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# ASSESSING FOREST FUNCTIONALITY TO PROVIDE SERVICES RELATED TO WATER RESOURCE

## An innovative tool for South Pacific Island countries

FULL REPORT

This project, « Assessing forest functionality to provide services related to water resource: an innovative tool for South Pacific Island countries”,  submitted in response to the 2017 call for proposals by the World Bank Development Data Group (DECDG) and the Global Partnership for Sustainable Development Data (GPSDD), is supported by the World Bank’s Trust Fund for Statistical Capacity Building (TFSCB) with financing from the United Kingdom’s Department for International Development (DFID), the Government of Korea, and the Department of Foreign Affairs and Trade of Ireland.

In association with

## WWF

WWF is one of the very first independent environmental protection organizations in the world. With an active network in more than 100 countries and with the support of nearly 6 million members, WWF works to halt the degradation of the planet's natural environment and build a future where humans live in harmony with nature, conserving global biodiversity, ensuring sustainable use of renewable natural resources, and by promoting the reduction of pollution and waste. Since 1973, WWF France has been working on a daily basis to offer future generations a living planet. With its volunteers and the support of its 220,000 donors, WWF France is taking concrete action to save natural environments and their species, promote sustainable lifestyles, train decision-makers, support companies in reducing their ecological footprint, and educate young audiences. But for change to be acceptable, it can only happen through respect for everyone. That's why WWF's philosophy is based on dialogue and action.

## Together possible.

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**PROJECT PRESENTATION**

Funding and support

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Focus areas

Environment: Climate Change, Environment: Urban Resilience

SDGs target

*In 2015, the UN adopted 17 Sustainable Development Goals (SDGs), aiming to "protect the planet from degradation…so that it can support the needs of the present and future generations". Through the SDGs, the UN recognises that conservation directly supports human health and wellbeing by providing goods such as water and fibre, and global public goods such as habitats for species and mitigation of climate change. Although trade-offs can indeed arise between conservation and economic development, the Rockefeller Foundation–Lancet Commission on planetary health states unequivocally that "the environment has been the foundation of human flourishing", suggesting that if environmental degradation persists then ongoing improvements in human health are likely to be reversed.*

The SDGs targets on which the project focuses:

- **SDG 6 - Clear water & sanitation**

6.5 By 2030, implement integrated water resource management at all levels, including through transboundary cooperation as appropriate.

- **SDG 13 - Climate action,**

13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

- **SDG 15 - Life on land**

15.4 By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development.

**SUMMARY**

In early 2016, WWF launched a pilot study to assess the functioning levels of existing water collection protection zones in New Caledonia by defining a forest ecosystem function based on the loss of water-quality-related ecosystem services.

The project relied on existing data and offered a reliable methodology based on satellite imagery analysis to assess and monitor forest ecosystem function in water collection protection zones. Given existing data in the territory three indicators were likely to provide information on these criteria: erosion risk (soil stabilization ecosystem service), dominant landscape type (moisture-buffer ecosystem service), and forest fragmentation (ecosystem resilience = sustainability). A decision tree then allows the functioning levels to be characterised based on the concatenation of these three calculated indicators.

This project aims to scale-up the pilot phase by updating data sources and improving the process to create a fast and large-scale tool to deploy the methodology over South Pacific countries with similar concerns.

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**BLUECHAM SAS** – An innovative Caledonian company whose core business is to build new solutions to develop greater knowledge and understanding to help protect our planet. Internationally awarded, BLUECHAM SAS is a pioneer in Geospatial Cloud Computing, providing high value added products and systems from earth observation satellites and scientific models. It increases its expertise through R&D projects in cooperation with international space agencies. BLUECHAM's clients are therefore guaranteed of obtaining the best possible data quickly and at the lowest cost.

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# Acronyms

| | | | |
|---|---|---|---|
| AI | *Artificial Intelligence* | Intelligence artificielle | IA |
| DAI | *Descending-Ascending-Iterative* | Descendant-Ascendant-Itératif | DAI |
| DAVAR | *Direction of Veterinary, Food and Rural Affairs of New-Caledonia* | Direction des Affaires vétérinaires, alimentaires et rurales | DAVAR |
| DEM | *Digital Elevation Model* | Modèle numérique d'élévation | MNE |
| DGM | *Digital Ground Model* | Modèle numérique de terrain | MNT |
| DIMENC | *Direction of Industry, Mines and Energy of New-Caledonia* | Direction de l'Industrie, des Mines et de l'Energie de la Nouvelle-Calédonie | DIMENC |
| DITTT | *Direction of infrastructures, topography, and ground transportation* | Direction des infrastructures, de la topographie, et des transports terrestres | DITTT |
| DoWR | *Department of Water Resource (of Vanuatu)* | Département de la ressource en Eau (du Vanuatu) | DoWR |
| DTSI | *Direction of technology and informatic information services* | Direction des technologies et services de l'information informatiques | DTSI |
| EPIC | *Erosion/Productivity Impact Calculator* | *Erosion/Productivity Impact Calculator* | *EPIC* |
| GIE | *Economic interest group* | Groupement d'intérêt économique | GIE |
| GIS | *Geographic Information System* | *Système d'information géographique* | SIG |
| IGN | *National Institut for geographical and forest information* | Institut national de l'information géographique et forestière | IGN |
| IRD | *Institut for research and development* | Institut pour la recherche et le développement | IRD |
| IRSTEA | *National Institut in science and technology research for environment and agriculture* | Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture | IRSTEA |
| ISRIC | *International Soil Reference and Information Centre* | Centre international de l'information et de référence sur les sols | ISRIC |
| LCM | *Land-cover model* | Modèle d'occupation des sols | MOS |
| RUSLE | *Revised Universal Soil Loss Equation* | *Revised Universal Soil Loss Equation* | *RUSLE* |
| SDD | *Sustainable Development Goals* | Objectif de Développement Durable | ODD |
| SPC | *Pacific Community* | Communauté du Pacifique | CPS |
| SRTM | *Shuttle Radar Topography Mission* | *Shuttle Radar Topography Mission* | *SRTM* |
| UNC | *University of New-Caledonia* | *Université de Nouvelle-Calédonie* | UNC |
| WWF | *World Wide Fund for nature* | Fonds mondial pour la Nature | WWF |

# 1 STUDY BACKGROUND AND OBJECTIVES

## 1.1 Background and issues

Forests the world over play an essential role as a habitat for the many plants and animals they protect from human activity. In addition to its biodiversity impact, the loss of forest cover is leading to a loss of the ecosystem services enjoyed by communities. Other effects include increased surface run-off, erosion and greater flood damage, while lower infiltration reduces ground water in the dry season and sediment transported into watercourses damages water-supply facilities and diminishes water quality for communities and aquatic life.

This is why the local WWF France branch in New Caledonia, established in 2001, has chosen to highlight the issue and emphasise how urgent it is to protect and restore forests in the South Pacific region. These island groups are often remote and depend heavily on their own agricultural produce to meet their main food needs. The *Freshwater under Threat – Pacific Islands* (UNEP, 2011) report highlights, however, that, against a backdrop of climate change, the islands' dependence on natural rainfall would jeopardise the both their economies and basic subsistence resources. It cites water management as one of the greatest challenges for dealing with the resource's vulnerability. Climate models predict that extreme events like droughts and cyclones will increase and small island countries and territories will need to safeguard their water resources, as, being islands, they will be unable to resort to alternative supplies or solutions that rely on neighbouring countries' resources.

As such, the countries' development sustainability depends on maintaining or restoring forests upstream from drainage basins that provide these key services, but little has been done to monitor forest health in terms of this specific water-resource protection role and optimising management. Committing to do so, however, which can be costly and labour-intensive in terms of practices and management, needs to be based on a sound understanding of the issues and challenges by decision-makers and communities.

The project's objective is, therefore, to assess forest functionality in drainage basins upstream from abstraction points so as to provide information for use by decision-makers and managers to safeguard water resources through the "green infrastructure" provided by forests. The method that has been developed uses freely available geospatial data for producing affordable baseline studies and then setting up large-scale long-term monitoring. It also provides a clear indication of health status using colour coding to represent and rank the functionality of drainage basins and provide guidance for the priority management measures to be adopted.

## 1.2 Countries and territories examined

In New Caledonia, mining, fires and invasive animal and plant species have caused the territory's forests to retreat. The rainforests located on the country's central mountain range, some of which are affected by major use conflicts, do not benefit from protection measures in proportion to the biodiversity assets they contain and the services they render to communities.

In 2015, WWF France's New Caledonia office focused closely on the services provided by forests in terms of one essential resource: water. A diagnostic tool was developed in New Caledonia in collaboration with Bluecham, a company specialising in environmental information convergence technology and remote sensing, to assess forests' ability to provide water-resource-related services.

The project aimed at offering a methodology for assessing and monitoring forest health as a decision-making tool for guiding restoration and protection initiatives. The results were based on 2008 data and were particularly alarming, as 90% of drainage-basin surface areas were considered as impaired or heavily impaired. This sent a major shockwave through the media with associations, government departments and politicians alike taking genuine ownership of the issue. A knock-on effect was felt regionally in 2017 through INTEGRE support (co-ordinated by SPC) and interest from neighbouring Vanuatu, Wallis & Futuna and Fiji was generated by discussions. The project was also submitted to a World Bank Innovation Fund call for projects and awarded a prize in 2018. The study was then repeated based on updated data in New Caledonia, Vanuatu and Wallis & Futuna.

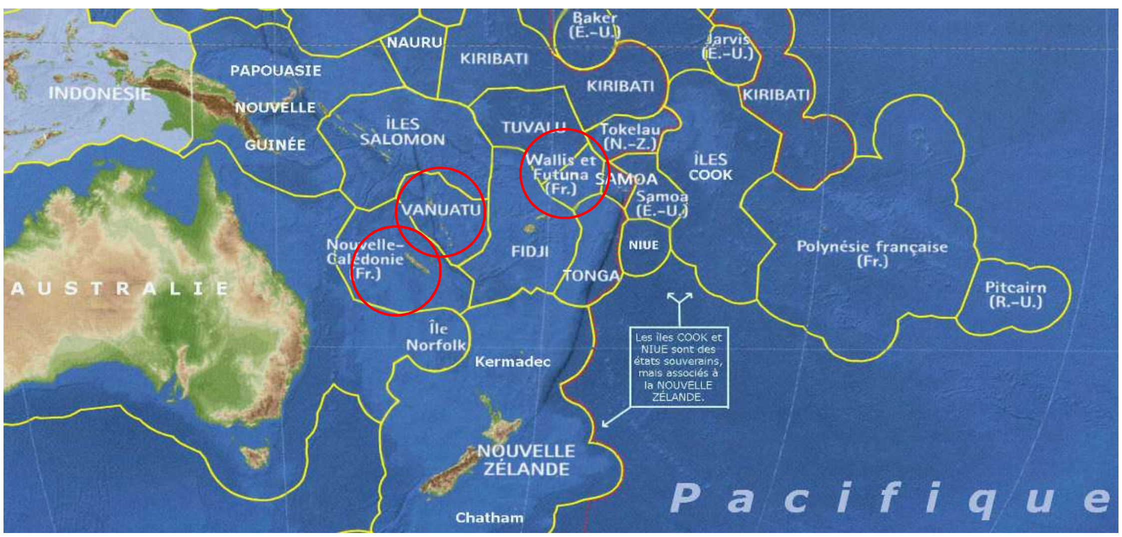


Figure 1 : Location of countries where the project was undertaken

## 1.3 Users and beneficiaries

The project aims at providing information to help guide drainage-basin management initiatives by defining which drainage basins require protective action and which need active restoration of forest landscapes in order to maintain or restore water resources. The target beneficiaries would therefore be:

- managers tasked with assuring water quality and availability for communities;
- public and private corporations managing drinking-water supply assets;
- public and private corporations and joint ventures operating in forestry or ecosystem conservation or restoration;
- all organisations tasked with mitigating natural disasters such as droughts, floods and landslides;
- all companies that depend on water resources for their operations, such as hydro-electricity generation, agriculture, food production and industrial refrigeration; and
- scientists, as the assessment provides large amounts of data on land cover, erosion hazards and forest distribution.

Phase one of the project, aimed at establishing an assessment methodology, was presented to various stakeholders. In New Caledonia, DAVAR (Department of Veterinary, Food and Rural Affairs) was included in the project from the outset. Multiple discussions and meetings were held to define the most appropriate scale for the study as well as the end use it would be put to, making DAVAR the perfect partner to facilitate the process of sharing the assessment with other stakeholders.
The project was then presented to neighbouring countries with SPC support. This process highlighted the interest shown by government departments in Wallis and Futuna, Vanuatu's Department of Water Resources (DoWR) and New Caledonia in the project.  They also expressed their support during the project development phase.

# 2 ASSESSMENT METHODOLOGY

## 2.1 Conceptual framework

### 2.1.1 Services provided by the forests

According to the Millennium Ecosystem Assessment, four types of ecosystem services can be identified (Millenium Ecosystem Assessment, 2003):

- provisioning services (e.g. food, drinking water, wood, fibre) for direct use by the human community;
- regulating services that help maintain an environment in a state where it is physically and biologically possible for human beings to live there (crop pollination, mitigating flooding, climate regulation, etc.);
- cultural services, which include recreational, aesthetic, intellectual and spiritual services;
- support services, which cover all the underlying processes of the ecosystem and provide the direct services mentioned above, including option values for future generations.

At present, no universal indicator can characterize the "health" or functionality of an ecosystem. Authors apply a set of indicators to measure different dimensions of the state of ecosystems (Maresca et al., 2011).

This study tends to characterize the functionality of forest ecosystems within watersheds in relation to the loss of ecosystem services associated with forest degradation. In fact, the degradation of forest ecosystems leads to a loss of associated ecosystem services, and therefore causes:

- a decrease in forest flora and fauna abundance and diversity (Brooks et al., 2002, Raherilalao 2001, Klein 1989, Laurance et al., 1998). Several references have shown that habitat loss has a greater impact on forest ecosystem biodiversity than fragmentation *per se* (Fahrig 2003, Hillers et al., 2008).
- a greater erosive risk, related to the loss of soil stabilization service (Brauman et al., 2007, Gyssels et al., 2005 and Keim and Skaugset 2003) causing, among other things, sediment pollution in rivers,
- a loss of service related to flood mitigation (Brookhuis 2016, Foley et al., 2007, Guillemette et al., 2005, Brauman et al., 2007, Bradshaw et al., 2007) and a loss of water availability service during periods of low water, which can lead to shortages (Brauman et al., 2007, Smakhtin 2001). These last two services (flood mitigation and maintenance of low water flow) can be grouped into a hydrological water buffering service.
- changes in local micro-climate (Laurance et al., 1998) or regional climate (Foley et al., 2007),
- a higher susceptibility to future degradation, particularly related to fires (Curt et al., 2015, Wade et al., 2003).

A loss of forest cover in drainage basins leads to a loss in ecosystem services, which in turn, *inter alia*, increases both sediment pollution in drainage basins and flood severity and reduces water availability in dry seasons. Apart from causing direct safety issues for property and the public, the cost attached to such dysfunctions can quickly escalate for local government authorities.

#### 2.1.2 Areas examined

Considering the important role played by forests in drainage-basin slopes channelling rainwater to one or more collection areas, the proposed approach was to define forest ecosystem functionality in terms of ecosystem service loss relating to water resources on all drainage basins upstream from abstraction points. As characterising functionality in terms of biodiversity is a complex task requiring an entirely separate study, the selected method focused on three criteria relating directly to ecosystem services, namely:

- soil-stabilisation ecosystem service loss;
- water-buffering ecosystem service loss; and
- fire-resilience ecosystem service loss.

These three criteria could be characterised based on three indicators: erosion hazard, landscape pattern and forest fragmentation. Each indicator was calculated for each drainage basin lying upstream from an identified water collection point.

### 2.2 Characterising the erosion hazard for each drainage basin

Forests play a threefold role in containing erosion. They reduce precipitation intensity, facilitate infiltration and stabilise soils with their root systems. When there is no forest cover, soils become more prone to rainfall aggressiveness, surface runoff and wind, with erosion increasing significantly.

The soil stabilisation service was therefore assessed by characterising each drainage basin's *erosion hazard* level.

