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Spatial modulation of the hydrological risk at Praia, Cape Verde

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Abstract. Hydrology modeling became a relevant topic for the Cidade da Praia, Cabo Verde, Africa, due to negative impact risk to local population and its assets. The modeling via Geographical Information Systems (GIS) can help the decision-making process of space occupation and characterization for this type of risk. Under the municipalities of Praia, the phenomenon of flash flood is common, causing soil erosion and landslide. This constitutes a risk for the local habitat, particularly in districts with a lack of strong human infrastructures. To simulate, analyze and generate risk maps using GIS to help this county governance authorities for decision-making, thus, becomes the main aim of this article.

1. Introduction

The county of Praia in Cape Verde features a large morphological diversity and some adverse weather conditions [1]. Environmental vulnerability and hydrological risk have always existed in this county, due to its own territorial morphology derived from the local climate and aggravated by human intervention upon the physical environment. On the other hand, the economic and social changes on the Praia county over several decades and the accelerated pace of the economic growth in recent years have led to strong pressures on the environment, leaving behind a negative imprint on the territories, which sometimes requires huge financial costs to reverse the situation [2].

GIS have the advantage of allowing simulations and develop spatial support systems in the sense of finding a balance in the development of human activities. For example, rainfall takes place with increased frequency in Cape Verde in an intensive and irregular manner. Between the months of September and October, there are records of, at least, one high intensity rain event, causing extensive damage and endangering the lives and safety of the population.

This writing goals the characterization of hydrological risk (flash flood) that the municipality of Praia (133,000 inhabitants) is subject to, especially in urban areas, a phenomenon that frequently occurs in regions featuring this dry tropical climate [3]. With this purpose in mind, we intend to produce a set of information that allows to (A) Model the physical environment of Praia county and determine the associated hydrological risks; (B) Provide the mapping of hydrological risk areas based on a surface runoff model; (C) Analyze and quantify the various factors of soil occupation risks associated with climatic, environmental and social aspects; (D) Highlight the importance of GIS in the planning urban areas at Praia.

This research paper is divided into seven sections. Starting with this introduction and followed by an overview of hydrological risk, the third section recalls the fundamental concepts of digital terrain models (DTM) and the theoretical references to the current drainage models (D8, NGFLOW and SCS). The following two sections include an overview of the county of Praia and the hydrological methodology used for the realization of rainfall simulation, analysis and generation of risk maps (section 6). The last chapter expresses some recommendations to the local government of Cape Verde.

2. Hydrologic risk

Territory disordering reflects on the potential danger of flooding, caused by the surface runoff increased and on the dry cargo effect (destruction of vegetation, increased erosion of slopes, soil sealing). However, for a correct assessment of the hydrological risk, it is essential to know the existing rainfall regime in the area. It is known that precipitation is a natural event, which has great variability in terms of its distribution in the planet's surface. This is a phenomenon that feeds the hydrological cycle and is the major factor for surface runoff, infiltration, evaporation, aquifer recharge and alike. Thus, precipitation is an essential element in studies of infrastructures planning and projection. Certainly, measuring rainfall data is crucial for identifying fields with conditions for agriculture, design of water resources, environmental assessment and quantification of soil erosion [4].

Within arid regions, the phenomenon of flash flooding can be particularly dangerous for several reasons. Although they are rare, these storms can discharge a large amount of water in a short time. Secondly, these rains usually fall in low permeability soils such as clay by greatly increasing the amount of runoff, overloading the rivers and drainage channels. Sometimes these regions do not have adequate infrastructural conditions to divert water such as manholes, underground holding tanks and retention basins, either due to lack of population, poverty or because the residents still ignore the real risk of flooding. Moreover, the lack of regular rain water to clean water channels can cause flooding because of a large amount of accumulated debris throughout the dry period which are then carried by floods.

Generally, the hydrological risk approach can be broken down into four stages, according to [5]: (A) Analysis of the region morphology by considering their historical values; (B) Survey on the changes and introduced by man (it can serve to counteract the effects or minimize the likely impacts); (C) Survey of existing vulnerabilities due to the presence of man (urban areas) or due to the economic lacking infrastructures; (D) Presentation of the risks/dangers chart and their respective spatial weighting. Note that this last step requires a thorough analysis, taking into account the evaluation of the intensity of risks, vulnerabilities and environmental conditions.

3. Digital model of lifting (DML) and drainage network (D8, NGFlow and SCS)

Digital Elevation Model (DEM) is a major key element in any hydrological phenomena study. Undoubtedly, the topography of the terrain influences the hydrological flow. However, the advent of GIS based on DEM has facilitated the hydrological modeling at different scales of watershed areas [6]. Figure 1 depicts the DEM in the southern region of the island of Santiago (municipality of Praia), where water spatial distribution in the basin requires the use of spatial data, particular at the borders of the river basins and sub-basins, slopes and drainage channels. Certainly, all these topographic attributes are determined by the DEM.

With regard to the dynamics of hydrological processes and movement of soil, slope is another significant factor. The definition of a slope, [4] considers the formula $\varphi = \Delta Z \frac{1}{100X}$, where φ stands for slope, ΔZ for the altitude variation and x equals the distance between the center of any GIS cells. Thus, it is possible to determine, at the pixel level, the current direction of the water that will take, allowing the generation of an image with flow directions. These channels are identified as cell lines, whose flow accumulation exceeds a specific number of cells. By computing the number of cells above a particular threshold setup for the drainage network, one can determine the accumulated flow in that cell [7]. The algorithm that describes the flow direction became known as the Deterministic Algorithm 8 or D8 [8]. This methodology is based on the fact that water is able to move in eight possible directions, as shown in Figure 2.

