Models to aid in flood risk management decision making in urbanized watershed

Telma Cristina de Figueiredo Gaspar | telma.f.gaspars@ist.utl.pt

EXTENDED ABSTRACT OF THE DISSERTATION SUBMITTED TO OBTAIN THE DEGREE OF MASTER IN:

ENVIRONMENTAL ENGINEERING

Instituto Superior Técnico | Technical University of Lisbon

Abstract

Floods are a phenomenon that has always been part of human history with which the man has been living for a long time. However, the growth of urban areas, often conducted in a disorderly manner, has contributed to the changing characteristics of floods and has increased the risks and damage to which populations are exposed during floods. But how does it affect it? And what can we do to live with it?

In order to answer this questions we studied the watershed Ribeira da Laje, located in Sintra, Cascais and Oeiras, which is known for being problematic regarding flash-floods. A model of the watershed was built, using the mathematic model HEC-HMS, and used to compute peak flows and the corresponding time, for different events of precipitation, for variable levels of soil sealing. A review of the legal framework about flood protections, and the usual ways of protection and mitigation of flood risks was also done, having always in mind the management of urbanization and flood risks.

Of the results obtained we can highlight the intensification of the peak flow with increased impermeability of soils and decrease of the respective time of peak. Of the analysis done we can also verify the importance of territory management for the response of a watershed to floods. Being so, we highlight the necessity of an integrated management that includes all the decision makers situated in the watershed's area, or in some other place that can influence directly the watershed. Finally, we emphasize the importance that protection and mitigation's plans can have in the impacts of floods

Keywords: flash-floods, hydrologic modeling, urbanization, peak flow, watershed

1. Introduction

At the 25th of November 1967, one of the biggest floods in Portugal occurred, with the death of more than 700 people. Some years later, at the 19th of November of 1983, another big flood happened, resulting in 10 deads. Those events happened in Lisbon, and at the near cities, and were both flash-floods. (Ramos & Reis, 2001).

From every kind of floods, flash-floods are the ones that, due to their characteristics and unpredictability more damages inflict. (Barredo, 2006) (Ramos & Reis, 2001).

Flash-floods are events, that happen in a short time, usually inferior to six hours(Borga, Anagnostou, Bloschl, & Creutin, 2011), caused by heavy rainfall.

Due to the intensity of the precipitation, there is a rapid saturation of the soil, which will reduce water infiltration into the soil, and consequently higher runoff.

This phenomenon is characterized by a rapid rise in the water level and large flow rates and is therefore difficult to predict, which can cause severe damage.

1.1 Factors

Any factor that increases the production and velocity of the flow makes the watershed more vulnerable to floods. Thus, the slope, the shape, the drainage density and the terrain of the watershed influence the response of the watershed to precipitation and may influence the occurrence of flash floods.

In order to reduce the runoff, it is essential to have good infiltration capacity, which is directly related to the water in the soil, namely the antecedent moisture conditions and the permeability of the soil.

This means, that the higher the initial moisture content of the soil, the lower the infiltration will be, and, the same way, the drier is the soil, higher is the infiltration. The same happens with the soil saturation.

As a consequence of the soil not being able to absorb the water, rather than infiltrating into the subsoil water will seep to the surface. This is what happens in the case of events where the heavy precipitation occurs after a series of pluviosos events that contributed to filling the voids of the soil.

The permeability of the soil affects directly his infiltration capacity, so that, in a non-saturated soil, the higher is the permeability, the higher is the infiltration. This property depends on the texture and structure of the soil, being that higher contents of sandy translates in a more permeable soil. (Varennes, 2003). However, even in permeable soils runoff may occur if the amount of precipitated water is such that it exceeds the capacity of saturation of the soil. When that happens, the soil loses the capacity of infiltration and the precipitated water is drained. Naturally the infiltration capacity is not constant during a rainfall event.

When studying the response of a watershed to the occurrence of precipitation, is also imperative to consider the use of the soil, as this will have a direct influence on how the watershed will behave.

If the watershed has a vegetation cover, some of the precipitation is intercepted and adheres to the foliage and stems, where it evaporates and does not contribute to runoff. The vegetation promotes infiltration, contributing thus to decrease the runoff.

Watersheds whose soil was, somehow, proofed behave differently. This results in most cases of human action, through the construction of urban areas, industrial parks, roads, railways, airports and other equipment, and has direct effect on reducing infiltration, and therefore increasing runoff.

