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Flood Hazard Assessment in Madeira (Portugal) – The Case Study of Machico

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Abstract: This study aims to carry out a proper flood risk assessment in Machico's main watercourse and purpose at least two different flood mitigation measures to prevent major impacts over the watershed. Furthermore, the assessment addresses the need for structural-measures — i.e. detention basins — towards mitigating flood hazards under high-intensity and short-duration precipitation events. It became possible to morphometrically characterize all the watersheds using empirical equations to gather specific parameters and indexes. A proper articulation between the hydrological and the spatial analysis using geographic information systems was then carried out. According to many parameters calculated the watershed of Machico proved to assume a very large-size and to be highly prone to flash floods. The spatial analysis took into consideration the watershed's Fill Rate using both Dutch and the Ternary Phase Diagram methods and allowed us to define criteria towards the establishment of detention basins as a valid flood mitigation measure. Finally, it was clear that the watershed corresponding to Machico's main watercourse induces the need to further implement either a detention basin or to modify the roughness coefficient of its river channel. Moreover, the comparison between the results obtained with DROTA's Flood Risk Report, allows us to consider this study's outcome both satisfactory and valid.

Keywords: Flood Hazard, Hydraulics, Hydrology, Spatial Analysis, Territorial Management, Urban Planning

1. Introduction

Climate change has been a major issue and has contributed to the drastic increase of natural extreme phenomena — *i.e.,* droughts and floods. Nowadays, flooding is considered as one of the most relevant hydrological risks since it endangers human settlement and causes a major impact on the socio-economic activities of a city [1–6].

We can easily verify that cities that do not care about urban planning, and reveal an unmeasured urban area growth, become more exposed to extreme and destructive events [7]. The HANZE database has recorded approximately 1564 flooding events between 1870 and 2016, where 879 were classified as flash-floods, 606 as river floods, 56 related to coastal floods, and 23 to compound events. [8].

Floods are often defined as extreme hydrological events and can be categorized according to their temporal disposition or origin, whether it happens due to natural or human influence [9, 10].

Considering the growing urbanization index and climate change, flooding events have become critical problems that cities worldwide must face, particularly in tropical regions [1, 5, 11]. This happens mainly because of the impervious surface ratio's growth and, therefore, the increase of the surface runoff to drain all the rainfall into a river's mouth [12]. Besides all of this, in most of the cities that lack urban planning, there can be found roads that either cross or choke a river mouth's, thus becoming a key factor to the growing risk of harming people or damaging their goods [13].

Urban areas are at higher risk since they concentrate on a city's housing and commercial fabric [14, 15]. Therefore, it is likely that because of urban growth, the number of extreme events with the risk of hurting people or causing damage to their properties and goods also increases [8, 16].

Contextually, it becomes necessary to perform a precise study that emphasizes all the parameters that contribute to an increased flood hazard — *i.e.,* geomorphology, geology, hydrology, impervious surface index, slope, drainage density — in order further to establish flood hazard mitigation measures [17]. Even though we still do not have enough knowledge or the resources to eradicate this type of scenario and mostly avoid casualties, it is unquestionable that we are working towards achieving those goals [13]. Citizens need to be aware and start cooperating with local authorities and local government to properly manage and reduce the risk in flood-prone areas of a watershed like Machico's.

Urban drainage is considered the key factor in preventing or at least mitigate the problems caused by the aforementioned phenomena, that is, by rapidly direct the flow of a watershed towards its river mouth. Although it minimizes the risk of an overflow of the stream bed, it does not take any action over the problem's origin — the anthropogenic pressure that humans exercise over the watershed [18–20].

In this sense, a modern concept of urban drainage is now being established, also focusing on the environmental side of the solution by detaining or at least retarding the natural flow of a watershed, thus minimizing the effects of the anthropogenic pressure and restoring the hydrological condition of the basin [21]. This type of solution brings back to the table elder and simple ways of people detaining a specific amount of the rainfall of a watershed, commonly used back then with irrigation purposes — *i.e.,* detention basins—, a structural flood mitigation measure particularly interesting in urban areas [20, 21].

In summary, structural flood mitigation measures reveal themselves to solve the control of a watershed's flow rate [22]. Therefore, the present study aims to perform the local hydrological analysis, acting as a base point to solve the gaps in structural and non-structural measures already put into force in Madeira's Autonomous Region.

Finally, its major goals will assess the morphometrical features of Machico's main watercourse, thus enabling us to obtain all the data to apply in flood risk parametric methodologies and evaluate each parameter's relevance to define the watershed as flood-prone; to check whether it is necessary to design a detention basin as a structural measure towards flood mitigation; to analyse the possibility of modifying the roughness coefficient of the watercourse's streambed and walls as a structural solution.

Moreover, this study does not aim to obtain different results from the ones already published by the regional and national authorities for hydrological and spatial management. Instead, it aims to cooperate in the revaluation of that characterization of Madeira's watersheds, which completion period they expect by the end of 2021, whilst using other methodologies that will either validate or imply the need to reanalyse the authorities' results. Simultaneously, it is part of a project with its primary goal to classify each watershed regarding its flood risk to the population.

2. Methodology

2.1. Study Area

Regarding the watershed under study — Machico's main watercourse —, it is in Madeira's western municipality of Machico. Moreover, the Madeiran archipelago is a North Atlantic group of islands that integrates the Macaronesian Region between the latitudes 30° 01' N and 33° 08' N and between the longitudes 15° 51' W and 17° 30' W [23]. With an estimated total area of 796,77 km^2, it is subdivided into four smaller islands, namely Madeira (736,75 km^2), Figure 1; Porto Santo (42,17 km^2); Desertas (14,23 km^2) and Selvagens (3,62 km^2) [24].

