination of soil susceptibility and precipitation. The factors chosen to represent erosion parameters were dependant on the availability of data in New Caledonia. Since the existing soil data (1:1 000 000 scale) did not correspond to the work scale, soil slaking susceptibility could not be determined. In the same way, there was no inventory of zones stripped by mining activities available (the DIMENC was drawing one up at the time the study was carried out).

The approach used to map erosions hazards was a multi-criteria assessment based on weighting each factor before adding them together. The advantage was that the weight of each parameter could be modulated. This methodology made it possible to produce a simpler qualitative model, and so, to consider and analyse several different scenarios.

The data were all resampled at 30 metres, which corresponded to the resolution of the satellite images used. These data were:

- The DITTT's topographical database, whose original resolution had been 10 m.
- 2005 DIMENC 1:50 000 scale map.
- Land cover map produced by processing Landsat7 data (2000-2001), with a spatial resolution of 30 m, processing SPOT3 images (1994-1996) with a resolution of 20 m, and the plant cover in vector format from the 1998 –2004 topographical database at a scale of 1:10 000.
- Rainfall data: mean annual rainfall from the 1991 – 2000 AURELHY model. The original dot grid had been 3 km.

Using these data, the author was able to extract the following indicators:

- The soil erodibility index from the geological map.
- The level of protection provided by plant cover, using the land cover map. In comparison to Dumas' work (2004), dirt roads were added to the land cover layer.
- Using the DTM, four indicators were extracted, i.e. slope, curvature of the horizon, profile curvature and drained surface area to assess the soil's susceptibility to runoff. These landform "curves" corresponded to geomorphometric parameters for both vertical convexity (highest slope line curvature) and horizontal convexity (contour curvature).
- Rainfall data from the AURELHY method at 3km were interpolated by Kriging.

Using these indicators and after a "standardisation" phase, the author set up a multi-criteria statistical model. The methodology was based on the following weighted linear combination:

$$E = \sum Pi.Si$$

Where: E = Evaluation,
Pi = Weight of Factor i,
Si = Value of standardised Factor i

This "standardisation" was done empirically on the basis of some rather unclear assumptions. It is regrettable that there is no physical description of the relations between the factors and processes to make it possible to better understand the author's simplifying assumptions and their operational interest.

The author defines the "standardisation" phase as recalibrating the original indicators or parameters to values between 0 and 255. For this transformation, linear and exponential functions were used depending on the factor to be standardised:

- A linear function for the drained surface area factor (S_d) calculated from the DTM that spread out values higher than 12.5 hectares, i.e. 140 grids of 30x30 m, to between 0 and 255. The author implicitly considered that there was no sediment mobilisation from diffuse runoff on the slopes (S_d<12.5 h) on drained surface areas below that value, which is surprising. The selection of a linear function linking linear erosion in concentrated runoff drains (S_d>12.5h) to the drained surface area (S_d) does not comply with the known relations between S_d and the flow rate (Q, see Geoffroy Wotling's thesis on the island of Tahiti).
- An exponential function that spread out mean rainfall values between 0 and 255, as the author considered that erosion increases exponentially with rainfall. This assumption invalidates the previous one used in Dumas' work (2004) and by Maurizot and Delfaut (1995).
- Exponential functions for the "slope" and "land cover" factors. There again, it is a shame that there were not any references, explanations or physical diagrams to support the operational assumptions linking parameters and processes.
- A linear function for the "dirt road" factor (density of dirt roads per sq km): Selection of the dirt road factor was, in fact, quite judicious for New Caledonia but also elsewhere. This factor is even more important when roads and dirt roads have been built without taking into account the erosion hazard they represent and without any work to reduce such hazards. We do not know if this is the case in New Caledonia. Probably in countries that have more limited technical and financial resources, this factor can become very significant.
- A linear function for "curvature" and "erodibility": this was the most innovative part of this work. However, it is still difficult to use the land shape model to locate potential erosion sites or sites that show signs of erosion based on simple rules at all scales, in all types of morphostructural context and for all types of erosion. In the end, while this idea is interesting and relevant, it is still not very usable. Proof of this is the fact that the "information layers" curvature was only given low weighting as seen in the following paragraph.

The author pointed out that rainfall erosivity is proportional to its amount and intensity (Le Bissonnais et al., 1998). However, the available data corresponded to the mean annual amounts over the period 1991 - 2000. However, the author considered that according to experts (Wotling G.), over several years, the amount of rainfall correlates to the intensity of rainfall events. This is a very important point since it is at the heart of the debate on rainfall erosivity, which is closely linked to its intensity. In many cases, there is no hourly or more frequent rainfall data. Generally, data are not very reliable for very high intensity events, particularly during tropical storms. Finally, the intensity and spatial extent of high intensity storms in mountainous zones are very hard to determine. Wotling's hypothesis will have to be rethought before it can be applied on a wide scale in the Pacific. Our own experience in tropical monsoon climates has demonstrated that the annual total is linked to the number of rainfall events and not to their intensity.

Once the factors had been standardised, considering that all the factors contributed in different measures to erosion processes, the author assigned different weights to the factors. Weighting was done by paired comparison (Matrice de Staay).
Two scenarios were proposed:

- The first scenario increased the influence of rainfall by assigning it the same weight as for slope, which meant that those two factors alone accounted for more than 50% of weighting :

INFORMATION LAYER	WEIGHT
Slope	0.2644
Rainfall	**0.2644**
Profile curvature	0.0486
Horizontal curvature	0.0486
Cumulative drained surface area	0.1152
Geology	0.1152
Plant cover and land usage	0.1152
Dirt roads	0.0284

The layers were combined using the WLC (weighted linear combination) technique, which allows erosion hazard values from 52 (low level hazard) to 202 (high-level hazard).
The author emphasised the important role rainfall played in the results, however the data used were too "smooth" to distinctly mark out those zones subject to the influence of the climate, which demonstrates the need for more precise weather data.