#### 2.2.1 Method used to define hazard classes and threshold values

Thresholds were determined by assessing the statistical distribution of the various erosion levels on the New Caledonian potential soil-loss map produced with the RUSLE (Revised Universal Soil Loss Equation) model.

The RUSLE model is a means of empirically modelling soils for water erosion. Initially applied to establish erosion on farmland, it estimates overall soil detachment by water (rainfall and both sheet and concentrated run-off) on each grid square (pixel) in the model. Soil loss is expressed in t/ha/yr.

The RUSLE model considers five basic factors in soil erosion: rainfall aggressiveness, soil erodibility, slope gradient and length, plant cover and conservation practices. The map values express possible average long-term annual soil loss (t/ha/yr).

Sediment production is estimated as soil loss by water erosion according to the RUSLE model adapted to New Caledonia by the SEPSAT$^{TM}$ EROSION treatment chain.

In order to describe the erosion hazard for each drainage basin, the erosion hazard-factor was assessed based on the RUSLE model as estimated by 50 m x 50 m square grids. Following research by Le Bissonais *et al*. (2002) and Le Bissonnais *et al*. (2004), integration was carried out on the spatial-unit scale defined by the drainage basins using a decision rule incorporating the surface-area percentages of the hazard classes. The method required the following preliminary stages:

1. Defining which erosion-hazard class (low, moderate, high or extreme) each pixel belonged to based on the soil-loss value estimated by the RUSLE model.
    - This was achieved by analysing the statistical distribution of the soil-loss values produced by the RUSLE model supported by bibliographical references for similar environments as well as regional and global literature.
    - The outcome for this stage was a map showing four erosion-hazard classes for the whole territory based on the RUSLE model.
2. Defining the relative size of each erosion-hazard class so as to characterise the overall erosion-hazard class for each drainage basin.
    - The erosion-hazard class percentage was calculated for each drainage basin.
    - By statistically analysing the distribution of each erosion-hazard class for all the drainage basins examined, decision rules could be defined based on statistical thresholds in order to provide a synthetic representation of the erosion hazard in each geographical unit.

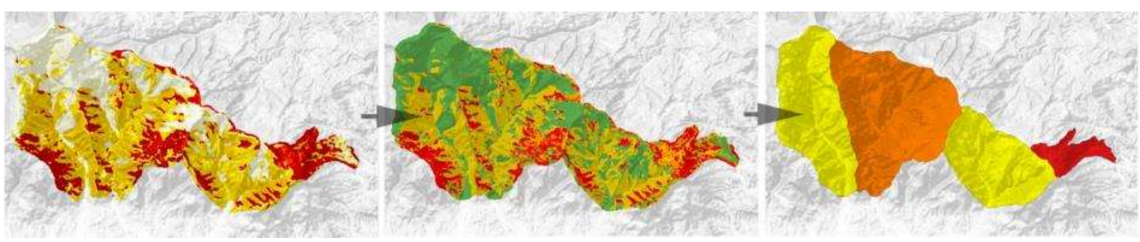

Figure 2: Erosion-hazard classification protocol by drainage basin (stage 2) based on the RUSLE model (left) obtained by determining hazard-class percentages (stage 1)

This method has the advantage of providing an overall erosion-hazard classification at working-unit level while factoring in the relative hazard intensity. It is therefore less prone to extreme values than average or median soil-loss estimates and better addresses high-hazard but less dominant areas of the landscape.

### 2.2.2 Defining erosion-hazard classes using RUSLE-model soil-loss values on mainland New Caledonia

This stage consisted of classifying the erosion hazard into four hazard classes (low, moderate, high and extreme) for each pixel based on the Tukey box-plot method using RUSLE-model soil-loss values.

#### *2.2.2.1 Analysis of the distribution of the soil-loss values produced by the RUSLE UNC model*

The Tukey boxes were created by statistical analysis of the distribution of soil loss values of the New-Caledonia University RUSLE model. These boxes characterize the variations of the sedimentary production values taken throughout New Caledonia around the central parameter that is the median. The interest of Tukey boxes for class discrimination of erosion values lies in the properties of this analysis being less sensitive to extreme values for the determination of median parameters and is adapted to the representation and identification of extreme asymmetrical distributions and presenting a very pronounced mode.

The analysis of the distribution as well as the construction of the Tukey box are carried out by taking into account all of the Grande Terre pixels of the RUSLE modeling produced by the UNC (terrestrial domain).

#### *2.2.2.2 Comparison with other RUSLE modelling work and defining erosion-hazard classification thresholds*

Dumas *et al*. (2010) consider values of 5 t/ha/yr to 30 t/ha/yr in New Caledonia as medium to high and mention measurements of 22 to 80 t/ha/yr on Fijian slopes with a 53 t/ha/yr average in the Waimanu drainage basin. These figures are considered particularly high, as they were obtained in forest areas. In French Polynesia, Dumas (2015) estimates that 85% of Tahiti Island has an erosion rate of less than or equal to 5 t/ha/yr. A mere 1% of the territory had values greater than 50 t/ha/yr.

In the wet tropical climate of Kerala, India, Prasannakumar *et al*. (2012) consider 0 to 1.5 t/ha/yr to be low erosion, 1.5 to 5 t/ha/yr moderate and greater than 5 t/ha/yr high.

In Madagascar, Payet, Dumas, and Pennober (2012) note soil loss of 0 to 1631 t/ha/yr and an average of 57 t/ha/yr in an East Coast drainage basin. Van Hulst (2011) reports average soil-erosion values of 194 to 1290 t/ha/yr in the Lake Alaotra mountain drainage basin.

Sadiki *et al*. (2004) found average erosion of 55.35 t/ha/yr in a drainage basin in Morocco's Rif Mountains ranging from a 0.09 t/ha/yr minimum to a 1159 t/ha/yr maximum. They classify erosion based on soil-loss tolerance figures used in the United States, which deem that, on average, soil can tolerate up to 7.41 t/ha/yr losses while continuing to produce high agricultural yields. Losses exceeding 20 t/ha/yr are high and deplete soil quality. Such an approach based on soil-loss tolerance could usefully be developed in the tropics and extended to soil fixation capacity.

In temperate regions, the Canadian ministry of agriculture defines erosion classes as follows:

| | |
|---|---|
| Very low (tolerable) | <6.7 t/ha/yr |
| Low | 6.7 –11.2 t/ha/yr |
| Moderate | 11.2 t/ha/yr – 22.4 t/ha/yr |
| High | 22.4 t/ha/yr –33.6 t/ha/yr |
| Severe | >33.6 t/ha/yr |

Table 1: Erosion-hazard classes as per the Canadian Ministry of Agriculture.

2iE & AUF also provide orders of magnitude for classifying soil loss in terms of eroded landscape:

| | | |
|---|---|---|
| Sheet erosion | : | 1 t/ha/yr |
| Rill erosion | : | 10 t/ha/yr |
| Gully erosion | : | 100 t/ha/yr |
| Lavaka erosion | : | 1000 t/ha/yr |
| Bank undercutting | : | 10,000 t/ha/yr |

Table 2 : Erosion hazard based on RUSLE-model soil-loss estimates (UNC)

The threshold values used correspond to the three quantiles characteristic of the statistical distribution of estimated soil loss values. Moreover, these are concordant in comparison with the different thresholds of erosion classes in the bibliography:

| | |
|---|---|
| Low erosion hazard | < 2 t/ha/year |
| Moderate erosion hazard | 2 t/ha/year – 23.3 t/ha/year |
| High erosion hazard | 23.3 t/ha/year – 102.1 t/ha/year |
| Very high erosion hazard | > 102.1 t/ha/year |

Table 3: Per pixel erosion hazard classes according to threshold values on soil loss estimates

### 2.2.3 Classifying erosion hazards for each drainage basin

RUSLE soil loss estimates are used to characterize erosion hazard at the water-collection perimeter level (PPCE). Following the methodology proposed by Le Bissonais et al. (2002, 2004), parametric rules based on the percentage of defined hazard class within water protection perimeters are used to determine the global erosion hazard for each water protection perimeter (figure 5).

The first step consists of the definition of erosion hazard classes for each pixel of the models based on threshold soil loss values. These thresholds correspond to the median (23.3 t/ha/year), the first and third quartiles (respectively 2.0 and 102.1 t/ha/year) of the statistic distribution of soil loss estimates based on the statistical analysis of the RUSLE soil loss estimates.

These thresholds (table 1) were compared to values found in the literature exploiting RUSLE model to characterize erosion hazard. They are in accordance with those obtained in the region as in New Caledonia or Fiji (Dumas et al. 2010), and French Polynesia (Dumas, 2015). Similar values are obtained in India under wet tropical climate (Prasannakuma et al. 2012). On the other hand, low erosion hazard values are higher under temperate climate while high to extreme erosion hazard are characterized by lower values (Lefebvre et al., 2005).

Then, the percentage of surface of each erosion class is calculated within each PPCE perimeter by pixel counting. Jenks analysis (Jenks, 1963) was performed on the distribution of the percentage values of each erosion class to determine the natural breaks in the distribution. These natural breaks are used in the decision-rules approach (table 2) to determine the global erosion hazard value for each PPCE varying between low to moderate erosion, moderate to high erosion, and high to extreme erosion.

| Percentage of area of hazard in the drainage basin | Affected class |
|---|---|
| • Low erosion hazard > 22% very high erosion hazard = 0 % | Low to moderate erosion hazard |
| • Very high erosion hazard > 0% very high erosion hazard ≤ 18% weak erosion hazard ≤ 22%<br>• OR high erosion hazard > 48% very high erosion hazard > 0% very high erosion hazard ≤ 18%<br>• OR very high erosion hazard > 18% high erosion hazard > 0 high erosion hazard + moderate erosion hazard > 29%<br>• OR very high erosion hazard + high erosion hazard + moderate erosion hazard > low erosion hazard and very high erosion hazard < high erosion hazard + moderate erosion hazard | Moderate to high erosion hazard |
| • Very high erosion hazard > 50 %<br>• OR very high erosion hazard > 18% high erosion hazard > 48%<br>• OR very high erosion hazard + high erosion hazard + moderate erosion hazard > low erosion hazard and very high erosion hazard > high erosion hazard + moderate erosion hazard<br>• OR very high erosion hazard + high erosion hazard + moderate erosion hazard >79% moderate erosion hazard < high erosion hazard + very high erosion hazard<br>• OR very high erosion hazard > 18% high erosion hazard > 0 high erosion hazard + moderate erosion hazard < 29% | High to very high erosion hazard |

Table 4: Definition of erosion hazard classes assigned to the New Caledonian drainage basins.

## 2.3 Describing drainage-basin landscape patterns

Forests are known to curb flood damage and many studies have demonstrated the link between deforestation and flood hazard intensity. Also, reduced interception and infiltration due to deforestation leads to less aquifer recharge. Not only is the flood hazard heightened as a result during heavy rains, but water may become scarce during low rainfall periods. Forests can therefore be considered water buffers facilitating water-cycle continuity and, if they disappear, this service will be lost.

In the Southwest Pacific islands under consideration, forests were deemed to represent the territories' native vegetation, while grassland, plain and shrub formations as well as bare soil were considered as the result of damage to the forests. The loss of this water buffer was thus assessed based on a *landscape-pattern* criterion.

### 2.3.1 Method for defining vegetation classes and threshold values

This indicator provides information on forest-ecosystem damage related to anthropogenic pressure and the associated services or loss thereof. Forest damage was defined based on the hypothesis of a climax forest covering virtually all the tropical and sub-tropical areas of the South Pacific before the first Austronesians arrived. Forms of rainforest degradation caused by continual fires, farming, logging and mining in relatively recent history (19th century till today) are supported by the literature. Forest-ecosystem degradation led to the formation of grassland and scrubland dominated by bushes and grass. In the most critical cases, areas of bare soil can be observed.

Unlike the erosion hazard, this landscape pattern provides an “overall indication” of a set of ecosystem services related to forest habitats based on the three criteria focused on in this report: soil stabilisation ecosystem-service loss, water-buffer ecosystem-service loss and fire-resilience ecosystem-service loss.

The thresholds and vegetation types determining the major landscape patterns were established by assessing the statistical distribution of the various vegetation types growing in the drainage basins based on the 2008 New Caledonia land-cover model.

The approach taken for characterising each drainage basin’s landscape pattern was similar to the method used for the erosion hazard and consisted of:

- arranging the land-use found in each pixel into major vegetation classes;
- examining the spatial distribution of each major class within each drainage basin in order to define a decision rule for characterising the landscape pattern; and
- implementing the decision rule in each drainage basin.

### 2.3.2 Vegetation types selected to characterise drainage-basin landscape

Vegetation classification varies between countries both in terms of name and what it covers and some terms are territory-specific, e.g. niaouli (*Melaleuca quinquenervia*) grassland in New Caledonia and *taofa* on Wallis & Futuna. A classification under three broad classes that were representative of a pattern was therefore developed by merging several plant types that fulfilled arguably similar water-resource functions.

- Forests = landscape pattern 1: environment dominated by tree and shrub formations
- Shrub formations, ligno-herbaceous and herbaceous = landscape pattern 2: mosaic of tree, shrub and herbaceous formations with the presence of bare soil and prevalence of shrub and herbaceous formations
- Bare soil and sparse vegetation = landscape pattern 3: open environment with a strong presence of bare soil, where the majority of vegetation is scattered and consists of herbaceous formations with some residual tree and shrub formations

Can be classed as respectively as:

- Slightly degraded to degraded forests
- Degraded to very degraded forests
- Very degraded to extremely degraded forests

For each drainage basin, the percentage of each vegetation class is calculated. An analysis of the distribution is carried out by creating histograms showing the percentage of basin coverage for each vegetation class (forest, shrub formations, lingo-herbaceous and herbaceous, sparse vegetation and bare soil).

### 2.3.3 Characterising drainage-basin landscape patterns

The distribution analysis for each class revealed natural thresholds (discretisation as per the Jenks method) that distinguished drainage-basin groups in terms of resemblance in the spatial cover distribution of each vegetation type.

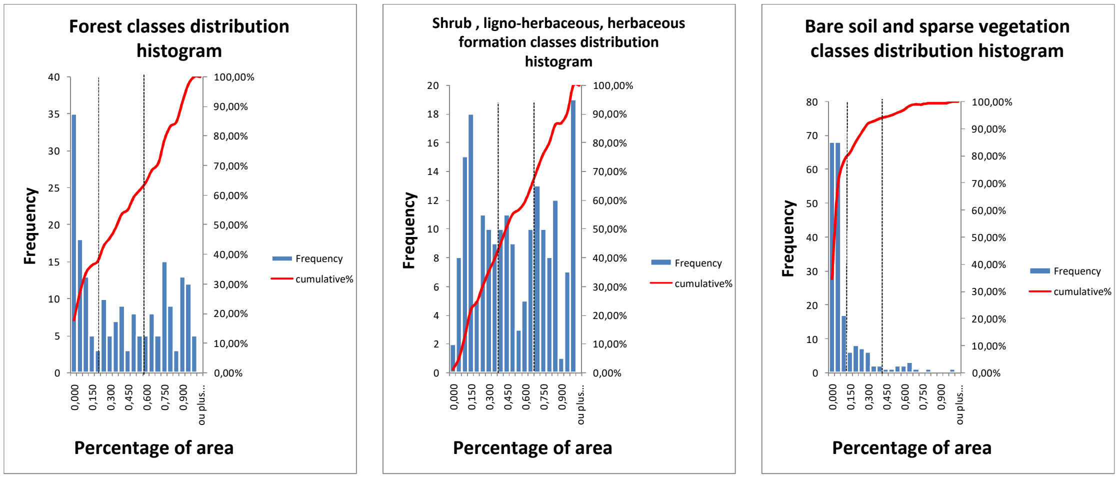


Figure 3 : Coverage distribution of each vegetation type

The landscape pattern was determined using a dominance triangle based on cover percentages for each major vegetation type divided according to the thresholds extracted by the Jenks method.