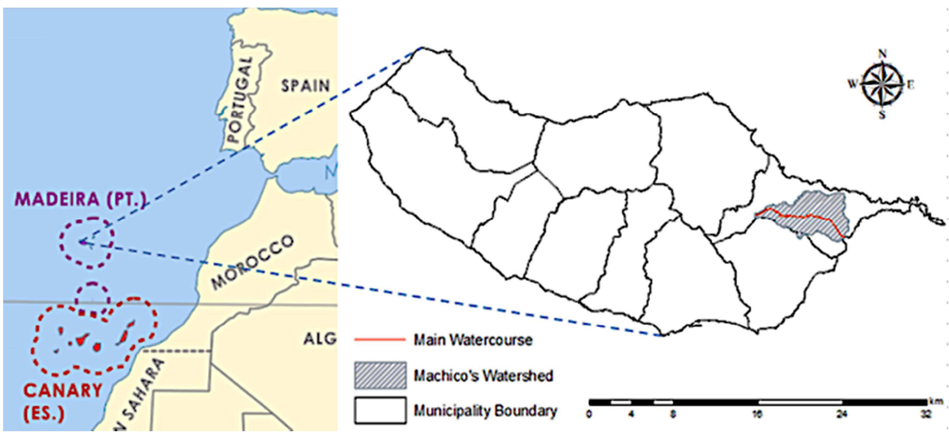

Figure 1. *Macaronesian Region - Madeira Island and Machico's Watershed. (Source: Authors by ESRI ArcGIS, 2020).*

Figure 2. *Conservation status of Machico's main watercourse river mouth.*

The watershed of Machico has approximately 24,649 km^2 and its main watercourse is 12,071 km long. The conservation status of the considered watercourse is heterogeneous, with its river walls covered with both round and sharp stones and the streambed with excessive vegetation and full of sediments deposed over time, as seen in Figure 2.

The conservation status is approximately the same throughout the watercourse, this being a parameter easily verified in situ. Due to its tiny slope, the average flow rate is subsequently low, resulting in more sediment and organic matter deposition that promotes vegetation growth.

The adopted methodology can be synthesized into 6 main stages/topics as shown in Figure 3.

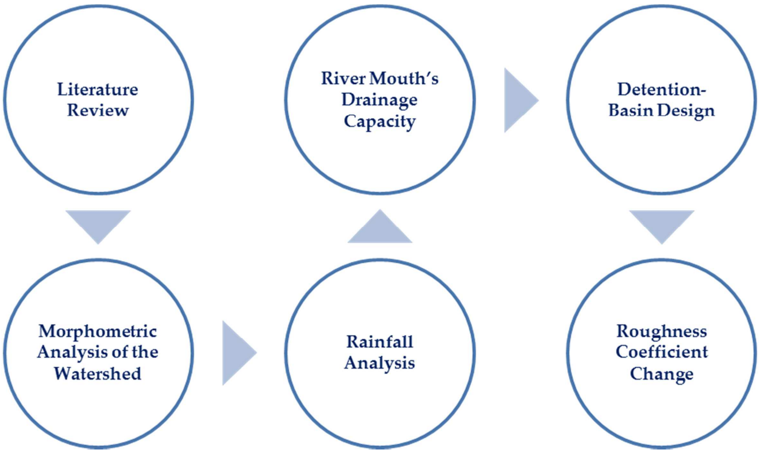

Figure 3. *Adopted Methodology's Organogram.*

The adopted methodology started with an extensive literature review to gather all the information needed to assess the morphometrical features of the Machico's watershed, taking into consideration the parameters (and the empirical equations) that many authors define as essential to consider a basin as flood-prone. The many stages of the adopted methodology shown in Figure 3 are described next.

2.2. Morphometric Analysis of the Watershed

The morphometric parameters include:

Gravelius compactness coefficient–K_C: A dimensionless coefficient that establishes the ratio between a given watershed's perimeter and the perimeter of a perfectly round basin. It can be calculated using Equation 1, with the basin being flood-prone as the coefficient gets closer to 1 [25].

$$K_C = P/\,2 \times \sqrt{\pi \times A} \quad (1)$$

with:

P=Watershed's perimeter, km;

A=Watershed's area, km².

Elongation Factor–K_L: A dimensionless coefficient that establishes the ratio between a given watershed's area and a rectangular-shaped watershed with the same area. It can be calculated using Equation 2, with the basing being considered elongated if the coefficient is bigger than 2 [6].

$$K_L = \frac{L_E}{l_E} = \frac{\frac{K_C \times \sqrt{A}}{1.128} \times \left|1 + \sqrt{1 - \left(\frac{1.128}{K_C}\right)^2}\right|}{\frac{K_C \times \sqrt{A}}{1.128} \times \left|1 - \sqrt{1 - \left(\frac{1.128}{K_C}\right)^2}\right|} \quad (2)$$

with:

L_E=Equivalent length, km;

l_E=Equivalent width, km;

K_C=Gravelius compactness coefficient, dimensionless;

A=Watershed's area, km².

Form Factor–K_F: A dimensionless coefficient that establishes the ratio between a given watershed's area and its length. It can be calculated using Equation 3, with the basing being considered elongated (and less flood-prone) as the Form Factor gets smaller [25, 26].

$$K_F = A/{L_B}^2 \quad (3)$$

with:

A=Watershed's area, km²;

L_B=Watershed's length, km.

A watershed's length can be obtained by measuring the distance between its river mouth and the farthest point. It should be noted that the watershed's length does not necessarily correspond to its main watercourse length, thus being longer due to its high sinuosity. Therefore, it is extremely important to morphometrically characterize the watershed understudy.

Using the DEM (Digital Elevation Model) files kindly provided by LREC (Madeira's Civil Engineering Laboratory), and GIS-Software — ArcGIS — it was then possible to morphometrically characterize the Machico's main watercourse. The geomorphologic data that was gathered from this analysis was used in each author's empirical equation to avoid the single method's constraints.

As suggested by many authors, the morphometric analysis should have its origin in the establishment of a watercourse hierarchy — Strahler or Shreve — according to its order of magnitude [27]. These classifications are obtained by performing a hydrological analysis of the DEM file, getting both the "flow accumulation" and "flow direction" rasters, and using the "Stream Order" tool.