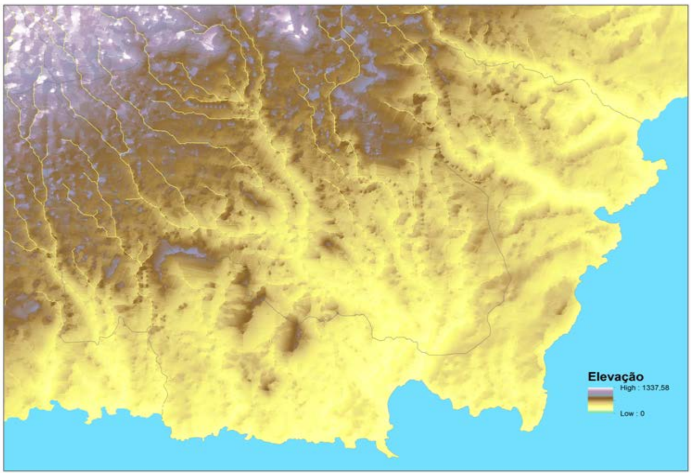

Figure 1. DEM of Praia County.

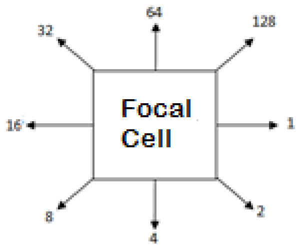

Figure 2. Directions codification of the flow at the cell level.

During the creation of the drainage system with GIS, the first step consists in filling small depressions existence on the model (fill sinks) that arise for geographical data entry errors. The correction of these depressions is an important step for the generation of the river system within the DEM. Thereafter, one delimits the contribution basins that are identified as a set of all cells that flow to a certain target cell from which drain lines are defined (Figure 3).

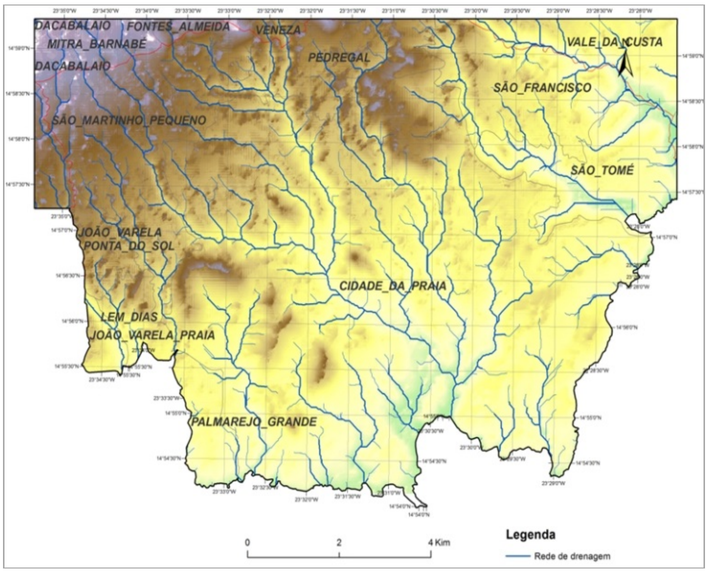

Figure 3: Draining network generated from a DTM.

In turn, the NGFlow model is based on the DEM as a spatial representation of weather stations, providing the precipitation data records and rainfall time series [9]. In situations where dams can be found, an increase of timely information is needed about the volume, length and release of water. To the input data, one adds the estimated water balance based on the precipitation data, soil storage capacity and potential evaporation. Therefore, the excess flow is formed by water that does not evaporate or infiltrates the soil. In order to calculate the excess runoff flow, we took into consideration equation 1. The left side of the formula describes the water absorption by the soil in a given time interval. Note that the absorption at t time corresponds to the absorption occurred in the previous time, plus the amount of precipitation minus evaporation. The right side of the equation describes the flow. While the soil capacity to absorb water is not met ($w(t) \leq w'$), the flow rate is zero. At the moment that the soil infiltration capacity is reached ($w(t) > w'$), it is then possible to determine the flow rate that corresponds to the water surplus (not absorbed by the soil in a given time interval).

$$\frac{W(T)}{\ddot{A}} = \frac{W(t-1)}{\ddot{A}} + P(t) - E(t) \; S(t) = \frac{(W(t) - W')}{\ddot{A}} \tag{1}$$

Under this equation, *S(t)* stands for the flow rate at a given *t* time of the simulation, *P(t)* indicates the precipitation, *E(t)* represents the evaporation; *W(t)* means the soil capacity to absorb water while *W* specifies the water holding capacity of the soil where *Ä* denotes the considered time interval.

The SCS-CN (Soil Conservation Service - Curve Number) method is widely used in hydrology for its simplicity and quality of results in estimating the direct surface runoff from a precipitation event [10]. In this model, the main elements that determine the surface runoff volume (effective precipitation) are the retention of rain on the ground depressions and infiltration. This effective precipitation estimate considers three variables: (A) precipitation in the time interval; (B) soil characteristics and moisture which defines the retention potential; (C) loss on early rainfall. As expected, the flow rate has an influence on the hydrological dynamics of soil due to its action on the surface, on the mass movement and on the flow time or concentration. The evaluation of this speed can be carried out by the Soil Conservation Service (Table 1).

Table 1. Speed in m/s based on the slope and soil occupation (Source: Soil Conservation Service, 1972).