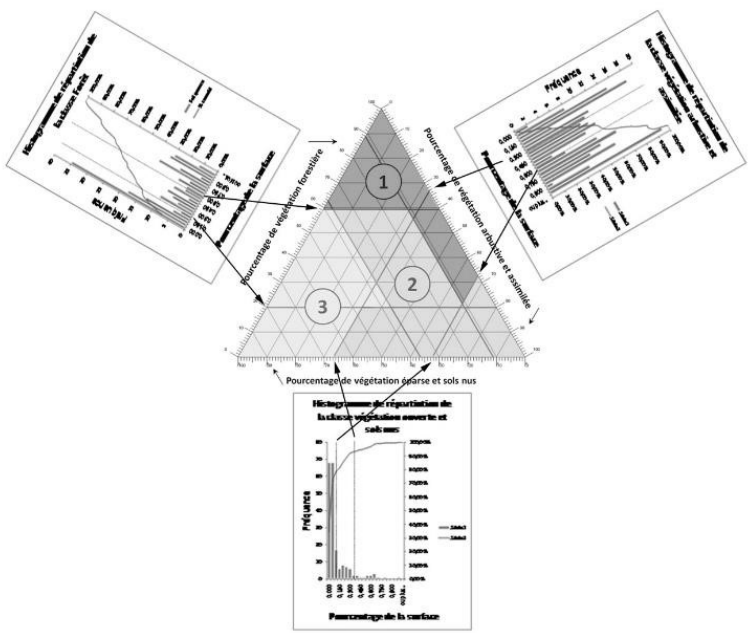


Figure 4: Methodology for characterising landscape pattern with a dominance triangle based on Jenks thresholds

As with texture triangles used in sedimentology and soil science, each axis of the dominance triangle was the percentage of major vegetation classes. The thresholds identified using the Jenks method were plotted along each axis and a straight line was drawn on the percentage isoline for each threshold. The straight lines divided the dominance triangle into sections, which were grouped according to thematic resemblance and three landscape pattern classes defined on the dominance triangle based on the percentages of each vegetation class.

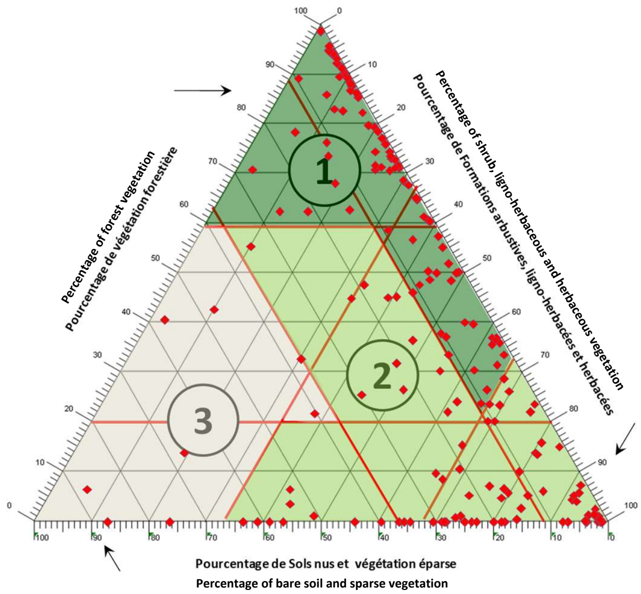


Figure 5: Landscape-pattern triangle and drainage-basin point cloud (in red)

The decision rules defining landscape-pattern classes based on the dominance triangle are provided in the table below:

| Ground surface area percentage | Landscape pattern class |
|---|---|
| • Forest vegetation coverage > 59 %<br>• Forest vegetation coverage ≤ 59% shrubbery and similar formations coverage > 33% shrubbery and similar formations coverage ≤ 68% sparse formations and bare soil coverage ≤ 11 % | **landscape pattern 1:** environment dominated by tree and shrub formations |
| • Shrubbery and similar formations coverage > 68%<br>• OR forest vegetation coverage ≤ 59% sparse formations and bare soil coverage ≤ 36 % sparse formations and bare soil coverage > 11 %<br>• OR forest vegetation coverage ≤ 59% shrubbery and similar formations coverage > 33% | **landscape pattern 2:** mosaic of tree, shrub and herbaceous formations with the presence of bare soil and prevalence of shrub and herbaceous formations |
| • forest vegetation coverage ≤ 59% sparse formations and bare soil coverage > 36 % forest vegtation coverage > 20%<br>• OR forest coverage ≤ 20% shrubbery and similar formations coverage ≤ 33% | **landscape pattern 3:** open environment with a strong presence of bare soil, where the majority of vegetation is scattered and consists of herbaceous formations with some residual tree and shrub formations |

Table 5: Definition of landscape-pattern classes for New Caledonian drainage basins

## 2.4 Characterising forest fragmentation

Forests share a large interface with human-modified environments and are more prone to human-induced impacts. This boundary between the disrupted open environment[1] and preserved forest remnants causes a microclimate that facilitates the spread of fire, wind acceleration and reduced intrinsic biodiversity in native forests. Forest borderland varies in width according to country and the extent of forest damage is and the effects can be felt 50 to 300 m inside the forest.

This type of fragmentation is distinctive of drainage-basin forest mosaics and is indicative of how vulnerable they are to relatively short-term external disruption.

Forest resilience and thus service sustainability can, therefore, be indicated by a fragmentation index showing the extent of ecosystem degradation and impairment related to human pressure.

### 2.4.1 Defining fragmentation

This is fragmentation *per se*, independent of habitat loss (as defined by landscape patterns). As such, this factor is only characterised in terms of forests as determined for the purposes of describing landscape pattern.

There are several different indicators for characterising fragmentation and a large number of indices are often found in the literature for such purposes. Fragmentation was estimated for each drainage basin using formulae found in Hurd, Wilson and Civco (2002), Ritters *et al*. (2000) and Mouhamadou *et al*. (2012).

Forest fragmentation literature is largely limited to comparisons in time between index values to estimate variation in fragmentation. There are currently no indicators or methodologies that capture forest fragmentation based on such factors.

Several factors defined in the literature were examined and all found to be based on ratios between the number, size and form of each individual continuous forest polygon in drainage basins. Some fragmentation indices showed a strong linear relationship between each other and so two indices with a lesser linear relationship were selected to prevent data redundancy in the analysis. A combination of diversity and shape indicators was selected.

The diversity index was complex and included characteristics from other indices, such as the dominance of a forest patch, when implemented. As such, the diversity indicator represented several fragmentation factors, such as dominance, number of patches and shape similarity, that complemented the shape indicator.

The indices reflected object fragmentation by capturing the number of forest patches and islands, single-dominant forests and forest shape and diversity within drainage basins. An increase in the number of patches in a class and a highly irregular shape were indicators of fragmentation in that class (Davidson 1998).

The total area ($a_{tj}$) covered by forest $j$ (in ha) was calculated based on the following equation, in which $a_{ij}$ is the area of the $i$-th patch of the forest $j$:

[1] = degraded environment based on the forested climax-vegetation hypothesis for the relevant territories

$$a_{tj} = \sum_{i=1}^{n_j} a_{ij}$$

The measurement was used in the formulae of both selected factors.

#### *2.4.1.1 Shape index*

The forest's shape index is calculated according to the formula below where *Pij* is the total perimeter of class *j*.

$$IF_j = \frac{P_{tj}^2}{a_{tj}}$$

The shape index is based on the principal of reporting perimeter over area. The more elongated or irregular the spots are, the higher the value of *IFj* and this value will decrease as the shapes becomes more circular (Bogaert et al. 2000):

- Some shape index values (0 to 50) characterize compactly shaped objects which are close to circular. A perfectly circular object has a shape index value of 12;
- Shape index values close to 100 characterize objects which are becoming gradually more complex e.g. a compact upper basin forest patch with a section descending along a creek at the bottom of the thalweg;
- High shape index values (over 1000) indicate complex and branched shapes (dendritic); The higher the index number over these values, the more complex the shape of the forest patch.

The shape index only characterizes the shape of forest patches. It does not provide information on the number of patches nor their homogeneity or heterogeneity.

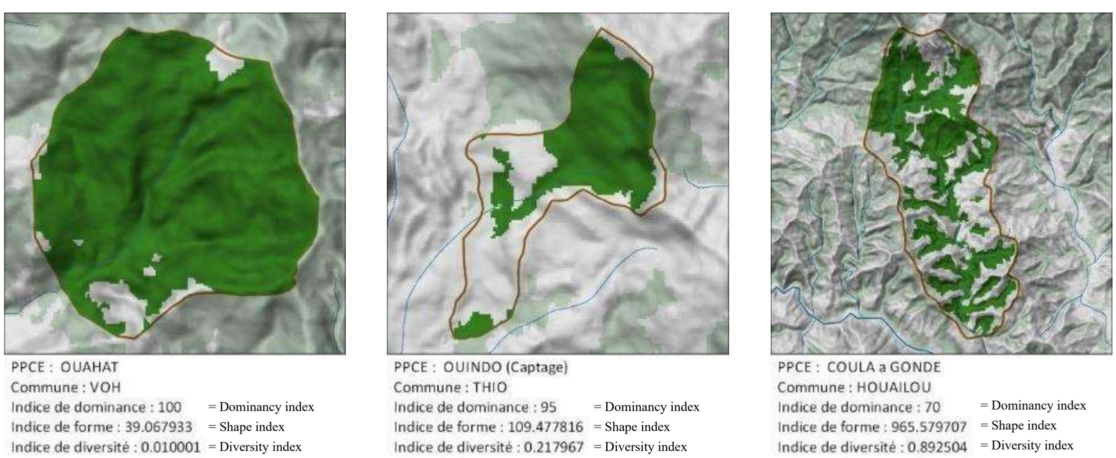


Figure 6 : Examples of shape index values

#### *2.4.1.2 Diversity of the spots' areas*

The diversity of the areas of the forest spots, denoted by Hj(a), was calculated following the index formula of Shannon (Bogaert et Mahamane 2005) where, *ln* represents the natural logarithm. The diversity indices based on Shannon's index are based on the principle that the more diversity increases,the more disorganization increases (entropy). This type of index is usually used to measure the relative abundance of ecosystems (FAO).

$$H_j(a) = \sum_{i=1}^{n_j} -\left(\frac{a_{ij}}{a_{tj}} \ln \frac{a_{ij}}{a_{tj}}\right)$$

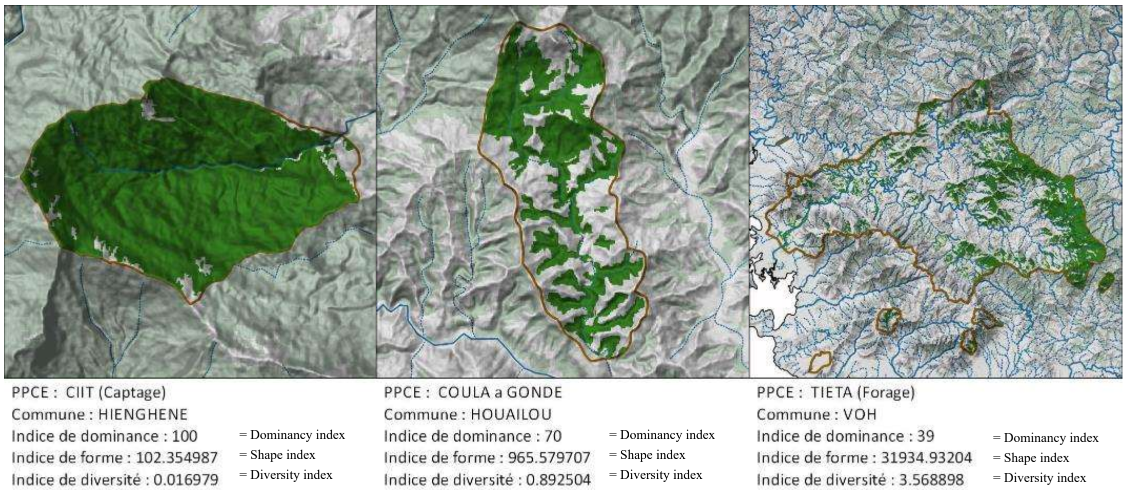


Figure 7 : Examples of diversity index values

This index measures the relative diversity of spots in the forest. The value *Hj(a)* will depend on the number of existing spots (*nj)*, on their relative proportions and on their heterogeneity. It is equal to 0 when the class only consists of one spot and its value will increase with the number spots and with equity between the areas of the spots of the class (McGarigal and Marks 1995).

- A diversity index value (near 0) indicates few forest patches and a homogenous shape
- A diversity index value near 1 indicates a slight diversification of types of forest patch shape, a small number of patches and a homogenous size
- A diversity index value near 2 indicates a larger heterogeneity of forest patches, a larger number of patches and more heterogeneous sizes
- A diversity index value greater than 2 corresponds to a strong heterogeneity of type, shape and size of forest patches associated with a significant number of forest patches.

### 2.4.1 Characterising drainage-basin forest fragmentation

As with drainage basin erosion-hazard and landscape-pattern characterisation, the index values revealed natural thresholds (discretisation as per the Jenks method), which grouped drainage basins in terms of similarities for each diversity- or shape-index value distribution.

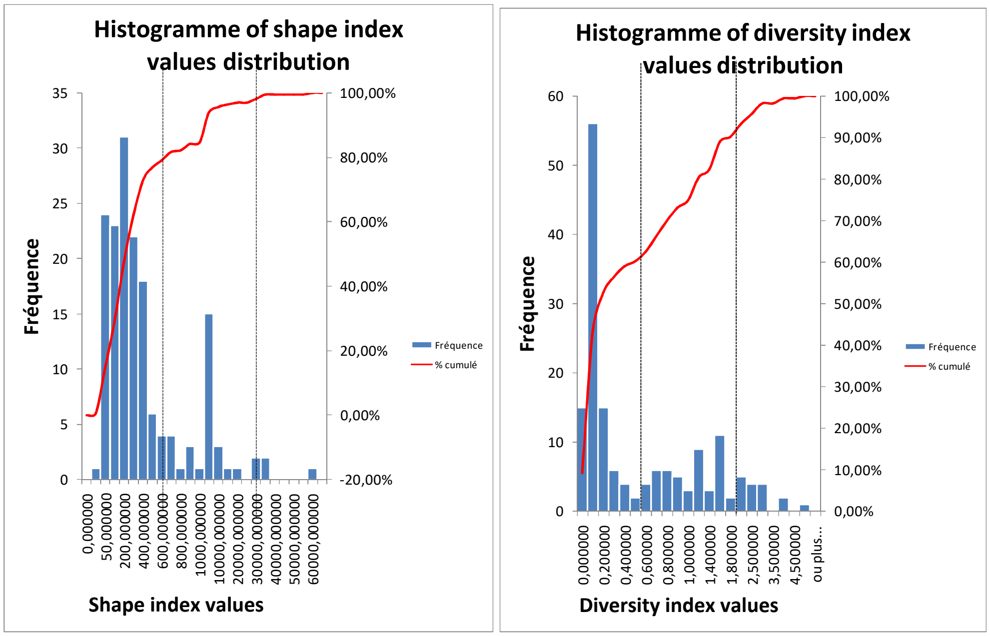


Figure 8: Distribution of forest-vegetation shape- and diversity-index values

The thresholds defined for each fragmentation index are summarized and the drainage basins are thus grouped together in 3 classes according to their shape index value and in 3 classes according to their diversity index value.

The characterization of the functionality as a function of fragmentation is carried out according to a decision tree from the 3 shape classes and the 3 diversity classes. The fragmentation is then logically qualified:

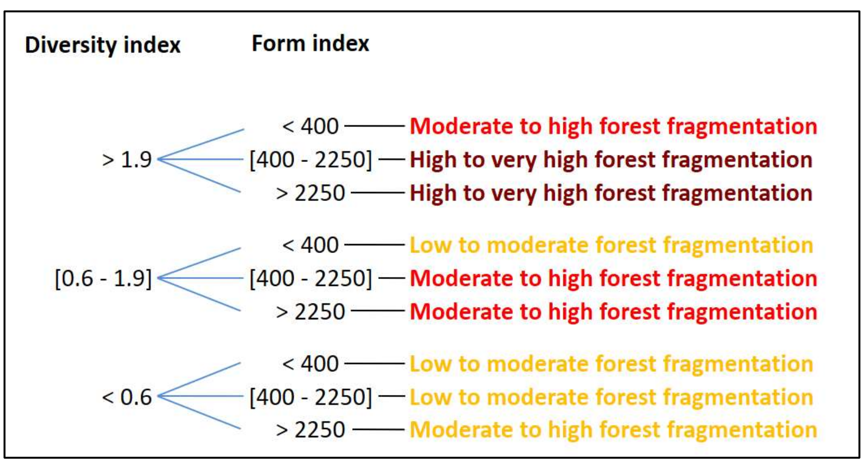


Figure 9 : Decision tree for the level of fragmentation

Drainage basins for which forest coverage is poor are put in the class of strong to very strong fragmentation

## 2.5 Determining the functionality of forest ecosystems for each drainage basin considered

The approach taken sought to define forest ecosystem functionality using three criteria other than biodiversity, which is much more complex and would require a separate study. This would restrict the study to the three indicators already discussed: erosion hazard, landscape pattern and forest fragmentation.