- In the second scenario, the author gave a lower weight to rainfall:

INFORMATION LAYER	WEIGHT
Slope	0.3204
Rainfall	**0.1359**
Profile curvature	0.0525
Horizontal curvature	0.0525
Cumulative drained surface area	0.1359
Geology	0.1359
Plant cover and land usage	0.1359
Dirt roads	0.0289

After the model was applied, hazard values were situated between 67 (low-level hazard) and 202 (high-level hazard). The resulting map was very close to that for Scenario 1.

Subtracting the results of the two scenarios gave differences that were low overall and appeared mainly in mountain ranges, which indicates places where heavy rainfall overrides all the other erosion factors. The author pointed out that more accurate weather data were needed to be able to really differentiate these zones. In fact, there is currently no simple solution to the problem of locating rain zones in mountainous regions, particularly in terms of intensity. All the operations designed to respond to this problem require a large investment in both resources and time, which is not possible as part of CRISP.

Validation was carried out by comparing the results of the “erosion hazard” model with the inventory of sites damaged by mining. A strong correlation was seen. This validation stage could be extended to other damaged zones outside mining areas.

The author also tried to assess the model by introducing layers with sharper spatial resolutions (land cover map by processing a SPOT5 image at 10 m, DTM at 10 m) in a limited geographic zone (two watersheds). This did not result in any significant differences from the previous model overall. The author explained this by the fact that certain layers which play important roles in erosion processes, such as geology, could not be improved. The author concluded that it was not vital to have sharp resolutions for certain layers and that it was important to ensure a certain level of consistency between the precision of each type of data.

A second method (statistical) of calculating the erosion hazard was used and consisted of carrying out a linear regression between field observations to determine a given hazard level and erosion factors. The results were similar to those from the first model but they were not totally identical as the statistical method gave more importance (higher weighting factor) to the climate component (rainfall).

In comparing the two methods used, multi-criteria modelling was based on expert opinion, certain interactions between erosion parameters could have been omitted, while statistical modelling was based on ground truths using the map the DIMENC provided, giving the locations of heavily eroded zones (damaged by mining). These ground truths did not cover natural erosion.

The author proposed a combination of the two methods for future studies.

3. Fiji Watersheds at Risk. Watershed Assessment for Healthy Reefs and Fisheries, (Atherton et al., 2005)

As compared to the two studies above, this one dealt with several clearly defined functional units, i.e. islands of more than one sq km and their watersheds. Small coastal watersheds were grouped according to their common influence along the same coastline. Although the study worked on watersheds and so, on objective hydrologic units, it was still qualitative in terms of predicting relative erosion. It did, at least, make it possible to compare watersheds to each other without claiming to provide estimates of coastal sediment inputs from rivers.

This study involved modelling and mapping watersheds in Fiji by taking into account the impact on marine habitat, particularly coral reefs, through a study of erosion in watersheds, the origin of inputs along the coast, and a study of man-made development. This work provided the first database on watersheds in Fiji, including secondary and the smallest watersheds.

The authors concentrated their work on determining soil erosion and runoff in Fijian watersheds.
In order to determine the watersheds’ boundaries, a 25 m DTM, a hydrographical network and a topographic map with 20m isograms were used. Islands with surface areas of less than 100 ha were not included.

The authors defined a “Relative Erosion Prediction” index that represented a relative measure for predicting soil erosion. It was this qualitative index that made it possible to compare watersheds.
The model formulated by Atherton et al., (2005) is based on five main environmental factors for erosion, i.e. slope, land cover, total rainfall, rainfall seasonality and soil erodibility.

They developed a simplified model from the reference USLE model described below:

Relative Erosion Prediction (REP) = slope factor + soil factor + rainfall intensity rainfall seasonality factor + land cover factor.

This model, which was strongly inspired by the methodologies of Watling (1994) and Bryant et al. (1998), made it possible to refine the work by integrating new land cover data.

A geographic database representing the five environmental factors was produced. The GIS layers were combined to get statistical indexes for each watershed, i.e. mean REP and total REP.

The model with data on all five factors was only used on the island of Viti Levu, while on the islands of Vanua Levu and Taveuni data on just three factors (slope, rain intensity and land cover) were used. The model was not used on any other island due to a lack of data, particularly slope and rainfall data.

Another index was developed during this study, i.e. the WDI (Watershed Development Index), that shows the impact infrastructures have on watersheds. The parameters used to determine this index were road density, the number of creeks that cross the road per sq km and deforestation (or the degree of deforestation).
By combining these parameters, they were able to get the WDI for each watershed.

The REP and WDI were combined to get the CTI (Composite Threat Index) showing the “risk” of erosion in the watershed. This approach to demonstrating the impact of infrastructures on each watershed is undoubtedly the most innovative part of this work. This method has the advantage of being easy to implement using standard tools. In that regard, it should be selected, with a few adaptations, to be used throughout the area covered by CRISP. An attempt could be made to combine it with the “dirt road” factor of the previous study.

This study made it possible to identify critical watersheds, those that need to be reforested and should benefit from land conservation measures. Most of the critical watersheds were located on Viti Levu, and only two were found on Taveuni.

The authors pointed out the need for field data on erosion so as to test and calibrate their model. And that it was important to continue the work on quantifying the impact that watershed damage has on adjacent reefs, precisely watersheds with a high CTI.

The authors recommended further studies:

- quantification of river flow and discharge rates in watersheds,
- collection of data on slopes, soils, rainfall intensity, rainfall seasonality and land cover on the outer islands,
- assessment of coral reef mortality from riverine sediment and other pollutants,
- assessment and mapping of reef habitats,
- quantification of soil erosion impacts from infrastructural developments,
- analysis of satellite imagery to study sediment plumes from watersheds after heavy rainfall events.

These recommendations clearly show that the authors wanted to develop their qualitative model into a more calibrated physical model validated by experimental data.

4. Spatial distribution of extreme rainfall and mapping “soil erosion” hazards in watersheds upstream from the Saint Gilles Lagoon (Reunion Island), (Batti 2005)

Batti (2005) was interested in mapping soil erosion hazards in watersheds upstream from the St Gilles Lagoon on the north-west coast of Reunion Island, a lagoon characterised by the island’s largest reef system.
In this study, the soil erosion hazard was defined as the probability that the erosion process would occur, i.e. the probability that solid particles would be washed off and transported (not to be confused with the erosion hazard).