Strahler's watercourse hierarchy is often used as the first stage in other studies. In this one, it was useful to further analyse the planimetric and altimetric data of the considered watershed recurring to the ArcGIS Software.

The Strahler hierarchy is deeply associated with a watershed's ramification or bifurcation ratio, in which each degree of ramification or bifurcation can be calculated using Equation 4 [6, 25, 28–32].

$$R_B = \frac{N_i}{N_{i+1}} \quad (4)$$

with:

N_i=Number of watercourses classified as "i"; dimensionless;

N_{i+1}=Number of watercourses classified as "i+1", dimensionless.

A dimensionless coefficient that establishes the ratio between the number of watercourses of different classes. Moreover, the average bifurcation ratio can be calculated by using Equation 5.

$$\overline{R_B} = \sqrt[i-1]{\prod_{i=1}^{i-1} \frac{N_i}{N_{i+1}}} = \sqrt[i-1]{N_1} \quad (5)$$

with:

N_i=Number of watercourses classified as "i"; dimensionless;

N_{i+1}=Number of watercourses classified as "i+1", dimensionless;

N_1=Number of first-order watercourses.

Much like the previous parameter, the average bifurcation ratio is dimensionless as it simply represents an arithmetic mean of bifurcation ratios. Another key parameter that needs to be considered to characterize a watershed morphometrically is the time of concentration, meaning the time needed for all the watershed area to contribute towards the drainage of the rainfall. [20, 33–35]. Bearing in mind that each author's empiric equation will lead to different times of concentration for the same watershed understudy, then was applied arithmetic mean to Kirpich (Equation 6), Témez (Equation 7), and Giandotti's (Equation 8) equations.

$$t_C = 57 \times (L^3/(H_{MAX} - H_{MIN}))^{0.385} \quad (6)$$

with:

t_C=Time of concentration, minutes;

L=Main watercourse's length, km;

H_{MAX}=Main watercourse's maximum height, m;

H_{MIN}=Main watercourse's minimum height, m.

$$t_C = \left(\frac{L}{i^{0.25}}\right)^{0.76} \quad (7)$$

with:

t_C=Time of concentration, hours;

L=Main watercourse's length, km;

i=Main watercourse's average slope, m/m.

$$t_C = \frac{(4\times\sqrt{A})+(1.5\times L)}{0.8\times\sqrt{H_M}} \quad (8)$$

t_C=Time of concentration, hours;

A=Watershed's area, km²;

L=Main watercourse's length, km;

H_M=Watershed's average height, m.

2.3. Rainfall Analysis

The next step of the present study consisted of an extensive probabilistic analysis of extreme short-duration and high-intensity rainfall events of Machico's watershed, throughout the years. Contextually, the annual maximum daily rainfall was considered (based on the automatic rainfall stations' records) and then applied to Gumbel's probabilistic distribution resorting to Microsoft Excel's programmed spreadsheets. The annual maximum daily rainfall can be calculated using Equations 9, 10 and 11.

$$P_{EST} = P_M + S' \times K_T \quad (9)$$

with:

P_{EST}=Annual maximum daily rainfall, mm;

P_M=Average annual rainfall, mm;

S'=Sample's standard deviation, mm;

K_T=Frequency of occurrence, dimensionless.

with:

$$S' = \left(\frac{\Sigma(X_i - X_M)^2}{n'}\right)^{0.5} \quad (10)$$

with:

X_i=Sample's value, mm;

X_M=Sample's average, mm;

n'=number of samples.

$$K_T = -\frac{6^{0.5}}{\pi}.\left\{0.577216 + \ln\left(\ln\left(\frac{T_R}{T_R - 1}\right)\right)\right\} \quad (11)$$

with:

T_R=Return period, years.

After estimating the daily precipitation intensity of a particular rare-event, Equations 12 and 13 was used to calculate the intensity of the precipitation.

$$I = \frac{P_{EST}\times k}{t_C} \quad (12)$$

with:

I=Rainfall's intensity, mm/h;

P_{EST}=Annual maximum daily rainfall, mm;

t_C=Time of concentration, hours;

k=Distribution coefficient, dimensionless.

with:

$$k = 0.181 \times \ln(t_C) + 0.4368 \quad (13)$$

with:

t_C=Time of concentration, hours.

The time distribution coefficient proves to be a key-parameter as the annual maximum daily rainfall is only valid for an extreme event that lasts 24 hours. Since the rainfall duration will eventually equal the time of concentration of the Machico's watershed, if we were to consider the total amount of rainfall on the hydrological analysis of the watercourse it would become too conservative and therefore the hydraulic infrastructures would be overdesigned [20].

2.4. River Mouth's Drainage Capacity and Peak Flowrate

Furthermore, the drainage capacity of the watershed's river mouth was calculated by using the Manning-Strickler's empirical equation (Equations 14 and 15) and compared to the expected flow rate of an extreme event with a 100-year return period. In order to estimate the expected flow rate of an extreme event with a 100-year return period, it was calculated using world-renowned author methodologies — *i.e.,* Forti (Equation 16); Pagliaro (Equation 17); Rational (Equation 18); Giandotti (Equation 19) and Mockus (Equation 20).

$$Q_M = \left(\frac{1}{n}\right) \times A_M \times R^{\frac{2}{3}} \times \sqrt{i} \quad (14)$$

with:

Q_M=River mouth's drainage capacity, m³/s.