None of the three indicators was completely independent of the others and the approach was both qualitative and weighted in terms of these indicators, as the erosion hazard included a ground-vegetation cover variable in addition to rainfall, surface run-off, slope length and gradient and soil erodibility variables. The ground-vegetation cover was itself used directly to build the landscape pattern criterion. The forest ecosystem's functionality was determined for each drainage basin by a decision tree based on the three criteria as presented in the figure below.

A functionality rating was attributed logically for each possible combination. When the "high to extreme erosion hazard" AND "landscape pattern 3" AND "high to very high fragmentation" criteria were concatenated, for example, the drainage basin was rated as having "highly impaired" functionality.

Analysing ecosystem functionality is a qualitative exercise based on a service-efficiency approach, e.g. a highly eroded drainage basin in a pattern-1 landscape would be labelled as having "highly impaired functionality" and the soil protection service provided by the ecosystem deemed defective. Greater weight would be assigned to the landscape-pattern indicator, however, when rating functionality, as overall services (water buffer, soil stabilisation and fire resilience) would be lost under the erosion-hazard criterion.

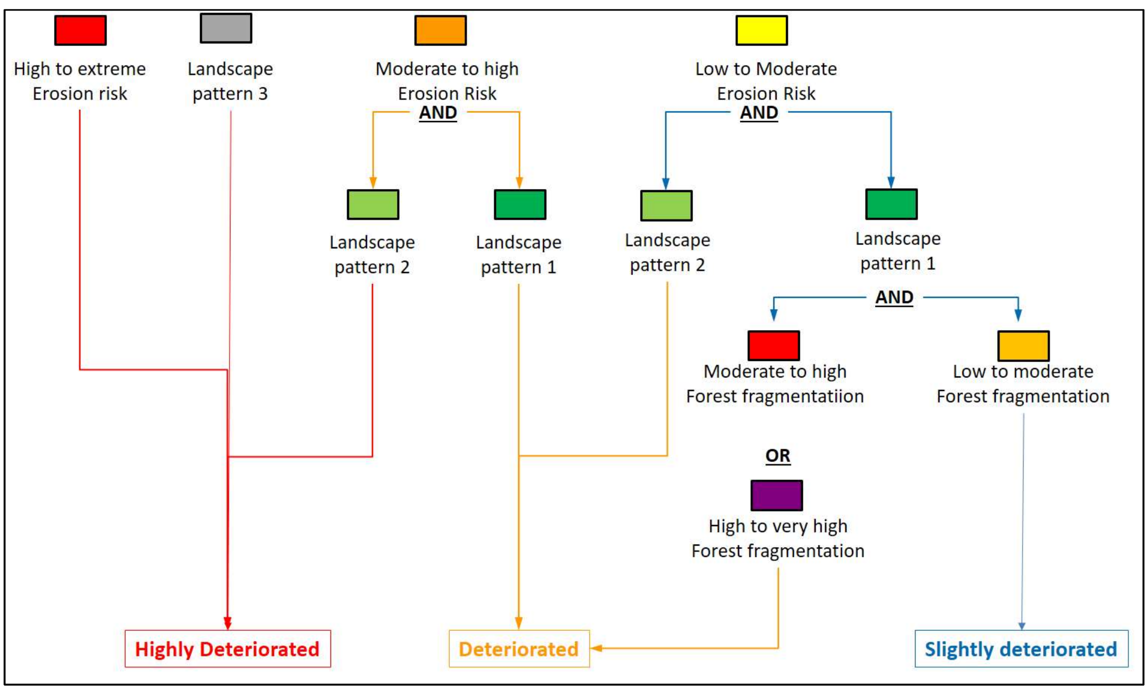


Figure 10: Decision tree for describing drainage-basin functionality status

The forest fragmentation gives greater finesse to the appreciation of the landscape pattern and allows discrimination against the functionality status “slightly degraded”, in the case where erosion is classed as weak to moderate and the case of landscape pattern 1, in an environment dominated by tree and shrub formations.

Thus, only drainage basins with :

- A landscape pattern of an environment dominated by tree and shrub formations, AND
- a weak erosion hazard, AND
- a weak to moderate fragmentation will be considered slightly degraded.

Each of the factors used had the following intrinsic shortcomings.

- Soil-loss estimates were obtained by modelling and only sheet erosion was factored in, not *lavakas* or other facies.
- The forest land-cover class does not reflect the degree of undergrowth damage from grazing deer and wild pigs.
- The land-cover classes obtained from LandLive were 90% accurate based on the training samples provided in New Caledonia.
- Each landscape-pattern class had uniform land cover with effects that varied in magnitude depending on where the various forms of vegetation were located.

# 3 DATA AND TECHNOLOGY USED

## 3.1 Data needs

This method was developed in New Caledonia, but could be applied to other territories with the same water-collection management issues, as long as the input data can be acquired. In order to calculate the relevant indicators, up-to-date plant-cover maps and sedimentary production models are required for the country.

Carrying out the same evaluation in Vanuatu and Wallis & Futuna required obtaining spatial data for mapping the entire country, i.e.:

- satellite images with field-reference data to create an updated land-cover model (LCM) on demand; and
- topographical and climate data (particularly rainfall) to supplement the LCM and then model erosion as per the RUSLE equation.

As the working units were drainage basins located upstream from abstraction points, each had to be delineated based on the abstraction points sent by the partners. In order to do so, the topographical data collected during erosion modelling were re-used.

Local partners were requested to supply the locations of water-abstraction points and join the assessment process so they could take ownership of the findings more easily.

As the objective was to provide a low-cost assessment tool that could monitor ecosystem development over time in these areas, it appeared that using free data would be key to ensuring that managers would take ownership of the method.

## 3.2 Freely available existing data

### 3.2.1 Satellite images

It was decided to select images acquired under USGS/NASA's Landsat and ESA's Sentinel programmes.

- The Landsat mission was initiated by NASA in 1972 and the satellites they launched had an estimated lifespan of at least 10 years. The latest arrival in the Landsat family, Landsat-8 was placed in orbit on 11 February 2013. Its two sensors were OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor). OLI operates in the visible, and near and average infrared regions, while TIRS operates in the thermal infrared region. Resolution is 1 :25 000 with a 16-day repeat cycle.[2]
- Sentinel-2 satellites are part of Europe's Copernicus earth observation programme run by the European Space Agency who operate a constellation of two satellites (Sentinel-2A and Sentinel-2B) which have a seven-year lifespan. Sentinel-2A was launched in June 2015 and 2B

[2] https://landsat.gsfc.nasa.gov/landsat-9/

in March 2017. The satellites are set up in such a way as to provide a 10 m to 60 m resolution image every five days.[3]

ESA and NASA co-operate on Copernicus and Landsat to ensure such missions continue for the coming 30 to 40 years, providing a set of satellite images that are well suited to general assessments at territory level. As images can be obtained more often, the collaboration makes up for hindrances such as clouds, changing or unsuitable incidence angles and, as in some cases, seasonal features.

Access to free data is particularly useful for developing long-term or large-scale monitoring at low cost.

### 3.2.2 Topographical data

In order to make national models as realistic as possible, the most accurate topographical data available that evenly covered whole territories were consistently sought.

#### *3.2.2.1 90 m SRTM DEMs*

SRTM (Shuttle Radar Topography Mission) earth topography data were collected during the Endeavour Space Shuttle's 11-day STS-99 mission in February 2000. The space shuttle was placed in orbit at an altitude of approximately 233 km at a 57° angle and had a SIR-C c-band aperture synthesis radar system on board and a second receiver-only antenna was deployed at the top of a 60 m mast 45° from vertical in a bistatic configuration. The system acquired simultaneous interferometric data with the space shuttle's onboard radar emitting and both antennae receiving (Rabus *et al*., 2003 ; SRTM@). The SRTM mission's elevation data have been available for free download since mid-2004 and are now available as digital elevation model (DEM) data with a 1 arc-second spatial resolution, i.e. approximately 30 m.

Figure 11 : Artist's impression of the Endeavour Space Shuttle's STS-99 mission (SRTM) to acquire simultaneous interferometric data

The advantage of these data is that they are freely available worldwide, but their resolution (30 m) and the lack of terrain elevation data (DEM as opposed to DTM) can lead to bias in terms of the actual ground level and distort drainage-basin delineation as a result. So, if other more accurate data are locally available, they should be used.

#### *3.2.2.2 IGN DTM for Futuna*

Wallis & Futuna is a French overseas territory and IGN (French National Institute of Geographic and Forestry Information) conduct reference geographic information production, maintenance and dissemination missions there. The Department of Forestry, Fisheries and Agriculture provided the project with 1/10,000 BD TOPO contour lines, which were converted into a 10 m grid DTM using the spline interpolation method.

[3] https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus

#### *3.2.2.3 DITTT DTM for NC*

In New Caledonia, DITTT (Department of Infrastructure) provide free access under licence to the BDALTI-NC database on the http://georep.nc/ website, which contains a 10 m grid DTM.

The DTM was developed using 1/10,000$^{th}$ topographical data (BDTOPO) published by DITTT and updated on 18 June 2012 covering the whole territory and GIE Sérail topographical data covering the Greater Noumea urban area. The 10 m DTM's elevation accuracy was estimated at ± 2 m, though wider discrepancies of ± 10 m were noted at specific points, such as some peaks or in very rugged areas. The data are available in TIFF format in WGS84 and Lambert NC RGNC 1991-93 projections and so the (mainly professional) public can carry out geoprocessing.

DAVAR (Department of Agriculture) additionally provided a corrected DTM for use in hydrology so that water flow could be more effectively modelled than with standard DTMs. Access to this "hydro DTM" was provided free of charge to the project under an agreement with DAVAR.

### 3.2.3 Climate data

Globally, the World Climate Rainfall Data model (Hijmans *et al*. 2005) provides free access to average monthly rainfall data ($P_i$) for the entire globe.

The data are provided in raster format and 30 arc-minute resolution, i.e. approximately 830 m. This global climate model was developed using various global and local databases compiled by the Global Historical Climatology Network. The model incorporates elevation based on the digital SRTM model described above (30 m resolution). It consists of interpolated average monthly climate data from weather stations over a 50-year period (1950-2000) based on existing data.

## 3.3 Existing data by country

The method used was based on acquiring multiple satellite data and developing a digital model in order to streamline the field-data collection phase. Some of the data compiled by local departments could, however, be improved and this needs to be considered to increase model accuracy.

Also, some information could only be acquired by contacting the appropriate authorities, as was the case, for example, when identifying the precise location of water abstraction points, which was the most important input for conducting an assessment.

### 3.3.1 New Caledonia

#### *3.3.1.1 Water abstraction points*

In New Caledonia, DAVAR (Agriculture Department) is responsible for protecting water resources through the Water Division. Responsibility for managing water is broken up into several territorial, provincial, municipal and other authorities. DAVAR is tasked with registering existing abstraction points in New Caledonia and setting the buffer zone boundaries around public drinking-water abstraction points.

In March 2018, there were 755 water-abstraction points in the DAVAR database divided into three types: surface water abstraction points, drainage ditches and boreholes.

In this project, the services provided by forests, as previously described, mainly affected surface-water abstraction points, which were dealt with first.

| | |
|---|---:|
| **Sub-surface water** | **230** |
| Boreholes | 227 |
| Wells | 3 |
| **Surface water** | **525** |
| Surface abstraction | 498 |
| Spring | 1 |
| Drainage ditches | 26 |
| **Overall total** | **755** |

Table 6 : Water-supply source distribution

#### *3.3.1.2 Drainage basins*

In addition to locating abstraction points, DAVAR has two layers of drainage-basin boundaries:

- water buffer zones - Regulated areas in which activities are prescribed so as not to harm water resources. There are three types of buffer zone (cf. figure opposite). As the work was conducted at drainage-basin level, the outer buffer zones were selected, i.e. 220 objects. This layer includes both surface-water and borehole buffer zones; and
- a drainage-basin model based on the "hydro DTM" in which a drainage basin upstream is considered for every catchment - This layer only includes mainland surface-water abstraction points, but none on the Isle of Pines (south) or the Beleps (north) as there are no hydrological DTMs in either location. The model has 294 drainage basins delineated on this basis.

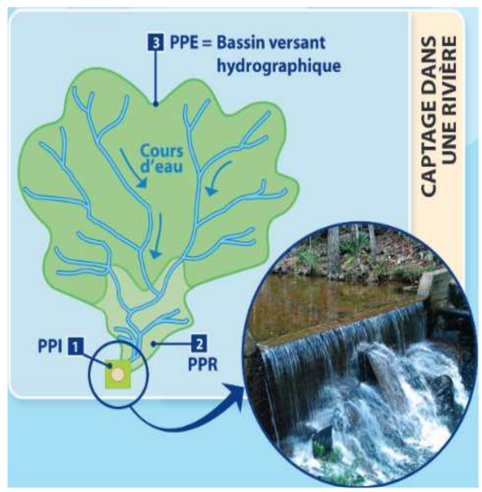


Figure 12: The three drainage basin protection perimeter levels (source: DAVAR)

#### *3.3.1.3 Reference data for land cover*

A land cover model for New Caledonia was developed in 2008 by DTSI (Department of Technology and Information Services), which provides a complete and uniform view of the territory at any given time and quantifies developments over time. Classification is provided by semi-automatic processing that has no absolute validity. This process was validated with a 75.5% kappa coefficient (DTSI). The land-cover model was a standard in 2008, but has since become obsolete other than as a training basis for other models.

Training data was additionally taken from the Bluecham SAS Sepsat™ Reference, Sepsat™ Vegetation and Sepsat™ Bdmang database. Bluecham started setting up this vegetation and land cover database 10 years ago in New Caledonia on a 1:2000 scale. The data are used by mining companies and government bodies and have been calibrated and validated by the following research institutes and/or botanical experts:

- IRD (Institute for Development Research);
- BOTANIC NC;
- Bota Environnement; and
- mining company environment units.