This study was based on the premise that the climate factor is a major cause of erosion on Reunion Island, particularly extreme rainfall events. So, most of the work concentrated on studying the spatial distribution of extreme rainfall events and integrating them into a cognitive model to map soil erosion hazards.

The data used for the study were:

- hourly rainfall figures at 17 stations, with the time lengths for recording rainfall that varied from 2 to 10 years,
- DTM with a 10m resolution,
- 1 :50 000 geologic map,
- 1 :50 000 morpho-pedologic map,
- land cover map extracted by processing a SPOT 5 image with a 2.5 m resolution.

The first part of the work, which was carried in several stages, concentrated on identifying the spatial distribution of extreme rainfall events:

- Analysis of weather data,
- Specific characterisation of extreme intensity distributions. The stochastic approach selected was based on determining Intensity-Duration-Frequency (I-D-F). The distribution rule used was the Gumbel distribution normally used to describe extreme values. The rain gradex, a Gumbel distribution parameter, was chosen to represent the variability of extreme rain events in space and time. It was calculated for all rainfall stations,
- Spatial distribution of the rain gradex, carried out according to the AURELHY method (Benichou and Le Breton, 1987), which takes into account landforms to determine the spatial distribution of rainfall zones, and the work of Wotling (2000), which based itself on the previous method in order to regionalise extreme rain events on Tahiti (context similar to Reunion Island). This involved first characterising the topographic environment of the study zone by using the main landform components and then correlating landforms with the rainfall variable, in this instance the gradex, to then determine, by means of a multiple linear regression (between the main landform components and the gradex), the spatial variability of the gradex.

In the second part of the work, the author applied a qualitative model to map the soil erosion hazard. The methodology applied was the IFEN/ INRA method developed by Le Bissonnais et al. (1998). It takes into account a certain number of factors, which, through their interaction, affect the erosion process. These factors are: soil, land cover, topography and climate. In order to characterise these factors, a certain number of parameters were considered:

- **Land cover** (data already provided and extracted from processing done on a SPOT image with a 2.5 m resolution).
- **Soil runoff potential,** extracted from morphopedological data. Due to a lack of physical data on soils, this parameter replaced raindrop impact force.
- **Topographic index** (Combined Runoff Erosivity Index), extracted from the DTM. This index combines slope and drained surface area.
- **Soil erodibility**, extracted from morphological and geological data.

- **Climate factor** was represented by the rainfall gradex.

A decision tree – based on expert opinion – inspired by the IFEN/INRA method made it possible to combine the first four parameters to determine the land's potential susceptibility to erosion. Then, using a decision tree to combine susceptibility and rain aggressiveness (Gradex), the author was able to determine the soil erosion hazard.

5. Conclusion

The advantage of these qualitative approaches is that they provide spatially distributed information that can be used as a support for decision-making by allowing rapid localisation of zones or watersheds at risk that should be given priority in terms of management and protection. These methods allow simulations to be made on the influence that climate change or land cover have on erosion but they do not provide any indication of the quantity of solid materials that might be carried into the lagoons and affect marine habitat.

However, the classifications made on the parameters used to determine the degree of their contribution to erosion are empirical and are rarely based on physical approaches. Introducing a physical formula to describe each parameter would provide a better estimate of their influence and their contribution to erosion processes.

II – Quantitative Approach

1. Insular Scale Hydrologic Response: Kaho'olawe, Hawaii, (Wahlstrom, et al., 1999)

According to the authors, erosion on the island of Kaho'olawe is mainly caused by overgrazing and military activities.
They based themselves on the highest rainfall events in order to carry out a numerical simulation of the hydrologic response. An event template KINEROS – a physically based model for predicting runoff and sediments over the timescale of a rainfall event – was applied in a GIS to get a quantitative estimate of infiltration, Hortonian runoff and erosion (the great depth of the water table and the low "saturated hydraulic conductivity: Ks" led the authors to consider that the dominant runoff is Hortonian).

The model used was based on three algorithms:
- an infiltration algorithm,
- a runoff algorithm,
- a sediment transport algorithm.

1.1 Infiltration

The description of infiltration was based Smith and Parlange's equation (1978), from Richards' equations. The soil's hydric characteristics are needed to carry out this equation:

$$i = ks.\frac{\exp\left(\frac{I}{B}\right)}{\exp\left(\frac{I}{B}\right)-1} \quad \text{and} \quad B = G(\theta s - \theta i)$$

where:
i: infiltration capacity (L.T^{-1}),
Ks: saturated hydraulic conductivity,
I: total quantity of infiltrated rain,
G: net capillary flow,
θs : porosity,
θi : stock (initial soil water content).

1.2 Runoff

The authors considered that runoff is generated when the rainfall rate is higher than the infiltration rate (Horton mechanism).
A simplified runoff equation was used, as they considered that runoff occurs on a flat surface. Flow was modelled as runoff in a single-dimension sheet:

$$\frac{\partial h}{\partial t} + \alpha m h^{m-1} \frac{\partial h}{\partial t} = q(x,t))$$

where:
h: runoff layer depth,
α and m: constants linked to slope, hydraulic roughness and the Reynolds number.
By applying the Manning equation we get:

$$\alpha = \frac{1.49 s^{0.5}}{n}, \; m = \frac{5}{3}$$

s: water line slope,
n: manning rugosity coefficient.

A numeric resolution of this equation was carried out using the finite differences method for each step of the chosen rainfall event.

Sediments were led towards a waterway (channel); the flow rate equation for the channel was as follows:

$$\frac{\partial A}{\partial t} + \frac{dA}{dQ}\frac{\partial Q}{\partial x} = q(x,t)$$

Where:
Q: the flow rate by unit of length (L^{2}T^{-1}),
A: the wet section of the channel (L^2).

The flow rate in the channel was modelled numerically, in the same way as flow rate on a flat surface.

