

# Modelling Torrential Rain Flows in Urban Territories: Floods - Natural Channels (The Case Study of Madeira Island)

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**Abstract:** The understanding of flood phenomena regarding torrential rain, occurring in natural channels within urban areas represents a crucial aspect to increase safety and life's standards of the populations, issues that are deeply related to a well-developed sustainable urban and spatial planning. In this regard, flows inside urban areas have great heterogeneity, therefore their characterization requires a formulation which explicitly incorporates this spatial variability. The present study intends to establish a parallel between the selected models, numerical and reduced, enabling to examine their contributions regarding the flow characterization and water height in natural channels within urban settlements located near the river mouth and inserted in hydrographic basins with accentuated orography, as is the case of Funchal urban area at Madeira Island. Based on the available resources, the geometric simplicity of the study case and the results, the most appropriate method is the programmed spreadsheet, providing prompt and reliable information for the design of better adapted hydraulic structures that can face this extreme phenomenon, checking the adaptability of existing structures, as well as in the decision-making process concerning urban planning, safeguarding the populations in similar conditions.

**Keywords:** Floods, Modelling, Natural Channels, Sustainable Spatial Planning, Urban Agglomerations

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## 1. Introduction

Floods occur when the water of watercourses or stormwater drainage systems overspill the drain sections and consequently occupy urban areas – i.e. streets, sidewalks, commercial areas, industrial areas, homes [1, 2]. The effects associated with this typology of event depends on geographical and climatic features of watersheds, as well as on anthropogenic factors – i.e. the occupation of the basin soil and the urbanization degree of potential flood zones, as it happens in Mexico [3], Poland [4], Spain [5]; Greece [6], Sudan [7], Italy [8] or Norway [9].

Thus, the occurrence of intense rainfalls translates into

severe floods in regions that are more exposed to this typology of phenomena, as is the case of the Madeira Island [10-12]. According to the analysis of climate change models undertaken so far, an increase in the frequency and intensity of these occurrences is expected, announcing future hardship and unsafety to urban agglomerations [13-15]. Also, the planned modifications of precipitation will have impacts on urban water cycles – i.e. the amount of water, intercepted or undercover courses, or even drained – leading to the necessity to incorporate this issues, with a stronger commitment attitude by the main-actors and politicians, in the processes of urban planning - especially regarding the design and management of drainage systems, and the

management of waters in urban areas [16-18]. Unfortunately, the above-mentioned uncertainties about the impact of those changes in precipitation are expected to continue in a long-term [19, 20].

In this regard, the considerable concentration of buildings, roads, and population in the surrounding areas of water courses lead to successive amendments of the original bedrock – i.e. transverse and lengthwise – which consequently will intensify the arising from a spontaneous flood – a recurring issue in Madeira Island [10, 21-24]. These flood events are originated in intense rainfall compressed in a short period of time, leading to the creation of a drastically variation on the flows, which mainly causes the obstruction of the channel by entrainment of debris – i.e. flash floods, or landslides – or in abundant rainfall over several days or weeks – i.e. full sluggish or progressive [25-30].

Here, can be exposed the dramatic case occurred on 20 February 2010, at Madeira Island, where after a long rainy season allied to an adverse weather situation has caused a massive alluvium that has reached strongly several urban areas at the South of the Island – particularly on the municipalities of Funchal and Ribeira Brava. Such disaster has made dozens of fatalities and missing persons, as well as high destruction of infrastructure and equipment [24, 31-33]. According to several authors, [34-40], that have previously studied this type of phenomena throughout time – worldwide and in different contexts – the exposed prevention and management measures are still in a grey zone and presents considerable differences from region to region.

Such events demonstrate the urgency to know in depth the behaviour of surface water in urban areas [41] and their interaction with the drainage systems, as well as the need to

correctly characterize the flow in natural channels [42] – i.e. through hydrodynamic simulation models, enabling to create enhanced tools to aid in the prevention and management of floods [43, 44].

In fact, an increase of literature related to modelling [45-47], floods [36, 20, 48-50], land management [10, 22, 51-53], and related parameters [54-67] has been produced throughout the last two decades, which benefits the elaboration of further and improved studies regarding the previously stated aspects. Still, further studies need to be developed aiming to fully understand the thematic from all the perspectives.

The present study intends to evaluate the contributions and adequacy of the selected models – programmed spreadsheet, HEC-RAS program and experimental model – regarding floods due to torrential rain in natural channels within urban settlements located near the river mouth and inserted in hydrographic basins with accentuated orography, applied to Funchal urban area at Madeira Island, based on parameters regarding the flow characterization (Fr, Re and n) and water height (h).

## 2. Methodology

A quantitative methodology was considered, a nomothetic one – methodology that deals with the establishment of general laws or the study of recurring phenomena, especially with natural events – once it promotes the development of research along with established protocols and specific techniques [46, 68, 69]. Thus, a case study method approach [17, 70-73] has been used. In the following, a scheme synthesizing the methodological approach is presented (Figure 1).

