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► **To cite this version:**

Frédéric Rousseaux, Valentine Judge. Simulating the evolution of stakes on Réunion Island in a context of coastal risk. 2017. hal-01604596

HAL Id: hal-01604596

<https://hal.science/hal-01604596>

Preprint submitted on 2 Oct 2017

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Simulating the evolution of stakes on Réunion Island in a context of coastal risk

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Keywords

Agent simulation, modeling, prospective, spatial analysis, Réunion, stakes, risk analysis, coastline

Abstract

This paper describes a model and a simulation tool which aim at help decision-makers and planners dealing with their processes for territorial prospective analysis. It is based on a practical study case, located on Réunion Island (France). This study has been carried out within the VULNERARE research program, granted by Foundation de France: one of VULNERARE aims is to estimate and assess Réunion's vulnerability in the next 30 years, in relation to coastal risk. This paper is specifically focussing on the dynamics and the future state of two important stakes: population and urban structures. Will urban development of littoral zones increase? How fast and which type of population will be exposed to flood risk in the future? First, this paper presents a spatial model of Réunion territory, as well as its parameters and its main variables. A second part presents a simulation tool - the computation of the model - that estimates the evolution of Réunion over 30 years. Then, a third part describes the simulation's results. Different scenarios are presented and results are overlaid to a natural risk prevention plan. Finally, the limits and relevance of the model and the simulation as tools for territorial engineering are discussed.

Introduction

Réunion (837 000 inhabitants) is an island (2511 km²) located in the south west of the Indian Ocean. Réunion is a French overseas department as well as a French overseas region. It is divided in 24 communes (figure 1). This is the most exposed French region to natural hazard such as cyclones, flooding, volcanic eruptions, and landslides. All the communes of the island are concerned by a risk prevention plan. Yet, many inhabitants settle and build new houses, not always legally, in high exposed areas, such as the coastal fringe, still very attractive. The more these stakes increase, the more important the risk is. Yet, taking into account these risks for planning strategies is crucial because consequences for the population may be really significant. It is currently possible to easily estimate the number of exposed people by overlaying gridded data population and hazard spatial data. But, it appears also relevant for planners and decision-makers to estimate the future number of exposed inhabitants, depending on different urban planning scenarios or on demographic forecasting. The main question we propose to discuss in this paper is: what will be the evolution in 30 years of two major issues of Réunion territory, the urban fabric and the population, in terms of density and demographic structure?

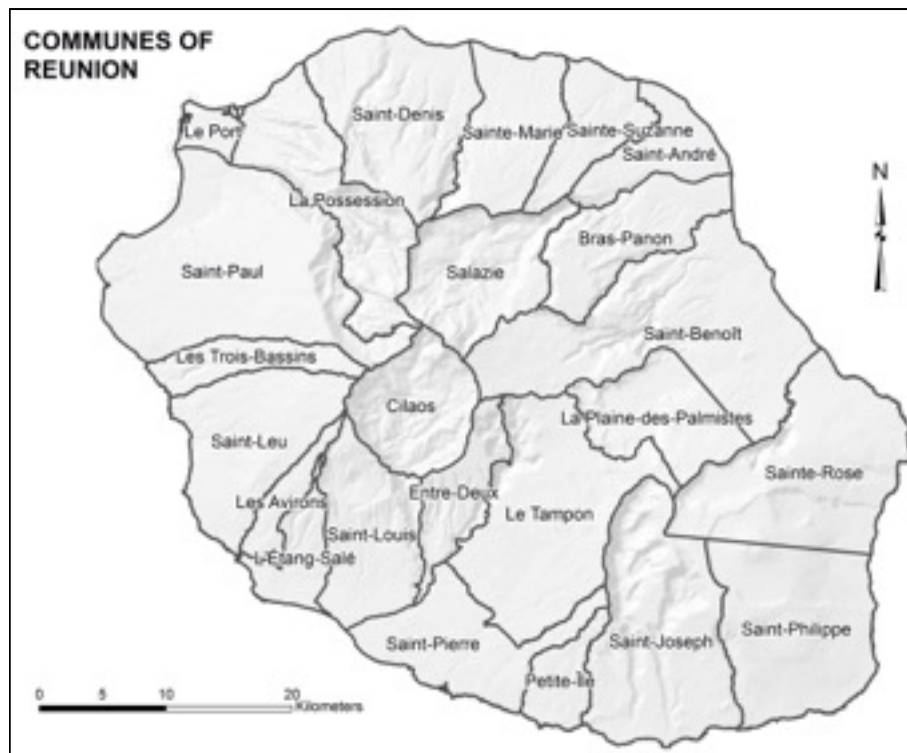


Figure 1. The 24 communes of Réunion

The first step to take into account when considering these questions is how to describe the stakes on the territory. The first part of this article explains how population and urban fabrics are spatially modeled with geographical data. The second part describe the process of simulation - how evolves the model - depending of different trended scenarios, calibrated as inputs of the simulation. The main principle used to represent this dynamic is based « *on the classical economically rational consumer that will choose a residential location by weighing the attributes of each available alternative - accessibility of workplace, shopping and schools* » (McFadden, 1977). Of course, there are lot of more criterions and some of them may vary during life, depending on age and incomes of households (Frenkel, 2013). This principle is a driver of population's moving in and moving out. And this dynamic has direct impacts on urban fabrics by sprawling or densifying. The third part illustrates some results and explores different trends scenarios in a context of risk analysis. Then, our conclusion focuses on the question of validity of this type of simulation. The model can it be, as describes Franck Varenne, (Varenne, 2010) « *a tool to facilitate mediation between various actors, with different representations and/or divergent interest* »?

State of the art

In social sciences, simulation covers many goals, described in (Rennard, 2006), including prediction (what will be the values of my inputs at $t+n$), education (what is happening in my simulation if trend values are modified?) and exploration/discovery (how variables are correlated to other variables?). If, from a scientific perspective, the first approach of this model is prediction, its concrete use and its operational dimension puts this model more in the « education » category. For decision-makers or for the general public, the spatial model often represents a sort of computer simulation of life, a serious game. The analogy with famous video games such SIMCITY is often put forward and cited by many researchers (Gilbert *et al*, 2006).

Prospective simulation involves a set of tools and methods to analyse different, plausible or not, evolution patterns of a territory. The operational aim is to help decision makers and planners to make intelligent decisions in accordance to a vision of future potential states of their territory. The prospective simulation allows to anticipate and to measure different evolution patterns by the variation of parameters values of the model (population, infrastructures, economical context). For that, prospective simulation uses the concept of scenarios (Poux, 2003). Nature, complexity, degree of abstraction and number of parameters depends on the final goal of the simulation.

Many articles present different spatial simulation models. They are classically used for urban expertise and research (Semboloni 2007, Crooks 2007, Wegener 1996), or for urban network analysis (Batty 2005, Torrens *et al.*, 2007). A important number of models also helps to predict land cover or land use. Parker (Parker *et al.*, 2003) provides an exhaustive presentation of such existing models.

When the analysis concerns only a specific territory, the model has to be first based on local assumptions. Specifically, on Réunion territory, Lajoie (Lajoie *et al.*, 2009) proposes a simulation model, based on cellular automata, at medium scale, of land use evolution with proprietary software named METRONOMICA. More recently, on the same area, David (David, 2011) develops during its PhD thesis an agent based model describing population dynamics linked to land use in a land planning context on GEAMAS-NG, an open source agent simulation platform.

By focusing specifically on the notion of stake - what can be physically exposed (Nathan, 2009) - and risk analysis, the contribution of this article is to propose, at a very large scale, the description and the dynamic of urban fabrics and its population (demographic and structure). The proposed simulation is first descriptive and based on individual strategies linked to residence location. For that, agent based modeling is a very suitable paradigm, very used in social sciences, and more especially for socio-spatial models. Agent based models have the ability to represent smoothly actions, interactions and decision processes from actors who « make » the territory. To do that, the model focuses on objects (stakes, households), on their location and their - assumed as significant in the real world - interactions.

A spatial simulation necessarily describes a given phenomenon and the space in which it is embedded. This description - the modeling - and the computation require appropriate (and often very specialized) software. Geographical databases, spatial analysis, cartographic representations are needed to realistically describe the spatial environment of the simulation, but geographical information systems (GIS) do not possess dynamic capabilities. On the other hand, agent-based modeling platforms allow simulation of phenomena in a dynamic context but lack geographic and spatial analysis tools. Agent-based models have an individual-centric structure that identifies the active entities (the agents) and defines their behaviour, which can be influenced by interactions with other agents as well as the environment. « *The environmental model is critical for the Multi-Agent System as it strongly affects the agents' decision making and behaviour.* » (Schule *et al.*, 2004). Coupling spatial capabilities (e.g., managing georeferenced vector data) and agent based simulation platforms (e.g. assigning behaviour and rules to geographic features) has already been implemented in open-source toolkits such as REPAST S based on the GEOTOOLS library (North *et al.*, 2007), REPAST PY (North *et al.*, 2007), linkable to ArcGIS, or the simpler NETLOGO and its GIS extension (Wilensky, 1999). In this paper, the simulation model is implemented in GAMA (Taillandier *et al.*, 2012), an open source agent based model platform. This software handles out both geographical data management and simulation process. Furthermore, the soft has extremely fast computation time, even with a significant amount of agents in the model. This last point is very interesting here, because it allows a strong interaction with decision makers and elected representatives when presenting or working directly on scenarios making.