1.3 Sediment transport

The sediment transport equation used made it possible to determine the net mass of sediment carried away at a given moment for each component of the watershed.

$$C_{mx} = \frac{0.05 u . u_*^{\;3}}{g^2 dh (S_s - 1)^2}$$

C_{mx} : maximum sediment concentration,
u : flow speed,
u_* : shear rate (friction velocity),
d: sediment diameter,
h: water level,
S_s : specific gravity of the sediment.

1.4 Applying the model

First, infiltration was calculated for each step in time and distributed spatially throughout the watershed in order to get the net rainfall.

To simulate runoff, the watershed was subdivided into smaller watersheds, with each smaller shed made up of a whole series of lateral runoff levels, each of which poured into a single channel. Each level was characterised by a single slope and a single slope length.
The soil's hydrologic parameters, e.g. ks, sorptivity S, were estimated by spatially distributed one-off measurements using geostatistical methods (ordinary Kriging of 135 measurements across the island). The sorptivity made it possible to estimate net capillary flow G, data that was unavailable.

The land cover was extracted from a Landsat image and represented plant density. The authors chose three categories based on the NDVI values.

The rain/flow rate simulation was coupled with the erosion simulation in order to estimate the spatial distribution of the erosion due to Hortonian flow. The simulation was carried out on three rainfall events that differed in their maximum intensities and overall durations and for four “ ks “ distribution scenarios. In this way, they got the spatial distribution of flows and the quantity of sediment displaced in each scenario and for each rainfall event.

A susceptibility analysis was carried out to characterise the impact that uncertainty about the soil's hydraulic properties and about rainfall data has on simulated runoff.

2. Conclusion

This article was analysed as it illustrates an approach to physically modelling flow and transfers applied to an entire 117 sq km island made up of 81 watersheds. In comparison to the expert opinion approach, it makes it possible to explicitly know the authors' simplifying assumptions, something which is rarely the case with quantitative approaches.
The model is also useful because it operates at the rainfall event scale with the resulting sediment erosion. It is at this scale that erosion processes can be understood. It is certainly not possible to use such a complex method requiring such a wide range of data (135 hydraulic conductivity and sorptivity measurements). But it does highlight the weaknesses and risks of purely spatial GIS approaches.

III – Comparative study

Factors Work	Land cover	Landforms	Soil	Climate	Modelling	Results
Dumas (2005), New Caledonia	Extracted from remote sensing data processing	Slope	Nature of substrate **>** Soil erodibility	Not taken into consideration	Cognitive Multi-criteria analysis	Map of soil susceptibility to erosion Susceptibility indicators by watershed
Luneau (2006), New Caledonia	Processed data from Landsat 7 (30 m), Spot (20 m) vegetation layer from 1998 – 2004 topographical database at 1 :10 000, unsealed roads. > degree of protection from plant cover.	DTM 30 m > slope, horizontal curvature, profile curvature, drained surface area.	1 :50 000 geologic map > soil erodibility index	Mean annual rainfall (1991 - 2000 AURELHY model), 3 km point grid > interpolation by ordinary Kriging > rainfall map	- Multi-criteria model - Mathematical model: linear regression	Erosion hazard map
Atherton et al. (2005), Fiji	Land cover map provided by Fiji Forest Department for most of the islands.	DTM at 25 m, hydrographic network, topographical map with isograms at 20 m > slope factor	Soil map by SOPAC Soil erodibility	Total rainfall and seasonal rainfall > Rain erosivity > two factors: Intensity factor (R factor of USLE) Seasonality factor	cognitive	Indexes : Relative Erosion Prediction / Watershed; Watershed Development Index / Watershed
Batti (2005), Reunion Island	SPOT 5 image (2.5 m) > land cover map	DTM 10m > slope, drained surface area > Topographical index (Combined Runoff Erosivity Index)	1 :50 000 geological map, 1 :50 000 morphopedological map > Soil runoff potential > Soil erodibility	-Hourly rainfall measurements at 17 sites. > spatial distribution of extreme rainfall events based on landforms (using DTM, resolution retrograded to 200 m)	Cognitive Multi-criteria analyse using an “expert opinion” decision tree	Erosion hazard map
Wahlstrom et al. (1999), Hawaii	Landsat Image > NDVI > 3 cover categories	DTM > slope and length of slope for each flow level	Physical characteristics of the soil > spatial distribution	Three rainfall events according to duration and intensity	KINROS model (Quantitative) simulation by rainfall event	-Spatial distribution by flow sheet on watersheds -Spatial distribution of sediment weathering -Quantification of total erosion

Work	Strengths	Weaknesses	Recommendations	Validation or attempts to validate
Dumas (2005), New Caledonia	Applied on a global scale and then on a local scale. Indicator for each watershed (correlation with marine unit susceptibility).	More in-depth analysis would be needed to justify the homogeneity of heavy rainfall in space. Empirical classification of the parameters	Correlate erosion indicators on watersheds with the marine units' degree of confinement.	None
Luneau (2006), New Caledonia	Took into account vertical and horizontal convexities. Comparison with a mathematical model.	Empirical standardisation not based on physical approaches. Correlation of mean water depths with rainfall event intensity: more in-depth analysis needed. Imprecise climate data	Combine cognitive and mathematical modelling.	Comparison of the model's results with the inventory of sites damaged by mining, but not those from natural erosion.
Atherton et al. (2005), Fiji	Definition of an "REP" index that allows comparison of erosion between watersheds. Introduction of rainfall seasonality. Introduction of a WDI index (degree of impact infrastructures have on watersheds)	Empirical classification of parameters.	Need field data on erosion. Quantify outflow rates. Collect data (soil, slope, rainfall and land cover). Quantify the impact on the reefs adjacent to watersheds. Quantify the impact of infrastructures. Evaluate, by remote sensing, the plume of turbid water following heavy rains.	None
Batti (2005), Reunion Island	Extreme rainfall map. Used landforms for spatial distribution of rainfall zones. Cognitive model already validated at other sites (in France).	Empirical classification of parameters. Model not validated in a tropical context	Integrate raindrop impact force parameter. Take into account the influence of urbanisation and the increase in impermeable surface areas.	None
Wahlstrom et al. (1999), Hawaii	Physically based model. Susceptibility study.	Need for a comprehensive database.	Use remote sensing to get information on certain physical parameters.	None

IV – Erosion mechanisms (HENENSAL, 1986)

“External erosion of soil by water: Quantitative approach and mechanisms”

We decided to include this very comprehensive overall study as it provides a framework for all the approaches studied above and should serve as a reference for future work.