The training database contains 30,987,218 pixels evenly distributed across the whole of New Caledonia and covering some 310,000 ha, of which 215,000 ha are above water:

| New Caledonia | no of pixels | ha |
|---|---|---|
| Water | 9,493,776 | 94,937.76 |
| Bare soil, intermittent vegetation | 396,761 | 3,967.61 |
| Laterite and alterite | 242,581 | 2,425.81 |
| Iron cap | 115,937 | 1,159.37 |
| Eroded natural surfaces | 251,881 | 2,518.81 |
| Built-up areas | 54,423 | 544.23 |
| Human-modified areas | 849,282 | 8,492.82 |
| Tall formations on ultramafic substrate | 4,829,087 | 48,290.87 |
| Tall formations on volcano-sedimentary substrate | 963,783 | 9,637.83 |
| Tree mangroves | 217,223 | 2,172.23 |
| Pre-forest or early seral-forest scrub, scrub thickets | 7,219,985 | 72,199.85 |
| Tree and bush grassland, niaouli (*Melaleuca quinquenervia*) grassland | 1,214,059 | 12,140.59 |
| Tree mangroves | 505,970 | 5,059.70 |
| Woody-grassy scrub | 4,003,994 | 40,039.94 |
| Grassland | 569,902 | 5,699.02 |
| Farmland | 58,574 | 585.74 |

Table 7 : Training database for ground occupation modelling in New-Caledonia

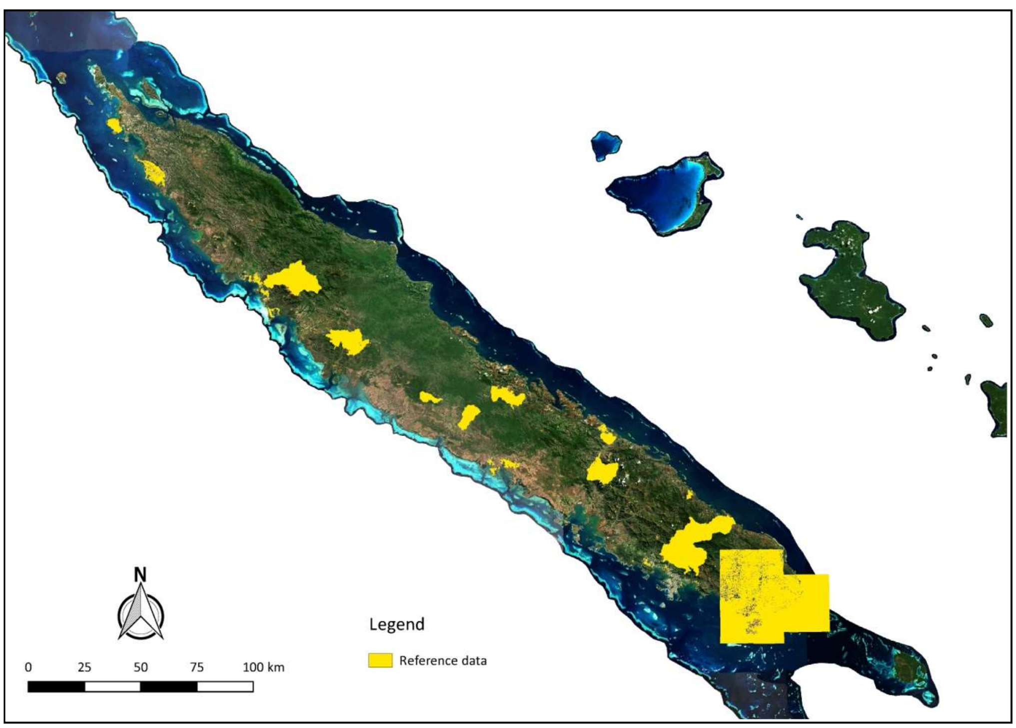


Figure 13: LandLive training area in New Caledonia

### 3.3.2 Futuna

On Wallis & Futuna, the Department of the Environment is one of the French central government and territorial agencies whose main task is to manage the natural and artificial physical environment and improve the living environment. It is tasked with leading, co-ordinating and using studies, enquiries, research and conferences on species and natural resource protection and development as well as handling pollution, hazards and nuisances.

That is why the project requested relevant data available at the department for diagnostic purposes starting at the design phase, i.e.:

- abstraction-point locations on Futuna Island; and
- reference land-cover maps.

The training data on Futuna benefited from the Department of Agriculture, Fisheries and Forestry's vegetation mapping programme on Wallis Island on a 1:2000 scale based on land surveys and satellite imagery analyses.

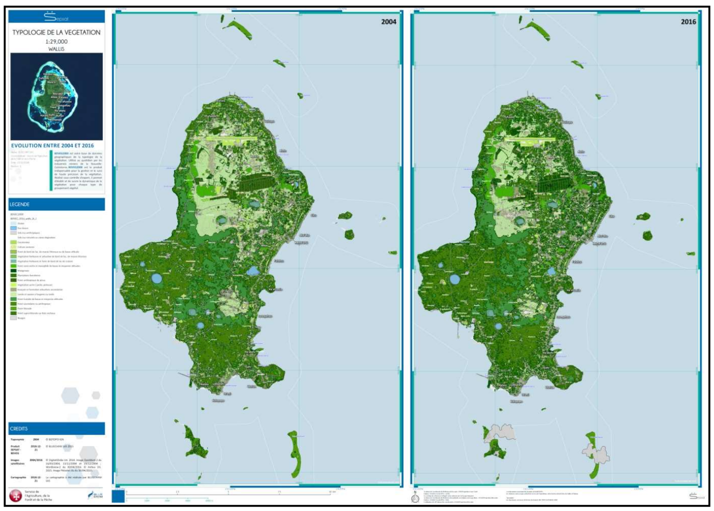


Figure 14: Wallis Vegetation map produced in 2004 and 2016 for the Department of Agriculture, Fisheries and Forestry.

The training database contained 1,652,616 pixels covering 16,500 ha, 7700 of which were above water.

| Futuna | no de pixels | ha |
|---|---|---|
| Water | 880 963 | 8 809,63 |
| Bare soil, intermittent vegetation | 12 680 | 126,80 |
| Built-up areas | 21 913 | 219,13 |
| Tall rain forest formation | 167 666 | 1 676,66 |
| Dense tree formations, coconut or pinus plantations | 23 294 | 232,94 |
| Open secondary forest, open forest | 315 407 | 3 154,07 |
| Dense thicket, fallow, gardens | 112 455 | 1 124,55 |
| Grassland, *toafa* | 72 838 | 728,38 |
| Farmland | 45 400 | 454,00 |

Table 8 : Training database for ground occupation modelling in Wallis & Futuna

The land-cover data were used to train the LandLive programme in order to model updated land-cover on Futuna based on 2018 Landsat-8 and Sentinel-2 satellite imagery.

As the department did not have delineation data for the relevant abstraction-point drainage basins, it will need to generate it during the assessment.

### 3.3.3 Vanuatu

In Vanuatu, the Ministry of Land's Department of Water Resources (DoWR) is responsible for managing water. As with the Wallis & Futuna Department of the Environment, collaboration with DoWR began at the design phase to ensure the data required for the assessment was shared.

DoWR supplied the entire database containing the abstraction points for the population's water supply. It was very comprehensive with nearly 5000 abstraction points divided into 11 categories.

| Type d'approvisionnement | Nombre de point |
|---|---:|
| Cart with small tank/drum or water truck | 38 |
| Dug well | 251 |
| Piped water supply from groundwater | 287 |
| Piped water supply from seawater | 4 |
| **Piped water supply from spring** | **346** |
| **Piped water supply from surfacewater** | **106** |
| Rainwater | 3236 |
| **Spring** | **210** |
| **Surface water (ponds/streams/lakes/rivers)** | **94** |
| Tubewell or borehole | 382 |
| Unknown | 28 |

Table 9 : Vanuatu water supply sources

In terms of ecosystem services identified as provided by forests, the only forms of abstraction selected as relevant for assessment purposes were surface water, springs, piped water supplies from surface water and piped water supplies from springs.

As the departments contacted couldn't provide land-cover data, LandLive was used to create a land-cover model.

Training data was entered based on recent satellite imagery (2017 and 2018) by photo-interpretation backed up by mapping work carried out by SPC for the REDD+ programme on Efate, Erromango, Malakula, Tanna and Santo islands.

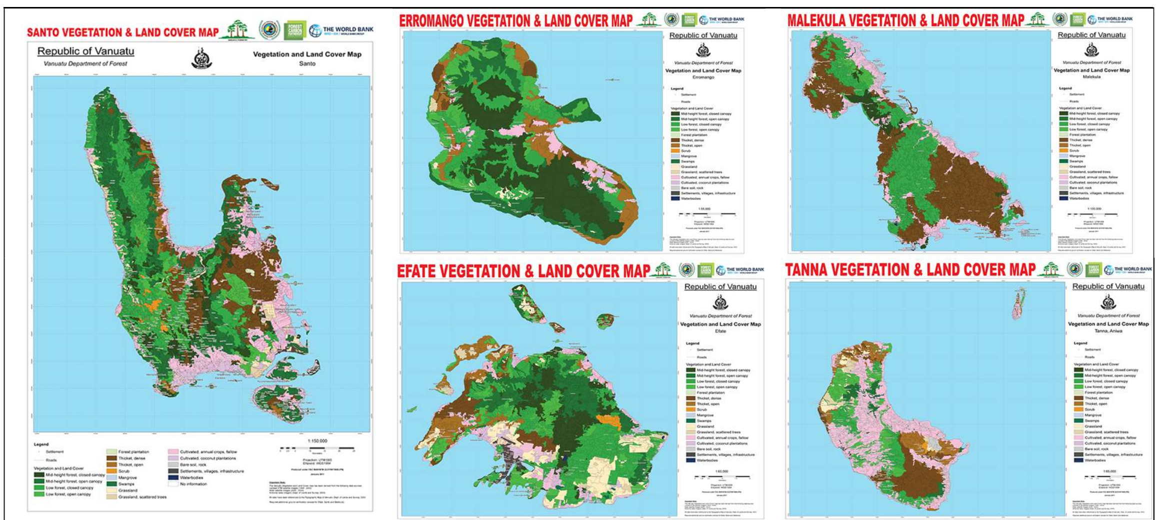


Figure 15 : Vanuatu REDD+ reference maps (http://reddplus.vu)

The database included more than 20 million pixels for 200,000 ha above water:

| Vanuatu | no of pixels | ha |
|---|---|---|
| Water | 970,823,402 | 9,708,234.02 |
| Bare soil, intermittent vegetation | 243,070 | 2,430.70 |
| Natural eroded surfaces | 25,451 | 254.51 |
| Built-up areas | 158,035 | 1,580.35 |
| Rainforest | 5,500,460 | 55,004.60 |
| Tree mangroves | 13,875 | 138.75 |
| Dense tree formations, coconut plantations | 4,263,638 | 42,636.38 |
| Open secondary forest, open forest | 1,899,842 | 18,998.42 |
| Dense thicket, fallow | 5,859,058 | 58,590.58 |
| Tree mangroves | 7,749 | 77.49 |
| Grassland, *toafa* | 2,027,739 | 20,277.39 |
| Farmland | 144,813 | 1,448.13 |

Table 10 : Training database for ground occupation modelling in Vanuatu

## 3.4 Summary of data used

| | New Caledonia | Futuna | Vanuatu |
|---|---|---|---|
| Water abstraction points availability | Yes | Yes | Yes |
| Drainage-basin delineation | Regulatory buffer zones<br>Automatic drainage-basin delineation | No | No |
| Topographical data | DITTT DTM<br>DAVAR hydro DGM | IGN DGM | SRTM DEM |
| Climate data | World Climate Rainfall Data | *ibid.* | *ibid.* |
| Land cover updated to 2018 | No | No | No |
| Land-reference and/or locally validated data | 2008 LCM<br>2014 LCM<br>BlueCham Database | SENV maps | REDD+ maps |

Based on the data available in each country, the drainage basins will need to be modelled for Futuna and Vanuatu and updated land-cover models created for all three jurisdictions.

# 4 DATA PROCESSING, TECHNICAL ISSUES AND SOLUTIONS

## 4.1 Creating a land-cover model

### 4.1.1 Satellite image pre-processing

As there were no recent models, images from the Sentinel-2 and Landsat-8 satellites were used to generate land cover using LandLive, a programme developed by Bluecham. In order to cover all the relevant areas with a 0% cloud objective, multiple satellite coverage was required in order to reduce cloud cover to a minimum.

The images were put through calibration, pre-processing and derived indicator calculations, such as NDVI, before being fed into the ANN (Artificial Neural Network) process.

The data were reprojected so it could be used in the RGNC 91-93 Lambert conformal conic projection system (EPSG:3163). Similarly, the Sentinel-2 data were acquired with Level 1C processing for standard ground correction (orthorectified and calibrated) based on the same specifications as for Landsat-8 data.

Under the project, New Caledonian land cover can be updated monthly by artificial intelligence (artificial neural network) based on Landsat and Sentinel satellite data which is stored in the LandLive monthly database. The data are 91.32% accurate (kappa coefficient: 0.9031[4]).

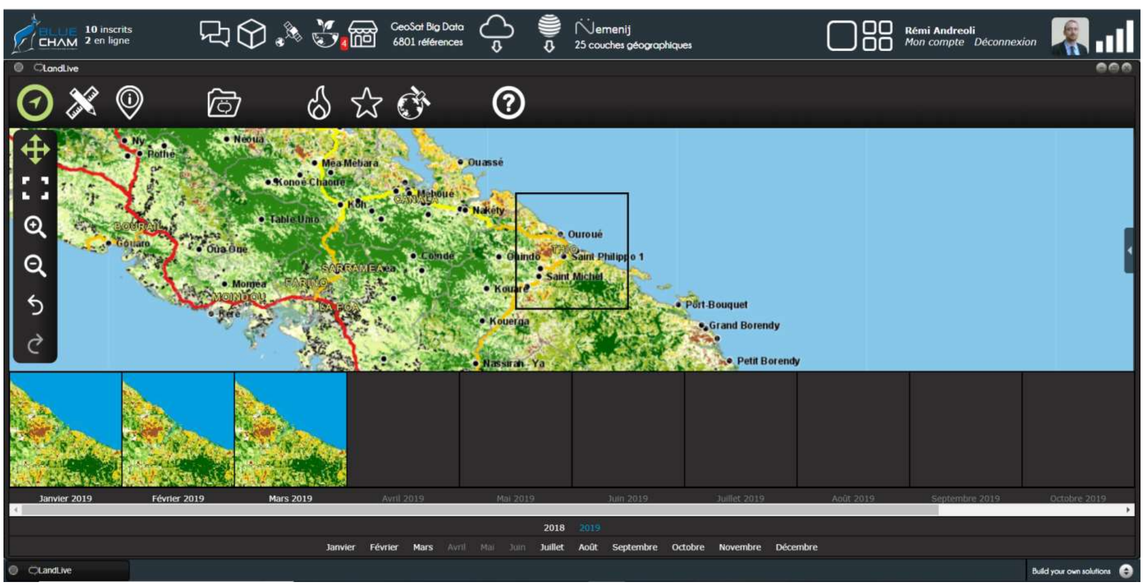


Figure 16: LandLive monthly land cover database

In radiometric terms, the data were calibrated to top-of-atmosphere (TOA) reflectance and sun-angle corrected, which normalised the signal value.

The panchromatic and multispectral data were merged to a 15 m resolution using the pansharpening method (Gangkofner, Pradhan, and Holcomb 2008).

[4] The kappa test measures the agreement between two raters on qualitative category discrimination. There is substantial agreement when the kappa coefficient exceeds 0.61 and excellent agreement over 0.81. The accuracy percentage is provided by a contingency table based on the total number of properly classified pixels out of the sum of pixels tested.

Two neochannels (NDVI and NDMI) and the texture parameters were calculated using the merged calibrated data.

<u>Normalised difference vegetation index (NDVI)</u>

The NDVI (normalised difference index) was proposed by Rouse (1974) and highlights the photosynthetic activity of vegetation. It is estimated using the following formula:

$$NDVI = \frac{\rho_{PIR} - \rho_R}{\rho_{PIR} + \rho_R}$$

With: $\rho_{PIR}$ calibrated near-infrared reflectance

$\rho_R$ calibrated red reflectance

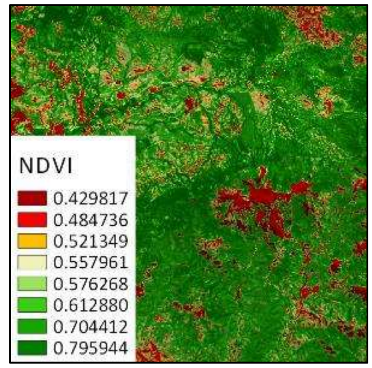

Figure 17: NDVI calculated based on calibrated Landsat-8 data

<u>Normalised difference moisture index (NDMI)</u>

The normalised moisture index (NDMI) reflects the moisture on surfaces. It is estimated using the following formula (Clandillon, De Fraipont, and Yesou 1995):

$$\text{NDMI} = \frac{\rho_{MIR} - \rho_V}{\rho_{MIR} + \rho_V}$$

With :

$\rho_{MIR}$ calibrated middle-infrared reflectance

$\rho_V$ calibrated green reflectance

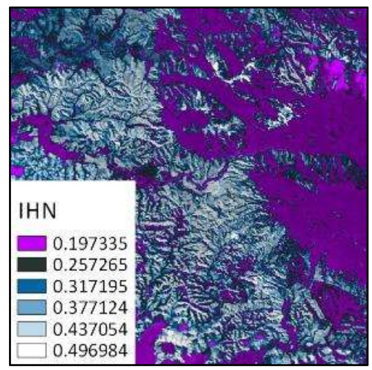

Figure 18: NDMI calculated based on calibrated Landsat-8 data

<u>Texture indices</u>

Texture indices were calculated using Haralick functions (Robert M Haralick, Shanmugam, and Dinstein 1973; Robert M Haralick 1974; R.M. Haralick 1979).
The indices help describe and distinguish the grain and texture of objects on the ground.