Slope in %	**Forests**	**Natural grasslands**	**Slope in %**	**Almost bare grounds**
0-4	0.3048	0.4572	0-2	0.6096
4-8	0.6096	0.9144	2-4	0.6096
8-12	0.9144	1.2192	4-6	0.6096
12-15	1.0668	1.3716	6-10	0.9144
			10-12	1.2192
			12-15	1.52

The estimated speed computation shown in the previous table can, hence, be performed by equation 2 (S represents the slope or gradient). In turn, the coefficient K is estimated taking into account Table 2.

$$V = K \times S^{0.5} \tag{2}$$

Table 2. K coefficient value of the flow speed assessment (Source: Soil Conservation Service, 1972).

Types of areas	Speed
Forest with a lot of foliage on the soil	0.076
Area with little cultivation	0.152
Meadow-grasses	0.213
Cultivated land	0.274
Bare ground	0.305
Flowlines	0.457
Paved surface	0.61

The time of flow path (the water flow distance from one location to another) is also an important variable in hydrological modeling. According to NRC [11], the flow time between two points in a water basin is determined on the basis of the principle of equation 3 (Tp: flow path time; n: roughness coefficient; l: stream length; $P_{24}^{0,5}$: 24 hours average of rainfall over the last two years; S: slope or gradient).

$$Tp = \frac{0{,}007x(nl)^{0.8}}{P_{24}^{0.5} \times S^{0.4}} \tag{3}$$

The determination of the roughness coefficient presumes the assessment of soil conditions and occupation. To this end, the NRSC has set a coefficient, complying with these factors as it is described in Table 3.

Table 3. Index of roughness, according to NRSC [8].

Hard surfaces (concrete, asphalt...)	0.011
Fallow soil	0.05
Cultivated land	
With coverage < a 20%	0.06
With coverage > a 20%	0.17
Formation of meadow-grassland	
Grassland	0.15
Dense grassland	0.24
Bermuda grass	0.41
Forest	
Relatively high density	0.8
Low density	0.4

The calculation of the discharge assumes this rational method for determining the specific discharge of each pixel in the runoff basin. It can be computed with the SCS estimate as described in equation 4 (Tp: time; Q: discharge peak for each cell (m^3/s); S: pixel area (ha); I: precipitation average intensity (mm/min); α: flow coefficient).

$$Q = 0.167 \times S \times I \times \alpha \tag{4}$$

By definition, flow rate equals the volume of a fluid flowing through a given section of a free channel per time unit (a free channel can be a river or a pipe, for instance). Thus, one can determine the flow rate as $F = A \times V$, in which A stands for the area in question and V for the speed of flow expressed in m³/sec. In order to measure this speed rate of a water course, one typically uses the windlass (an apparatus provided with a propeller and a rotation meter). This measurement is universally used to determine the flow of a natural watercourse and consists in determining the cross-sectional area and the average speed in any section.

Finally, the surface runoff in rivers and channels is represented mathematically by two differential equations that describe mass or volume preservation and the quantity of flow movement, named the equations of Saint Venant [12] where Q equals volumetric flow rate, A is the area of the wet section, X stands for the distance in the longitudinal direction, t denotes time and qL represents the input or output flow per unit of width.

$$\frac{\partial Q}{\partial X} + \frac{\partial A}{\partial T} = q_L \qquad (5)$$

4. The city of Praia

The archipelago of Cape Verde is located in the Atlantic Ocean, approximately 450 km from the West Coast of Africa, between the latitude of 14º48'00 and 17º12'13 " North and the meridians 22º23'59 " and 25º20'40 " West . This archipelago consists of 10 islands and 8 islets, organized into two groups, according to each geographic location: Windward and Leeward. The archipelago has a total land area of 4033 km^2 whose corresponding coast line extent is 1,020 km.

Cape Verde's climate is part of an extensive range of arid and semi-arid climates in the heart of the Sahelian region (situated between the subtropical high pressures of the Atlantic and the equatorial low pressures). This track of African territory (Senegal, Mauritania, Mali, Burkina Faso, Chad, Sudan, Ethiopia, Erithrea, Djibouti and Somalia) has a precipitation regime, ranging from 150-300 mm per year.

The county of Praia is located in the south of the Santiago island and covers an area of 102 km^2 (about 10% of the surface of the island of Santiago). It is bordered to the North by the mountain of Antonia Peak and to the South by the limits of the maritime coastline. Administratively, it has borders with the municipalities of São Domingos and Ribeira Grande de Santiago.

Towards morphology, the elevations of the islands of Santo Antão, St. Nicholas, Santiago and Fogo reach an altitude above 1,300 m. Yet, the highest altitude corresponds to Pico on Fogo Island, with 2,829 m, followed by the Crown Top on the island of Santo Antão with 1,985 m. The Antonia peak in Santiago reaches 1,395 m and Monte Gordo, in St. Nicholas, presents 1,304 m. Considering the geomorphological characteristics of Praia, there was a sharp erosion lately and, along with the poor vegetation cover, it creates a positive situation for dynamic erosion (Figure 4). The existing valleys in the area are relatively well embedded between the highlands (achadas), among which some relevant elevations stand out, such as the Hill of Vacas with 392m, the Ilhéu or Hill of São Filipe with 274 m, Red Hill with 195 m, Hill of Gonçalo Afonso with 235 m and the Hill of Ilhéu with 259 m.

The drainage networks extend from the highlands of the North (Hill of Rui Vaz) to the South of the county, flowing into the Atlantic. As it can be observed, there is a main basin where there is a set of flow networks that converge downstream. It turns out that the urban area of the municipality is located at the crossroads of these drainage networks (Figure 5). However, the existing security infrastructure cannot always withstand the water discharges coming from upstream areas.

