**FCTUC DEPARTAMENTO DE ENGENHARIA CIVIL**
FACULDADE DE CIÊNCIAS E TECNOLOGIA
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# Quantification of flood risk in urban areas with dual drainage 1D/2D models

**Dissertação apresentada para a obtenção do grau de Mestre em Engenharia Civil na Especialidade de Hidráulica, Recursos Hídricos e Ambiente,**

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**Coimbra, Janeiro, 2015**

## ACKNOWLEDGEMENTS

Os meus sinceros agradecimentos a todos os que me ajudaram, aturaram e contribuíram para que eu conseguisse realizar este trabalho.

Gostaria de agradecer aos meus orientadores, Professor Nuno Eduardo da Cruz Simões e Professor José Alfeu Almeida de Sá Marques pelo seu apoio, disponibilidade, partilha de conhecimentos e incentive.

Agradeço aos meus amigos e colegas que me companharam ao longo destes cinco anos e meio de percurso académico.

Quero agradecer à minha namorada Inês pela ajuda e paciência para me aturar nos piores e melhores momentos.

E um especial agradecimento à minha familia, principalmente aos meus pais e irmã por puxarem por mim e me incentivarem ao longo da minha formação: sem eles nada de isto seria possível.

# ABSTRACT

Floods affect millions of people and cause uncountable economic and social losses every year, making up more than half of the natural disasters in the World (WMO, 2009). Urban floods and their prevision, prevention and mitigation methodologies are increasingly worrying topic for today’s society, due to the raise of extreme hydrological condition cases (Furumai and Matsuura, 2006), the ever-increasing urbanization of the environment, and the high concentration of inhabitants in urban centres.

In the last years, this combination of a continuous increase of urbanization of spaces and extreme rainfall events have shown that drainage systems do not always respond appropriately to the resulting increase of flow (Lima et al, 2013), leading to an intensification of flood risk. Consequently, this situation caused the need to create measures to undermine this serious problem in urban drainage: in October 2007, the European Union published the 2007/60/CE Directive, in which the reasons that lead to this increase of likelihood of floods were highlighted, as well as its consequences over the population and environment. The Directive also recommends the elaboration of flood hazard and flood risk maps by all the Member-States.

The objective of this dissertation is to use a dual drainage 1D/2D model on the software Infoworks ICM to create flood risk maps, and to assess the risk with a quantitative methodology. The methodology will be applied to a study case in the Zona Central catchment in Coimbra. The impact of the floods is displayed as flood risk maps based on depth-damage and depth-velocity curves by analysing the results in the software ArcGIS.

***Keywords****: Floods, urban drainage, dual drainage 1D/2D models, flood risk, flood risk maps, quantitative methodology.*

# RESUMO

As inundações afectam milhões de pessoas e causam incontáveis prejuízos económicos e socias todos os anos, perfazendo mais de metade do número de desastres naturais em todo o Mundo (WMO, 2009). As inundações urbanas e suas metodologias de previsão, prevenção e mitigação são um assunto cada vez mais preocupante para a sociedade de hoje, devido ao aumento de casos de condições hidrológicas extremas, à cada vez maior urbanização do ambiente, e à elevada concentração de consumos de água e habitantes em centros urbanos.

Nos últimos anos, esta combinação de um aumento contínuo de urbanização de espaços e eventos de precipitação extrema tem mostrado que os sistemas de drenagem nem sempre conseguem responder adequadamente ao aumento de caudal resultante destes fenómenos(Lima et al, 2013), levando a uma subida do nível de risco de inundação. Consequentemente, esta situação leva à necessidade de se criarem medidas para contrariar este problema grave na drenagem urbana: a União Europeia publicou em Outubro de 2007 a Directiva 2007/60/CE, na qual são realçadas as razões que levam a este aumento de probabilidade de ocorrência de inundações e as suas consequências sob a população e ambiente. Esta Directiva recomenda também a elaboração de mapas de risco de inundação por parte dos Estados-Membros.

O objectivo deste trabalho é elaborar mapas de risco de inundação usando modelos de drenagem dual 1D2D no software Inforworks ICM, e quantificar o risco com uma metodologia quantitativa. A metodologia será aplicada a um caso de estudo numa bacia urbana de Coimbra. O impacto das inundações é demonstrado em mapas de risco de inundação baseados em curvas altura-prejuízos e altura-velocidade, através da análise dos resultados no software ArcGIS.