1.2 Urbanization and floods

(Leopold, 1968) noticed four effects, interrelated but separable from, in the hydrology of an area due to changes in land use caused by urbanization: changes in the characteristics of the flood peak, changes in total runoff, changes in water quality and changes in the hydrological amenity, meaning the sensations and impressions induced in the observer.

Not always done in an organized way, urban areas often develop in high-risk areas without proper infrastructures and increase the risk of disaster when there is a flood. For the purposes of this paper we will consider the flood risk as a combination of the probability of flooding and the damage caused by it, which can be expressed in monetary units, loss of life or other units. This way, this risk is greater for regions with very high population density, where the damages will also be higher.

As previously mentioned, urbanization will mainly impact the permeability of the soil, in a negative way, and therefore infiltration.

These effects can be observed in the comparison of hydrographs before and after urbanization:

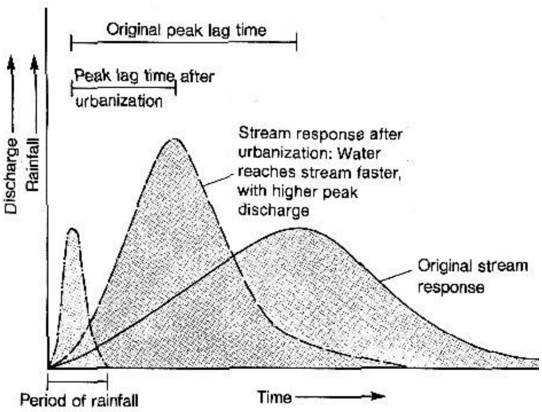

Figure 1 Hydrograph before and after urbanization. Source: (Mico, 2013)

From Figure 1 we can identify the main differences between the hydrographs. Thus, for a watershed with an urbanized area, the peak flow is higher than it was before the urbanization, and the time of peak is smaller.

1.3 Mitigation measures

In flood risk management there are two strategies we can consider: reduce the intensity of floods, meaning reduce peak flood, flows and increase the time of peak. The reduction of peak flows reduces the damage caused by flooding, either by decreasing the area subject to flooding or reducing the water level, in the flooded areas. The increase the time of peak will give us the time required for evacuation of people and property from the flooded areas. (Green, Parker, & Tunstall, 2000).

According to (Europeias, 2004), flood risk management can be seen as a systematic cycle that includes the elements: prevention, protection, preparedness, emergency response and recovery experience. (Europeias, 2004) defines these elements as:

Prevention: "Preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas; by adapting future developments to the risk of flooding; and by promoting appropriate land-use, agricultural and forestry practices."

Protection:"Taking measures, both structural and non-structural, to reduce the likelihood of floods and/or the impact of floods in a specific location."

Preparedness:" Informing the population about flood risks and what to do in the event of a flood;"

Emergency response:" Developing emergency response plans in the case of a flood."

Recovery and lessons learned: "Returning to normal conditions as soon as possible and mitigating both the social and economic impacts on the affected population."

2. Case Study: Characterization of Watershed Ribeira da Laje

The Ribeira da Laje starts on the eastern slopes of Sintra and flows into the estuary of the Tagus, on the beach of Santo Amaro, in Oeiras.

Table1 presents a summary of the geometric characteristics of the watershed:

Table 1 Geometric characteristics of the watershed Ribeira da Laje

Parâmetro	Valor
Total área (km^2)	40,10
Sintra (km^2)	25,15
Oeiras (km^2)	9,77
Cascais (km^2)	5,18
Perimeter (km)	37,20
Length of the main watercourse (km)	16,72
Length of the drainage network (km)	61,60
Maximum height of the main watercourse (m)	185,00
Minimum height of the main watercourse (m)	0,00
Average height of the watershed (m)	137,86
Average slope of the watershed (%)	1,16
Index Gravelius	1,66
Form Factor	0,14
Index stretching	6,47
Equivalent rectangle	
Length (km)	16,11
width (km)	2,49
Drainage density (km^{-1})	1,88

2.1 Climate

According to (Oeiras C. M., 2010), the average monthly temperatures range from a minimum of approximately 11 º C and a maximum of about 22 ° C, being the colder months between December and January, and the warmest months between June and September.

Relative humidity range throughout the year, with approximately 55% in the driest month in August and 73% in January.

The precipitation is typical of Mediterranean climates, being concentrated in the months of autumn and winter and scarce in the warmer months of summer, between June and September.