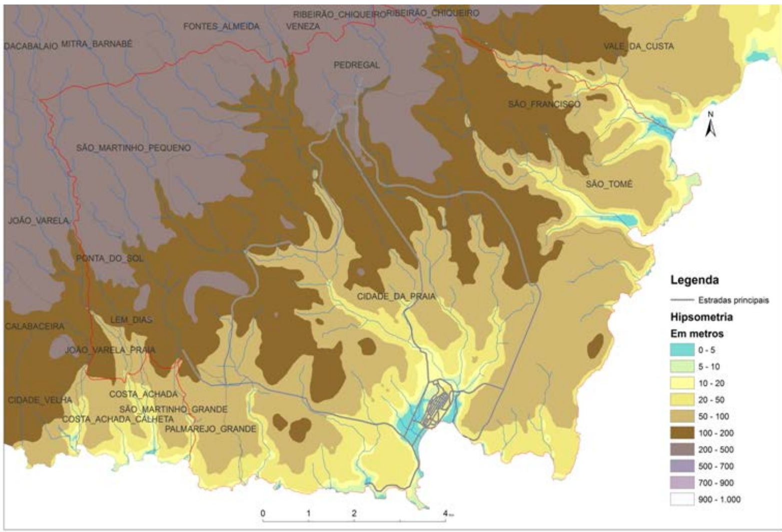

Figure 4: Hypsometric southern map of Santiago Island.

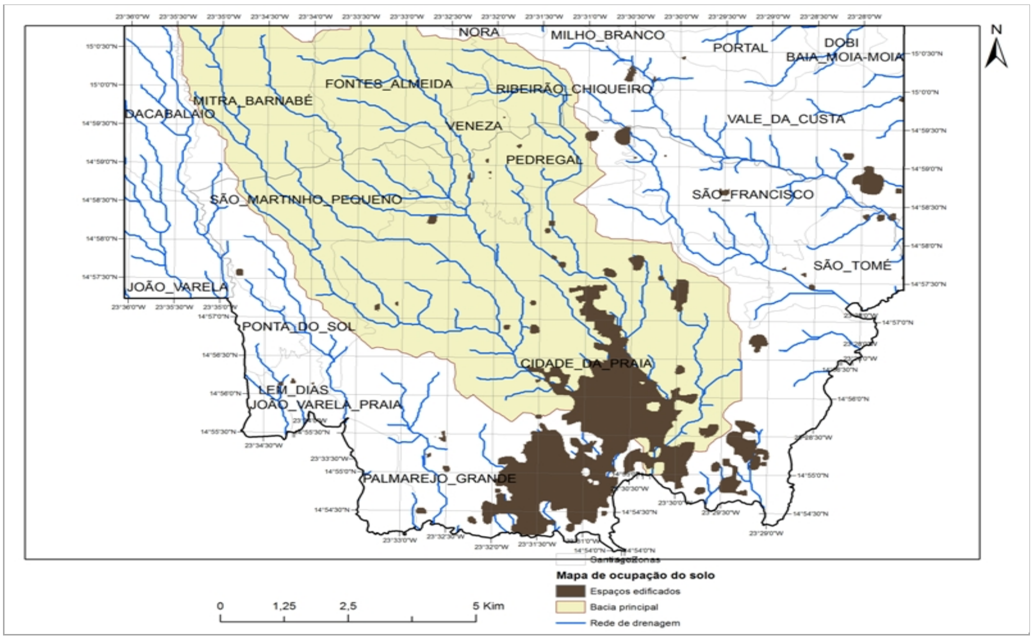

Figure 5: Drain main basin, edification areas and network drain.

The average annual rainfall in the Cape Verde archipelago is no more than 300mm in the lowlands (less than 400m high). According to [13], the precipitation of downward trend has been recorded since the 60s, reflected negatively on the conditions of farming and water supply. The areas under the influence of hot and dry air masses that blow from the eastern quadrant during the Harmattan (December/January) are the driest, corresponding to an average rainfall of only 150 mm. In spots located more than 500m above sea level and exposed to the trade winds, rainfall can exceed 700 mm. In relation to water balance, it is considered that about 20% of the precipitation water is lost by surface runoff, 13% goes towards aquifers recharging and 67% will disappear by evaporation [13].

However, extreme precipitation in the form of flash floods is a phenomenon that occurs in all latitudes, including arid regions and desert climates. This phenomenon has been a reason for concern to the scientific community due to its increasing frequency as a result of recent climate changes. These effects of extreme precipitation are sometimes more serious due to the existing lack of vegetation cover that could reduce the impact on the ground. Moreover, notwithstanding the existence of side protection dikes, certain cross-sectional passages of circulation in the city streams do not hold the sufficient height to allow the flow of water when intensive precipitation occurs (Figure 6).

Figure 6: Superficial draining at Safende riverside.

5. The hydrological methodology

The present hydrological risk simulation is based on a model with three main components: (A) Flow module, in which considers the various layers of soil types/occupation and of precipitation; (B) Flow path time module, in which the DEM and flow rate are considered; (C) Discharge module, which results from the interaction of the fallen precipitation and the pedagogical and geomorphological processes characteristics. As expected, the different layers interact together, having an influence on the runoff dynamics. For this research, the water discharge at the end of the drainage basin was simulated. The graphical user interface provided by the Model Builder is significant, as most of the functions are already integrated within ArcGIS (Figure 7). The first component is the flow. Based on the SCS procedure, several parameters are taken in consideration such as the Curve Member, the initial infiltration and the potential one. These elements play a key role in the final activity when determining the flow coefficient that is obtained by the ratio between the total precipitation and the flow amount. This calculation presupposes the raster format associated to all layers: soil type, foregoing moisture of soil (amount of moisture before precipitation), land use, precipitation and DEM. The intermediate results obtained are the curve number, initial infiltration and maximum potential of moisture retention.