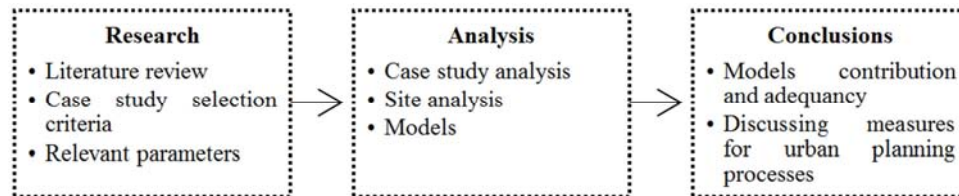


Figure 1. Methodological approach scheme.

### 2.1. Study Area

The Madeira Archipelago is located in the North Atlantic Ocean, between latitude 30° 01' N and 33° 08' N and between longitude 15° 41' W and 17° 16' W. Covering an area of 802 km<sup>2</sup>, the Madeira Archipelago is composed of the

following islands: Madeira (742 km<sup>2</sup>) (Figure 2), Porto Santo (43 km<sup>2</sup>) (Figure 2), Desertas (14 km<sup>2</sup>), and Selvagens (3 km<sup>2</sup>). At Table 1, it is presented a summary of the main physical features of Madeira Island [74-78].

Table 1. Physical features of Madeira island (adapted from França & Almeida, 2003).

Physical features	
Average altitude	646 m
Highest peak	Pico Ruivo (1862 m)
Average slope	56%
Perimeter	177.3 km
Area	742 km <sup>2</sup>
Predominant soils	Andosols (42%)
Average daily temperature:	
Maximum (August)	23°C
Minimal (February)	5.4°C

Prevailing winds:	
Direction	N-NE
Maximum average velocity (and direction)	30 km/h (S-SW)
Weighted average annual precipitation	1628 mm

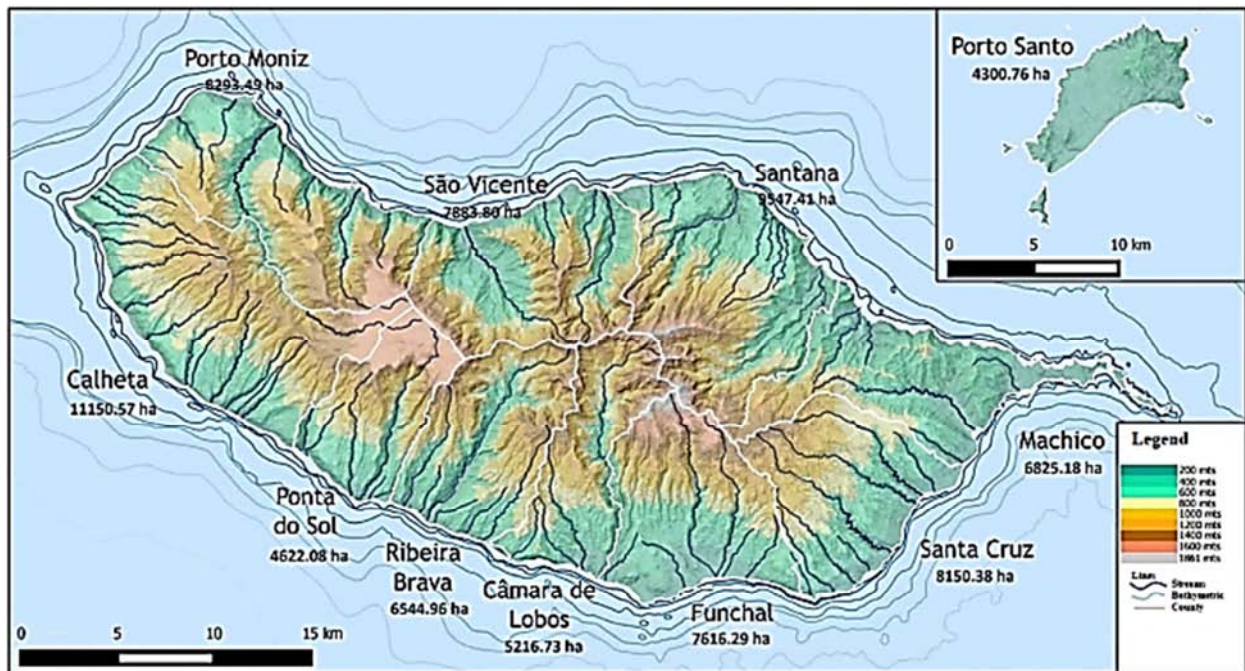


Figure 2. Madeira Island relief chart (source: Wikimedia Commons).

The Archipelago presents singular conditions that contribute to the occurrence of potentially dangerous floods [79, 24]. Among these critical conditions could be highlighted that: in the archipelago exists more than 120 watersheds occupying almost the entire territory (741 km<sup>2</sup>), being that, approximately, 95% have an area smaller than 25 km<sup>2</sup>; the 7 biggest basins (with exception to basins of Funchal) corresponds to 40% of the total Island surface - if the Funchal's basins are considered, the percentage rises to 45% (10 basins); riversides have, in general, short lengths (below 21 km) and the time of concentration is relatively low (less than 2 hours) in comparison with the correspondent watersheds; rugged terrain promotes vertical impulsion of maritime tropical air masses coming from the southwest; free surface flow's fast convergence into the river channels and the high drainage density levels; deeply changed volcanic geological substrate and consequently less permeable; embedded v-shaped valleys, enabling greater interaction between landslides and river dynamics [80, 77, 81, 78].