2.2 Soils

According to the soil classification, the watershed is mainly occupied by soils of the type C, which are characterized by low intensity of infiltration and, therefore, a risk of runoff above average and a high risk of erosion.

Considering this classification, taking into account the type of land use, we estimated a curve number, CN, of 87 for the watershed, as proposed in (Hipólito & Vaz, Hidrologia e Recursos Hídricos, 2011) for streets and dirt roads.

2.3 Land Use

In recent decades, the watershed Ribeira da Laje has suffered an intense growth of urban areas, which has contributed to the increase in impervious area and, consequently, to increased risk of flooding. Currently, about half of the watershed area is occupied by urban centers, being that urbanization is more intense in the northern area (Municipia, 2011).

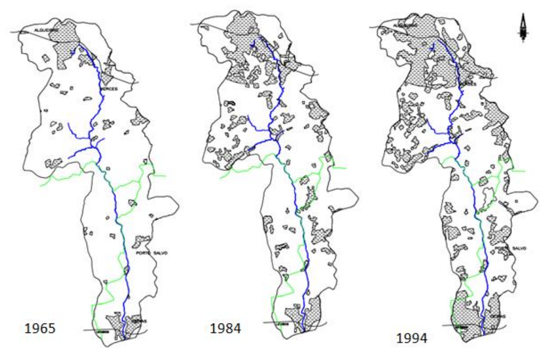

Figure 2 Evolution on urban areas. Source:(SARAIVA, CORREIA, & CARMO, 1998)

2.4 Management elements of Ribeira da Laje

Integrated in the Tagus Hydrographic Region, at a broad level, the management Ribeira da Laje fits the Management Plan of the Tagus Hydrographic Region (PGRHT), which takes as its main objective the protection and management of water. One of the points addressed in PGRHT is the problem of flooding, and the need to correct and mitigate their risks. In this sense, the Ribeira da Laje is identified as a critical area in PGRHT.

With more detail, the problem of flooding in the watershed Ribeira da Laje is addressed in the PDM (Plano director municipal) of Sintra, Cascais and Oeiras, existing in all of them the recognition of the need to rectify the situation.

Another mean of protection used at Ribeira da Laje is its classification as adjacent area, which was implemented in 1986, following studies of the flood of November 1983.

According to the legal provisions, adjacent areas are assets subject to restrictions on public use and, as such, it is forbidden to construct buildings that obstruct the free passage of water and the destruction of their vegetal coating (Art. 25 of Lei No. 54/2005).

2.5 Critical places

For the analysis of the floods in Ribeira da Laje, we considered 3 critic places, which are characterized by a high level of urbanization and are known for being problematic during intense rains, namely:

- Talaíde;
- Povoação da Laje;
- Final section, from Largo Marques de Pombal to the base level

3. Floods characterization

To simulate the occurrence of floods in the watershed Ribeira da Laje, we used the deterministic mathematical model HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System).

To run these simulations, it is mandatory to build three components of the model: the basin model , the meteorological model and control specifications. The model computes the response of the basin to the meteorological conditions, based on precipitation-flow relationship, over a period of time and at specified intervals in the specification of control.

3.1 Basin Model

To create the model, the watershed was divided into 15 sub-basins, with similar areas.

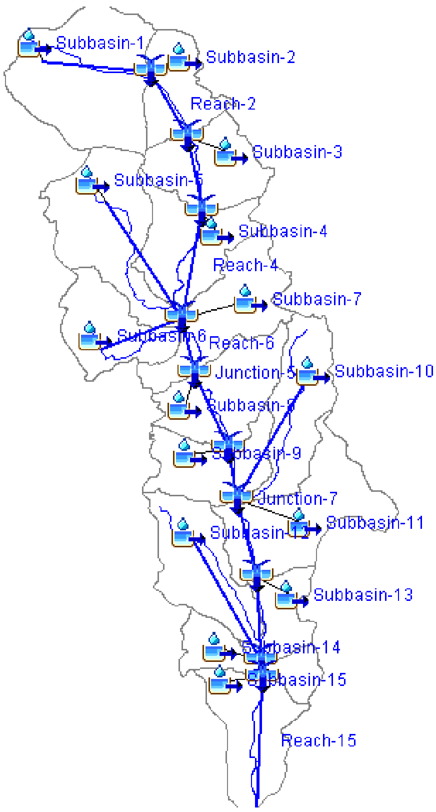

Figure 3 Basin Model of Ribeira da Laje

To calculate the time of concentration we used Temez's formula:

$$t_c = 1{,}115 \frac{L^{0{,}95}}{\Delta H^{0{,}19}} \quad \textbf{1}$$

- t_c-Time of concentration of watershed (h);
- L- Length of the main watercourse (km);
- ΔH - Maximum difference of heigh in the course of the main water (m).