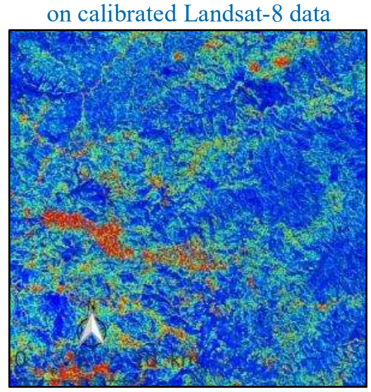
Figure 19: Texture (variance) calculated based on calibrated Landsat-8 data

### 4.1.2 Exogenous data

In addition to satellite images, exogenous data were fed into the processing model, including the following, whenever available:

- rock and soil data;
- population density or urban areas; and
- roads.

#### 4.1.3 Creating a LandLive land cover model

The corrected satellite images then undergo a multilevel artificial neural network process to define land-cover classes in an automated manner.

The first process chain developed was an iterative TDBU (top-down/bottom-up) process. The method had to follow prescribed instructions and needed to be unfrozen by an operator when issues occurred. The process had many drawbacks that could become burdensome when processing data for an area as large as New Caledonia:

- lengthy processing time (5 to 6 months for a 20,000 km² area);
- a semi-automated method requiring lengthy operator hours for corrections;
- remains frozen, if the operator is unable to provide the information; and
- an operator error can affect the entire chain.

As the surface areas to be processed were large and the aim was to develop a tool that could be updated fairly frequently, the process needed to be enhanced. This was done by developing artificial intelligence that would identify reasons for land cover fairly quickly and, above all, autocorrect as experience was acquired. It therefore had to be more efficient with repetitive tasks.

However, as much input data as possible need to be supplied, and so reference data has to be obtained from the various jurisdictions, e.g. land cover models, vegetation maps and forest inventory points.

The operator only intervenes during the training phase to provide reference input data, check that input data (satellite images) are consistent with output data (in this case, land-cover classes) and correct any discrepancies.

Fresh data can be incorporated and new neural connections developed by a machine-learning process that includes change detection and a priority allocation process by majority vote so that the AI can autocorrect.

Processing was enhanced to speed up satellite imagery analysis for large surface areas and update land cover on a monthly basis.

The tool, known as LandLive, was designed to:

- access new images acquired by satellite constellations; and
- process them to determine land cover.

Developing AI is particularly relevant to the study of environmental issues, because:

- the environmental sciences examine areas in their totality and so produce considerable amounts of data; and
- machine learning is able to manage and is fed by copious amounts of data in order to sort, refine and supply more consistent results.

### 4.1.4 Adjustments

A neural network made up of five neural sub-networks was developed to determine the land-cover classes as accurately as possible. The final results were then compiled in a single database to obtain the final product - LandLive.

For New Caledonia, the whole process requires approximately four days instead of the five months taken by standard methods.

The process produces 1:25,000 resolution images that can be updated monthly with 94% accuracy in terms of the reference input data samples.

When implemented in the project, the method revealed stark vegetation differences between New Caledonia and Vanuatu. As AI experienced difficulty capturing this, the processing chain and the initial Vanuatu training set had to be adjusted. When the data chain developed for New Caledonia was implemented, reference map errors were too high and so it was decided to train the network specifically for each jurisdiction.

LandLive coverage of Futuna was also revised using the new neural network and also produced better results.

The LandLive output classes depend on the country and can be processed (grouped or separated) based on needs.

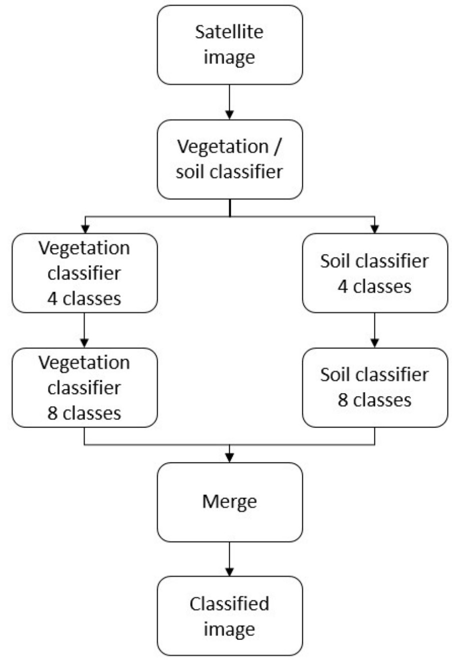


Figure 20: Process for determining land-cover classes

This is what was done in this project. Detailed vegetation data was used for modelling erosion, but the various categories were then merged into three major land-cover classes to calculate landscape-pattern and forest-fragmentation trends.

## 4.2 Updating the erosion hazard: Sepsat™ Erosion

### 4.2.1 Sepsat™ Erosion modelling

**Sepsat™ Erosion** is an indicator that reflects soil susceptibility to natural or human-activity-based disturbances in terms of sediment production. It was based on the hybrid RUSLE model (Wischmeier and Smith 1978) that was developed and adapted to New Caledonia by Bluecham in partnership with the University of New Caledonia, IRSTETA and IRD (Allenbach *et al.* 2015).

**Sepsat™ Erosion** was created using 2018 satellite data and the **LandLive** vegetation classification.

**Sepsat™ Erosion** accounts for DTM topographic data by calculating the topographic erosion-susceptibility factor as accurately as allowed by available data.

**Sepsat™ Erosion** is based on the Wischmeier and Smith (1978) RUSLE equation:

**A = R.K.L.S.C.P**

**A** is soil loss expressed in the K factor unit of measure for the period selected for the R factor

**R** is the runoff factor following rainfall

**K** is the soil erodibility factor

**L** is slope length

**S** is slope angle

**C** is the plant-cover factor

**P** is the cultivation-method and soil-protection practice factor

The **Sepsat™ Erosion** results are soil-loss estimates due to water erosion expressed in t/ha/yr. The **Sepsat™ Erosion** results are comparable to modelling carried out by P. Dumas (UNC), but the model differs from the methodology proposed by the University of New Caledonia in the way some model factors are calculated.

#### *4.2.1.1 L and S topographical factor calculation*

The LS(r) factor was calculated based on the (Tarboton 2005) formula:

$$LS(r) = (m+1)\ [A(r) / a_0]^m\ [\sin b(r) / b_0]^n$$

where r(x,y) is the point on the slope, A is resolution, b is slope and m and n are adjustment factors based on data resolution and slope length.

In the **Sepsat™ Erosion** model, P and C factors are incorporated in the LS factor calculation. In New Caledonia, mining infrastructure currently accounts for most soil protection practices (P factor). Whenever available, the data were directly incorporated into the digital terrain model.

In order to account for plant cover (C factor), plant-cover density (Dv) was estimated based on the LandLive product:

| Land-cover classes | C factor |
|---|---|
| Water | 0 |
| Built-up areas | 1 |
| Residential area vegetation | 0.5 |
| Parks and dense vegetation | 0.32 |
| Crops | 0.4 |
| Bare ultramafic soil | 1 |
| Sparse vegetation on ultramafic soil | 0.8 |
| Grassy and Woody-grassy scrub | 0.2 |
| Dense and early seral-forest scrub | 0.02 |
| Forests on ultramafic soil | 0.001 |
| Bare volcano-sedimentary soil | 1 |
| Grassland | 0.72 |
| Moderately sparse niaouli grassland | 0.1 |
| Dense niaouli grassland | 0.01 |
| Forests on volcano-sedimentary substrate | 0.001 |

Table 11: C factor parameters based on plant cover

Vegetation density (Dv) was incorporated in the LS factor to obtain $LS_C$ as in:

$$\mathbf{LS_C = LS(r) \times (1 - Dv)}$$

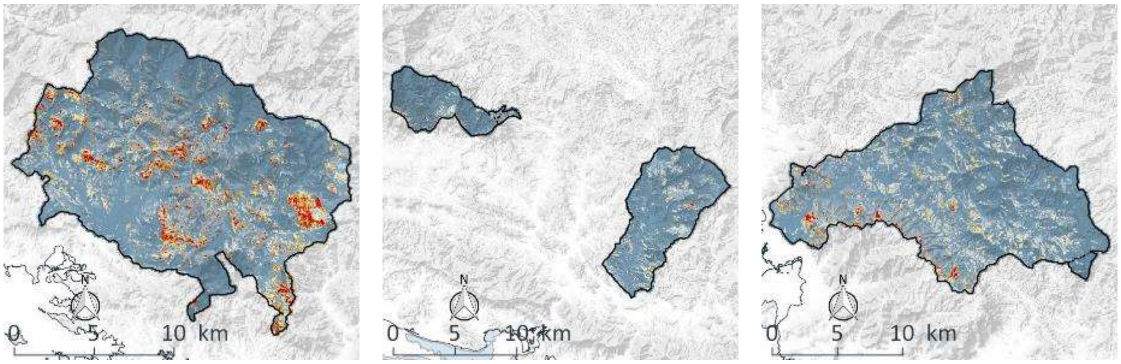


Figure 21 : LSC factor on drainage basins in Dumbéa (left), Bourail (middle), Voh (right)

*4.2.1.2 Estimating soil erodibility (K)*

The soil-loss potential depends on substrate type and soil cohesion, particle size and formation. Unless soil-loss experiments are conducted by simulating rain or loss estimated using the Wischmeier and Smith (1978) method, empirical values are commonly used based on the Stone and Hilborn D. (2011) canvas. Vegetation is used at very high resolution as a soil proxy and K values are mainly obtained from soil cover and type.

For New Caledonia, the soil types were identified by matching the "bare soil" classes with IRD soil and DIMENC geological data. In the Sepsat™ Erosion model, the Stone and Hilborn (2011) factors were used and adapted to New Caledonia as per Dumas *et al*. (2010) in order to determine soil-loss potential values.

| **Class** | **K t.ha.h/ha.MJ.mm** | **Class** | **K t.ha.h/ha.MJ.mm** |
|---|---|---|---|
| Sparse scrub | 0.036876 | Laterite | 0.03951 |
| Woody-grassy scrub | 0.027657 | Ravines, lavaka | 0.046095 |
| Early seral forest | 0.005268 | Lithosol / bedrock | 0.03951 |
| Forest on ultramafic substrate | 0.005268 | Soil on alluvium | 0.0421 |
| Sparse vegetation on volcano-sedimentary soil | 0.0421 | Impervious surfaces (A) | 0 |
| Moderately sparse niaouli grassland | 0.0395 | Built-up areas (A) | 0 |
| Dense niaouli grassland | 0.027657 | Field crops | 0.027657 |
| Forest on volcano-sedimentary substrate | 0.027657 | | |
| Water | 0 | | |
| Iron cap | 0.0053 | | |

Table 12: K-factor parameters as adapted to New Caledonia based on Stone & Hilborn and Dumas et al. (2010) K values

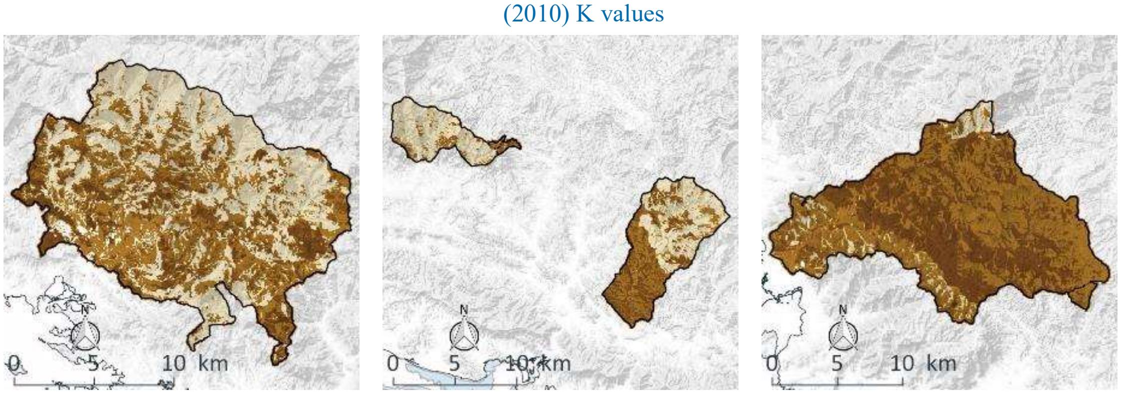


Figure 22 : K factor on drainage basins in Dumbéa (left), Bourail (middle), Voh (droite), from beige (low value) to dark brown (high value)

For Vanuatu and Futuna, the K factor was estimated using the EPIC method as per the following Sharpley & Williams (1990) formula:

$$k = \left(0.2 + 0.3e^{\left(-0.0256SAN\left(1-\frac{SIL}{100}\right)\right)} \times \left(\frac{SIL}{CLA + SIL}\right)^{0.3} \times \left(1 - \frac{0.25C'}{C' + e^{(3.72-2.95\ ')}}\right) \times \left(1 - \frac{0.7 \times \left(\frac{1-SAN}{100}\right)}{\left(\frac{1-SAN}{100}\right) + e^{\left(2\ .9\times\left(\frac{1-SA}{100}\right)-5.51\right)}}\right)\right)$$

With SAN: % sand

SIL: % silt

CLA: % clay

C': % organic carbon

based on soil data for the 0-5 cm ISRIC soil database standard depth (Sharpley and Williams, 1990).

### *4.2.1.3 Estimating rainfall intensity (R factor)*

In order to make it comparable to modelling by P. Dumas and reflect average soil loss, the R factor was calculated based on the Arnoldus (1980) formula recommended by P. Dumas (item 2.1.2.2.).

The model's R factor was calculated based on World Climate Rainfall Data (Hijmans *et al*. 2005) average monthly rainfall ($P_i$). The R factor was calculated as per the Arnoldus (1980) approximation:

$$R = \sum_{i=1}^{12} \frac{P_i^2}{P}$$

With: $P_i$ = average monthly rainfall (mm) for month (i)

P = average annual rainfall (mm)

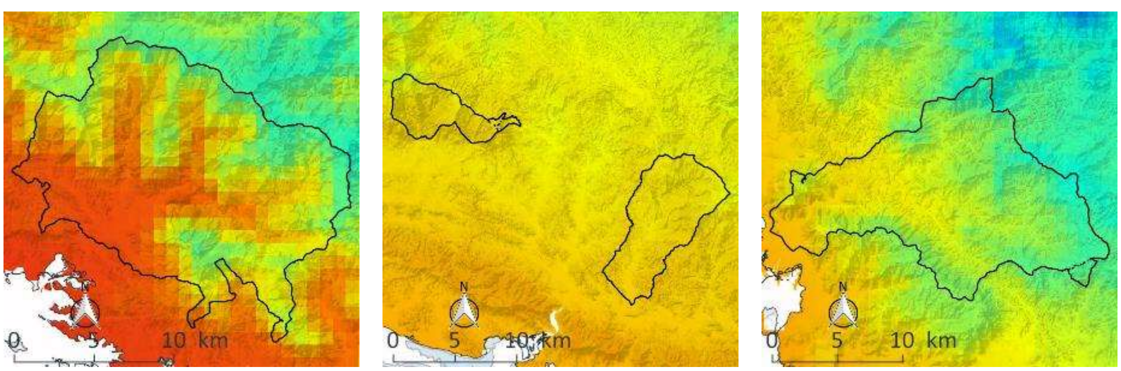


Figure 23 : K factor on drainage basins in Dumbéa (left), Bourail (middle), Voh (droite) – the gradient indicates the intensity of rainfal

## 4.3 Delineating drainage basins

### 4.3.1 Modelling drainage basins

Drainage basins were modelled by spatial analysis using available open-source libraries (QGIS, SAGA, GDAL, GRASS).

Based on one or more outflow points and a surface input data, the tool plots a whole drainage basin flowing to such points.

Applying it to a whole country for a large number of outflow points (aka abstraction points) proved more complex due to the large volume and varying availability of data and because the location data was sometimes inaccurate, leading to anomalous results. Corrections were made and automated in order to obtain the most relevant data possible, but the system was unable to fully make up for the poor point location and some manual corrections based on ground truth.