Also, intense short duration precipitation is the factor that triggers the most dangerous floods, caused by the conjunction of several factors such as: the weakening of the Azores anticyclone during the Winter; increasing passage of low-pressure centers with frontal systems associated; increased meridian circulation and invasions of cold air at high altitude – leading to the creation of low-pressure valleys and their respective stationary depressions, the so-called cold air drops; stronger convective activity; the large thermal gradient between the low and middle troposphere [80, 82, 83,

78].

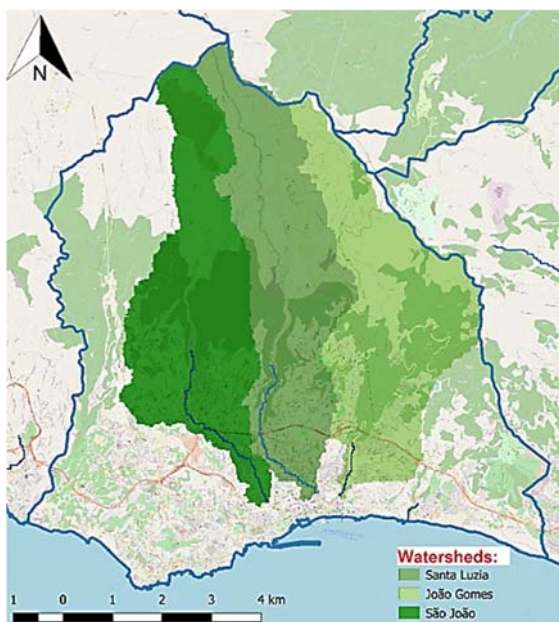
Considering the several events of flood - disastrous for urban agglomerations located at the river's mouth and its surrounding areas - the selection of Funchal and its three watersheds with their main streams as cases study (Figure 3) to develop such study is seen as appropriate since it presents a lot of factors that contribute to torrential rain flows in urban agglomerations, such as: natural channels; densely populated areas - occupied by buildings, from housing to services and commerce; flood background [24]; and also issues related to urban planning and land management processes [10] conditioning the design of the channels - in fact, some infrastructures are located upstream occupying the riverbed and banks, constricting it in width, and before 20 February 2010, where the lack of maintenance in the riverbed have influenced the height available for the flow, which has increased the likelihood of flood [80].

Geographical Information Systems (GIS) tools - i.e. ArcMap software (from ESRI company) - has been used for the characterization of watersheds and streamlined acquisition of parameters, since it has a wide range of tools in the areas of hydrology and data edition. From the Digital Terrain Model (DTM) files in ".asc" format, geographic information, provided by the Regional Direction of Spatial Planning and Environment (DROTA), has been organized and processed from ArcGIS software, complemented with Excel and AutoCAD, obtaining the required parameters that enabled the characterization of watersheds of São João, Santa Luzia and João Gomes (Table 2).



*Table 2. Summary of the watershed's characteristics.*

Parameter	São João	Santa Luzia	João Gomes
Summary of the watershed's characteristics			
Area (km <sup>2</sup> )	14.957	14.315	12.684
Perimeter (km)	32.920	31.220	31.400
Gravelius compactness coefficient	2.400	2.327	2.486
Elongation factor	16.064	14.955	17.375
Form factor	0.156	0.144	0.171
Average altitude (m)	733.800	830.100	852.567
Average height (m)	733.800	830.100	852.567
Main watercourse length (km)	12.012	11.789	11.340
Maximum altitude of the main watercourse (m)	1763.041	1787.000	1595.000
Average slope of the main watercourse	140.500	144.600	139.600
Equivalent height of the main watercourse (m)	1283.800	1260.500	1410.300
Equivalent slope of the main watercourse	0.116	0.111	0.128
Slope 10-85	0.142	0.151	0.160
Relief index	0.180	0.179	0.186
Watershed average slope (degrees)	25.313	28.038	24.966
Watershed average slope (%)	50.185	60.007	49.759
Network form ordered by Strahler method	Order 5	Order 5	Order 5
Number of watercourses	221.000	258.000	188.000
Total length of watercourses (km)	43.510	40.300	34.700
Network form ordered by Shreve method	221.000	258.000	188.000
Average bifurcation ratio	3.801	3.990	3.810
Time of concentration (hours)			
Témez	0.940	0.899	0.907
Ven Te Chow	0.873	0.866	0.855
Giandotti	1.545	1.424	1.338
Average time of concentration	1.127	1.063	1.033
Watershed response time (hours)	2.908	2.815	2.736
Drainage density (km/km <sup>2</sup> )	0.086	0.088	0.091
Average route on the ground (km)	0.940	0.899	0.907
Sinuosity	1.233	1.220	1.324
Network density (number of watercourses/km <sup>2</sup> )	14.776	18.023	14.822
Watershed maximum height (m)	1763.041	1787.000	1595.000
Watershed length (m)	9795.362	9959.646	8575.931
Directrix (m)	9656.248	9557.692	8435.858

*Figure 3. Location of Funchal watersheds with their main streams.*

Based on the studies put forward by [76, 77], from a geological perspective, Funchal is constituted essentially by

superior, intermediate complex and sedimentary cover on the river mouth: superior complex - local lava spills with tephra, between a million and six thousand years, extrusive igneous rocks; intermediate complex - lava sequences with tephra, separated by erosion levels, age between 1 and 2.5 million years, extrusive igneous rocks; sedimentary cover - riverine and marine sedimentary-gravels, mudslides, beach sands, and sedimentary rocks [74, 75, 78].