The lag time used was:

$$t_l = 0{,}366 t_c \quad \textbf{2}$$

Table 2 Characteristics of the sub-basins

Sub-Basin	Area (km2)	length of the water - course (km)	Lag time (min)	Concent. time(min)
1	4,48	2,28	27,75	75,82
2	2,15	1,29	16,55	45,22
3	2,15	1,48	20,30	55,46
4	2,71	2,01	26,23	71,68
5	3,56	3,57	35,81	97,83
6	2,51	2,19	25,38	69,34
7	2,99	1,05	17,24	47,11
8	2,52	1,54	23,03	62,92
9	2,13	0,83	13,28	36,27
10	2,55	3,84	33,92	92,67
11	3,42	1,49	21,35	58,35
12	3,07	3,19	30,82	84,20
13	1,28	1,47	20,04	54,75
14	1,63	0,26	6,04	16,51
15	2,96	2,46	34,39	93,95

For the model of the sub-basin the following calculation methods were considered:

• **Loss rate method:** Method that quantifies the losses by infiltration in the watershed. The method used was: "SCS curve number".

The input required for the method is: curve number and impermeabilization of each subbasin.

• **Transformation method:** Method that calculates the runoff in the watershed. The method used was "SCS unit hydrograph".

The input required for the method is: Lag time.

- **Routing method:** Method that simulates movement of the water in the reach. The method used was "Muskingum".
  The input required for the method is: Muskingum K, Muskingam X and the number of subreaches.

3.2 Meteorologic Model

The only meteorological phenomenom considered was precipitation. The method used to simulat the rainfall was "specified hyetograph", and the same hyetograph was used in all the sub-basins. The hyetographs were obtained for the return periods of 2, 10, 50, 100 and 500 years.

To calculate the hyetographs, we applied the IDF (intensity-duration-frequency) expressions proposed by Claudia Brandão in 1995 (Pereira, 1995), for the return periods of 2 and 10 years to Lisbon , and the expressions presented in the study (Claudia Brandão, 1998), to the station IGIDL, for return periods of 50, 100 and 500 years.

Table 3 IDF expressions

Período de retorno	Expressão IDF
T = 2 anos	$I = 221 \times t^{-0.607}$
T = 10 anos	$I = 386 \times t^{-0.627}$
T = 50 anos	$I = 412{,}14 \times t^{-0.595}$
T = 100 anos	$I = 451{,}14 \times t^{-0.594}$
T = 500 anos	$I = 541{,}23 \times t^{-0.592}$

To simulate precipitation in the watershed, we created a fictional meteorologic station, with one hyetograph that would be the only station to contribute to the amount of rainfall.

Since we are considering the precipitation measured at a specific point, and not in an area, we used a rainfall depth-area adjustment factor of, that for the wastershed Ribeira da Laje was 0.97, according to the curves adjustment (Dallas, 2007).

3.3 Results

3.3.1 Simulation I

Initially we characterize the present situation of the watershed, using an estimated impermeabilization for each sub-basin, of:

Table 4 Impermeabilization of each subbasin

Sub-bacia	Impermeabilização (%)
1	45
2	40
3	50
4	25
5	7
6	10
7	10
8	5
9	10
10	7
11	30
12	35
13	15
14	35
15	70
Média total	23,33

There were two different scenarios of soil moisture considered: medium antecedent soil moisture (AMCII) and high antecedent soil moisture (AMCIII). These two different scenarios were simulated with the curve number. AMCII considered a CN of 87 and for the AMCIII CN was considered 94. The latter value was estimated using the expression:

$$NC\ \ III\ = \frac{23NC\ II}{10+0{,}13NC\ II} \qquad 3$$

		Confluência 7		Confluência 9		Troço final	
		Q_p (m^3/s)	T_p (h)	Q_p (m^3/s)	T_p (h)	Q_p (m^3/s)	T_p (h)
A1	T1	44,9	5,80	46,6	6,68	47,3	7,18
	T2	87,6	5,60	91,1	6,57	92,6	7,07
	T3	121,7	5,52	127,2	6,48	129,8	6,98
	T4	138,3	5,47	144,4	6,47	147,4	6,97
	T5	177,5	5,40	185,1	6,42	189,0	6,92
A2	T1	64,5	5,45	67,2	6,45	68,6	6,95
	T2	113,4	5,35	117,4	6,37	119,6	6,90
	T3	149,2	5,32	154,9	6,33	158,3	6,83
	T4	166,4	5,32	172,7	6,32	176,6	6,82
	T5	206,2	5,30	214,0	6,13	218,8	6,80