1) Modeling the territory

The objective of the modeling of the territory of Réunion is to measure and to analyse the evolution of two types of stakes: Population and urban structures. This modeling is carried out with statistic data, geographical data and a GIS. Then, the simulation process, described in part two, makes the model dynamic and allows analysing evolution of stakes. Operationally, it should help to localize and to visualize potential futures vulnerable areas. The making of this model relies on two different goals for the researcher: a better understanding of urban and demographic dynamics on the territory and the use of a common tool with decision makers and elected representatives.

The model describes the state and the evolution of urban structures. Each urban structure corresponds to a level of urbanization of the territory. Then, each structure evolves depending on the amount of households who moves into: the more important the number of household is, the faster the urban structure evolves toward a higher level. The dynamic of households (which stands at the microscopic level, individual)

is simulated on the whole Réunion territory. It impacts urban structures that are at the mesoscopic level (100m² pixel). And the aggregation of pixels of the same structure arises new urban fabrics and new urban shapes, visible at the macroscopic level. The dynamic of households depends on their degree of satisfaction. It may evolve depending households surrounding. The satisfaction degree is linked to two types of parameters:

- A social parameter: is households with similar wealth surround the household?
- A spatial parameter: is the household is not too far from services he needs (school, stores, network, activities...)? This parameter varies depending age class of the household. Does the household live in a urban structure to which he aspires? The type of amenity and the type of urban structure targeted may be different for a 20-30 years household and for a 40-50 years household.

If the household is unsatisfied, after a certain number of cycles, it will move out. The household will move in a plot with a similar or higher degree of attractiveness. From a theoretical perspective, this is a combination of a Schelling model, in a non-isotropic space and a spatial model of attractiveness based on distance/time to a large set of amenities. The calibration of values parameters is empiric and is adjusted with statistic dataset from the French national statistic institute (INSEE). Values are also adjusted by surveying the population of Réunion in order to better target their aspirations. Finally, the space is not isotropic. It is not buildable at a same level everywhere. The model adds a set of constraints that will limit or prohibit constructability areas. As a consequence, it will orientate the way the urban structure evolves, by densifying or by sprawling, depending on the constructability of the area - the buildable index.

1.1) Structure of the model

The model consists of two class of agent: the household agent class and the plot agent class, as described in figure 2. The study is carried out at a very large scale. The space is divided into cells measuring 100m². One turn of the simulation is equivalent to one year in the real world.

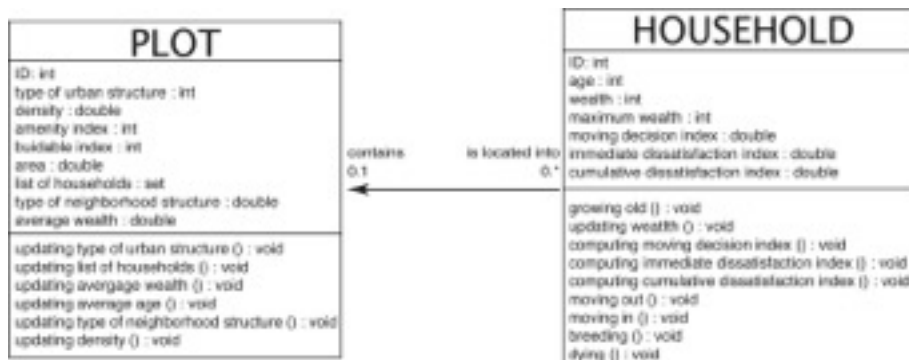


Figure 2 : UML class diagram of the model

1.2) Geographical data used in the model

The main interest when working with geographical data with the multi agent paradigm is to consider each geographic object as an agent class in the model (Taillandier *et al*, 2012). The model describes agents plots and households from the aggregation, by multi criteria analysis, of a large set of data, extracted from BDTOPO¹ (National French Institute large scale database) and gridded population data from INSEE.

1.2.1) Households

Population is represented with a set of households, located on the whole territory of Réunion. Gridded population from INSEE database contains information such as number of persons, number of households, number of person per age group, total income, etc. In the model, age attribute is computed per household, and not per person for two reasons. First, it is necessary to optimize the amount of agent in the model.

¹ Base de données topographique - topographic database

Second, move in and move out processes concern more often households, rather than individual person. The « -20 years old » age group is reintegrated to other age groups because it is considered that this age group is often attached to an existing household for move in and move out process. Each household has a wealth attribute, randomly distributed and a different range of values for each age group. Wealth attribute is not an exact value but has to be considered as a relative social marker that helps to classify households from low to high income. The distribution is generated by a trend, estimating that old households are generally richer than young households. For each household, wealth value increases during the start of each cycle randomly. Household agents can make different action that will be described in part 2.

1.2.2) Plots

Plots are 100 meters square cells. The whole territory is divided into cells. Plots are described by four attributes:

1.2.2.1) The population:

The population corresponds to the number of household in a cell. It is an interpolation of the total population, computed from 2012 INSEE dataset. These geographic data provide information on population, age group and reproductive rate (computed from natural balance of Réunion).

1.2.2.2) The amenity index:

The amenity index is computed for each cell of Réunion territory. This parameter represents the quality of life and the attractiveness of an area. Households are attracted by pleasant equipment or environment and are repulsed by others. The amenity concept reflects tangibles and intangibles benefits of immediate surrounding and/or social neighbourhood of an area. As *homo oeconomicus*², each household tries to maximize its benefits by moving in an area where a set of amenities is important to him. As examples, primary school, hospital, view on the sea or a park attract more than a waste incineration, a railroad track, an airport or industrial areas, considered as potential sources of nuisance or pollution, notwithstanding amenities may vary during life: primary schools attract only households with young children (household from 20-30 and 40-50 age group). Amenities are hardly evaluated in financial terms. They raise two questions: their weight and the notion of their « proximity ». We propose to answer these two questions through surveying inhabitants of Réunion Island. The questions are focused on services or equipment that have positive affect (Fig 3) or negative affect (Fig 4) for their residential location choice. Proximity concept and amenities weighting are primarily addressed in an online survey. A sample is attached figure 5 (Fig 5).