A_M=River mouth's section area, m²;

R=Hydraulic radius, m;

i=River mouth's average slope, m/m;

n=River mouth's roughness coefficient, $m^{-1/3}$ s, Table 12.

with:

$$R = \frac{B+2\times h}{A_M} \quad (15)$$

with:

B=River mouth's width, m;

h=River mouth's height, m;

A_M=River mouth's section area, m²;

In this case, it was necessary to use georeferencing systems to estimate the river mouth's section area.

$$Q_{Forti} = A \times \left(b \times \frac{500}{125+A}\right) + c \quad (16)$$

with:

Q_{Forti}=Forti's Peak flow rate, m³/s;

A=Watershed's area, km²;

b=2,35 for maximum daily rainfall intensity under 200 mm and 3,25 for maximum daily rainfall intensity over 200 mm;

c=0,5 for maximum daily rainfall intensity under 200 mm for maximum daily rainfall intensity over 200 mm.

$$Q_{Pagliaro} = A \times \left(\frac{2900}{90\times A}\right) \quad (17)$$

with:

$Q_{Pagliaro}$=Pagliaro's Peak flow rate, m³/s;

A=Watershed's area, km².

$$Q_{Rational} = \frac{C\times I\times A}{3.6} \quad (18)$$

with:

$Q_{Rational}$=Rational's Peak flow rate, m³/s;

C=Surface runoff coefficient, Table 13;

I=Rainfall's intensity, mm/h;

A=Watershed's area, km².

$$Q_{Giandotti} = \frac{\lambda\times A\times P_{MAX}}{t_C} \quad (19)$$

with:

$Q_{Giandotti}$=Giandotti's Peak flow rate, m³/s;

λ=Reduction ratio, Table 14;

A=Watershed's area, km²;

P_{MAX}=Rainfall's height for an event of equal duration and time of concentration, mm;

t_C=Time of concentration, hours.

$$Q_{Mockus} = \frac{2.08\times A\times P_{EST}\times C}{\sqrt{t_C}+0.6\times t_C} \quad (20)$$

with:

Q_{Mockus}=Mockus' Peak flow rate, m³/s;

A=Watershed's area, km²;

P_{EST}=Annual maximum daily rainfall, cm;

C=Surface runoff coefficient, Table 13;

t_C=Time of concentration, hours.

As suggested, one of the main design criteria for detention basins — considering the safety of the population and their goods — is that the maximum flow rate must always remain under 85% of the watershed's drainage capacity [36]. Alternatively, this author also suggests that it should be designed a weir to maximize the watershed's drainage capacity in case a short-duration and high-intensity rainfall occurs, thus not allowing the watercourse to overflow.

Based on the aforementioned criteria, the Fill Rate must be calculated by using Equation 21, and in case the drainage capacity of the watershed proves to be insufficient a detention basin must be designed.

$$FR = \frac{Q_P}{Q_M} \times 100 \quad (21)$$

with:

FR=Fill Rate, %;

Q_P=Peak flow rates for each of the considered methodologies, m³/s;

Q_M=River mouth's drainage capacity, m³/s.

The parameter Fill Rate is related to the river mouth's section area that is filled with rainfall. Therefore, when the FR gets over 100% it means that the watercourse can no longer contain the amount of rainfall and will necessarily overflow. Therefore, must be designed a detention basin that will act as a structural flood mitigation measure.

2.5. Detention-Basin Design

When the discharge capacity of a river mouth proves insufficient to remove all the stormwater flowing through a given catchment, it becomes necessary to construct a Cipolletti weir to throttle and control the flow, Equation 22. Once the flow capacity of the weir is set to an acceptable value, a detention basin can be designed based on the rainfall duration. Two main methods were used for this purpose, namely the Dutch (Equation 23) and the Ternary Phase Diagram - TPD (Equation 24).

$$Q_S = 1.86 \times L_{SD} \times {H_D}^{1.5} \quad (22)$$

with:
Q_S=Discharge rate, m³/s;
L_{SD}=Weir's bottom width, m³/s;
H_D=Maximum height of water above the bottom of the weir, m.

$$V_A = (Q_P - Q_S) \times t_C \times 3600 \quad (23)$$

$$V_A = \frac{(Q_P - Q_S) \times (2 \times t_C - 2 \times [Q_S/\{Q_P/t_C\}])}{2} \quad (24)$$

with:
V_A=Retained flow, m³;
Q_P=Rainfall flow rate, m³/s;
Q_S=Discharge rate, m³/s;
t_C=Time of concentration, hours.

The Equation 24 was formulated thanks to the geometric analysis of the Ternary Phase Diagram (Figure 7), taking into consideration that an event would last at least twice the time of concentration for the given watershed since a raindrop that would eventually fall over the watershed and specifically in its farthest place would need at least the time of concentration to reach the river mouth.

The main difference between both methodologies is because the Dutch method does not contemplate the delay and damping of the flood hydrogram, which leads to the overdesign of the structure [37], as displayed in Figure 4, with qs: Discharge rate; tc: time of concentration; tmáx: maximum duration (base); td: delay; $H_{a,MAX}$: Maximum storage capacity; i (t_{MAX}): Rainfall's intensity corresponding to the maximum duration.

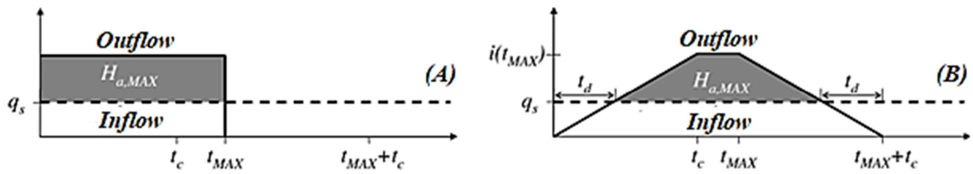

Figure 4. *(A) Dutch Method; (B) TPD Method (Source: [37]).*

It is observed that in the Dutch method storage begins immediately after precipitation, which is not the reality since storage starts only when the flow rate drained downstream of the watershed exceeds the drainage capacity of the weir.

2.6. Modification of the Roughness Coefficient

Moreover, a structural mitigation measure taken into consideration was changing the roughness coefficient of the walls and streambed of the watercourse, therefore avoiding the reduction of the drainage capacity due to friction. This methodology consists of changing the value of the parameter n in the Manning-Strickler equation, improving the flow rate of the given watercourse by considering another material for the river wall coverage.

3. Results

The results presented in this section are the result of applying the equations described in the previous section. Initially, to assess the morphometrical features of Machico's mains watercourse it was carried out an individual analysis of the parameters presented in Table 1, without correlating them, to evaluate the relevance of each of them to define the watershed as flood-prone.