In this document, the author concentrates more specifically on the quantitative aspect of rainwater erosion and the mechanisms of external erosion from moving water. He presented the work of certain authors and their sometimes different points of view on the influence of specific erosion parameters. We looked at erosion factors, the quantitative approach and the concept of erosivity and erosion mechanisms according to Henensal.

According to the author, the most important parameters are rainfall and landform along with land cover. The author noted the figures from Golubev’s work (1983), which estimated that erosion is 10 times higher on cultivated lands than on pasture and 100 times higher than erosion in forests, along with the work of Morgan, who indicated that a decrease of 30% in forest brings about a five-fold increase in erosion.
These figures can be used to standardise the land cover factor (cf., Part V).

1. Rainwater erosion factors

Henensal summarised rainwater erosion factors as:

- erosion agents,
- intrinsic soil resistance factors,
- erosive action adjustment factors.

- **Rainwater erosion agents and the concept of erosivity**

Rainwater erosion agents are:

- the force of raindrops striking the ground,
- possible runoff of some of the rainwater on the ground.

Henensal defined rain erosivity R over a certain period and the corresponding runoff as the potential power of this rainwater or runoff has to bring about soil erosion over that same period. The R calculation uses the kinetic energy of rain.

- **Soil resistance factors and the concept of erodibility**

The factors involve three large sets of parameters:

- structural parameters: clumping, fissures, porosity, soil density, water content, permeability,
- texture parameters: particle size, plasticity,
- physical-chemical parameters: clay content, ion richness of water in the soil.

- **Erosive action adjustment factors**

The author set out two large sets of parameters:

- topographic factors (L: slope length, S: slope),
- protection factor:
  - ❖ C: nature and percentage of plant cover,
  - ❖ P: represents the way in which the earth is farmed, e.g. the direction of tilling in relation to the slope; treatments and pesticides used.

2. Quantitative approach to erodibility and erosivity

- **Wishmeier's Universal Soil Loss Equation**

Research on soil erodibility is carried out on experimental strips. After several trials by different authors, Wishmeier (1959) managed to formulate a universal soil loss equation (USLE).
The USLE's principle is to compare erosion from any site to erosion on a fallow farm control site that is 22 m long and has a 5° slope (9%).
Wishmeier's equation is written as follows:

$$E = R.K.L.S.C.P$$

E: soil loss by unit of surface area over a given T (same unit as K),

R: number of units characterising rainwater erosivity during T,
K: soil erodibility: soil loss by surface area unit and by observed erosivity unit on land that has given intrinsic characteristics in the following conditions: 22 m long strip, 9% slope and it is worked fallow (periodically tilled),

L: slope length factor: ratio of the observed slope on the study plot to the slope if the plot was 22 m long,

S: slope gradient factor: ratio of the observed slope on the study plot to the slope if the plot had a slope of 9%,

C: plant cover factor: ratio of soil loss observed on a study plot with a given plant cover to the loss if the ground was bare and kept in worked fallow,

P: anti-erosion cropping technique factor: ratio of observed soil loss on a study plot tilled mechanically in a certain manner and protected against erosion in a certain way to the loss if the land was worked more frequently in the direction of the highest slope.

LS and CP are determined with nomograms proposed by Wishmeier and Smith for organic farmland with slopes of less than 20%, then by Israelsen et al. for uncultivated land with steep slopes (>20%).

Calculating erosivity R

Rainwater energy **W** is directly linked to its intensity **I**. According to Wishmeier and Smith:

$$W = 13.32 + 9.78\log_{10}(I)$$

With a maximum for I of 80 mm/h (above that intensity, raindrop size does not continue to increase),

I in mm/h,
W: kinetic energy in J/m²/mm^{-1} for each series of rainfall.

For **tropical rainfall,** Hudson gave the following formula for kinetic energy:

$$W = 29.8 - \left(\frac{127.5}{I}\right)$$

The total kinetic energy of a storm is equal to the sum of the energies of the rainfalls in each series.

Wishmeier and Smith (1960) simplified the overall expression; they eliminated light rainfall; i.e. rainfall events of less than 12.7 mm and separated by more than 6 hours, on the condition that no more than 6.3 mm fall in 15 minutes.
Under those conditions, erosivity R is shown as:

$$R = W_{tot}.I_{30}$$

W_{tot}: total kinetic energy.

For Wuillaume (1969), in tropical zones, it is the rainwater during the first 20 minutes of the shower that best represents rainwater erosivity, because it is during that period that the ground becomes saturated and maximum intensity occurs.

In tropical climates, Hudson (1959) proposed eliminating from the calculations all rainfall or series of rainfall whose intensity is less than 25 mm/h.

For Wishmeier, the sum of the heavy rain values for a given period is the numerical measurement of the rainwater's erosive potential during that period. The total annual mean of the **W.I** values of heavy rainfall in a locality is the erosivity index for rainfall in that locality.

3. Mechanisms of external erosion from moving water

- **Raindrop impact force/soil capping**

Depending on the amount of kinetic energy and soil characteristics (grain size, structure, density, water content), you can see that:

- when a raindrop strikes the ground, it breaks into smaller drops that splash back up;
- some or all of the soil particles at the point of impact are pulled up and projected a certain distance away, either inside the smaller raindrops or separately;
- there is a certain amount of compacting of the ground surface, at least above the altered film on the surface.

Depending on the soil's texture and physical and chemical composition, this pounding action can completely destroy the soil's original structure. "Soil caps" can form, which makes the ground much less permeable and increases runoff and erosion.