Also, from a geographic point of view, the study area is mainly urban. Regarding the vegetal sphere, the vegetation is composed of ground cover plants found, mainly, in urban green spaces and on the banks and bottom of riversides - presence of flexible vegetation, except for the areas where the bottom is covered by concrete.

## 2.2. Methods and Concepts – Relevant Parameters and Formulas

Relevant parameters, such as: time of concentration; peak flow rates; velocity; Froude and Reynolds numbers; and Manning's coefficient; are subject to punctual revisions throughout time about their formula, theoretical foundation, and application. In this sense, it will present the following parameters considering this improvement dynamic.

### Time of concentration

**Table 3.** Formulas to calculate the time of concentration (adapted from Lousada & Camacho, 2018).

Formula	
Témez	$t_c = 0.3 \times (L/i^{0.25})^{0.76}$
Ven Te Chow	$t_c = 0.8773 \times (L/\sqrt{i})^{0.64}$
Giandotti	$t_c = [(4 \times \sqrt{A}) + (1.5 \times L)] / (0.8 \times \sqrt{H})$
Average	$\bar{t}_c = (\sum t_{c,i}) / n$

(i) - inclination of the main water course average; (L) - length of main water course (only Témez) or largest water course to a given point (km); (A) - basin area to a given point (km<sup>2</sup>); ( $\bar{H}$ ) - average height of the basin, measured from the section dimension (m); (n) - number of formulas used.

The time of concentration of a basin ( $t_c$ ) is the time required for all the area contribute to the runoff in the output. Still, it can also be defined as the time required for a drop of water lying on the hydraulically farthest point of the basin to reach the output section. Thus, is considered as a constant feature of the basin, regardless of the characteristics of rainfall. At Table 3, are listed several expressions from which it is possible to define the time of concentration for a given section of the watershed [59, 60, 84-86].

#### Peak flow rates

The peak flow rate is an important indicator for preliminary assessment of the flood risk [43, 87]. It can be determined based on: empirical formulas - i.e. considering the accumulated experience and the area of the watershed; kinematic formulas - i.e. considering the concepts of time and concentration of critical precipitation; statistical formulas - regarding the analysis of a set of values for a given section [88, 59].

Based on the existing manuals - [88, 59, 61-63, 65, 66] - the formulas were selected based on their limitations and presented in Table 4.

**Table 4.** Formulas to calculate the peak flow rate.

Formula	
Forti	$Q_p = A_b \cdot [b \cdot 500 / (A_b + 125) + c]$
Iskowski	$Q_p = K_{IS} \cdot m_l \cdot \bar{P} \cdot A_b$
Pagliaro	$Q_p = A_b \cdot [2900 / (90 + A_b)]$
Whistler	$Q_p = A_b \cdot [1538 / (259 + A_b) + 0,054]$
Rational	$Q_p = C \cdot I \cdot A_b$
Giandotti	$Q_p = \lambda \cdot A_b \cdot h_{max} / t_c$
Mockus	$Q_p = 2,08 \cdot A_b \cdot P_e / (\sqrt{t_c} + 0,6 \cdot t_c)$
Témez	$Q_p = C \cdot I \cdot A_b / 3$
Average	$\bar{Q}_p = (\sum Q_{p,i}) / n$

( $A_b$ ) - watershed area (km<sup>2</sup>); (b, c) – constantes; ( $K_{IS}$ ) - variable coefficient between 0.800 and 0.017, depending on the category of soils, vegetal cover and relief; ( $m_l$ ) - variable coefficient with the basin area; ( $\bar{P}$ ) - average annual rainfall (mm); (C) - coefficient of rational formula that depends on the typology and occupation of the soil of the watershed or flow coefficient of Témez formula; (I) - intensity rainfall average for a given frequency of occurrence and duration equal to the time of concentration of the watershed (mm/h); ( $\lambda$ ) - parameter in the function area; ( $h_{max}$ ) - height of precipitation for a duration equal to the time of concentration and a certain return period (mm); ( $t_c$ ) - time of concentration (h); ( $P_e$ ) - effective rainfall (cm); (n) - number of used formulas.

### Velocity

Depending on the velocity, it is possible to predict the existence of sediment deposition or erosion. Several authors - i.e. [63]) or [67]- have defined that the minimum and maximum velocity (U) for this channel typology are 0.75 and 4.50 m/s, respectively, occurring sediment deposition if  $U < 0.75$  m/s and erosion if  $U > 4.50$  m/s.