The first parameter to be studied refers to the area of the hydrographic basin, which has a primary role for the analysis of the volume of water flown to the mouth, where they can be classified as Very Large > 20 km²; Large > 10 km²; Average > 1 km² and Small < 1 km² [38]. Hence, as can be seen in the previous table, the river basin under study has a "Very Large" classification, which also suggests a greater propensity for floods concerning smaller hydrographic basins. It is notorious that the dimension analysis parameter is arbitrary and may differ according to the type of analysis to be performed [38], as well as the propensity to floods.

Table 1. *Parameters Calculated or Extracted from ArcGIS.*

Parameter	Value
Area (km²)	24.649
Perimeter (km)	34.700
Main watercourse length (km)	12.071
Maximum Altitude of the Main Watercourse (m)	984.999
Minimum Altitude of the Main Watercourse (m)	0.000
Average Concentration Time (hours)	2.249
Gravelius compactness coefficient (dimensionless)	1.972
Elongation Factor (dimensionless)	10.122
Form Factor (dimensionless)	0.311
Number of Watercourses (units)	833.000
Average bifurcation ratio (dimensionless)	5.169
Strahler classification (dimensionless)	5.000

Because of the moderate variation of the elongation and hypsometry of this watershed shown in Figure 5, meaning that the ratio between the watershed's altitude and length is not too high, therefore the watershed does not reveal itself to be flood-prone.

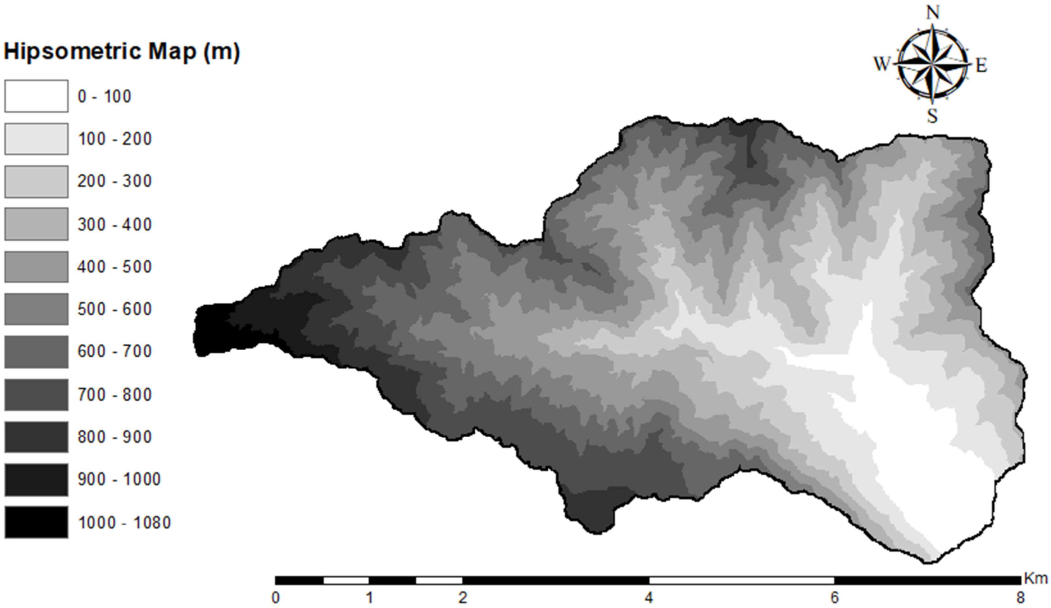

Figure 5. *Machico's Hydrographic Basin–DEM File (Source: Authors by ESRI ArcGIS, 2020).*

Finally, concerning the drainage network of the watershed, as shown in Figure 6, the number of watercourses suggests a high drainage capacity–i.e., the ratio between the number of watercourses and the basin's area), and subsequently a higher predisposition to floods.

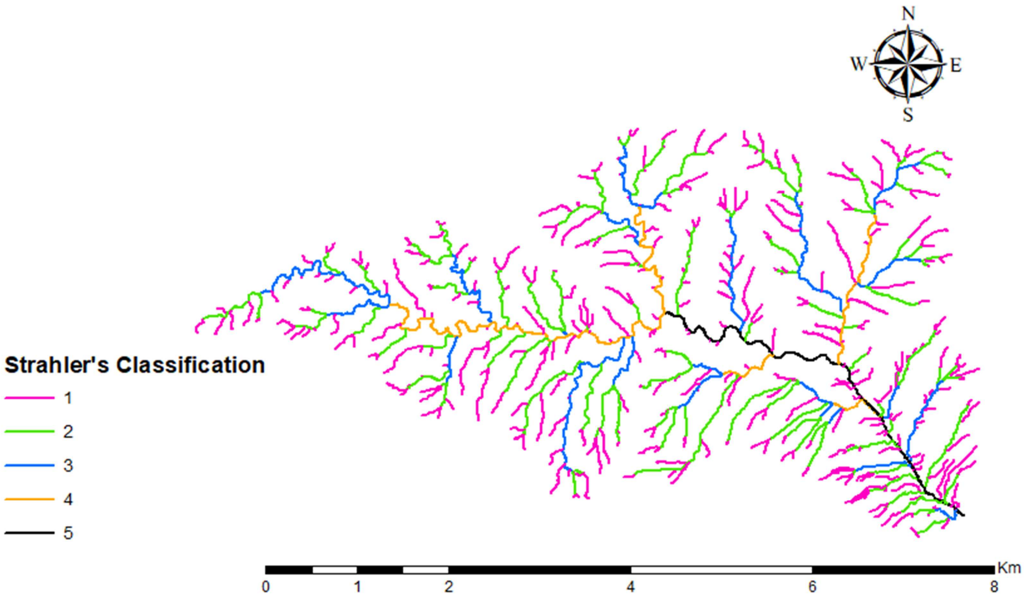

Figure 6. *Strahler's Classification (Source: Authors by ESRI ArcGIS, 2020).*

For the rainfall analysis, the data provided by the National Water Resources Information System (SNIRH) were used with sample data for sixteen years, presented in Table 15 and Figure 8. In the probabilistic treatment of the Gumbel's Distribution, the values presented in Table 2 were obtained.