Where:

- A1 - AMCII
- A2 - AMCIII
- T1 = 2 anos
- T2 = 10 anos
- T3 = 50 anos
- T4 = 100 anos
- T5 = 500 anos

3.3.2 Simulation II

Now we want to study how changes in the rate of soil sealing affect the response of the watershed to precipitation, namely with changes in peak flow and time of concentration.

To do so, we changed the impermeabilization of each subbasin, in a way that those with a initial higher level of urban area are the ones with the bigger growth.

The results obtained were organized in graphics, to simplify the analysis.

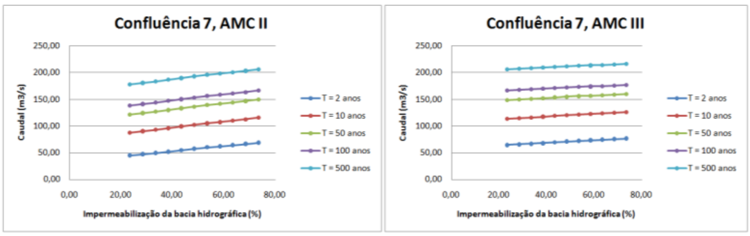

Figure 4 Peak flows vs impermeabilization rates: Confluência 7

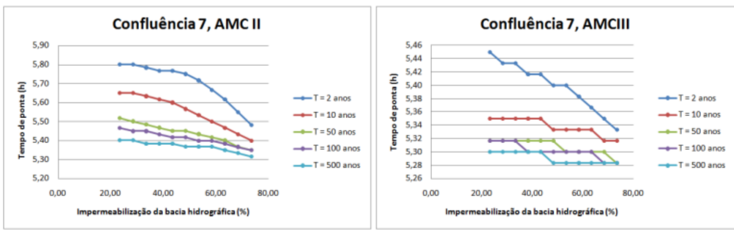

Figure 5 Time of peak vs impermeabilization rates: Confluência 7

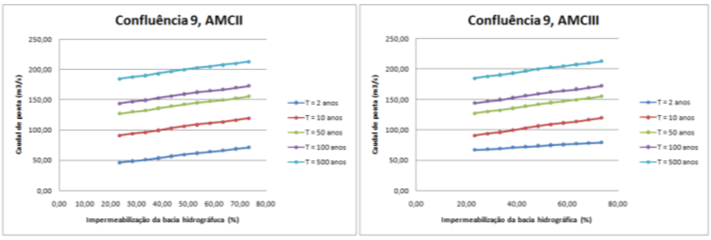

Figure 6 Peak flows vs impermeabilization rates: Confluência 9

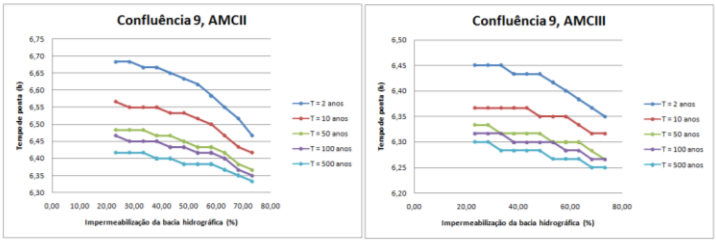

Figure 7 Time of peak vs impermeabilization rates: Confluência 9

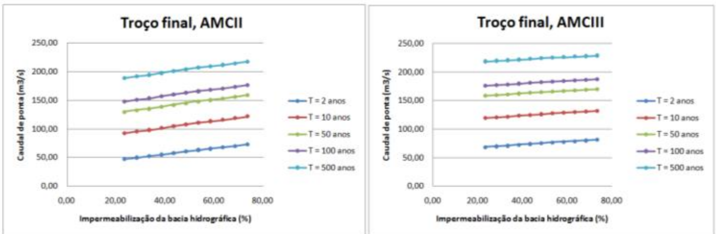

Figure 8 Peak flows vs impermeabilization rates: Troço final

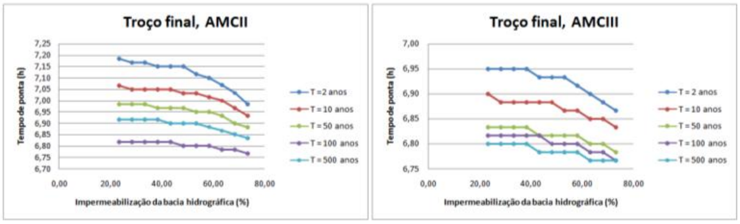

Figure 9 Time of peak vs impermeabilization rates: Troço final

3.3.3 Flow height

In order to understand how much the height of the flow would increase, with the changes of the flow, we used one expression, to each critic zone, to see the relation between the flow peak and the height of the flow. These expressions were obtained from simulations done in (Municipia, 2011).

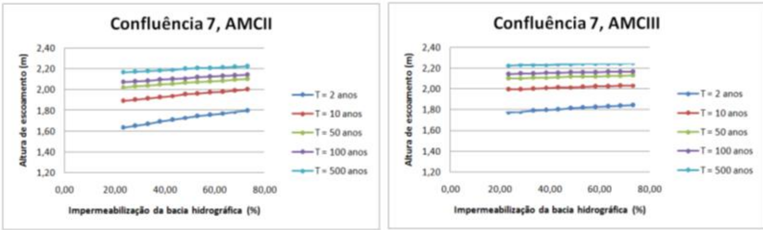

Figure 10 Height curves vs impermeabilization: confluência 7

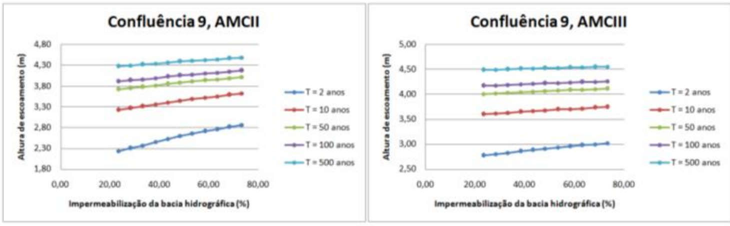

Figure 11 Height curves vs impermeabilization: confluência 9