#### Froude and Reynolds number

The Froude number is a dimensionless number, used in hydraulic outlets of free surfaces, representing the ratio of a characteristic speed and the speed of gravitational wave or the ratio between the forces of inertia and gravity forces, separating the runoff regime typologies into three types according to their relationship with the critical level of the water in the canal [64, 66, 59, 89, 90]. A way of classifying the flow is through the Froude number ( $F_r$ ), given by the equation:

$$F_r = u / \sqrt{g \times h} \quad (1)$$

Where:

u - represents the characteristic velocity (m/s);

g - represents the gravitational acceleration (m/s<sup>2</sup>);

h - represents the hydraulic depth (m), resulting from the equation  $h = A/B$  (being A the cross-sectional area, m<sup>2</sup>, and B the width of the free surface, m).

Thus, it is possible to classify the flow as: Fluvial flow (slow), if  $F_r < 1$ ; Torrential flow (fast), if  $F_r > 1$ ; Critical flow, if  $F_r = 1$  [66, 59].

According to [62, 59], the coefficient, number or Reynolds module (abbreviated as  $R_e$ ), is a dimensionless number used in fluid mechanics, enabling the calculation of the flow regime of a given fluid on a surface. Reynolds number illustrates the importance of viscosity in the generation of a flow and, in the case of a channel, is given by the following equation:

$$R_e = u \times R_h / \nu \quad (2)$$

Where:

$R_h$  - represents the hydraulic radius (m), ratio between the area of the wet section ( $A$ , m<sup>2</sup>) and the wet perimeter ( $P$ , m);

$\nu$  - represents the kinematic viscosity of fluid (m<sup>2</sup>/s);

So, it is possible to classify the flow as: Laminar flow, if  $R_e < 500$ ; Turbulent flow, if  $R_e > 2000$ ; Transitional flow, if  $500 < R_e < 2000$  ([59, 67]).

#### Manning's Coefficient

A well-knowledge of the state of the riverbed can be defined by his degree of roughness (Manning's coefficient) - a critical indicator regarding the influence it has on the flow [10, 91-96]. For a proper study of the uniformity regime in a free surface flows, is used the function of Manning, through the following equation:

$$Q = \left(\frac{1}{n}\right) \cdot A \cdot R^{2/3} \cdot \sqrt{i} \quad (3)$$

Where:

Q - flow (m<sup>3</sup>/s);

A - flow cross-section (m<sup>2</sup>);

R - hydraulic radius (m);

i - to reduced water heights, consider the channel sill slope, as to significant water heights, consider the continuous head loss;

n - Manning's coefficient ( $m^{-1/3}s$ ).

The hydraulic radius (R), is the quotient between the transverse section of the flow and its wet perimeter [97, 98, 59]. Thus, the R value is calculated from the section's geometric characteristics. Usually, in the channel under study, we have the following equation:

$$R = \frac{A}{P} = \frac{b \cdot h}{b + 2h} \quad (4)$$

Where:

P - wet perimeter (m);

b - rectangular section width (m);

h - free surface height relative to the bottom of the channel (m).

### 2.3. Probabilistic Analysis

To perform an effective characterization of flow in a natural channel the parameters should be analysed regarding Reynolds number, the Froude number and water height obtained through different methods of modelling - essential features for a well-development of the channel design. Thus, it was necessary to calculate the time of concentration and also the subsequent calculation of the peak flow rates. However, some formulas demand to define the precipitation intensity - which is obtained through a precipitation vs duration graph, along with a probabilistic analysis (Figure 4).

Daily precipitation's data for Funchal, was obtained through the National Information System of Water Resources database (SNIRH), since it's the most complete source. Once collected, the data were organized, analysed and assessed throughout the following processes.

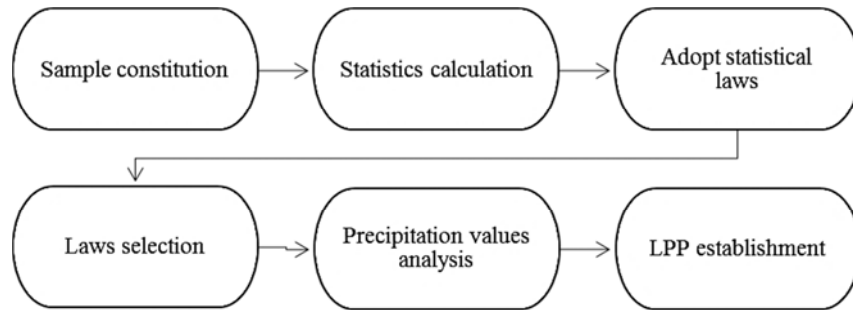


Figure 4. Phases of the probabilistic analysis.

Regarding the analysis of hydrological variable values for daily durations - the sum of 1 to 5 days - for the intended return periods (Table 5).

Table 5. Maximum precipitations for a given duration, return periods and probabilistic laws.

Duration (hours)	Law	Maximum annual precipitation (mm)		
		10 Years	100 Years	1000 Years
24	Galton	165.72	248.60	334.42
48	Gumbel	218.06	311.71	403.67
72	Gumbel	257.46	365.98	472.53
96	Gumbel	288.68	407.32	523.81
120	Galton	321.92	447.94	570.31

So, based on pairs of values and laws selection, it has considered a return period of 100 years, enabling to define a Line of Pluviometric Possibility (LPP) (Figure 5).