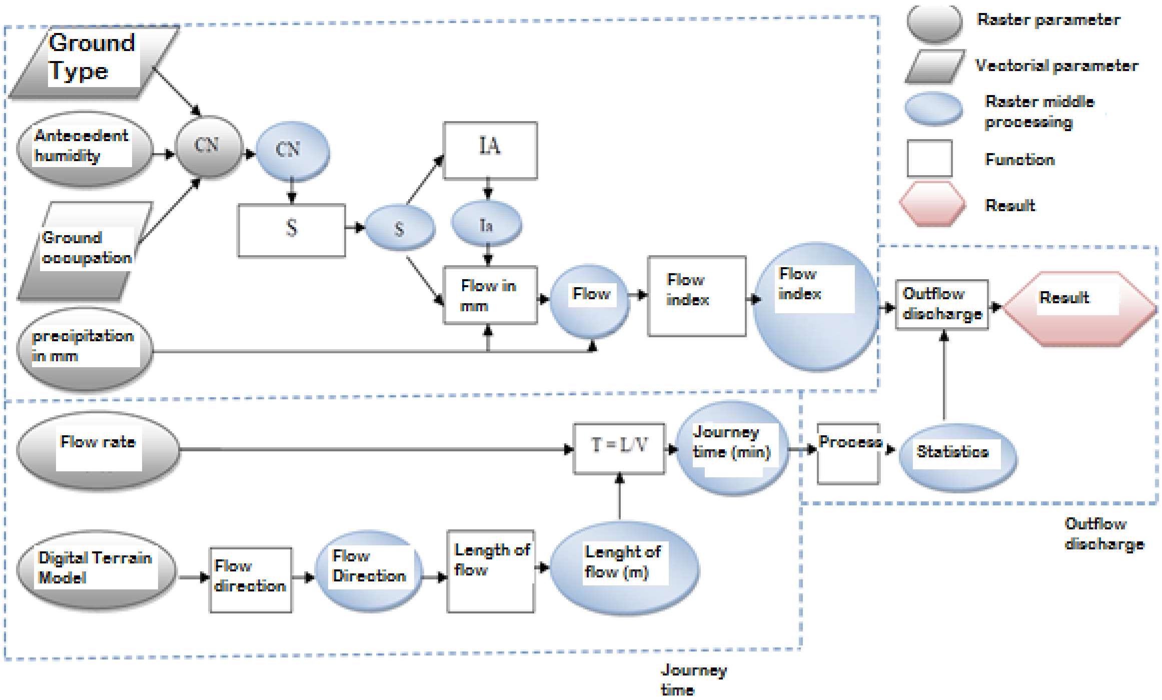

Figure 7: Simulation model for the hydrologic flow.

For framing soil types, it was considered the different soil groups according to the FAO classification [14]. The map of Figure 8 shows the predominant soil types of the county of Praia. As demonstrated, there is a predominance of the Xerossol class that is distributed throughout the northern and northwestern regions of the county of Praia. These soils display a reddish coloring of great thickness. Next, in terms of expressiveness, there are the Cambisol soils, which are little developed soils from non-limestones formations. These soils are usually associated with rocky outcrops, often being characterized by a high proportion of stony elements. One can also identify lithosols belonging to the group of non-climatic erosion mineral soils, which are young, little evolved and associated with outcrops of hard consolidated rocks and basalts. There is still a small portion of undefined soils, which occupies the Plateau neighborhood of Praia.

The foregoing humidity is a parameter that can be modified, depending on the time acclimatization: condition I for dry soils, condition II for moderate soils and condition III for wet soils. Under the land layer drawn from Landsat TM5 images (Figure 9), one can see a predominance of bare ground and rocks in over 80% of the county of Praia's area. However, there is some scattered green area, consisting of bushes and acacia trees, a species that was introduced in the last 40 years, framed in the national afforestation program.

The discharge makes up the final phase of the flow process. This index takes place at the pixel level (see equation 4 and 5) and, subsequently, it is followed by the accumulation of the discharges, resulting on the flow output. As expected, the total flow in the drainage basin is obtained by the sum of discharges. Finally, we proceed to the discharge values reclassification by the equidistance of the flow path time. In this case, we selected a temporal equidistance of every 30 minutes.

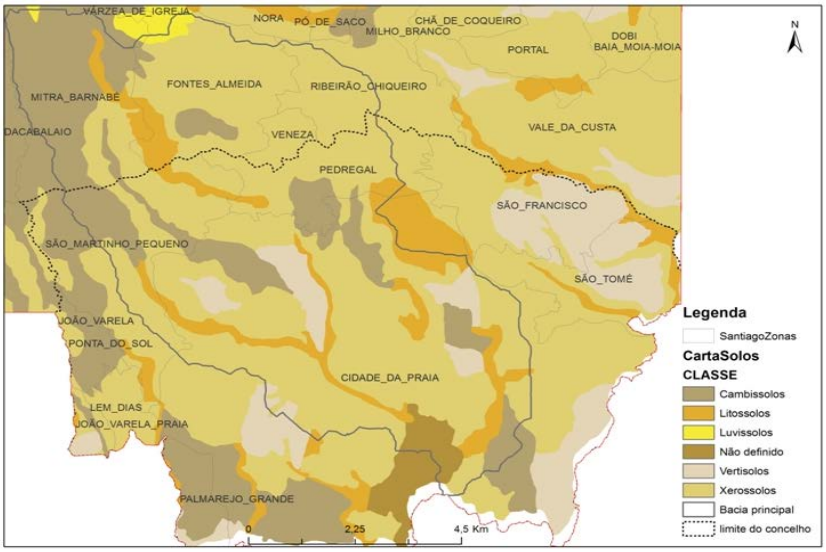

Figure 8: Soil southern map of Santiago Island.