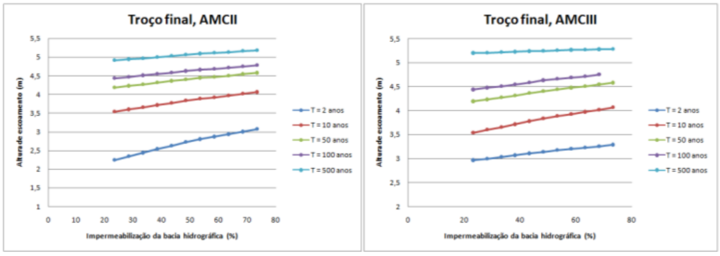

Figure 12 Height curves vs impermeabilization: Troço final

The expression used were:

Confluência 7	h=0.388 ln(Q)+0.157
Confluência 9	h=1.480 ln(Q)-3.456
Troço final	h=1.924ln(Q)-5.051

Table 5 Expressions used for the height curves. h- height (m); Q-Peak flow (m^3/s)

4. Conclusions

Analysis of the results indicated that the urbanization of the watershed, assessed through impermeabilization, has a direct effect on the peak flow and response times of the watershed, which seems to be relatively linear according to the model used. Another very noticeable results is the importance that antecedent soil moisture has to the intensity of the flow, resulting in peak flow much higher than those observed in drier soils and lower times of peak. That way, it is important to consider this factor in analyzes of flash floods, where rainfall intensity is high and the soil can quickly become saturated.

Although the increased urbanization of the watershed has visible impacts to any simulation done, the effects seem to be greater for antecedent conditions of lower soil moisture, as explained earlier.

From the analysis done we infer that, for the region under study, the height of the flow is not greatly affected by the variation of soil sealing. It is important to confront the results obtained, which are a maximum increase of 5.3 m, with the scales used for the delineation of the maps of flood risk of PDM's.

According to the Decree n º. 10/2009, of 29 May, the maps to the PDM can go up to a scale of 1:25000, and this is an inappropriate scale for maps of flooded areas and flood risk areas.