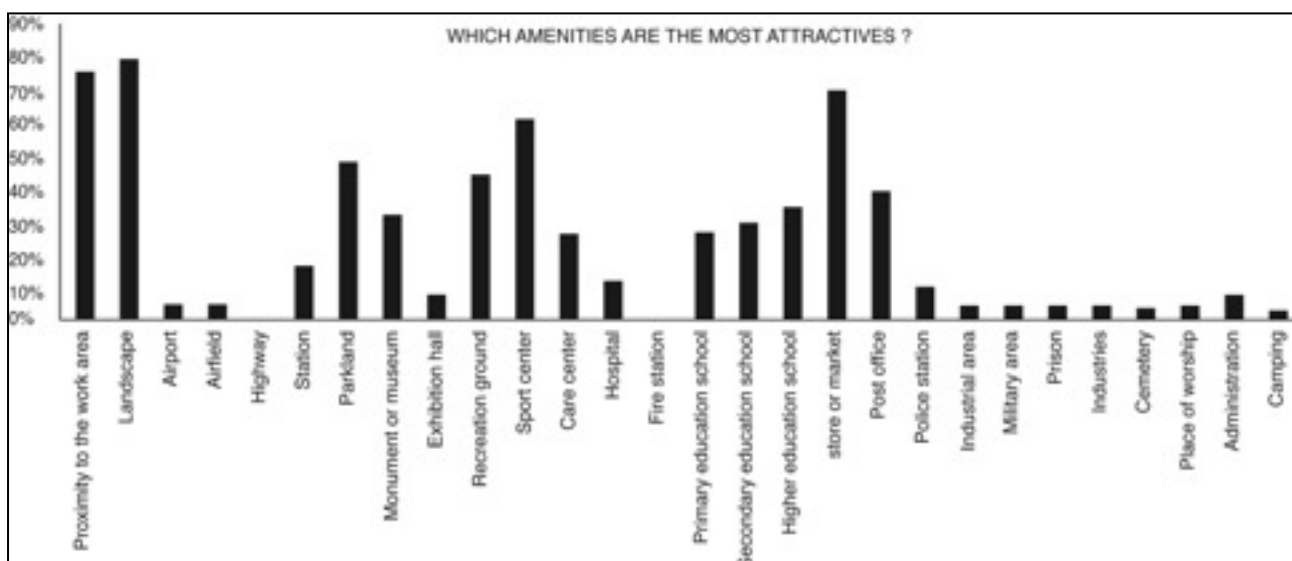


Figure 3 : Equipment with a positive impact on an area

² as described by John Stuart Mills

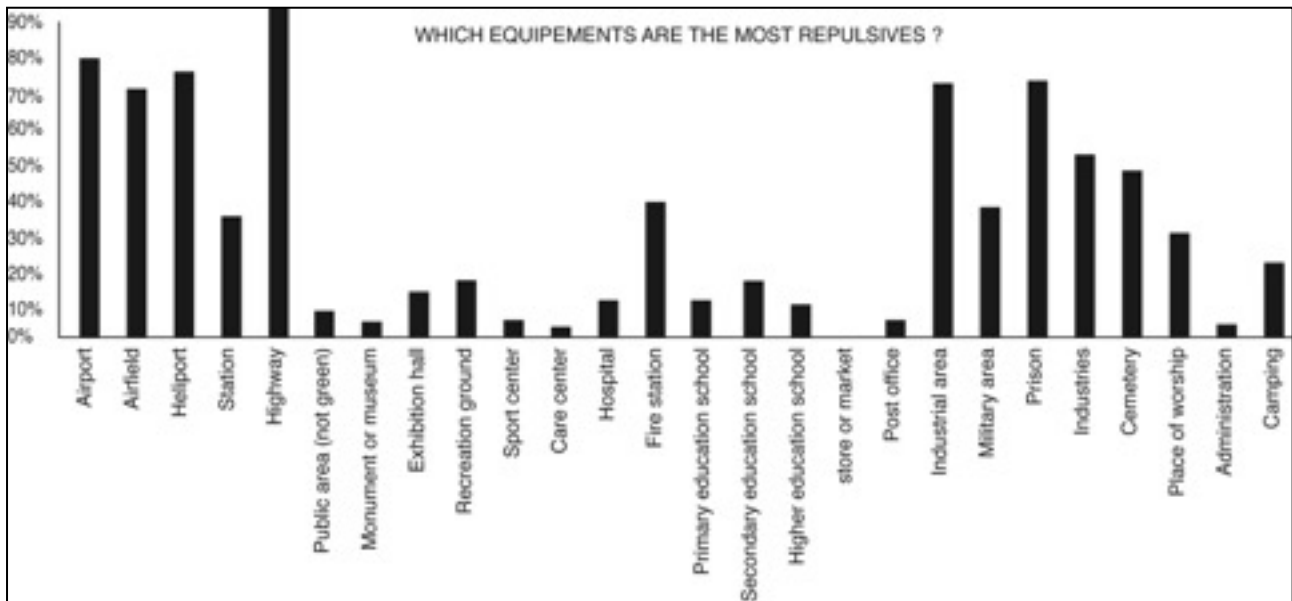


Figure 4: Equipment with a negative impact on an area

The sample of the survey is not consequent (40 persons) but it targets specifically Réunion inhabitants where culture, insular and tropical context may influence perceptions. The method is to propose a very short amount of questions (less than 10) in order to encourage responses, to focus on priority and to highlight exploitable information.

3. Which elements have a positive impact on your residential location ?

<input type="radio"/> Proximity to the work area	<input type="radio"/> Secondary education school
<input type="radio"/> Landscape	<input type="radio"/> Higher education school
<input type="radio"/> Airport	<input type="radio"/> store or market
<input type="radio"/> Airfield	<input type="radio"/> Post office
<input type="radio"/> Highway	<input type="radio"/> Police station
<input type="radio"/> Station	<input type="radio"/> Industrial area
<input type="radio"/> Parkland	<input type="radio"/> Military area
<input type="radio"/> Monument or museum	<input type="radio"/> Prison
<input type="radio"/> Exhibition hall	<input type="radio"/> Industries
<input type="radio"/> Recreation ground	<input type="radio"/> Cemetery
<input type="radio"/> Sport center	<input type="radio"/> Place of worship
<input type="radio"/> Care center	<input type="radio"/> Administration
<input type="radio"/> Hospital	<input type="radio"/> Camping
<input type="radio"/> Fire station	<input type="radio"/> Dam
<input type="radio"/> Primary education school	<input type="radio"/> Others, describe : <input type="text"/>

4. When you are walking, what means "near" if you need to go daily or regularly in this place ?

5. When you are driving, what means "near" if you need to go daily or regularly in this place ?

Figure 5: Sample of the online survey form

From the location of a large set of equipment (more than 40), and with a road network analysis, services areas are computed for each feature class (Fig 6). Areas with the higher potential of attractiveness are logically located near major urban centers and immediate suburbs. Other intangibles criterias are added such as sea view. Coastal areas appear more attractive than inlands areas for obvious reasons of accessibility, even if it is not the only reason: West coast and North-West coast do not appear very attractive, mainly because of the lack of network and services and the proximity of the active Volcano Piton de la Fournaise. Finally, coastal areas appear clearly differentiated between them.

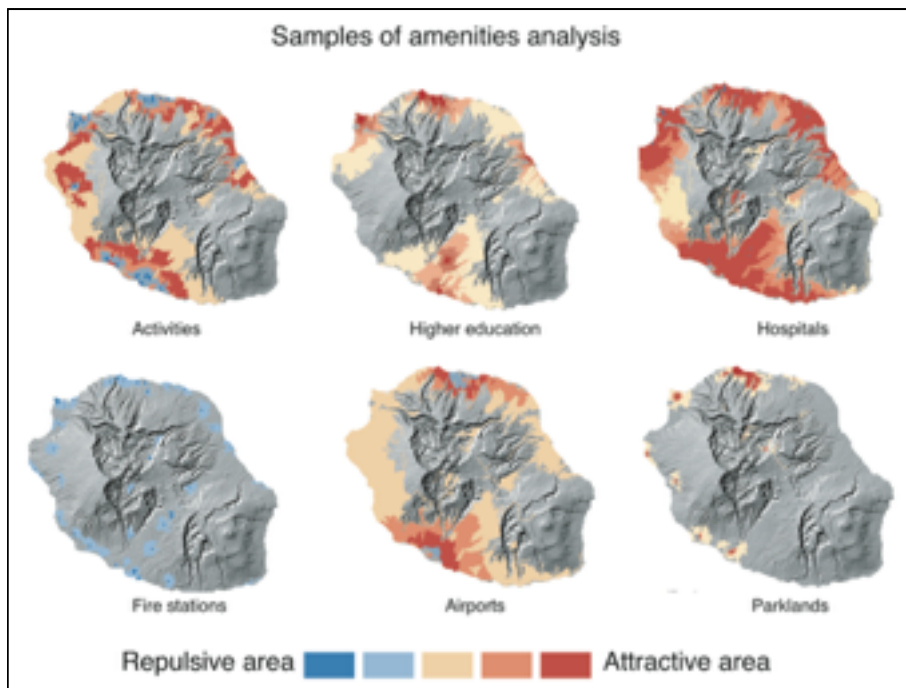


Figure 6: Examples of different amenities proximities computation³.

The map of amenity index shown in figure 7 is computed by multi criteria analysis from the whole set of amenities analysis data and weighted according to their importance.

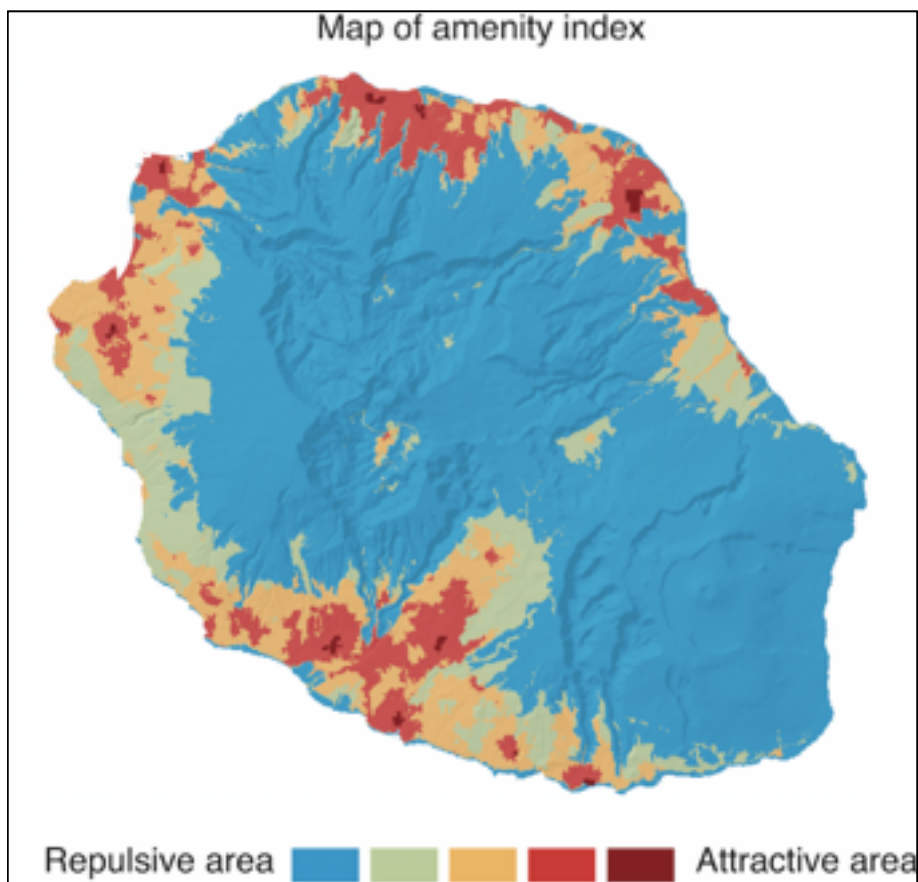


Figure 7: Map of amenities index areas

1.2.2.3) The buildable index:

³ Some equipments are repulsive at short distance and attractive from a certain distance. e.g. : Airports or big malls

The buildable index represents a degree of constructibility for each plot. It is computed considering physical constraints (slopes, land cover), regulation constraints (protected natural areas, risk prevention plan...) and a probabilistic approach - What categories of land use has been the most often built during these thirty last years on Réunion. The higher the buildable index is, the higher the probability the plots have to receive new households for settling is. This buildable index, shown in figure 4, is computed on the whole territory of Réunion. It is again, the result of a multi criteria analysis.