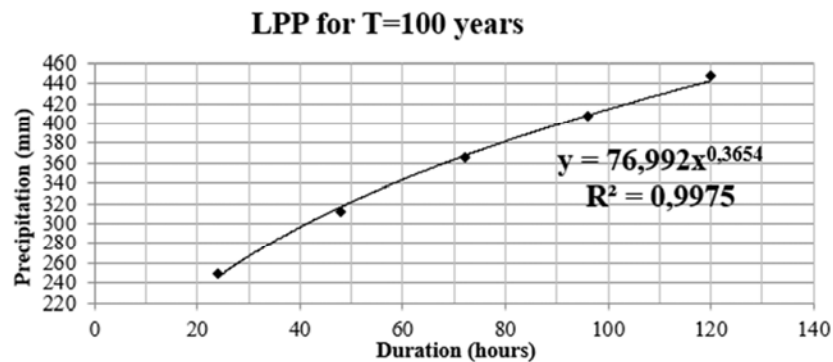


Figure 5. LPP for a 100 years return period.

Through the analysis of the LPP, along with formula selection, it is possible to calculate the precipitation values and, consequently, their intensity.

#### Peak flow rates values

The obtained values for the different formulas have disparities between them, in fact, those disparities may be

explained by the core used to develop the formulas. So, to minimize such disparities, it has been determined the average value of the flow rate - which is used for calculation, simulation, and modelling (Table 6). Also, pre-established values of coefficients were adopted (Table 7).

Table 6. Peak flow rates.

Peak flow rates for the studied watersheds			
Parameter	São João	Santa Luzia	João Gomes
Flow (m <sup>3</sup> /s)			
Forti	133.049	127.892	114.588
Iskowski	198.404	190.241	169.359
Pagliari	413.267	397.963	358.221
Whistler	84.777	81.326	72.489
Rational	670.879	664.949	601.589
Giandotti	331.810	347.747	322.576
Mockus	336.907	335.147	302.129
Témez	341.314	338.297	306.062
Average	<b>313.801</b>	<b>310.445</b>	<b>280.877</b>

Table 7. Adopted values for formulas used to calculate the flow rate.

Formulas	Adopted values
Forti	b, c - constants that have, respectively, the values of 3.25 and 1.00 for a maximum daily precipitation between 200 mm and 400 mm
Iskowski	K <sub>is</sub> - for category IV, takes the value of 0.6; m <sub>i</sub> - interpolated value between 10 and 40 km <sup>2</sup>
Rational	C - residential zone - houses in the town center, takes the value 0.5; C <sub>r</sub> - for a return period of 100 years, takes the value 1.25
Giandotti	λ - takes the value 0.346, because the watershed areas are less than 300 km <sup>2</sup>
Témez	C = 0.926; P <sub>0</sub> = 5.644; CN <sub>II</sub> = 90; CN <sub>III</sub> = 95.392

## 2.4. Modelling

Before starting modelling (Table 8) it was necessary to identify the riversides selected as case studies. The analysis has considered the Manning's coefficient (artificial turf and natural rockfill, both depict the vegetation cover, rocks,

aggregates and coarse material found in the coating of the riverside of Funchal - (Figure 6)) and other features, such as: longitudinal slope, flow normal height for different rates, flow curves and specific energy.



Figure 6. Artificial turf and natural rockfill.

For a fast flow, upstream controlled, the adopted boundaries conditions for each model, are: Programmed spreadsheet, and HEC-RAS program - upstream height is

equal to the critical height; Experimental model - upstream height is equal to the value of the first point reading.

Table 8. Modelling.

Modelling	Description
Programmed spreadsheet	To determine backwater curves - programmed in Visual Basic, "programming language" - have been based on pre-established spreadsheets. The performed tasks by the program, are an iterative process, once they adopt the finite difference method with successive approximations until it reaches the pre-established tolerance. Limitation: Applicable only to rectangular and trapezoidal sections, with or without width reduction/increase, constant slope and flow; in this case, does not compute sediment transport.
HEC-RAS program	Integrated software systems that allow evaluating dimensional flows, in natural or natural channels, as well as to assess the sediment transport degrees and even their water quality. The system consists of: a Graphical User Interface (GUI), hydraulic analysis components, capabilities to store and manage data, graphs, and reporting capabilities. Limitation: Performance based on previous information collected in the stream (mainly water height) which, at the time, didn't exist.
Experimental model	A multifunction channel is a base unit that offers a wide range of experiences related to hydraulic engineering. After adjusting the inclination and flow values, it should be used equipment that allows measuring, enabling to obtain values of water height at the pre-established points. The value of the water height is given by the average between the obtained values in each test. Limitation: Applicable only to rectangular sections, constant slope and flow; doesn't allow sediment transport (doesn't have the required accessories).

### 3. Results

The obtained outcomes correspond to flows study performed through the programmed spreadsheet, HEC-RAS program and experimental model - regarding to São João river, mixed coating (artificial turf and natural rockfill) (Table 9). The remaining studied sections - Santa Luzia, João

Gomes and their junction - have followed a similar procedure, leading to similar conclusions.