The maps for "Planos de Promenor" (detailed plans) must be made at a scale of 1:2000, which is a significantly more sensitive to variations in the magnitude of the meter unit.

Analysing the PDM's of Oeiras, Sintra and Cascais, and other relevant documents to the work, we can see that it doesn't seems to exist a joint management of common resources, not being noticeable a policy of integrated territorial management. With this in mind we believe that there should be an effort to make that happen, because it would allow a consistent management of the watershed, with the maximization of available resources and the harmonization of management policies that enable greater control of land use and occupation of soils, as well as the risks to populations.

Finally we must consider the protection and mitigation measures of flood risk, and their applicability to the flash floods. In an place with a high urban occupation, it becomes difficult to implement measures involving major changes in the structure of current territorial organization. However, we must preserve the locations of flood plains and enforce legal instruments of protection in order to prevent the tendency of occupation of the riverbanks remains.

For the case of watershed Ribeira da Laje, with particular means of protection, as the title of the zona adjacente, the authority must be more restrictive in licensing the use and transformation of soils and in penalties for breach of predicted measures. When properly implemented, this tool can be useful to land management to mitigate the risks of flooding, having the ability to prevent the occupation of areas of high flood risk.

Another problem related to flash floods is the short time in which they occur, which does not facilitate the effective implementation of a monitoring plan in real time, enabling the triggering of emergency plans in time to act in its early prevention and protection of the population. However, warnings to the population in the medium and long term, in case of prediction of heavy rainfall, can and should be practiced. Furthermore, the population should be informed of the risks involved and the need for territorial management that allows proper management of flood risk and as far as possible should be involved in the development of flood risk management plans.

5. Bibliography

Ambiente, A. E. (2010). *Mapping the impacts of natural hazards and technological accidents in Europe.* Copenhaga.

Barredo, J. I. (2006). Major flood disasters in Europe: 1950–2005. *Natural Hazards* , 125-148.

Borga, M., Anagnostou, E. N., Bloschl, G., & Creutin, J. D. (2011). Flash Flodd forecasting, warning and risk management:

the HYDRATE project. *Environmental Science and Policy* , 834-844.

Dallas, U. (2007). *Rainfall Depth-Area Adjustment*. Retrieved Setembro 13, 2013, from UT Dallas: http://www.utdallas.edu/~brikowi/Teaching/Applied_Modeling/SurfaceWater/LectureNotes/Rainfall/Rainfall_Depth_Area_Adjustm.html

Europeias, C. d. (2004). *Gestão dos riscos de inundação. Protecção contra cheias e inundações, sua prevenção e mitigação .* Bruxelas: Comissão das Comunidades Europeias.

Francisco, C. S. (n.d.). *Inundações*. Retrieved Setembro 2013, 02, from Portal São Francisco: http://www.portalsaofrancisco.com.br/alfa/inundacoes/inundacoes-8.php

Green, C., Parker, D., & Tunstall, S. (2000). *Assessment of Flood Control and Management Options.*

Hipólito, J. R., & Vaz, Á. C. (2011). *Hidrologia e Recursos Hídricos.* IST Press.

Leopold, L. B. (1968). *HYDROL.OGY FOR URBAN LAND PLANNING-A GUIDEBOOK ON THE HYDROLOGIC EFFECTS OF URBAN LAND USE.* Washington: United States Department of the Interior.

Mico, C. D. (2013). *Environmental Data Clearinghouse*. Retrieved October 01, 2013, from Cara D. Mico: http://landstudy.org/Resources.html

Municipia, E. S. (2011). *Estudo Hidrológico e Hidráulico das bacias Hidrográficas de Oeiras para elaboração de carta de zonas inundáveis de acordo com o Decreto-Lei nº.115/2010.* Oeiras.

Oeiras, C. M. (2010). *Plano Municipal de Emergência de Protecção Civil.* Oeiras.

Ramos, C., & Reis, E. (2001). As cheias no sul de Portugal em diferentes tipos de bacias hidrográficas. *Finisterra* , 61-82.

SARAIVA, M. G., CORREIA, F. N., & CARMO, V. (1998). *AVALIAÇÃO EX-POST DE MEDIDAS NÃO-ESTRUTURAIS DE DEFESA CONTRA CHEIAS NA BACIA HIDROGRÁFICA DA RIBEIRA DA LAGE.*

Varennes, A. d. (2003). *Produtividade dos Solos e Ambiente.* Lisboa: Escolar Editora.