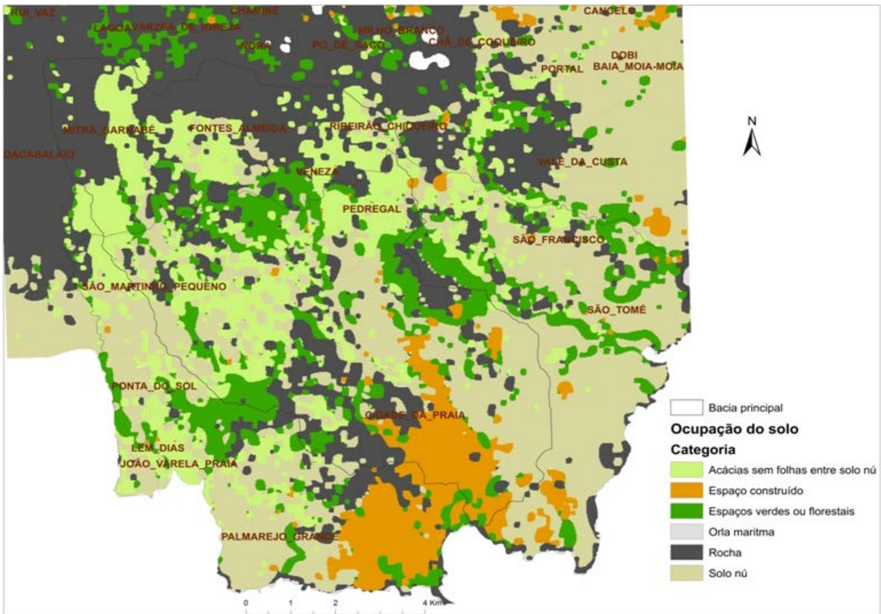

Figure 9: Soil map occupation in the southern island of Santiago.

6. The county of Praia: simulation findings

The precipitation data was obtained from the sensor 3B42 of the TRMM satellite. The historical rainfall records indicate some variation of rainfall occurring in the county. As a rule, higher areas receive a greater amount of rainfall as shown in Figure 10 [4]. The central region of the island matches with the areas of higher altitudes whilst lower precipitation rates are situated along the coast. As a reference, the county of Praia presents an annual variation between 73-163 mm of rain.

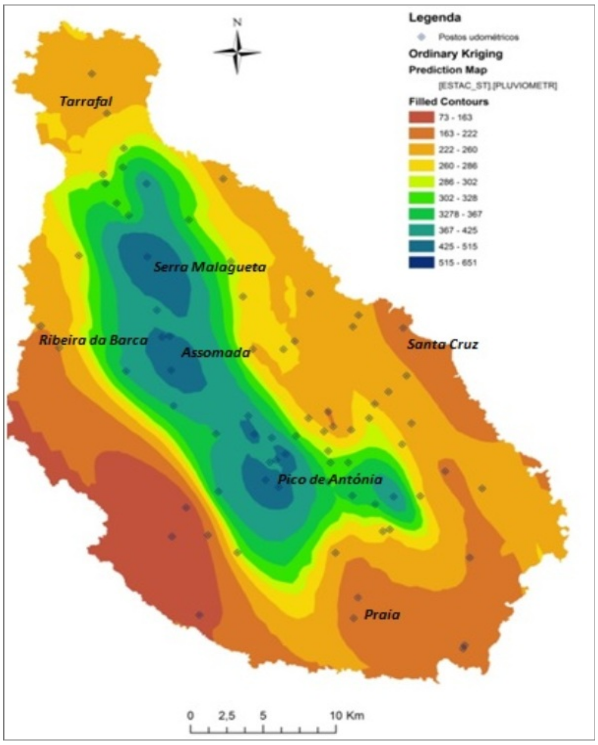

Figure 10: Average precipitation map of Santiago Island [4].

It is particularly notable that the TRMM satellite estimates precipitation in a resolution of 0.25 x 0.25, corresponding to an area of 2,162 km^2. Given the size of Santiago, approximately 900Km^2, this resolution covers 2.4 times the island of Santiago. In order to carry out this study, it was considered the rainfall data occurred on October 22, 2010 (Figures 11 and 12).

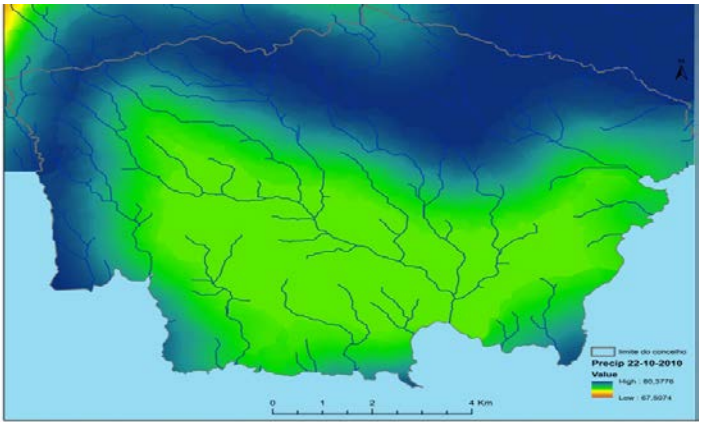

Figure 11: Precipitation map on October 22, 2010.