With the determination of the expected precipitation intensity for a recurrence time of 100 years and using the methodologies previously explained, the peak flow rates of full, presented in Table 3. It is evident that the surface flow coefficient used in the Rational Method corresponds to the value of 0.700 (Table 4), that is, it was considered a region with a considerable urban index where 70% of the precipitate volume will be directed to the mouth through surface flow since the area under study is characterized as a commercial region, presented in the Table 13.

Table 2. *Rainfall parameters.*

Parameter	Symbol	Value
Average Annual Rainfall (mm)	P_M	112.025
Standard Deviation (mm)	S'	53.844
Frequency Factor	K_T	3.136
Time Breakdown Coefficient	k	0.259
Annual Maximum Daily Rainfall (mm)	P_{EST}	280.916
Precipitation Intensity (mm/h)	I	72.883

Table 3. *Peak Flow Rates.*

Methodology	Flow Rate (m³/s)
Forti	292.306
Pagliaro	623.486
Rational	379.424
Giandotti	280.141
Mockus	379.090

Table 4. *Adopted Surface Runoff Coefficient (Source: [39]).*

Urban Areas		
Land Occupation		**Surface Runoff Coefficient**
Commercial Areas	City district	0.700–0.950
	Periphery	0.500–0.700

Table 5. *Adopted Giandotti´s Reduction Coefficient (Source: [40]).*

A (km²)	λ	"C" Equivalent
< 300	0.346	1.250

It was used the value of λ presented in Table 5 to calculate Giandotti's flowrate.

Table 6. *Assessment of the Need for Implementing a Detention Basin.*

Parameter	Value
River's Mouth Width (m)	24.000
River's Mouth Height (m)	3.000
River's Mouth Flow Rate Capacity (m³/s)	358.512
Pre-measured Fill Rate (%) - Forti	82
Pre-measured Fill Rate (%)–Pagliaro	174
Pre-measured Fill Rate (%) - Rational	106
Pre-measured Fill Rate (%)–Giandotti	78
Pre-measured Fill Rate (%) - Mockus	106

Subsequently, the analysis of the flow capacity of the estuary through the equation Manning-Strickler and the verification of the need to implement a detention basin was carried out, obtaining the values shown in Table 6. Since the walls and the riverbed are covered by different materials and consequently have different roughness coefficients, the weighted average was taken for this parameter, with the walls consisting of mortared stone masonry in good condition (n=0.020) and the bed consisting of a rocky canal vegetated in poor condition (n=0.040). A slope of 0.01 m/m was assumed to account for a similar gradient to that at the mouth of the river, where it reaches a minimum and critical value due to the low gradient.

Examination of Table 6 shows that the fill rate is above the established limit of 85% for the methods of Pagliaro, Rational, and Mockus and that the installation of flood control measures is imperative. Since the discharge capacity of the estuary was found to be insufficient, a detention basin was designed to control the discharge of the Machico catchment, considering the spatial disposition and all the infrastructures in the surrounding area.

First, the Cipolletti´s weir was sized to regulate runoff and drain the estuary within its discharge limits. The characteristics of the Cipolletti´s weir are shown in Table 7.

Table 7. *Application of Cipolletti's Weir.*

Parameter	Value
Width of the Weir Sill (m)	22.000
Head on Weir Crest (m)	3.000
Weir's Exit Water Flow Rate (m³/s)	212.627
Post-measured Fill Rate (%) - Pagliaro	59
Post-measured Fill Rate (%) - Rational	59
Post-measured Fill Rate (%) - Mockus	59

Thereafter, detention basins were designed using the Dutch and TPD methods. It is important to emphasize that both methods have a simplified character, as they tend to neglect several factors and features and may represent oversizing. Another pivotal aspect of this design procedure refers to the possibility of keeping the height and width of the stream to reduce the environmental and urban impacts due to the implementation works of the measure. Therefore, the only geometric variable of the detention basin will be its length, so the length of the basin must be smaller than the total length of the main watercourse (calculation criterion). After performing the calculations, the values presented in Table 8 were obtained.

Table 8. *Design of the Detention Basin.*

Parameter	Value
Width of Detention Basin (m)	24.000
Detention Basin Height (m)	3.000
Length of Detention Basin (m)–Dutch Method (Pagliaro)	46209.209
Length of Detention Basin (m)–TPD Method (Pagliaro)	30450.512
Length of Detention Basin (m)–Dutch Method (Rational)	18759.575
Length of Detention Basin (m)–TPD Method (Rational)	8246.862
Length of Detention Basin (m)–Dutch Method (Mockus)	18722.056
Length of the Detention Basin (m)–TPD Method (Mockus)	8221.105

Finally, the modification of the roughness coefficient was studied as another structural flood mitigation measure, whilst maintaining the streambed's vegetation characteristics. Thus, the values presented in Table 9 correspond more precisely to the improvement of the state of conservation of the stream, towards reducing the loss of flow capacity caused by excessive friction between the fluid and the coating material.

Table 9. *Modification in the Roughness Coefficient.*

Parameter	Value
Roughness Coefficient of the Walls - Modified	0.012
Bed Roughness Coefficient - Modified	0.030
River's Mouth Flow Capacity - Modified (m³/s)	488.881
Fill Rate–Post–Modified (%) - Pagliaro	128
Fill Rate–Post–Modified (%) - Rational	78
Fill Rate–Post–Modified (%) - Mockus	78

The modified roughness coefficients of the walls correspond to a surface with cement mortar in good condition, while in the stream's bed to a stony bed vegetated in good condition, as presented in Table 10.