The first step is to analyse how land cover evolves: by comparing land cover - from the Corine land cover database - between 1990, 2000 and 2006, categories that have statistically the highest probability to turn into artificial areas are highlighted. As a frequent example, newly artificial areas (categories 1 in 2006 Corine land cover database) are first natural areas (in 1990), before turning into agricultural areas (in 2000). Generally, on Réunion territory, an important increase of artificial areas is noticeable.

Physical parameters are also taken into account such as slope. This is a key point concerning constructibility. Réunion is an island of rugged slopes and substantial changes in elevation, mainly because of the erosion of the volcanic surfaces. An important slope limits building and/or increase costs. To detect them, a digital terrain model (DTM) from French national mapping agency (BD ALTI 25 meter precision) is used. Lajoie and Hagen-Zanker (Lajoie *et al*, 2009) consider slope higher or equal to 30% as a limiting factor concerning urbanization on Réunion Island.

Proximity to urbanized areas is also taken into account. Areas located in immediate surrounding of existing urbanized areas have a higher probability to be built, mainly because of existing networks such as road, electrical or water. Stores or activity are already settled and they attract new households. This is the concrete aspect of what the urban sprawl is. Distances to existing urbanized areas are computed as a distance cost, weighted by slope.

Land use plans are also integrated to estimate the constructibility of plots. Réunion Island is covered by several regulatory zones and protected areas related to hazard (risk prevention plans), and habitat conservation.

Finally, This all set of parameters is weighted to compute the buildable index on Réunion territory, as shown on the map (Figure 8).

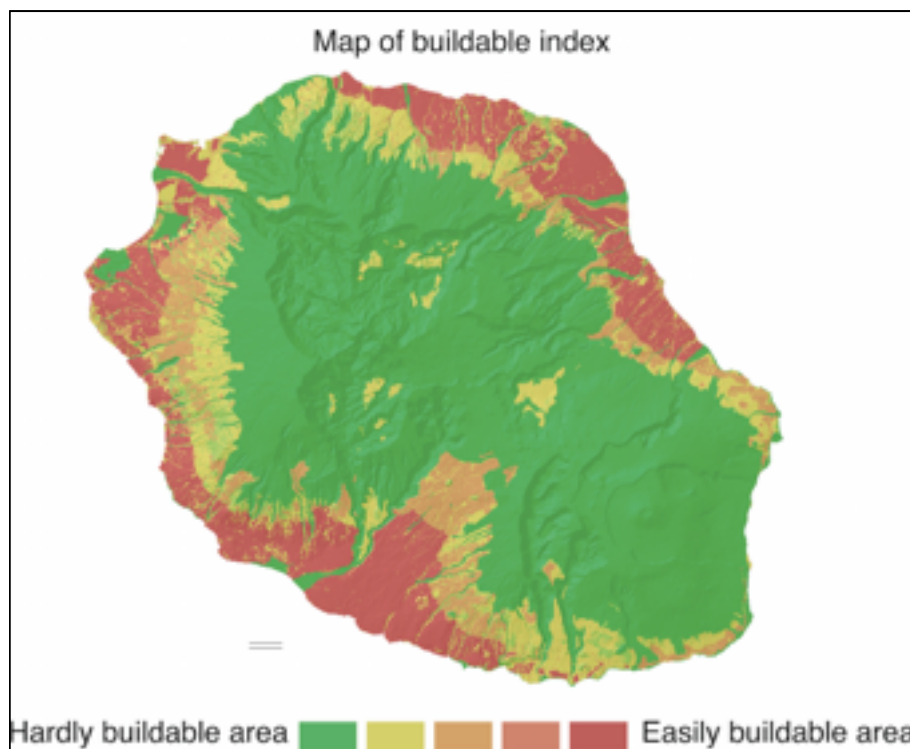


Figure 8: Map of Buildable index

1.2.2.4) The urban structures categories:

Three parameters appear relevant to describe urban structures on Réunion Island: Shape of buildings, Land cover and spatial distribution of buildings. According to Long (Long, 2003), building's structure can be described with building's height weighted by floor area, volume, perimeter, compactness, and land cover (surface of roads, vegetation and water). Spatial distribution is calculated with total number of buildings and average space between them for each plot (cell). These parameters enable to classify homogeneous urban structures categories. The method is based on a K-Means clustering as described in (Long, 2007). This non-hierarchical classification method consists as a partition of data that aims to partition observations into clusters to highlight the structure repartition of space data⁴. Réunion Island is covered with 5 different urban structures categories, as described in table 1 (table 1): 4 categories, which can evolve in an upper category (1,2,3,4), and one excluded category (7), that describes industrial and activities areas. The category 7 is not used for the simulation because it is submitted to very specific processes of evolution and these dynamics haven't been explored yet. Even if Corine land cover data can help to model some changes on this category, it is still difficult to predict the evolution of industrial and activities areas.

Urban structure category	Description
Category 1	Natural areas, no building
Category 2	Agricultural areas, few buildings
Category 3	Low density urban areas
Category 4	Dense urban areas
Category 7	Non habitable areas (water plans + industrials and activities areas)

Table 1: Description of urban structures categories

Classification's results are verified by crossing with IGN topographic database (BDTOPO) and Corine land cover database (figure 9). As an example, only the classification process cannot directly characterize industrial or activities areas. To do that, Corine land cover database allows distinguishing these areas from urban areas.

Finally, a « category 5 » representing potential futures « very dense areas » is integrated in the model. This category does not exist today but it is intended to represent a probable future urban structure category. This one will be composed of higher and denser building than those existing today. This category is expected to emerge in actual urban center, as a result of a densification process.

⁴ « In this method, K points are assigned as center of K classes, the euclidian distance is calculated from each elements to centers. Elements are assigned at the nearest center's class. Centers of each class are calculated again et the previous process is reiterated until tue algorithm converge on a stable position by minimizing the variance» (Long, 2003)

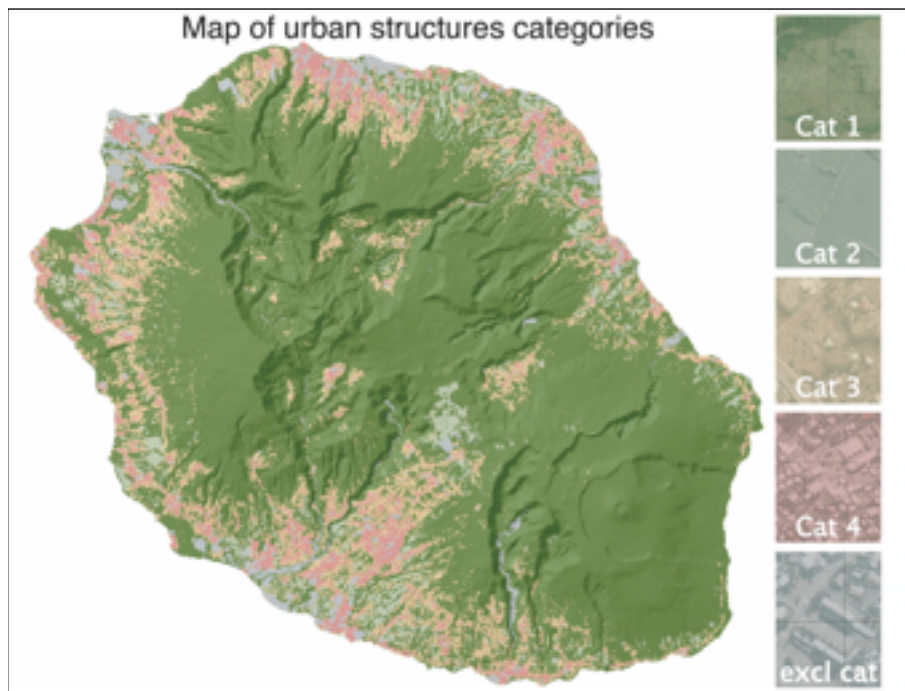


Figure 9 : Categories of urban structures

1.2.2.5) The unavailable data

Local urban planning documents are not available on the whole territory. That is why they are useless for this model. However, The real impact of this information is to balance strongly. A previous study lead on the French city Nantes in 2011 (Rousseaux, 2011) has integrated these documents and shown the low impact on urban evolution because of the important volatility (frequent changes of shape of areas or planning rules). These documents are not effective for urban predictive analytics.