The impact of raindrops changes depending on the sheet of water already on the ground. On thin sheets of water, the drops cause turbulence that increase particle separation; the deeper the sheet of water, the less impact raindrops have.

Other parameters must be taken into consideration: Slope has an effect by decreasing the normal raindrop impact force component. Raindrop impact forces on inclined surfaces differ widely depending on whether the surface is "windward" or "leeward".

- **Capillary action (slaking, dispersion, swelling)**

When water enters non-saturated ground, it can compress air in the pores. Three stages are then seen:

- air is trapped in the agglomerates;
- the air is compressed;
- the agglomerates split apart when the air pressure is greater than their mechanical strength.

- **Suddenly inundated ground tends to: slake** *(fall apart and lose the shape the soil had in open air)* **– disperse - swell up - is no longer affected by petrifaction.**

If the ground slakes, dispersion can be high, with fairly vigorous disintegration that takes the forms of fragmentation into mini-agglomerates or fairly small aggregates. In certain cases with clay or sandy soils, these units can become very small.
If the ground does not slake, it may swell.
By destroying the initial structures in all or in part, these behaviours diminish the soil's cohesion and mechanical strength in varying degrees and prepare the ground, in different ways, for erosion forces such as stripping and transport.

- **Dynamics of rain– infiltration – runoff relations**

The factors that influence distribution of water between runoff and infiltration are: ground permeability, rainfall intensity and land slope.

- ***Instantaneous infiltration capacity***

I_i: instantaneous rainfall intensity (mm/h),
f: instantaneous infiltration capacity (or infiltration rate) in mm/h.

Where $I_i < f$, infiltration is complete and there is no runoff.
Where $I_i > f$, between the ground surface and the saturation front, the ground is waterlogged. There is runoff and temporary surface storage of water in small depressions in the surface. There is only partial or no infiltration of rainwater. Runoff may bring about transport of particles detached by the force of the raindrops' impact.

- ***Changes in infiltration values at one point over time***

Over time, infiltration gradually decreases until it reaches a constant value, which is sometimes zero. The time required to reach this minimum value varies from a few minutes to a few hours depending on rainfall and ground permeability.

In trial conditions, according to Quibel et al. (1979), the cumulative depth h of the quantities of infiltrated rainwater over a time t can be expressed as:

$$h = a\sqrt{t} + b$$

a and b : constants for given trial conditions (soil, density, initial moisture profile).

In 1939, Horton proposed:

$$f = fc + (f0 + fc)e^{-Nt}$$

fc = constant infiltration rate (obtained at a specified time period after the rain),
f0 = infiltration rate at the beginning of rainfall,
N = constant (depends on the type of soil and vegetation).

There are four phases:

1- soil absorption phase (**$I_i < f$**) or else Phase 2,
2- transition phase with increasing runoff,
3- steady state: maximum constant runoff, infiltration = **fc**,
4- when the rain stops, a relatively short draining phase.

In other cases, **fc** clearly depends on rainfall intensity and ground slope.
Infiltration also depends on the shape of the hyetograph [cf. Henensel's analysis of Nassif and Wilson's work (1976)].

- **Topography's role in erosion**

Erosion depends on certain geometric characteristics (gradient and shape of slope, length of the steepest slope line).

- Slope inclination: the greater the slope, the higher erosion will be. Certain authors consider that erosion E by surface area unit is proportional to the m^{th} power of slope P in %:

$$E = \lambda . P^m$$

According to Hudson and Jackson (1959), for tropical rainfall, m = 2.

- Role of slope shape: according to experiments by D'Souza and Morgan (1976), differences in soil loss between flat convex or concave shapes becomes significant at 10% slope. Above that, erosion is higher on convex slopes than it is on concave slopes. <u>The increase is linear</u>.
- Role of slope length L: The role of slope length is controversial, certain authors admit that erosion increases with the length of the slope. In fact, longer slopes allow higher accumulation of runoff. These authors link L to erosion with a power function:

$$E = \lambda . L^n$$

The values of n vary from one author to the next (Cf. Henensal's work).
Other authors contest this theory.

Wishmeier proposed a topographic factor L.S that combines slope and its length. Calculations can be done using a nomogram.

- **Role of rills in erosion**

Fairly deep rills form after a certain number of erosive rainfalls. Henensal thought that the quantities eroded by a rainfall with a given erosive power are greater on ground covered by rills than on an initially smooth surface. Rills do, in fact, concentrate the energy of runoff.

- **Runoff hydraulics and critical erosion speeds**

In this part, Henensal described runoff processes and concludes by noting the importance of raindrop impact force and rainwater runoff, which is vital for transporting detached particles. He noted the importance of rapidly moving concentrated runoff as compared to simple runoff. Henensal presented the work of Hjulström, who had produced a diagram to make it possible to use runoff speed and particle size to determine the weathering, transport and deposit processes for such solid particles. This diagram alone is not enough to determine the erosive nature of runoff and the turbulent nature of runoff also has to taken into consideration. Henensal also described the concept of soil shear strength.

Henensal concluded by highlighting the need to define lab tests and then erodibility criteria that correspond to the real mechanisms soils are subjected to. This would make it possible to classify soils according to their erodibility.

V – Methodology proposals

All the above studies agree on the same erosion factors:

1- Climate factor
2- Topography factor

3- Land cover factor
4- Soil or substratum erodibility factor

However, their formulas and parameters differ so much that one might question the relevance of their results. We think that the way to express these factors and to translate them into parameters requires thought and thoroughness particularly as we are contractually (expected to design) a simple robust model that can be adapted to all Pacific island contexts, which is far from a trivial matter.

Following this comparative study, we propose a qualitative approach but one that is based on the physical process itself and adopts a physical formula that links erosion parameters.
We should point out that what interest us is surface water erosion, i.e. diffuse erosion in sheets and minor forms of linear erosion.

1. Characterising erosion factors

1.1 Climate factor

We propose brainstorming on the weather issue. Seasonal variations must be considered depending on the climate regime. Equatorial climates do not generally have dry seasons whereas in tropical settings, there are generally two seasons (dry and wet) without or without tropical storms.
The question that is raised with regards to the study settings is what type of rainfall generates erosion?