Attending to the limitations of each model, the only parameters that can be compared between each method are water height (h), Manning's roughness coefficient (n), Froude and Reynolds numbers (Fr and Re), which are in bold in Table 9.

**Table 9.** Summary of the outcomes for the São João river section, mixed coating.

São João river section - mixed coating									
Programmed spreadsheet									
Section	L (m)	b (m)	h (m)	Q (m <sup>3</sup> /s)	U (m/s)	i (m/m)	n (m <sup>-1/3</sup> s)	Fr	Re
Upstream	0	10	4.603	313.801	6.818	0.03	0.032	1.015	16177729.050
Downstream	23.2	10	2.716	313.801	11.553	0.03	0.028	2.239	20132432.630
HEC-RAS									
Section	L (m)	b (m)	h (m)	Q (m <sup>3</sup> /s)	U (m/s)	i (m/m)	n (m <sup>-1/3</sup> s)	Fr	Re
Upstream	0	10	4.640	313.801	6.763	0.03	0.038	1.003	16114837.106
Downstream	23.2	10	2.950	313.801	10.637	0.03	0.038	1.978	19540506.881
Experimental model									
Section	L (m)	b (m)	h (m)	Q (m <sup>3</sup> /h)	U (m/s)	i (m/m)	n (m <sup>-1/3</sup> s)	Fr	Re
Upstream	0	0.086	0.0737	9.500	0.417	0.03	0.038	0.490	11197.548
Downstream	2.32	0.086	0.0567	9.500	0.541	0.03	0.027	0.727	13107.498
Experimental model (after processing)									
Section	L (m)	b (m)	h (m)	Q (m <sup>3</sup> /s)	U (m/s)	i (m/m)	n (m <sup>-1/3</sup> s)	Fr	Re
Upstream	0	10	4.238	313.801	7.473	0.03	0.053	1.160	16970106.817
Downstream	23.2	10	3.260	313.801	9.715	0.03	0.037	1.719	18979256.833

Regarding the parameters that characterize the flow (Fr and Re), all the models present, at the downstream section,  $Fr > 1$  and  $Re > 2000$ , i.e. a fast and turbulent flow, distinctive of a flood. In the experimental model, the Froude number is lesser than 1 at the upstream section, explained by a slower flow at the inflow segment.

The Manning's roughness coefficient for the spreadsheet decreases from 0.032 to 0.028 due to the decrease of water height, as in HEC-RAS program the value 0.038 doesn't change because it's a pre-assigned value before each simulation.

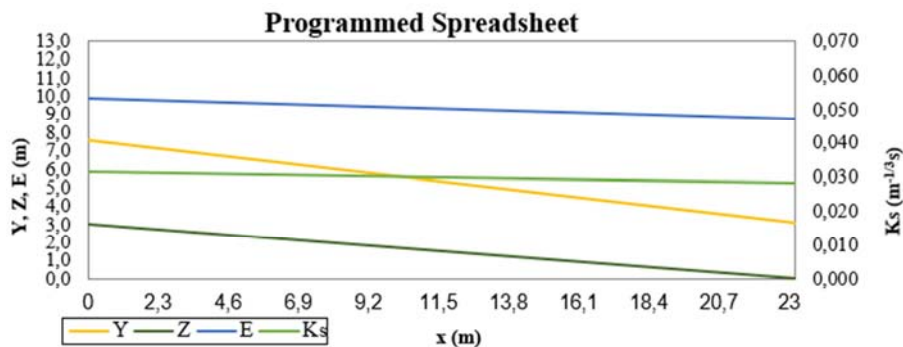
In the experimental model, the upstream value of Manning's roughness coefficient is significantly higher than the spreadsheet due to the different materials that constitute the experimental model (acrylic walls, stainless-steel bottom and mixed coating (artificial turf and natural rockfill)) and scale effects, whereas the other two models consider the initial value of 0.032 or 0.038, corresponding to the mixed

coating (artificial turf and natural rockfill).

The water height varies from model to model, but the only values we can use, for design or decision-making purposes, are the ones regarding the spreadsheet.

The reason of the previous statement is that HEC-RAS doesn't consider the variation of the Manning's roughness coefficient, unless measurements of water height are available, allowing the correction of n, which didn't exist at the time; and the bottom of the experimental model at the inflow segment is higher than the study section, as the outflow segment suffers a sudden decrease, producing a higher value upstream and a lower one downstream, compared to the other two models.

The following graphs (Figures 7, 8, and 9) represents the different used methods of analysis containing: energy line (E), free surface elevation (Y), bottom elevation (Z), and roughness coefficient (Ks).