2) Simulation of the model

2.1) Process, structure and initialization of the model

This part describes the order of each process and updates of variables.

- Households can do the following actions: to grow up (every cycle), to enrich itself (every cycle), to reproduce itself (at a given age), to move out (depending on the satisfaction index), to move in (if move out is in progress), to die (depending an increasing probability from a given age).
- Plots can do only one action: to evolve (depending on the number of households living on it and urban structure category of neighbour plots).

For each action, the process is described in the following part of this paper. Variables updates as occurring synchronously at the end of each action, unlike asynchronously occurring that updates all variables simultaneous at the end of one cycle. At this current state of implementation of the model, agents don't learn from their choices and don't change their strategy depending on previous actions.

At its initialization, dataset of the model represents 382520 plots agents (655x584 cells), and around 300000 households agents. A lot of parameters can be controlled toward a general user interface (birth rate, neighbourhood tolerance, amenities and buildable index weighting, etc.). Initialization of plot's variables depends on input's geographical data values, from the four raster as described in part one. Each plot knows its urban structure category (and it's neighbourhood structures categories), its population, its attractiveness and its buildable index.

2.2) Description of agents and sub models

2.2.1) The plot agent

The plot agent corresponds to a pixel of a grid. The extent of the grid is similar to raster used in part one. The plot agent is characterized with four attributes: population, urban structure category, buildable index and attractiveness index. The dynamic of this agent is not spatial and is linked to one sub model. This model controls the urban structure category dynamic.

2.2.1.1) Description of the plot's sub model

At initialization, plot is characterized with four values as described above. Only the urban structure category value can be modified. The dynamic of this one is based on two parameters: the number of households situated on the plot and the buildable index. The buildable index influences how fast the urban structure category of the plot evolves. The urban structure category is evolving depending on a given number of households. When the threshold of household is reached, then the plot evolves in an upper category. This threshold is a modifiable parameter. Each threshold is different, depending on the buildable index and the structure category. When the buildable index is low, then the structure evolves more slowly. It also means that the plot needs a more important number of households to evolve. Some areas on Réunion have a buildable index equal to zero and will not be build whatever the household pressure exerted.

A last constraint concerns the neighbourhood of the plot. There cannot be more than two level of difference between neighbourhood structure categories. If a plot is in category 4 and majority of its neighbourhood is equal to category 2, then the category five will not be reached until the majority of plot turn 3. This constraint helps the model to have a more realistic urban evolution. it allows to have coherent urban fabrics and avoid category five plots in the middle of nowhere. To sum up, the plot agent is aware of its neighbour (Moore neighbourhood) and it can be constraint by its immediate surrounding. The cycle of the plot agent is described on figure 10.

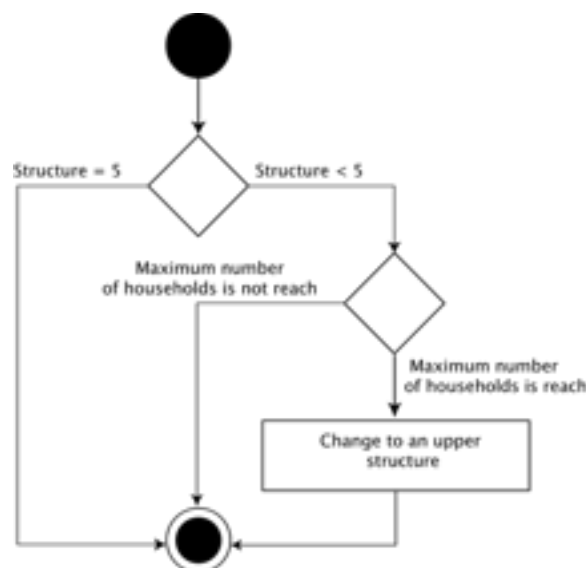


Figure 10 : The cycle of plot agent

2.2.2) The household agent

The set of household agents represents the population on Réunion Island. Households corresponds to 2,8 persons (INSEE, 2010). This agent is created with values of the population grid. Depending on this value, a number of agent is created for each plot (pixel). Each agent has four attributes: age, wealth, immediate dissatisfaction index and cumulate dissatisfaction index.

2.2.2.1) Description of the household's cycle of life sub model

The initialization of the age of household is based on 2010 INSEE data (table 2). Because it doesn't make sense in the reality, the model does not create a 0-20 age group household. Population from this group are dispatched in 20-59 age groups. In the model, age groups start from 20 to 30 years to 80 years and above. There is an age group every 10 years.

	REUNION 2007		REUNION 2040	
	Population	%	Population	%
0 to 19 yo	278400	35,1	289700	22,4
20 to 59 yo	426500	53,7	497400	46,6
60 to 79 yo	76000	9,6	210900	21,3
80 yo and more	13200	1,7	62800	9,7
Total population	794100	100	1060800	100

*Tableau 2: Population of Réunion per tranche age group in 2007 and 2040
(Source: population projection, INSEE 2010 - trend scenario)*

After 80 years old, household can die. For each cycle, he has an increasing probability of death.

2.2.2.2) Description of the household's enrichment sub model

Wealth's household corresponds to a social level. This is a basis for a comparison with other households. The aim is here to recreate a social ranking. At the initialization, wealth value is randomly distributed in each age group. Older households have more chances to be rich than young households. The annual (one cycle) increase wealth value is based on starting wealth of the household. From this value wealth is randomly increased between 0 and 10%. From 60 years old, household is considered as retired and wealth remains constant and does not increase anymore. Wealth parameter is important because it helps to model the segregation process. Many studies (Schelling, 1970) have highlighted that population have tendencies to socio spatial segregation, and they tend to settle in a neighbourhood they consider as representative of their social class. Concerning this urban simulation, it has strong impact on shape's cities evolution by sending poor population far from amenities. This sub model is based on the classic Thomas Schelling's segregation model. A boolean function of satisfaction characterizes the household agent. This function has also a tolerance parameter. If the difference between the wealth of the candidate household and the average wealth of households of the plot, then the household is not satisfied. The parameter can be used with a rough value or with a cumulated value and a number n of cycle.

2.2.2.3) Description of the household's move in and out sub model

As explain below, household make an evaluation of its neighbourhood. Household behaviour is based on a hedonistic reasoning: his aim is to live on a plot with the higher attractiveness degree, in relation to his group age and his social class. When household has to move out, he consults a list of potential plots, with an attractiveness degree similar or higher than his plot's current degree. Then, he checks the average wealth of targeted plots. If more than one plot fits, there is a random choice. It is also necessary that the number of household in the plot have not reach its maximum allowable (only in the case of a category five plot). Household agent does not present collective behaviour: each agent is looking for its best plot without any interaction with other agent (cooperation, predation, learning).

It is possible to limit the number of moving out action during each cycle, in order to avoid massive and unrealistic population movements. Indeed, in the real world, even if a household is unsatisfied, he may not have the immediate opportunity to move out. A synthesis of household actions is presented in picture 11.

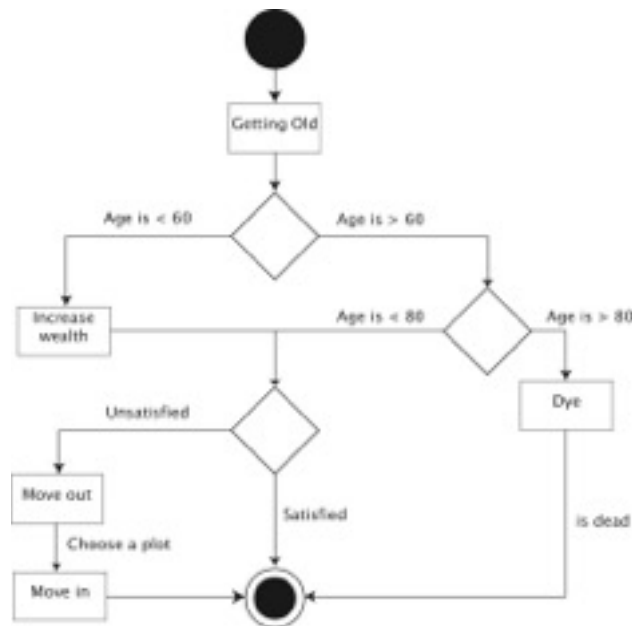


Figure 11. The cycle of household agent

This model allows us to simulate (at 30 years) the spatial distribution of population for the whole Réunion territory. It is possible to access to two type of information:

- A spatial information with urban structure category, number, age and wealth of agents for each plot, as maps
- Statistics with the number of households in each group age and the number of plots in each urban structure category, as charts

With these data, an evaluation of exposed stakes (urban structures and population per age group) to coastal risk and landslide can be performed.