According to Henensal, it is the kinetic energy of the rain that weathers solid particles. This energy is directly linked to rainfall intensity. Kinetic energy depends on the drops' sizes and speed of fall. But the more intense rain is, the greater its size and speed. According to Zahar and Laborde (2001), annual, seasonal and even daily rainfall amounts alone cannot explain erosion since they tend to smooth out rainfall variables over time and, in this way, mask the erosive characteristics of showers. Hudson (1981) demonstrated this on a yearly scale at the Mazoe Research Station (Zimbabwe). He noted that there was no relationship between annual rainfall, erosion and runoff, whether in percentages or total amounts. So, rainfall intensity constitutes a more important erosion factor than rainfall amounts do.

Due to a lack of drop-size data, we propose that the heaviest-rain-intensity events be studied. So, at the very least, hourly rain gauge data will be needed.

Of the various attempts to formulate a rain erosivity index *R,* Wischmeier's (1959) seems today to be the most universal and the best known. This index takes into account the combined effect of the amount of rain, its intensity and duration. It is equal to the product of the kinetic energy by maximum 30 min intensity.
Without maximum 30 min intensity data, erosivity cannot be estimated using Wischmeier's formula. However, Hudson proposed, for tropical settings, a new formula that links kinetic energy **W** and hourly intensity **I**:

$$W = 29.8 - \left(\frac{127.5}{I} \right)$$

Hudson also proposed that all rainfall or all series of rainfall whose intensity was less than 25 mm/h be eliminated from the calculation; in those conditions he considered erosivity **R** to be equal to W.

Standardising the intensity parameter can be done by applying Hudson's formula, which, under the above-mentioned conditions, becomes:

$$R = 29.8 - \left(\frac{127.5}{I} \right)$$

Where, I ≥ 25 mm/h.

Studying intensity variability at thresholds higher than 25 mm/h means characterising the variability of extreme rainfall events in space and time. For this step, we can base ourselves on the work of Batti (2005), who used the HAURHELY method for spatial distribution of rainfall zones in an island context on Reunion Island.

1.2 Topographic factors

According to Henensal (1986), erosion "E" depends on the slope's gradient, and also on its shape and the length of the greatest slope line.
Using Luneau (2006) and Dumas' proposals, the topographic indexes to be calculated from the DTM would be:

- **slope:**
  The following relation between erosion and slope will be taken into consideration:

  $$E = \lambda . P^m$$

  Where m = 2 in tropical settings (according to Hudson and Jackson (1959).

  The important point to remember from this relation is that erosion is proportional to the mth power of the slope. This will be used to standardise the slope factor.

- **horizontal convexity and vertical convexity:** according to Henensal (1986), the erosion increase rate is relatively low for slopes of less than 10 %; for higher slopes, the increase for convexity is linear. Linear standardisation of these two factors could be applied. Concerning these two convexities, they are key elements that make it possible to describe the model shapes of watersheds and valleys and infer from them links with erosion processes. They are, in a certain manner, the "morphological signature" of a monostructural context exposed over the long-term to a hydroclimate system. We will come back to this concept of morphologic signature.

- **drained surface areas:** the drained surface area factor can be introduced to improve the slope factor (Batti, 2005) and, in this way, form the combined index for runoff erosivity.

1.3 Land cover factor

Classification can be based on the degree of land cover protection by using HR remote sensing images.
This will allow us to locate built and sealed zones and better define the structure of the tree layer, e.g. dense forest, sparse forest, savannah.
Calculating the NDVI (Atherton et al., 2005) could be an interesting indicator for estimating the degree of protection plant cover provides.

We will take into account Golubev (1983) and Morgan's (1979) observations to standardise the land cover parameter:

- Erosion on crop land is 10 times higher than that on pasture land.
- Erosion on crop land is 100 times higher than that in forests.
- A 30%decrease in forest brings about a five-fold increase in erosion.

Using these rules, we will be able to chart out the degree of protection provided by land cover.

The use of metric-resolution satellite data (HRI) as compared to standard decametric SPOT or LANDSAT type data must be discussed. Certain members of the team think that such data are vital insomuch as they would allow reasoning based not on groups of pixels but rather on landscapes composed of identifiable geographic objects directly relevant to erosion. We will use two examples to illustrate the value of a landscape interpretation of satellite images:

- For open plant formations (natural or somewhat eroded) going from clear forest to shrub steppe, the spatial structure and statistical distribution of the sizes of the crowns can reveal their stage of development with direct consequences on the properties of diffuse or other runoff in the watershed.
- For forms of gullying linked to linear erosion or the nature of channels and their banks, HRI directly provide tangible information on the processes (such as runoff in channels) and the processes (sic) (length and nature of the low-flow channel, characteristics and stability of banks that are somewhat stabilised by vegetation).

Here again, it would be unrealistic to claim that at this point in time we have a validated method and an operational tool to allow us to consider the HRI landscape approach to studying erosion as operational. This point will have to be discussed before a standard is defined in terms of remote sensing results for defining land cover.

1.4 Soil or substrate erodibility factor

With a view to uniform geologic and soil data and consistent nomenclature from different sources, depending on the islands to be studied, we propose a "morphologic signature" approach to characterising this factor, as mentioned above. The principle is to infer, as far as possible, petrography using the landform model, in practice from DTMs that absolutely must be consistent, e.g. SRTM. The method was tested in the Balkans (Depraetere and Riazanoff, 2004) and does not claim to be operational yet. Some simple tests were carried out on the main island of New Caledonia (identifying Ophiolite massifs with "pseudo-karstic" signatures), on Espiritu Santo (differentiating between the coral lime massifs on the eastern plateau and the cracked crystalline mountains in the west) and on Efate (strong contrast in models depending on the thickness of the coral layers). There is a case for trying to draw up simple rules to link the model to dominant water erosion processes.

Raindrop impact could be integrated if physical soil data are available.