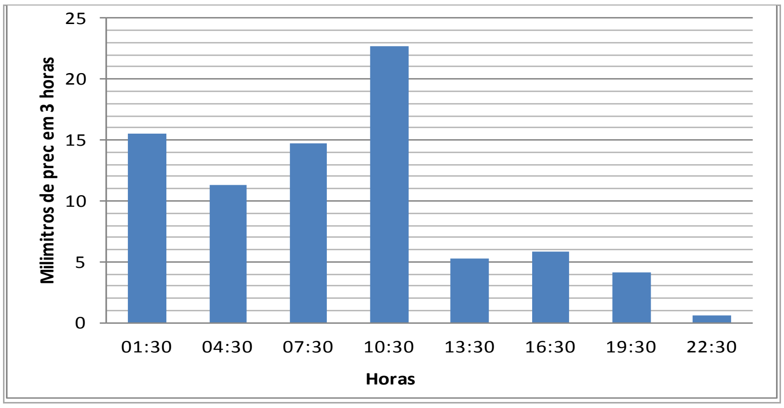

Figure 12: Time precipitation distribution on October 22, 2010.

By definition, the potential infiltration presents the soil's capacity to retain water. Figure 13 illustrates the sectors with greater retention capacity, according to the existence of some dispersion towards the infiltration potential level. These differences are linked to the pedagogical features, degree of vegetation cover, soil occupation and land use. As one might expect, the built-up areas, rocky zones and bare ground spaces are generally of lower potential retention, implying a higher degree of surface runoff.

The flow path time is another significant variable as far as it influences the flow volume in a specified section of the basin, either in volume or in terms of duration. The approach used for determining the flow time is based on [15] formula. In a simplified manner, it defines the flow time as the ratio between the flow length and the average speed over the entire area of the basin. Subsequently, the stream length is used to estimate the flow time for its relationship with the average velocity of the basin flow. Afterwards, this flow time is reclassified every 30 minutes and applied to the basin for the delimitation purposes of the different patterns. Thus, spaces are shown after having been reclassified according to the flow path time. Figure 15 characterizes the flow time of surface runoff generated from the ratio between the watercourses length in different parts of the basin and the average speed recorded across the basin. Certainly, the flow time is shorter as it moves towards downstream.

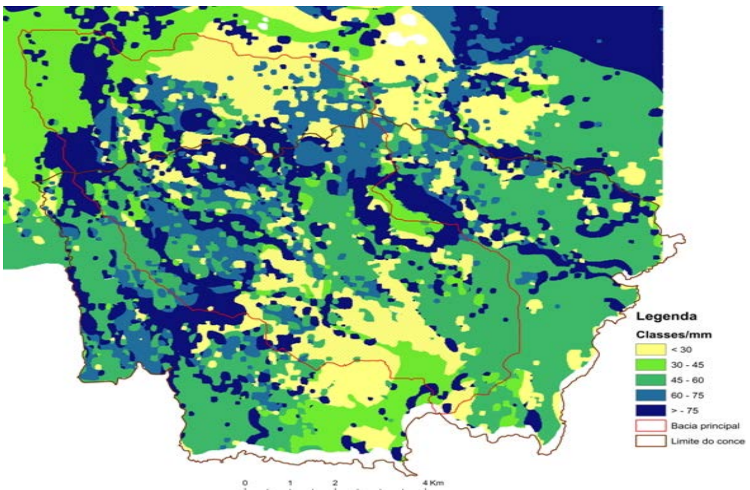

Figure 13: Potential infiltration map in mm at Praia County.

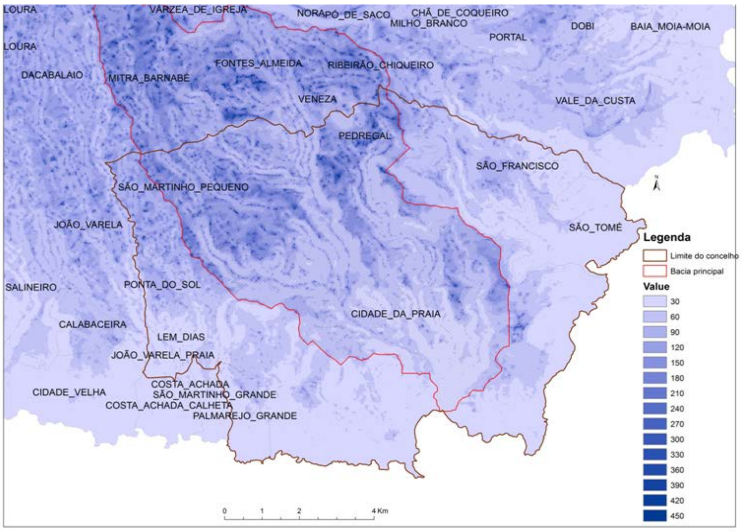

Figure 14: Time map of flow route.

The flow speed involves the *K* coefficient and the relief slope of the basin. After an analysis of the basin conditions for determining this constant, we chose the value 0.305, resulting from the fact that most of the space within the drain basin is almost a bare soil. It is noted that the average flow velocity is 1.9 m^{-1}, with the minimum speed of 0.053 m^{-1} and a maximum of 6.49 m^{-1}. As expected, higher speeds occur in the areas of greater slope, which are well represented in regions further north of the county, coinciding with the most mountainous areas.