Appropriation of this model, by non-specialists, has to be clear, simple, and even, playful - as a game. This last point remains how important it is to work with a very friendly and understandable user interface tool. It would also allow very short computation time when simulation is running mainly because it is important to answer and to show results as fast as possible to decision-makers requests. This is this kind of mediation between decision-makers and the tool that allows the more efficient interaction on modeling's commitments. GAMA, the simulation platform used for this study, fulfils the necessary conditions with a very simple code structure and even with a very large amount of agent. Computation time for one single cycle are always under 30 seconds. Simulated results on maps and information on charts are then accessible to decision-makers in a very short time for discussion and potential changes.

3) Results: presentation of different scenarios of evolution of Réunion territory

Different proposals of scenarios and corresponding results are presented in this last part. Each of them play with different parameters, not to give any accurate forecasting, but to illustrate how the simulation can be used with decision-makers as a tool for discussion. First, two simulation results of two different scenarios based on birth-rate variation parameter are discussed. Then, three scenarios, based on planning strategies cases studies are proposed. Finally, an overlay between hazard simulation of a natural risk prevention plan and a result of a population simulation illustrates the operational interest of this model.

There are two main types of scenarios (Poux 2003): the trend scenario follows the most plausible assumption on the territory. The second type of scenario proposes a more contrasted vision, more explorative. This low likelihood scenario may be interesting to present because it highlights strongly trends and exaggerated results may influence decision makers. For this last scenario, it seems interesting to work on

the population parameter. A huge increase of the Réunion population will have very important impacts in terms of human and urban stakes and more globally in future coastal risk management.

3.1) The trend scenario

The trend scenario is set from INSEE database and adjusted on their predicted fertility rate⁵. From 837 000 inhabitants in 2012, Réunion Island is expected to reach 1 061 000 inhabitants in 2040. The figure 12 presents the evolution of household's density over 30 years. The figure 13 presents the evolution of urban structures categories.

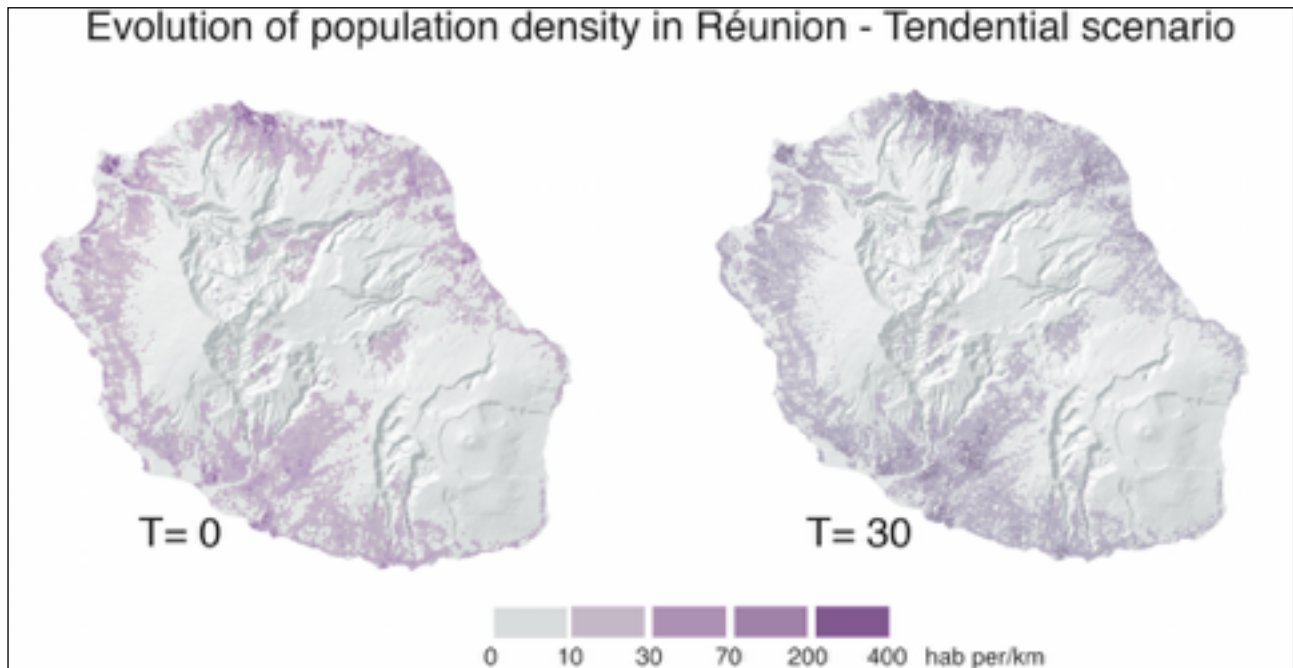


Figure 12 : Tendential scenario, evolution of population density over 30 years.

A relative densification of the population and an evolution of urban structures can be observed around cities centers, as Saint Denis in the North and Saint Pierre in the South of the island. Proximity to numerous amenities, a very important road network, and for Saint Pierre, a relatively flat ground, make these areas very attractive for the population. The commune of Tampon in the South, located in the hinterland of Saint Pierre increases strongly also its population. This commune, located near a important administrative center, Saint Pierre, is very well connected, has low slopes, no natural areas and is very agricultural in 2012. These features explain why its population should increase 30 years after. At a global scale, there is no important urban sprawl. Important transitions occur between category 3 (low density urban areas), 4 (dense urban areas) and the new category 5 (very dense urban areas). As a reminder, urban structures of category 5 don't exist at the initialization of the model. They characterize a potential densification of present city centers. In this trend scenario, population pressure is not very important (+225000 inhabitants over 40 years). Plot in category 1 (natural areas, no building) and 2 (agricultural areas, few buildings) present a low attractiveness, mainly because of their distance to existing network, their lack of infrastructure and their ground with important slopes.

⁵ In 2009, the fertility rate is 2.38 children per woman

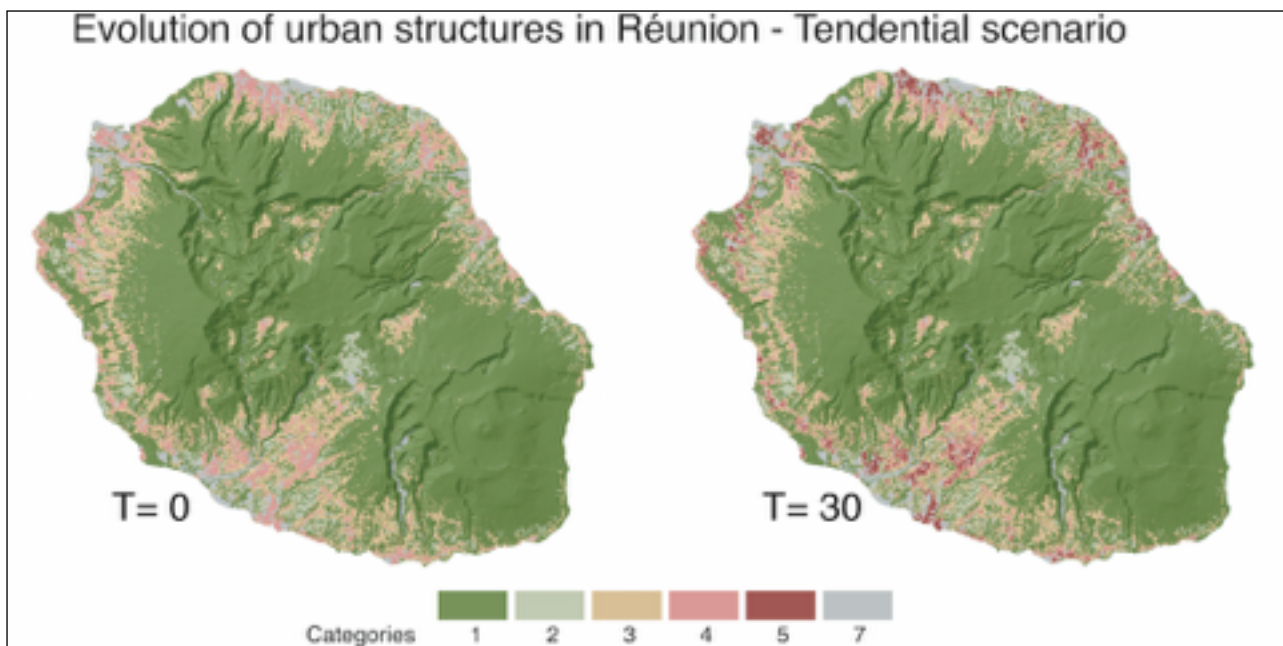


Figure 13 : Tendential scenario, evolution of urban structures over 30 years.

This densification phenomenon rather than urban sprawling is a major point of the spatial planning document of Réunion⁶. This document explains how it is important to reconcile demographic rise, housing and infrastructures needs and natural and agricultural resources⁷.

3.2) The important population growth scenario

This scenario illustrates an evolution with a strong immigration and a very high birth rate. Figure 14 shows the evolution of population density, much marked than the trend scenario.