4. Discussion

Since the primary purpose of this research was the recommendation of a simplified measure for mitigating the impacts of downstream floods, the structural design of the holding basin for the Machico's Watershed proved to be effective in controlling the flow rate at the outfall, where the fill rate value went from 174%, 106%, and 106%, for the Methodologies of Pagliaro, Rational and Mockus, respectively, to 59% - i.e., below the pre-established limit. As the values obtained to confirm the flood risk analysis carried out by the leading regional authority (DROTA), it is considered that there is acceptable accuracy in this study, Table 11.

Table 10. *Adopted Manning-Strickler Roughness Coefficient (Source: [40]).*

Type of channel and description	Very Good	Good	Regular	Bad
Channels with stony bed and vegetated slope	0.025	0.030	0.035	0.040
Cement mortar surfaces	0.011	0.012	0.013	0.015

Table 11. *Watersheds with Significant Flood Risk. (Source: [42]).*

Municipality	Watershed
Machico	Ribeira de Machico Ribeira do Junçal Ribeira da Maiata

It is patent that the proposal of this research aims to origin the least possible impact on the existing waterway and its surroundings. In this sense, it was decided not to alter the dimensions of the cross-section of the streams, both in width and in height. Furthermore, the only dimensional variant of the holding basin was its length. Based on this assumption, the Dutch method presented considerable oversizing, as the total length of the holding basin found must be larger than the full length of the mainstream, which denotes the need to change one more of the flow sections, particularly height or width. Consequently, despite the efficiency in the flow rate regularization, the Dutch method did not apply to the urban conditions previously imposed. Therefore, after substantiating the non-applicability of this methodology in this specific case, the TPD method was adopted.

Concerning the TPD method, the same conditions were imposed, notwithstanding, the methodology showed applicability, considering that the total length of the holding basin is smaller than the full length of the main watercourse, except for the peak flow rate calculated by the Pagliaro method, which presented a very dissimilar value of the other methodologies.

Considering the alteration in the roughness coefficient of the stream, it was decided to remain with the characteristic of vegetation in the stream bed, since the complete removal of the vegetation cover would have to be very frequent. Even so, it is considered that the stream bed remains in good condition and with less dense vegetation than it is currently. Regarding the walls, maintenance should not be constant since abrasion wear would occur solely with the presence of considerable volumes of water with sediments of significant granulometry.

The modification of the roughness coefficient in the channels was a successful measure to mitigate the effects of the floods, where the Fill Rate is established within the previously addressed criterion–i.e. the precipitate flow corresponds to less than 85% of the mouth flow capacity. It is highlighted that both methodologies are applicable–i.e. TPD method and the modification of the roughness coefficient–can be employed together to shorten the length of the holding basin by optimizing the mouth flow capacity.

As aforementioned, the methodologies used are simplified in nature, that is, they do not consider local particularities. As an outcome, the measures tend to possess too high a safety margin, resulting in oversizing of the hydraulic structures in question. Induced by the impossibility of exploring all aspects that compose a more accomplished and effective analysis in this academic exercise, other studies can be carried out with the purpose to complement or optimize the results obtained here, such as analysis of soil infiltration capacity; analysis of the flow capacity of the implemented urban hydraulic system aiming to reduce the storage volume of the holding basins; sediment deposition analysis; verification of the deterioration of the canal walls by abrasion; analysis from the perspective of urban growth and its influence on the increase in flow, among others.

5. Conclusions

The results of this study show that the catchment area of the main watercourse of Machico is at risk of flooding, which is confirmed by DROTA's Flood Risk Report. Although one of the streams has a considerable width, its depth is relatively shallow, and the presence of vegetation in the streambed makes the discharge capacity of its estuary insufficient when compared to the expected discharge determined by the methods of Pagliaro, Rational, and Mockus.

Also, the Dutch Method could not be considered as an active measure to reduce or even prevent flooding impacts because the length of the detention basin obtained by using this method was much greater than the actual length of the watercourse. In contrast, the length of the detention basin obtained by the many methods of Ternary Phase Diagram is shorter than the actual length of the watercourse, which proves that it is a valid option and that it is not necessary to increase its width. The only exception was Pagliaro's method, where the determined flow was higher than the average, leading to an oversizing of the infrastructure itself.

Finally, changing the roughness coefficient of the channel proved to be a pragmatic yet very effective way of mitigating the effects of flash floods by increasing the discharge capacity of the estuary and then reducing the degree of filling to 85% (as recommended).

This study allowed us to characterize another watershed in Madeira and will undoubtedly be an important contribution to the project of classifying each hydrographic basin of the island, taking into account the risk of flooding and the resulting impact on people's lives.

Appendix

Table 12. *Manning-Strickler Roughness Coefficient (Source: [40]).*

Type of channel and description	Very Good	Good	Regular	Bad
Mortared stone masonry	0.017	0.020	0.025	0.030
Rigged stone masonry	0.013	0.014	0.015	0.017
Dry stone masonry	0.025	0.033	0.033	0.035
Brick masonry	0.012	0.013	0.015	0.017
Smooth metal gutters (semicircular)	0.011	0.012	0.013	0.016
Open channels in rock (irregular)	0.035	0.040	0.045	-
Channels with bottom on land and slope with stones	0.028	0.030	0.033	0.035
Channels with stony bed and vegetated slope	0.025	0.030	0.035	0.040
Channels with concrete coating	0.012	0.014	0.016	0.018
Earth channels (rectilinear and uniform)	0.017	0.020	0.023	0.025
Dredged canals	0.025	0.028	0.030	0.033
Clay conduits (drainage)	0.011	0.012	0.014	0.017
Vitrified clay conduits (sewage)	0.011	0.013	0.015	0.017
Flattened wooden plank conduits	0.010	0.012	0.013	0.014
Gabion	0.022	0.030	0.035	-
Cement mortar surfaces	0.011	0.012	0.013	0.015
Smoothed cement surfaces	0.010	0.011	0.012	0.013
Cast iron coated tube with tar	0.011	0.012	0.013	-
Uncoated cast iron pipe	0.012	0.013	0.014	0.015
Brass or glass tubes	0.009	0.010	0.012	0.013
Concrete pipes	0.012	0.013	0.015	0.016
Galvanized iron pipes	0.013	0.014	0.015	0.017
Rectilinear and uniform clean streams and rivers	0.025	0.028	0.030	0.033
Streams and rivers cleared rectilinear and uniform with stones and vegetation	0.030	0.033	0.035	0.040
Streams and rivers cleared rectilinear and uniform with intricacies and wells	0.035	0.040	0.045	0.050
Spread margins with little vegetation	0.050	0.060	0.070	0.080
Spread margins with lots of vegetation	0.075	0.100	0.125	0.150