Drainage basin modelling was carried out in four main stages:

- Stage 1: carry out the water DTM
- Stage 2: correct abstraction-point locations
- Stage 3: delineate the topographic drainage basin
- Stage 4: post-process anomalies

#### *4.3.1.1 Carrying out the water DTM*

The water DTM was obtained from a raw DTM in the following steps:

- fill depressions by making slightly sloping flat surfaces and following the landscape's general topography as per the Wang and Liu method
- calculate the flow and flow-accumulation direction planes;
- determine the streams by modelling and numbering based on the Strahler method; and
- highlight the modelled streams based on their order in the DTM to ensure the water flows to the outflow points.

#### *4.3.1.2 Correcting abstraction-point locations*

As abstraction point co-ordinates are generally taken from the field, inaccuracies due to GPS flaws or access issues can lead to mismatches between the abstraction point's true location and the surveyed position. Such slight discrepancies can lead to major errors by moving the point outside a flow line and only showing a few adjacent pixels as the "drainage basin". Work was therefore done to correct point locations in order to place them back into flow lines. Several techniques were tested before a satisfactory method was found.

| | Method | Method shortcomings |
|---|---|---|
| **Method 1** | Calculate the flow accumulation factor and link the abstraction-point to the nearest stream (searching within a 200 m radius). | Problem: the nearest stream accumulation can be located in "micro-valley" where the abstraction point is unlikely to be situated. In addition, DTM inaccuracies can lead to clearly visible errors in smaller drainage basins. |

| | | |
|---|---|---|
| **Method 2** | Calculate the stream-accumulation factors and link abstraction-points to the highest stream-accumulation value detected within a 200 m radius. | Stream-accumulation values increase with section length, which may lead much further downstream than necessary. |
| **Method 3** | Divide the first stream accumulation into reaches and then allocate Strahler numbers[5] to them.<br>Link abstraction points to the reach with the highest Strahler number within a 150 m radius and not to the highest stream-accumulation pixel. | There could be a bias towards supply points when hydrogeological phenomena dominate the terrain. |

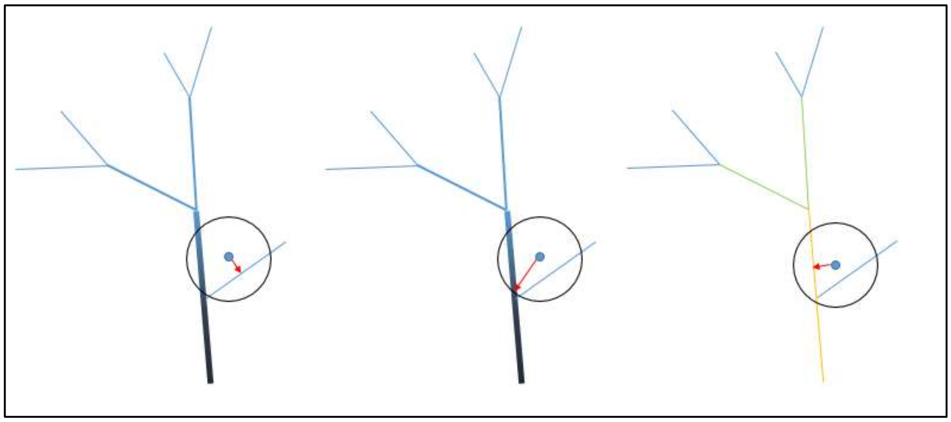

Figure 24: Diagrams of the various methods. Method 1 (left), method 2 (centre) and method 3 (right)

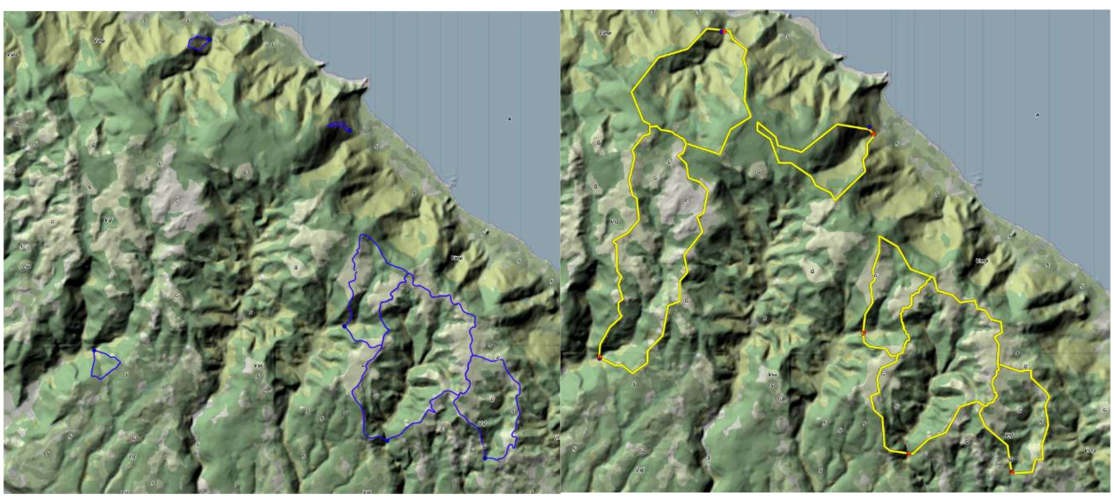

Figure 25: Comparison between automatic delineation methods 1 (left) and 2 (right) on Futuna

[5] *Strahler stream-order classification (Wikipedia French-language definition):*

*In the Strahler stream-order classification, any channel without a tributary is numbered 1. The value of each stream is then calculated as follows: an n+1 stream flows from the confluence of two n streams. The Strahler order for a drainage basin is the order from the stem to the outflow point. Improvements have been made to the method by Shreve and Scheidegger to bring it in line with the flow rate in the stem.*

#### *4.3.1.3 Delineating drainage basins*

The drainage basins were modelled using White Box Spatial Analysis Tool and SAGA libraries running on QGIS.

| |
|---|
| *Whitebox Tools is an advanced geospatial data analysis engine developed at the University of Guelph's Geomorphometry and Hydrogeomatics Research Group. Whitebox Tools can be used to perform common geographical information systems (GIS) analysis operations, such as cost-distance analysis, distance buffering, raster reclassification and much more.* |

*Source: QGIS Support*

This type of tool can be found for many GIS software packages and helps delineate drainage-basin boundaries located upstream from outflow points (aka abstraction points) based on a DTM.

#### *4.3.1.4 Corrections and post-processing*

Despite enhancing drainage-basin definition by linking to the highest Strahler number in a given radius, some drainage basins still appeared inconsistent, often because they were too small. This may have been due to defective abstraction-point location, the DMT grid size not reflecting the terrain sharply enough or the nature of such collection points, particularly “springs” that can emerge upstream from a thalweg, due to dominant hydrogeological effects in terms of the surface, and thus not have a related visible drainage basin above ground.

For the few remaining anomalous drainage basins (< 4000 m²), the choice was made to link them to the elementary drainage basin (that discharged into the sea) that they were a part of.

Shortcomings encountered:

- Collection points connected to elementary drainage basins: although this option may be appropriate for abstraction points located near the coast, it is less so for inland points;
- Springs where hydrogeological factors dominate locally and are not closely related to the visible features on the surface: linking them to particular drainage basements, however, is a means of indicating potential infiltration areas where it would be advisable to regulate activity based on the pollution hazard to underlying aquifers.
- Repositioning collection points located in very small drainage basins, even though they have been correctly located: when a larger river is located less than 100 m away from the GPS point, it is deemed that the point is erroneously sited and actually located on the larger watercourse. The catchment point could well, however, be located on a smaller tributary. This bias can only be overcome by liaising with the appropriate authorities in relevant territories.

# 5 RESULTS

## 5.1 Drainage-basin functionality: an analysis by country: New Caledonia

The 270,000 inhabitants live in three provinces spanning a total of 18,575 km², but the Loyalty Islands were excluded (18,117 population on 1981 km²), because their water supply came from very distinctive boreholes into underground water lenses rather than abstraction points.

The results were examined by compiling three geographic data sources in consultation with DAVAR:

- outer buffer zones (OBZs) for water: areas defined by regulation, often including the whole watershed upstream in order to protect the water resource. A single OBZ can include several abstraction points as well as boreholes. OBZs accounted for 3997 km² on the mainland and Isle of Pines;
- this data was supplemented by drainage basins modelled by DAVAR: automatic modelling of drainage basins upstream from surface-water collection points on the mainland only, i.e. 482 km²; and
- automatic delineation developed for the project by Bluecham was used to top up the above sources, particularly in the Belep Islands, adding another 11 km² of assessed drainage basins.

Based on this compilation, forest functionality spanning 4490 km² of the mainland and outer islands' 16,595 km² was assessed.

| **Functionality** | **Surface area (km²)** | **of which compliant DBs** | **of which non-compliant DBs** |
|---|---|---|---|
| 1 – Heavily degraded | 3,349 (75%) | 3206 km²(80%) | 143 km² (29%) |
| 2 – Degraded | 872 (19%) | 568 km² (14%) | 304 km² (61% |
| 3 – Slightly degraded | 269 (6%) | 223 km² (55%) | 46 km² (9%) |
| **Overall total** | **4,490 km²** | **3,997 km²** | **493 km²** |

NB: A larger proportion of the non-compliant drainage basins was in better health, highlighting the importance of rendering them compliant as soon as possible to ensure their functionality is maintained.

A detailed examination of the indicators for classifying the drainage basins in the various health categories helped more specifically define the required action at drainage-basin level in order to enhance the quality of the ecosystem services provided.

The high-to-extreme hazard alone explained the heavily impaired functionality of over 70% of drainage basins and so it would appear that erosion-control measures would be key in any attempt to improve drainage-basin functionality.

In drainage basins with a moderately high erosion hazard (8.5%), however, work also needs to be done on restoring forest landscapes, as nearly half of them had a predominantly scrub landscape pattern, placing them in the heavily impaired functionality class. The other half was "saved" by a predominantly forest-type pattern, meaning they could escape classification in the impaired functionality class.

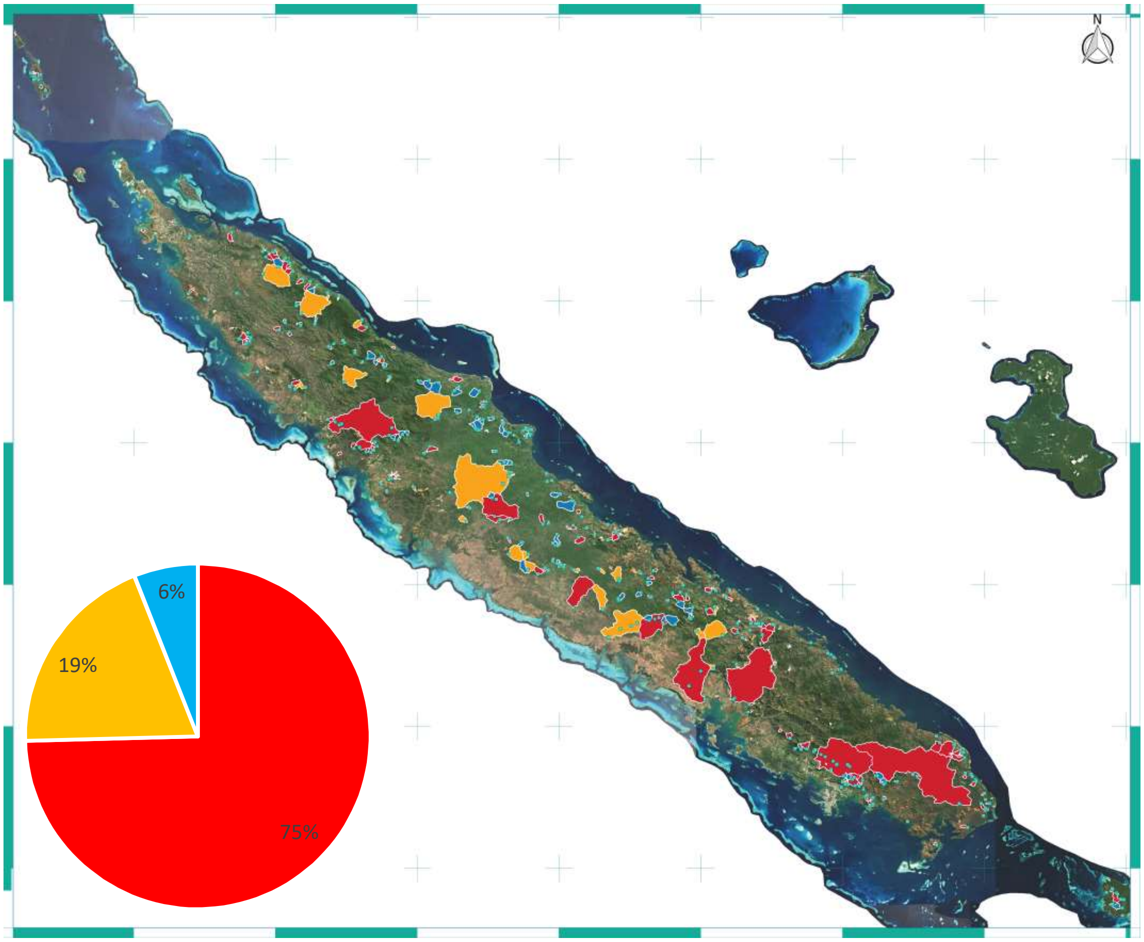


Figure 26 : Results of the diagnosis over Grande-Terre, Bélep Island and Isle of Pines (New Caledonia)

## 5.2 Drainage-basin functionality: an analysis by country: Wallis & Futuna

3225 inhabitants live on Futuna (2018 figures), i.e. barely a quarter of the island group's total population. Six abstraction points currently operate on Futuna, each in a distinctly separate drainage basin. Together they cover 4.17 km², i.e. 9% of the entire island.

Two of them were in a slightly impaired state and only one is qualified as heavily impaired. In surface-area terms, the two "slightly degraded" basins were smaller than the rest and thus cover only 27% of the global collection area. On the other side, the "heavily degraded" area is the same size but is concentrated in one basin alone.

The three basins deemed degraded had a moderate erosion hazard, but its effect was moderated by its extensive forest cover (landscape pattern 1: forest dominancy). The island was, nevertheless, found to have an undergrowth depletion issue due to wandering wild pigs. While the assessment provided an initial indication of the required priority management measures, more in-depth research into the state of the undergrowth would pave the way for more effective water-resource protection initiatives.

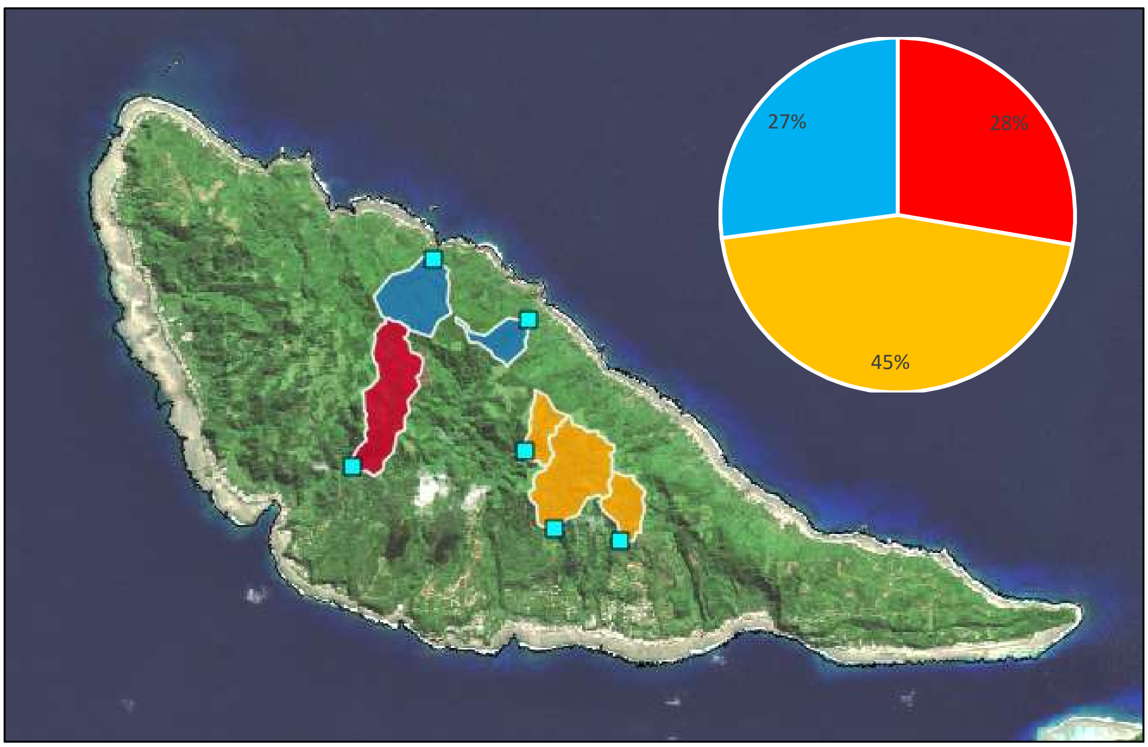


Figure 27 : Results of the diagnosis in Futuna Island (Wallis & Futuna)

## 5.3 Drainage-basin functionality: an analysis by country: Vanuatu

Vanuatu has a very comprehensive database on its population's water resources. It contains all the population's water-supply sources, including rainwater tanks and private wells, totalling nearly 5000 sources. While rainwater tanks and mobile water-supply tanks were systematically excluded, there were still 1660 abstraction points left over.