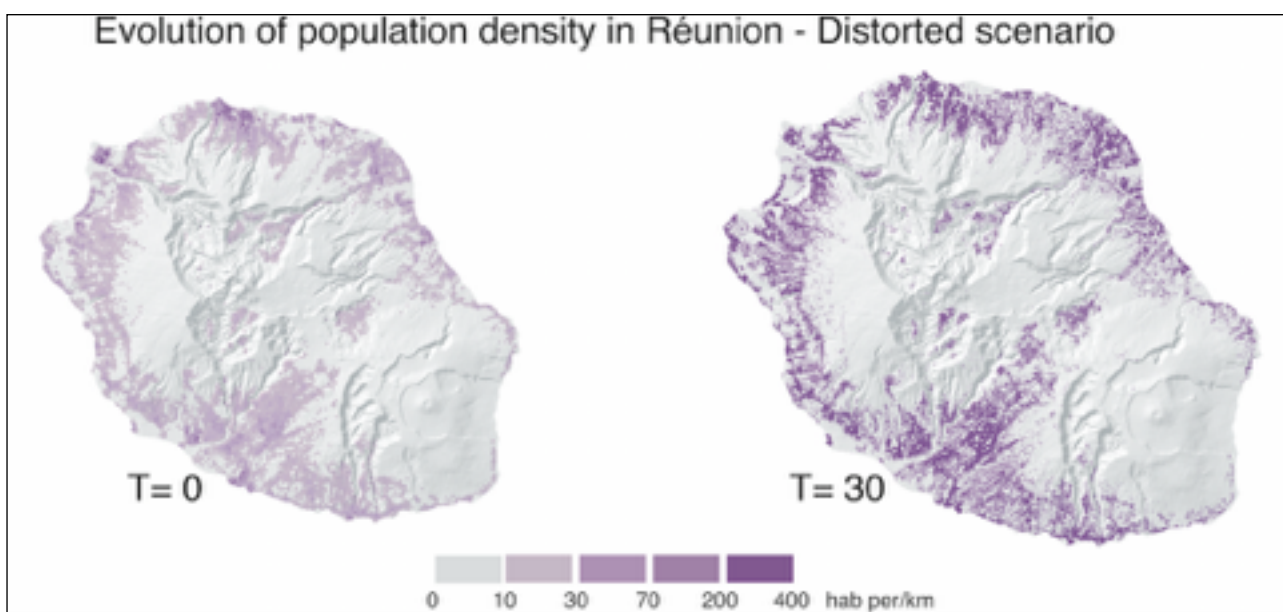


Figure 14: Important population growth scenario.
Evolution of population density over 30 years.

⁶ Schéma d'Aménagement Régional 2011 de La Réunion

⁷ « concilier essor démographique (1 million d'habitants d'ici 2030), besoins en logements, en équipements urbains, en emplois tout en préservant le capital territorial naturel et agricole » (Schéma d'Aménagement Régional de La Réunion, 2011)

The Figure 15 presents the evolution of urban structures categories over 30 years on Réunion.

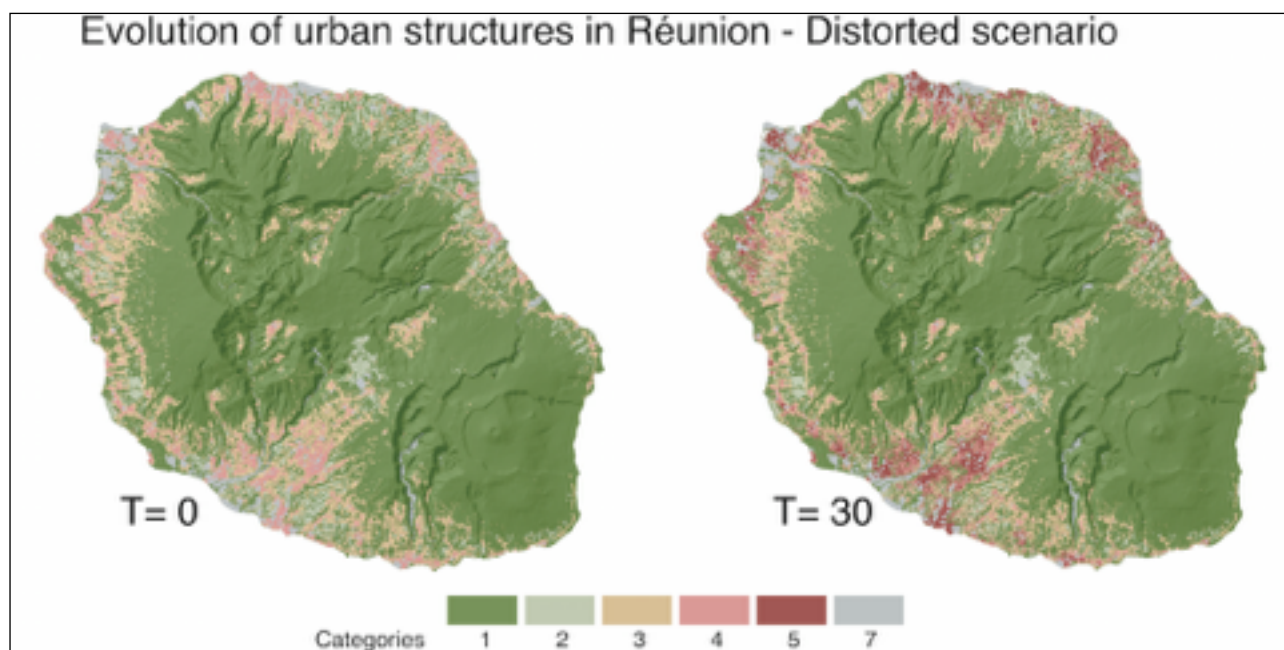


Figure 15 : Important population growth scenario.
Evolution of urban structure categories over 30 years.

These results, more distorted, highlight a more important sprawling of the population. The impact is visible on urban structures, particularly on high vulnerability areas, such as coasts. Areas with a substantial evolution are the same than the previous simulation but are much more pronounced. New areas with significant population density appear: Attractive areas, after Saint Denis and Saint Pierre, are located on municipalities of Le Port and Saint Paul at the west of the Island: the topographic surface corresponds to a relative small flat area⁸ favourable to new urbanization zones. At the Northeast of the island, Saint André seems to correspond to a good area for future urbanization. By contrast, the eastern side, Between Saint Benoit and Sainte Rose does not present any urban area, mainly because of a complex topography and its proximity to the very active volcano Piton de La Fournaise.

3.3) Exploration of alternative urban scenarios on Saint Denis municipality

This part focuses on the municipality of Saint Denis de La Réunion to observe how urban parameters can influence the simulation. Saint Denis is particularly rugged with few lowlands formed as a thin coastal fringe. Perpendicular to the sea, canyons slice the ground of the municipality. Constructibility is very low except on the coastal fringe, where the vulnerability is the most important. The municipality is one of the most attractive of the Island, mainly because of an important economic activity. Many activities and industrial areas reduce more and more buildable areas and arise the question of competition between living and activities areas. A first simulation shows, as a reference, the trend evolution of this commune, based on the scenario described in part 3.1 (simulation 1 - figure 16). The second scenario proposed (simulation 2 - figure 16) turns into constructible plots, activities and industrial areas. Because they are located in very attractive zones and offer a high buildable degree (flat ground, well connected), they are densely populated and built after 30 years. Because these areas are densely built, sprawling is very limited in other areas. The third simulation remains industrial and activities areas non-buildable but shows the local impact of a new and very attractive equipment (simulation 3 - figure 16)

⁸ Les Hauts de Saint Paul, la Saline les Hauts, Saint Gilles les Hauts

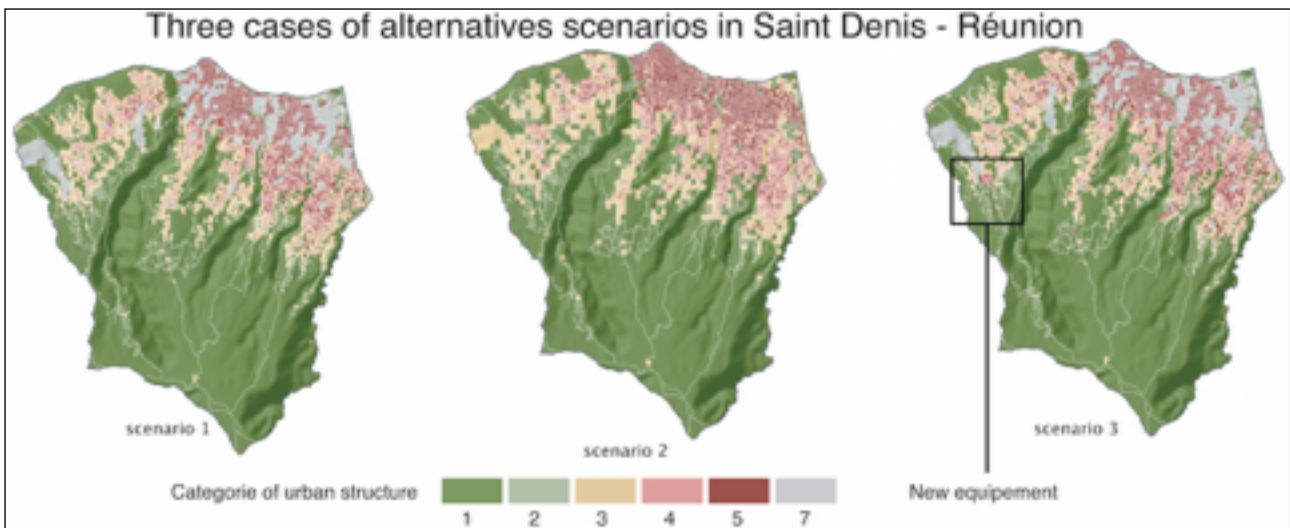


Figure 16: Three cases of scenarios with different urbanisation procedures.