The discharge is the last element obtained from the overall model. This is obtained by the interaction of rainfall parameters in mm/min, flow time and infiltration potential (soil capacity to retain water). From this latter factor, we may obtain the flow coefficient (effective precipitation). Subsequently, the precipitation that was initially in mm per hour is now converted to mm per minute in order to make the discharge reclassification in every 30 minutes easier. It should also be noted that the discharge is initially obtained at the level of the pixel and reclassified in areas depending on the flow path time by ArcGIS 10 Spatial Analyst (Zonal Statistics function).

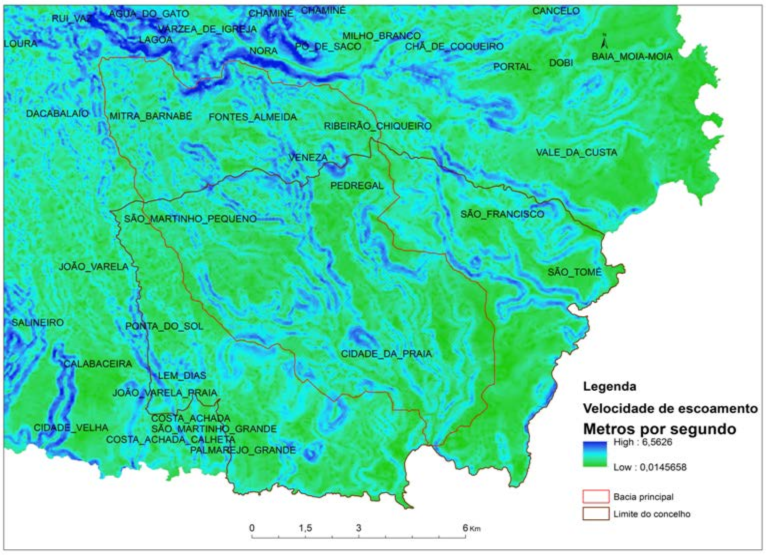

Figure 15: Flow speed.

Figure 16: Basin flow at Praia county and the water volume drained in m^3 during 450 minutes.

Figure 16 shows the discharge result from the precipitation data. This allows the water volume evaluation in cubic meters that crosses throughout the final section at intervals of 30 minutes for 8 hours. It is demonstrated that 76% of the precipitation volume stems from the flow coefficient that passed through the final part of the basin in 120 minutes and 99% crossed in 300 minutes.

Finally, Figure 17 shows the flow to the main basin, already reclassified at an equidistance of 30 minutes in terms of flow time. There is, however, some inconsistence of the results for the sectors with lower discharge that occurs further within the basin region, supposedly associated with areas of low permeability and rapid surface runoff.

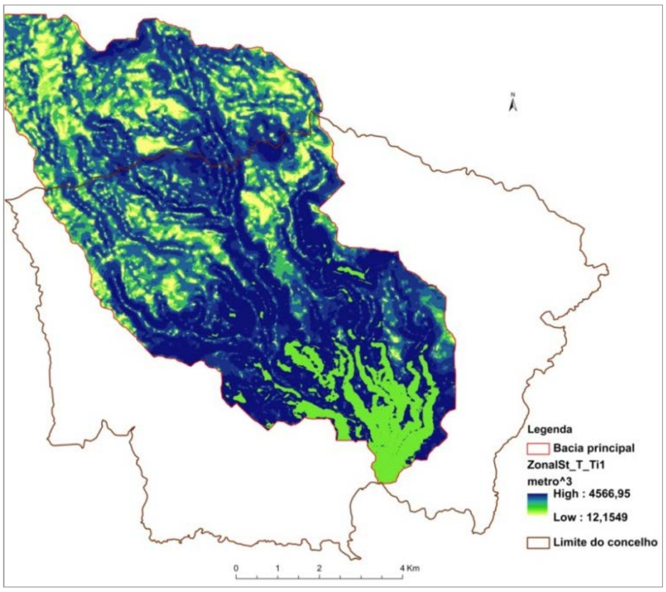

Figure 17: Accumulated drain map.

7. Conclusion

In the county of Praia, there is a large population growth living under a hydrological risk area, especially along the water streams. The morphology and configuration of the surface runoff network in the surrounding areas of this county increase that risk mainly due to the confluence of several basins that flow into the urban area. Indeed, the areas of greatest hydrological risks in the county of Praia are in the lowland areas (along the flow streams). Despite the existence of lateral protection dikes in these streams, there is water overflow in some zones (particularly in Vila Nova creek) because of the large amount of material carried from the slopes and the highland areas of Fontes Almeida, St. Martinho and Mitra Barnabé. Moreover, there is a certain shortage of infrastructures for torrential correction in several ramps of the city and along the side protection dikes delimiting the rivers, where one can find a high density of soil occupation, especially in the settlements of San Pedro, Safende, Calabaceira, Vila Nova and Fazenda.

In this sense, it is recommended interventions in these risk areas in order to protect households that are at the edge of these flood lines, despite the financial costs. The intervention on these slopes becomes a priority in order to change the arrangement of the surface runoff lines. This intervention may consist of afforestation and construction of grooves to prevent excessive transport of soil debris toward the low lying areas of the city during precipitation.

Certainly, GIS solutions can play an essential tool for the surveillance and prevention of hydrological phenomena in this municipality. GIS adds a set of spatial information, facilitating the identification of existing vulnerabilities. For example, in this project we tried to define a model to characterize the hydrological risk flexible enough to operate at different scales or to be applied in other geographical areas with the necessary adjustments. Municipal authorities are, therefore, in a position to setup a warning and risk prevention system, as well.

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