The assessment covered the 1660 points, but the surface-water abstraction-point sub-category, which was the most relevant to the parameters developed for this study, was extracted for analysis.

| Supply type | Official data | Second selection |
|---|---|---|
| Vehicle-mounted drums or tanks | 38 | |
| Wells | 251 | |
| Water drawn from aquifers | 287 | |
| Desalinated seawater | 4 | |
| Piped water supply from springs | 346 | 346 |
| Piped water supply from surface water | 106 | 106 |
| Rainwater | 3,236 | |
| Spring | 210 | 210 |
| Surface water (pond, stream, lake or river) | 94 | 94 |
| Boreholes | 382 | |
| Undetermined | 28 | |
| **TOTAL** | **4,982** | **756** |

The whole assessment covered nearly 1230 km², i.e. 10% of the 12,200km² country, but unlike New Caledonia and Futuna, it was difficult to assess the surface area affected by the various degradation levels for the whole country, because multiple drainage basins were superimposed due to the series of abstraction points along the same watercourses. The results are therefore presented based on the number of points in each level of degradation.

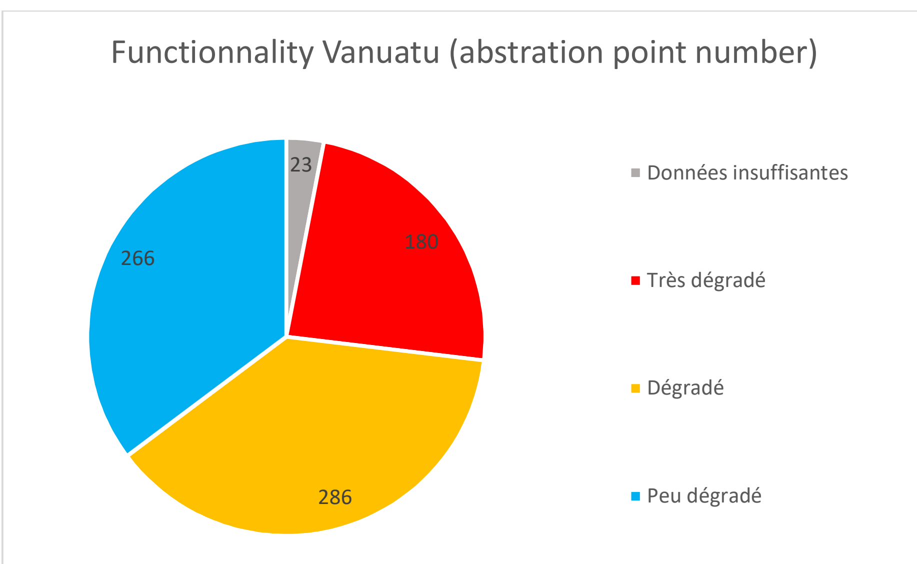

Figure 28 : Results of the diagnosis in Vanuatu (nord area)

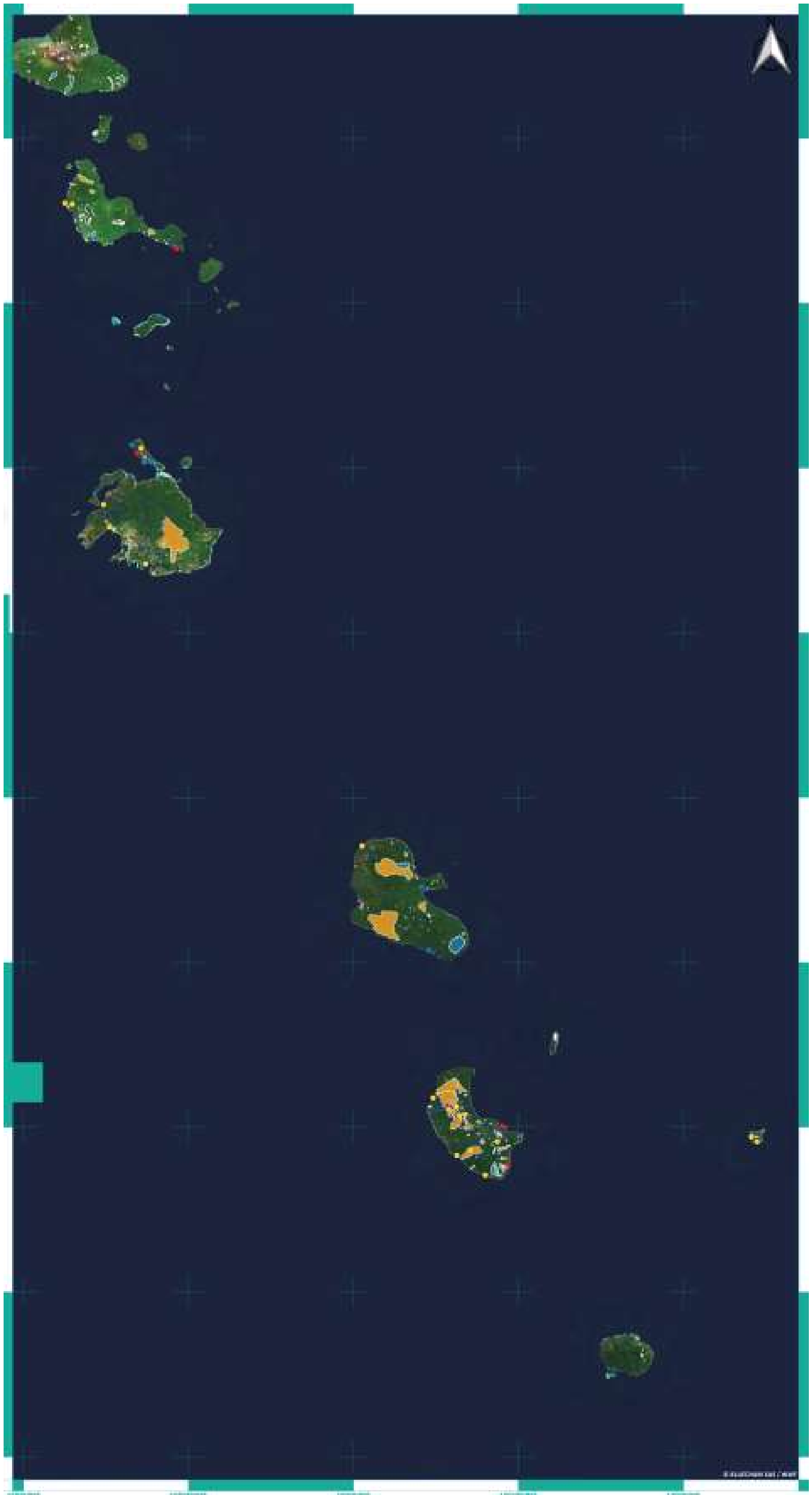

Figure 29 : Results of the diagnosis in Vanuatu (south area)

# 6 ASSESSMENT AND PROSPECTS

## 6.1 The method's technological advantages

The project's aim was to provide a tool for conducting a uniform large-scale assessment with a subsequent follow-up capacity.

The project was therefore based on:

- free satellite images and public-domain climatology and topography data obtained from global programmes (Landsat-8, Sentinel-2) and World Climate Rainfall Data in order to:
    - ➢ carry out a large-scale uniform assessment suitable for defining management policy for a whole territory; and
- the co-operation programme between NASA and the European Space Agency to ensure continuity in data acquisition for the coming 30 to 40 years using the Landsat-8 satellite launched in 2013 with a 10-year minimum estimated lifespan and Landsat-9 that is already in the pipeline to replace it, which:
    - ➢ guarantees long-term monitoring;
- developing artificial intelligence to speed up and reproduce the process and direct large-scale processing in the cloud-storage system, which:
    - ➢ reduces costs and significantly accelerates the processes that facilitate scale changes and low-cost deployment in other countries.
- automating the entire process, in order to:
    - ➢ facilitate handling by managers.

The data and method selection criteria put data accessibility and enhanced processing first for cost-reduction purposes and then sustainability and broad information-source coverage second so that assessments could be repeated based on the same criteria and comparisons made in time and space.

## 6.2 Shortcomings of the current method

### 6.2.1 Application shortcomings

As currently designed, the evaluation cannot be carried out on low islands where water is extracted from underground water lenses, as the issues and role of forests are very different, although the fragmentation and landscape-pattern indicators could serve some purposes. The erosion criterion would not, however, be applicable and water-circulation, porosity, pollutant-seepage or seawater-upwelling factors would be more relevant.

### 6.2.2 Shortcomings of a drainage-basin-level approach

The location of forest remnants in drainage basins, e.g. on riverbanks or in high-erosion areas, may also contribute, however unequally, to maintaining water quality, but is not considered by this method. Agricultural pollution studies based on nitrogen content have shown that the buffer effect of riparian woodlands lowered input by 5 to 30% per metre of woodland (Sabater *et al.*, 2003).

### 6.2.3 Shortcomings of forest characterisation

While this method is an easy way of assessing large forests, its evaluation of forest health is hampered by the fact that satellite imagery can only determine vegetation's highest layer.

A forest is only considered "whole" if all the vegetation strata are present. Forest undergrowth (shrubs, saplings, herbaceous plants and floor litter) not only plays a functional role by cushioning the impact of drops and slowing down run-off, but also contains young saplings that are tomorrow's forest and so a strong indicator of current forests' sustainability. It could not, however, be incorporated in the methodology.

Studies quantifying plant density below the canopy, such as ESA's Biomass mission slated for 2023, will provide a means of including this factor in the method in order make forest-functionality assessments more accurate.

## 6.3 Management prospects

### 6.3.1 An assessment and monitoring tool for all levels

One of the model's advantages is that it is upgradeable. Greater accuracy, fresh information and new criteria can gradually be added to it as new technology develops and further assessments can be devised to overcome the shortcomings highlighted above.

Despite these limitations, this assessment method provides country-level forest-health indicators and helps more precisely identify measures to be taken within a municipality or even a specific drainage basin.

The assessment also addresses forest dynamics by including the sustainability issue and the importance of maintaining ecosystem "support" services. Studies regularly highlight the important role played in disturbance resilience by the biodiversity forests contain. By taking fragmentation into account, both forest fragility during disturbances and intrinsic biodiversity, which is synonymous with resilience, can be assessed.

The method and acquired data are hosted on a cloud and lend themselves to various purposes aimed at improving land-use planning and development in terms of preserving water resources, such as:

- delineating existing water collection boundaries;
- assessing the potential for new abstraction points; and
- monitoring progress in water and drainage-basin management.

### 6.3.2 Assessment towards improved management

The assessment results provide an overview of collection-area impairment in major administrative divisions, such as municipalities, provinces or countries and help prioritise the necessary action.

Forest preservation should be seen as an opportunity to add value to or increase natural capital as the "green infrastructure" needed for the development, security and well-being of communities and not as a burden for governments.

The "real costs" of degraded ecosystem services or their "replacement costs" in the event of forest loss can quickly escalate for government agencies and users in the form of water treatment, infrastructure maintenance and using alternative sources.

When the soil-stabilisation service is compromised and turbidity levels rise, for example, Noumea city council treats the water with alum to coagulate the suspended matter before decanting it. In 2017, 31 tonnes were required at a rate of XPF 100/kg, i.e. a cost of over XPF 3.1 million to the municipality.

This specific operating cost for treating suspended matter comes on top of the capital cost incurred in setting up treatment plants. Studies by RESCCUE in 2016 evaluated the cost of building treatment plants (for flocculation, decantation, filtration and disinfection) with different capacities and found that providing them for the whole country's municipalities and tribal reservations would require an investment of over four billion francs plus an annual operating budget of more than 260 million francs to offset the loss of the soil-stabilisation service provided by forests.

Ecosystem-service payment policies could, therefore, be envisioned for areas where forests are healthy and responsible activities acknowledged as "helping to protect water resources", etc.

Wherever forests are degraded, extensive restoration can be undertaken by drawing on funds for restoring depleted soil, reforestation and carbon storage.  This often requires major investments, but would be cost-effective in the long run because of the direct and indirect benefits and services it would recover.

At the more targeted scale of a drainage basin, the analysis of the decision tree indicators allows for a finer orientation of managers in the selection of the priority measures to be implemented. Protection is necessary to guarantee the conservation of a good state of forests or the success of the undertaken intervention, but restoration actions can also be specified in order to recover the functionality of drainage basin vegetation:

- Reconnection restoration: to reduce forest fragmentation and increase forest resilience
- Targeted restoration: to revegetate bare soil and fight effectively against erosive phenomena
- Protection: in order to promote "passive restoration" allowing vegetation to maintain itself or become a forest again…
- Sustainable development: to promote activities that respect the services provided by the forests, such as organic farming, agroforestry and responsible forestry.

*Example 1:* when the erosion hazard is low with a forest landscape pattern, reducing forest fragmentation can restore functionality. If fragmentation is moderate or high because of a high form index, priority should be given to restoring forest patches to a circular shape, i.e. reducing forest borderland areas. Depending on environment quality and existing hazards, passive restoration in the form of heightened protection for existing vegetation can be considered to ensure forests grow back.

*Example 2:* a heavily degraded drainage basin can be due to a combination of factors, chief of which would be erosion.

- If erosion is heavy, erosion control by, for example, actively reforesting steep slopes would be the priority.
- If it is moderate, however, efforts to transition the landscape from pattern 2 (scrub) to 1 (forest) would raise its functionality status back up to the next level.

Once again, the calculation breakdown for the relevant factor, in this case landscape pattern, specifically indicates which measures to prioritise, i.e. whether by bare-soil prevention by planting or by protecting intermediate scrub formations to support their development into forest in the medium term.

On Futuna, for example, drainage basins become heavily degraded first and foremost because of an extremely high erosion hazard, despite a wooded landscape pattern, and so erosion-control (reforesting the steepest areas) and vegetation-conservation methods must be given priority.

#### 6.3.3 A range of prospects

Assessment quality can be improved with access to more accurate local data, but as it stands, the tool can currently be deployed in any geographical setting based on globally available data. It can be used in other island countries with high islands and drainage basins, such as Papua New Guinea, the Solomon Islands and Samoa, as well as on Indian Ocean islands. It is currently being extended to drainage basins in the Fiji Islands.

This assessment underlines the pivotal role played by forests in preserving water resources and provides guidance for facilitating and enhancing management. Forests are not a land-use planning constraint, but rather genuine natural capital that communities need to reconnect with in a mutually beneficial relationship in order to sustainably maintain the asset for future generations.

**This assessment aims at providing decision-makers with an early-warning and advocacy tool in order to improve management of this green infrastructure that forests represent in terms of water resource preservation. At a time of worldwide climate crisis, communities have everything to gain by investing in nature-based solutions in order to protect their livelihoods. This tool has been made available to the scientific community with a view to pursuing ongoing improvement. It has also been made available to government agencies, who are requested to take ownership of them in order to devise concrete measures on the ground for the good of forests and Mankind.**

**For further information**

Infography : Restaurer la forêt au service de l'Homme (french)

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Project overview : public summary

# The New-Caledonia office in numbers

**2001**

opening year of the WWF France New-Caledonia office

**3**

partner territories included in the forest assessment project

**+ than 600**

volunteers involved in New-Caledonia

**+ than 100 000**

trees planted in order to restore the New-Caledonian forest

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