**Figure 7.** Outcomes for the programmed spreadsheet for São João section - mixed coating.



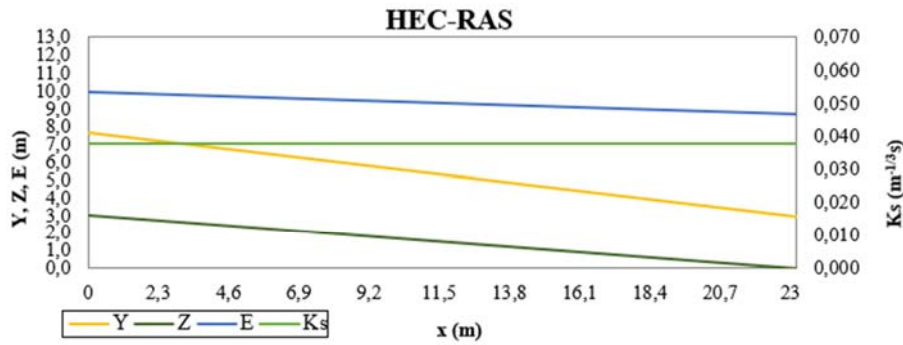


Figure 8. Outcomes for the HEC-RAS program for São João section - mixed coating.

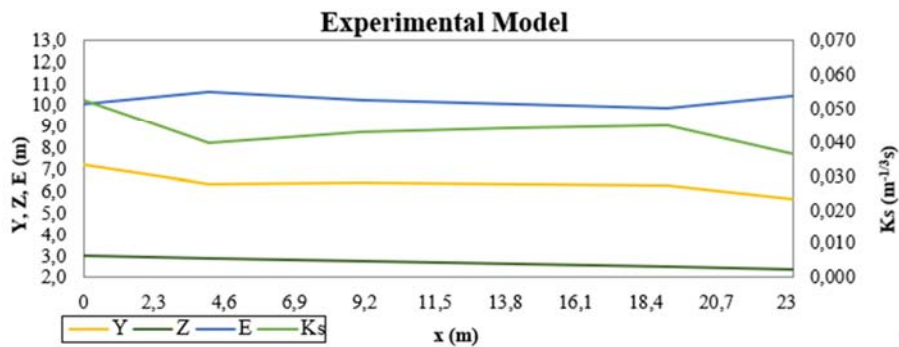


Figure 9. Outcomes for the experimental model for São João section - mixed coating.

Regarding the quality of the results, the better outcome is from the spreadsheet, followed by the HEC-RAS program and the experimental model.

The HEC-RAS performance depends on the information collected in streams, such as water height, which is used to calibrate the model; as such doesn't exist, the model results cannot be used.

Through the analysis of the graphs, the bottom elevation as the free surface elevation and the energy line decreases progressively from upstream to downstream, as velocity increases in that same direction.

The experimental model has an imperfection in its bottom that occurs midway, causing the effects observed in Figure 9, influencing the outcome and its usefulness.

Regarding velocity (Table 9), although there is no sediment deposition ( $U > 0.75$  m/s), still, there is sediment transport and consequently erosion of walls and bottom of the channel as the velocity exceeds the maximum value.

## 4. Discussion and Conclusion

The case study develops around sections of pre-existing channels constructed after the event of February 20, 2010, aiming to characterize the flow and obtain water heights due to a flood with a return period of 100 years, based on three different models and accomplished, with satisfactory results, by the programmed spreadsheet model, ideal for situation of scarce data and/or resources [99-105].

Along the research, a programmed spreadsheet was created to determine backwater curves based on previous existing sheets, presenting limitations such as: applicable

only to rectangular and trapezoidal sections with constant slope and flow, i.e. for geometrically simple study case as this one. Nonetheless, it presented the best outcome justified by its data requirement (geometric data and resulting data from precipitation analysis), simplicity, low time consuming and cost, compared to the other two models [99-105].

Through the HEC-RAS program, it is possible to reach a larger and varied range of analyses in comparison with the programmed spreadsheet, as well as the insertion of parameters that the programmed spreadsheet does not consider (i.e. sediment transport), useful for complex cases. However, the model needs calibration obtained from data collected in streams (unfortunately non-existent at the time) and it's a time-consuming process, doesn't compensate using it in this situation [99-105].

The experimental model enables to verify the influence that some hydraulic infrastructures have on the flow. However, considering the absence of such infrastructures, the effects of scale reduction in comparison with the other previously mentioned methods, its cost and test time, doesn't compensate using it in this situation [16, 99-106].

Regarding the water height, combining the section height and the water height, along with the channel, it's possible to verify if the channel is prepared for this event and identify possible errors and liabilities. Furthermore, considering the time it takes the sediments to settle in the bottom of the channel and its height, it's possible to establish an adequate maintenance period to remove these sediments [79, 107-112].

The present study has defined, as well as previously

researches - i.e. [10-20], are some of the examples - that in fact, there are specific core guidelines regarding the prevention and mitigation of floods.

Through the analysis of Funchal's unsuccessful example and its consequences, involving urban planning and land management considerable errors, some basic guidelines are exposed: avoid further constructions inside the riverbanks or floodplains (mostly upstream); promote punctual accesses to the riverbed guaranteeing its cleaning (keeping the projected depth); foster a change of land use policies – mainly for areas where it is impossible to widen the channel, due to previous land occupation; act on riverbanks and their surrounding areas in order to prevent future landslides into the streams; develop engineering strategies for impermeable areas, near the streams, leading to a consequently reduce the flow [79, 107-114].

So, if the previous measures substantiated, in similar study cases, by a simple programmed spreadsheet are considered, by planners, main actors, and decision-makers, it leads towards safer and sustainable cities.

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