Figure 17 shows the influence of the buildable index on population distribution. In these results, the variation of this parameter values is observed. In the reality, it would correspond to a more or less permissive approach regarding urban planning rules or risk prevention plans. Indeed, physical parameters (landcover, slope) are still taken into account. When urban planning rules are not strictly followed (low weighting of urban planning rules), population settlement has a tendency to sprawl. Households settle mainly on the coastal fringe, flat ground areas and on the upper areas of canyons (simulation 2 and 3 - figure 17). When urban planning rules are strictly applied (high weighting of urban planning rules), a more important density of population is observed in city center areas (simulation 1 - figure 17). The thin coastal fringe on the west part remains almost inhabited excepted in areas already built in 2010.

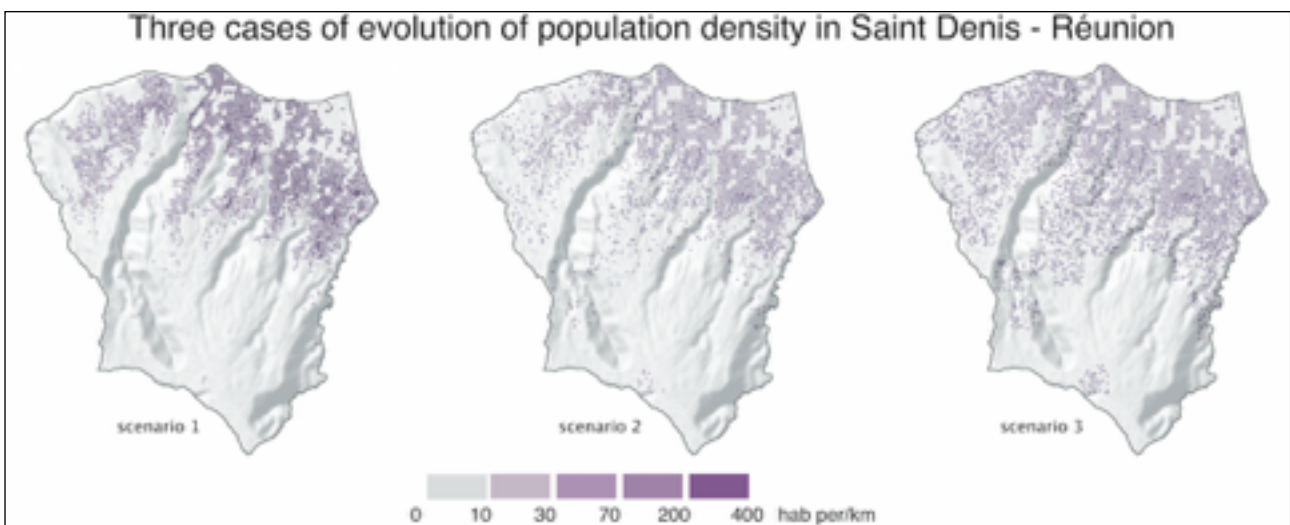


Figure 17 : Three cases of scenario based on different level of respect of urban planning rules. From high level of respect (sc. 1), to low level (sc. 2) and to absence of respect (sc. 3). Impact on population repartition

3.4) Presentation of simulation results overlaid with a risk prevention plan

The main operational goal, that lead this modeling process is to help to measure if future risk areas will increase, decrease, or moving, by overlaying future stakes and hazard simulation (mapped from risk prevention plan). From previous scenarios 1 and 3, showed above, comparison of the number of persons exposed at flood and landslide hazards are estimated (figure 18). Density of population is computed by overlaying risk prevention plan and results of simulations (30 years). It remains also possible to overlay any other hazard simulation. Results highlight how many more people can be exposed depending on buildable index (weighting of urban planning rules).

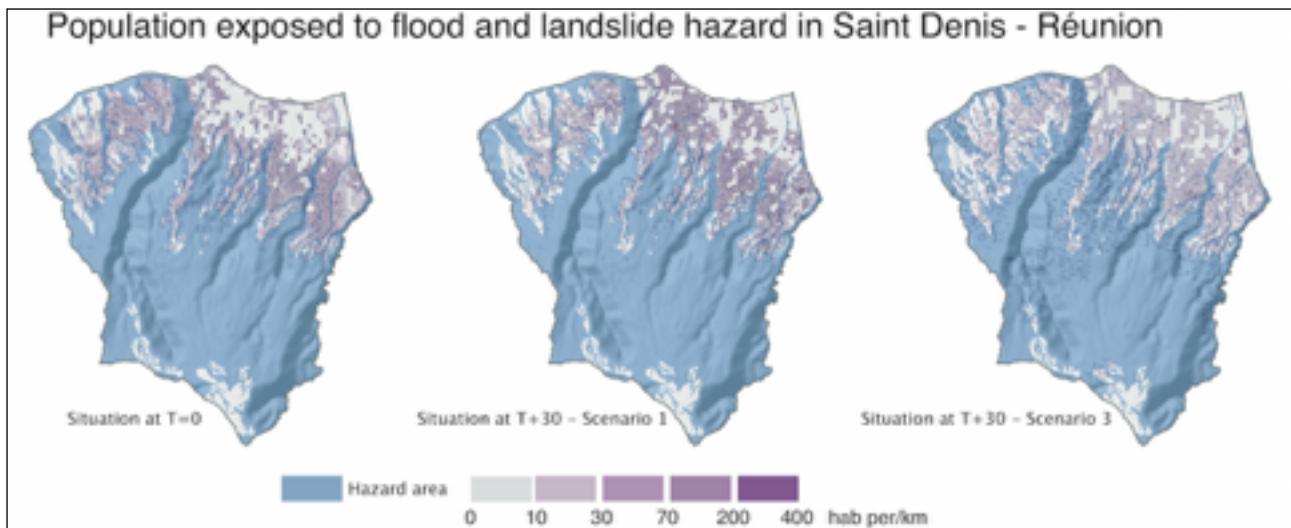


Figure 18 : Population exposed to flood and landslide hazard in 2012 and in 2040 based on scenario 1 and 3

In all scenarios, number of exposed people increase despite a very low buildable index in risk areas, mainly because of these areas still remains very attractive (flat ground and proximity to network and amenities). At a global scale, by overlaid gridded population data (INSEE 2012) and risk prevention plan, about 176 000 persons live in these areas in 2012 by 837 000 inhabitants on the whole Island, representing more than 20% of the total population. In the tendential scenario, this number increase to 197 000 in 2040 by 1 061 000 inhabitants, representing 18% of the total population. In this case, most of the new settlements follow urban planning regulation and risk prevention plan. But, in the scenario 3, with a very low weighting of urban planning rules, the number of exposed inhabitants in 2040 is about 285 000, representing 27% of the population mainly because of a diffuse distribution and a west coastal fringe more peopled. These results concern only the count of people into risk prevention plan zones. But the contour of these areas may be larger in case of extreme disaster incidence.

These scenarios have been chosen to present some basic examples of modifications that can be made in the simulation. They represent classical studies cases, often proposed by decision makers and planners, interested to focus on a new equipment impact or new urban rules.

Conclusion

In this paper, we have presented a model and a simulation tool to highlight the evolution of two categories of stakes (population and urban structures) on Réunion Island in a context of coastal risk prevention. Specifically, we have showed the following: with a simple model and an easy-to-use simulation tool, the computation of different scenarios at very large scale can help decision makers to visualise future potential vulnerable areas. It allows them to have a concrete visualisation of tomorrow's territory depending on actual planning and political actions. It can also provide maps and simulation results as frameworks or discussion basis for urban planning process. Probably, such highlight of results is not easy because they are only prediction and finally, different trends of stakes evolution can be visualized and mapped *ad libitum*. But this type of model cannot explain how and why they evolve. This is the modeling process, the making itself, with decision makers, planners and modelers, which helps to understand the dynamics of the territory. This is why participation of actors has to start from the very beginning of the modeling process, especially on risk and stakes matters.

At this point, the model is used to formulate new questions. During the process, this is planners and decision maker's knowledge that allows improving values of parameters in the model. And finally, results are, beyond a computational calculation, the constitution of a shared and semi empirical representation of a future state of the territory.

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