2. Modelling erosion hazard

Modelling will be based on crossing the previously standardised factors (method already developed by Luneau 2006) in a GIS. Additional work is needed to define the weighting coefficients that determine each factor's importance in terms of erosion.

Bibliography

Atherton A., Olson D., Farley L. & Qauqau I. (2005). Fiji Watersheds at Risk. Watershed Assessment for Healthy Reefs and Fisheries. Final Report to the United States Department of State OESI Grant # SFJ600 04 GR 004.

Batti A. (2005). Spatialisation des pluies extrêmes et cartographie de l’aléa érosion des sols dans les bassins versants en amont du lagon St Gilles (île de la Réunion). Rapport Mastère SILAT – stage IRD – unité ESPACE, 55 p.

Benichou P., Le Breton O. (1987). Prise en compte automatique de la topographie pour la cartographie des champs pluviométriques statistiques. La Météorologie, 7ème série (19), pp. 23-34.

Bryant, D., Burke L., McManus J., and Spalding M. (1998). Reefs at risk. A map-based indicator of threats to the World’s coral reefs. WRI, ICLARM, WCMC and UNEP, New York.

Depraetere C., Riazanoff S. (2004). “The new Digital Elevation Model data set from the Shuttle Radar Topography Mission : Hydrogeomorphological applications in the Ohrid region (Albania, Greece and Macedonia)”, Systèmes d'observation et d'information sur l'eau pour l'aide à la décision BALWOIS, Ohrid, République de Macédoine, 25-29 Mai 2004.

Dumas P. (2004). Caractérisation des littoraux insulaires : approche géographique par télédétection et S.I.G. pour une gestion intégrée, Application en Nouvelle-Calédonie. Thèse de doctorat, Orléans, 402 p.

Golubev G.N. (1983). Economic activity, water resources and the environment: a challenge of hydrology. Hydrological Sciences – Journal des Sciences Hydrologiques 28(1): 3.

Henensal P. (1986). L’érosion externe des sols par l’eau. Approche quantitative et mécanismes. Rapport de recherches Laboratoire Central des Ponts et Chaussées N° 138.

Hudson N. (1981). Soil conservation, Batsford Academic and Educational Ltd London pp. 324.

Hudson N. W., Jackson D.C. (1959). Results achieved in the measurement of erosion and run-off in southern Rhodesia. Paper presented to the third Inter-Africain Soils Conference, Dalaba.

Le Bissonnais Y., Montier C., Daroussin J., King D. (1998). Cartographie de l’aléa «Erosion des sols » en France. Edition IFEN, Collection Etudes et Travaux n° 18, août 1998, 77 p.

Luneau G. (2006). La spatialisation de l’aléa EROSION DES SOLS en Nouvelle-Calédonie. Méthodologie définie sur les communes de Dumbéa, Païta, et Boulouparis. Rapport de stage Master 2 professionnel géométique. Université de Toulouse, 75 p.

Maurizot P., Delfau M. (1995). Cartographie de la sensibilité à l’érosion, Province Sud de Nouvelle-Calédonie, Rapport BRGM N° R38660, 72 planches.

Morgan R.P.C. (1979). Soil erosion, Longman, London, pp. 113.

Quibel A. Devars J.P. (1979). Compte rendu d'essais d'infiltration. Document interne au centre d'Expérimentation Routière du CETE de Rouen, Mars.

Smith R.E., Parlange J.Y. (1978). A parameter-efficient hydrologic infiltration model. Water Resources Research 14: 533-539.

Vuillaume G. (1969). Analyse quantitative du rôle du milieu physico-climatique sur le ruissellement et l'érosion en zone saheliènne. Cah. ORSTOM, series Hydrology 6: 87-132.

Wahlstrom E., Loague K., Kyriakidis P. (1999). Insular Scale Hydrologic Response: Kaho'olawe, Hawaii. Hydrologic response: Kaho'olawe, Hawaii. Journal of Environmental Quality 28: 481-492.

Watling, D. (1994). Determination of potential forest functions. Department of Forestry, Suva.

Wishmeier W.H. (1959). A rainfall erosion index for universal soil-loss equation, Soil Science Society of America Proceedings 23(3): 246-249.

Wishmeier W.H. et Smith D.D. (1960). A universal soil-loss equation to guide conservation from planning. 7th Intern. Congress of soil Sciences, Madison, Wisc; USA.

Woolhiser, D, A., R.E. Smith, and D.C. Goodrich. (1990). KINEROS, A kinematic runoff and erosion model : Documentation and user manual. USDA, ARS-77.

Wotling G., Bouvier Ch., Danloux J., Fritsh J.M. (2000). Regionalization of extreme precipitation distribution using the principal components of the topographical environment. Journal of Hydrology 233: 86-101.

Zahar Y., Laborde J-P (1998). Génération stochastique d'averses et de leurs index d'érosivité pour la simulation de la dynamique érosive en Tunisie centrale. Hydrological Sciences-Journal-des Sciences Hydrologiques, 46(2) avril.

Coral Reef InitiativeS for the Pacific
Initiatives Corail pour le Pacifique

COMPONENT 1A - Project 1A4

Overview of methods for modelling erosion in island settings

Summary

The aim of this report is to give an overview of the studies done on soil erosion in the mountain islands with tropical climate. This work does not claim to be exhaustive in this field. It refers to some recent case studies in the South Pacific and Indian Ocean in order to define future work fitting in the GERSA 1A4 project of the CRISP programme.

The main studies analysed are Dumas (2004) and Luneau (2006) in New Caledonia, Atherton et al. (2005) in Fiji, Batti (2005) in Reunion Island and finally Wahlstrom et al. (1999) in Hawaii. These studies are approached here on the more general frame of Henensal (1986) researches on the processes of erosion.

The objective is to try to integrate more physics into the definition of the environmental factors controlling the processes of erosion. Erosion is considered here as the set stemming from the triptych wrench / transport / sedimentation.

This approach and definition are a prerequisite to provide and ensure a discerning assessment of terrigenous contribution by the rivers in the lagoons of Pacific insular environments.