Table 13. *Surface Runoff Coefficients (Source: [39]).*

Urban Areas		
Land Occupation		**Surface Runoff Coefficient**
Green Areas	Lawns in sandy soils	0.050–0.200
	Lawns on heavy soils	0.150–0.350
	Parks and cemeteries	0.100–0.350
	Sports fields	0.200–0.350
Commercial Areas	City district	0.700–0.950
	Periphery	0.500–0.700
Residential Areas	Town-center villas	0.300–0.500
	Villas on the outskirts	0.250–0.400
	Apartment buildings	0.500–0.700
Industrial Areas	Dispersed industry	0.500–0.800
	Concentrated industry	0.600–0.900
Railways		0.200–0.400
Streets and Roads	Paved	0.700–0.900
	Concrete	0.800–0.950
	In brick	0.700–0.850

Table 14. *Giandotti Reduction Coefficients (Source: [40]).*

A (km²)	λ	"C" Equivalent
< 300	0.346	1.250
300–500	0.277	1.000
500–1000	0.197	0.710
1000–8000	0.100	0.360
8000–20000	0.076	0.270
20000–70000	0.055	0.200

Table 15. *Precipitation Historical Data (Source: [41]).*

n	Year	(mm)
1	1998/1999	48.000
2	1999/2000	61.000
3	2000/2001	160.000
4	2001/2002	90.000
5	2002/2003	68.900
6	2003/2004	65.000
7	2004/2005	111.000
8	2005/2006	105.000
9	2006/2007	87.700
10	2007/2008	79.400
11	2008/2009	137.200
12	2009/2010	193.000
13	2010/2011	162.200
14	2011/2012	43.200
15	2012/2013	217.700
16	2013/2014	163.100

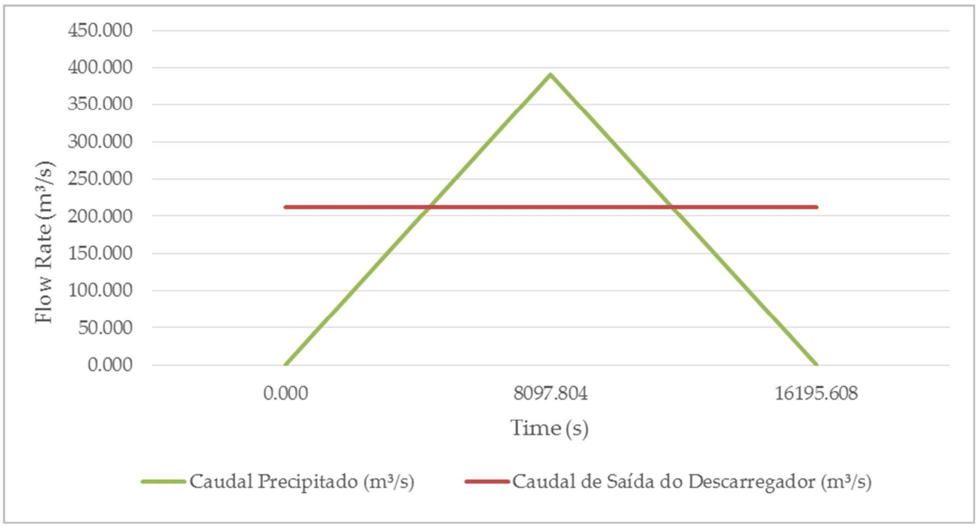

Figure 7. *Ternary Phase Diagram.*

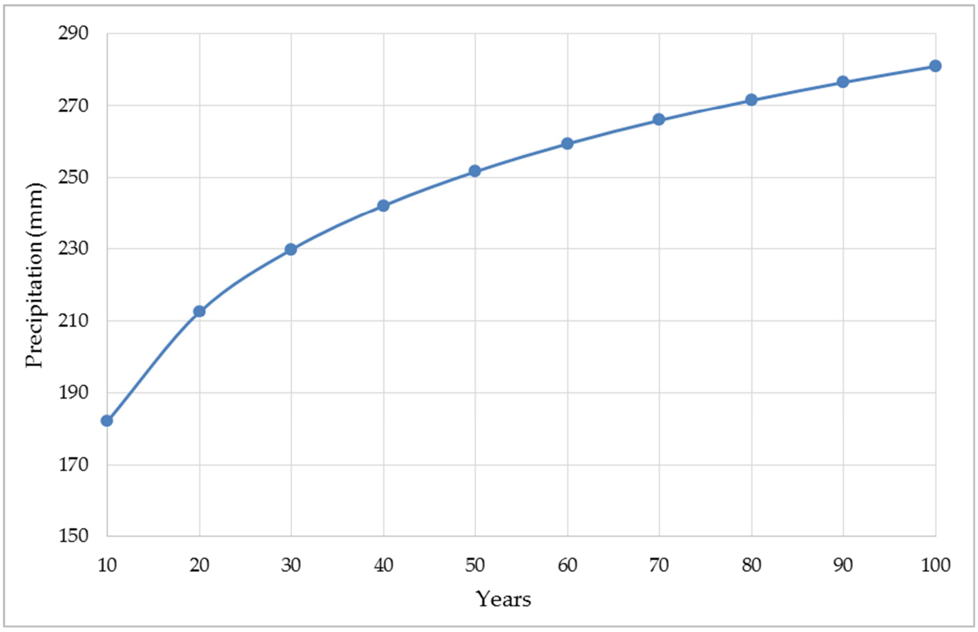

Figure 8. *Expected Rainfall for Machico's Watershed.*

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