***Palavras-chave:*** *Cheias, drenagem urbana, modelos de drenagem dual 1D/2D, risco de inundação, mapas de risco de inundação, metodologia quantitativa*

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# SYMBOLS

| | |
|---|---|
| A | Cross-sectional area of channel segment [m2] |
| C | Runoff coefficient |
| g | Acceleration due to gravity [ms-2] |
| h | Water depth [m] |
| I | Rainfall intensity [mm/h] |
| $f_{capac}$ | Maximum infiltration capacity of the soil at the time t |
| $f_c$ | Initial infiltration capacity of soil at initial time $t_0$ |
| $f_0$ | Final constant infiltration capacity of infinite time t |
| K | Decay time constant. |
| Q | Flow rate [$m^3s^{-1}$] |
| p(h) | Probability of occurrence of the hazard [-] |
| R | Risk [-] |
| $S_f$ | Friction slope [-] |
| $S_{fx}$ | Friction slope in x direction [-] |
| $S_{fy}$ | Friction slope in x direction [-] |
| $S_0$ | Bottom slope [-] |
| $S_{0x}$ | Bed slope in x direction [-] |
| $S_{0y}$ | Bed slope in y direction [-] |
| t | time [s] |
| u | Velocity in x direction [$ms^{-1}$] |
| v | Velocity in y direction [$ms^{-1}$] |
| x | Primary flow direction [m] |
| y | Perpendicular flow direction to x [m] |

# ABBREVIATIONS

1D – One-dimensional

1D/1D – Dual drainage model (1D sewer and 1D overland network)

1D/2D – Dual drainage model (1D sewer and 2D overland network)

2D – Two-dimensional

AOFD – Automatic Overland Flow Delineation

CS – Collection Systems

DTM – Digital Terrain Model

DEM – Digital Elevation Model

EA – UK Environmental Agency

EN – European Standart

EPA – Environmental Protection Agency

GBP – UK Pound Sterling

GPD – Gross domestic product

ICM - Integrated Catchment Management

IFM – Integrated Flood Management

LiDAR – Light Detection and Ranging

GIS – Geographical Information System

SUDS – Sustainable Urban Drainage Systems

SWWM – Storm Water Management Model

UNISDR - United Nations International Strategy for Disaster Reduction

UWRG - Urban Water Research Group

WMO – World Meteorological Organization

# 1 INTRODUCTION

## 1.1 General framework

Urban floods and their prevention and mitigation methodologies are an increasingly worrying topic for today's society, due to the raise of extreme rainfall events, the ever-increasing urbanization of the environment, and the high concentration of inhabitants in urban centre. The combination of a continuous increase of urbanization of spaces and extreme rainfall events have shown that drainage systems do not always respond appropriately to the resulting increase of flow, leading to an intensification of flood risk.

In October 2007, the European Union published the 2007/60/CE Directive, in which the reasons that led to the increase of likelihood of floods were highlighted, as well as its consequences over the population and environment. The Directive also recommends the elaboration of flood hazard and flood risk maps by all the Member-States. It also refers to four different types of flood events: coastal, urban, fluvial and flash floods. This study will be focused in the urban flood events.

## 1.2 Objectives of this study

The main objective of this dissertation was to create flood risk maps using dual drainage 1D/2D models, to assess the risk with a quantitative methodology and apply it to an area prone to flooding. The case study chosen was the Zona Central catchment in Coimbra, in which the Praça 8 de Maio and Igreja de Santa Cruz are contained. Studies about this area have already been made, like Dias (2014) and Paula (2013), but they involved a 1D/1D dual drainage model: this study provides a different and more complex approach to the case study area by considering two-dimensional overland flow (1D/2D dual drainage model).

The more specific objectives derived from the methodology adopted were:

- An extensive literature review on the subjects urban drainage, flooding and elaboration of flood risk maps;
- Implementation of hydrological/hydraulic modelling on a dual drainage urban drainage network with a 1D/2D model on the software Infoworks ICM;

- Elaboration of floodable area and flow velocity maps using 1D/2D dual drainage models;
- Quantification of the flood risk using depth-damage and depth-velocity curves, and the creation of different flood risk maps;
- Analysis of the resulting maps regarding its impacts towards buildings, pedestrians, vehicles and public transports.

With the software InfoWorks ICM and the 1D /2D dual drainage model provided, computational simulations were made for different return period values, from which the results were then used to create flood risk maps. The quantitative methodology adopted to analyse the consequences of the floods took into consideration three different aspects: the direct monetary losses caused to buildings by the floods, the risk created in terms of the combination depth-velocity, and the impact upon transports.

## 1.3 Thesis Structure

In the first chapter a general framework of this study is displayed, with a brief introduction to urban drainage modelling, floods causes and consequences, and flood risk maps.

The second chapter serves as a literature review and introduces the backgrounds to urban drainage systems, modelling, whilst showing the recent softwares and data management tools that researchers nowadays use. A brief introduction to flood risk and the elaboration of its maps is also done in the final subchapter of the literature review.

The third chapter describes the case study of the catchment of the city of Coimbra, and the methodology adopted regarding urban drainage modelling and elaboration of flood risk maps in order to solve the real life case study.

The fourth chapter shows the results and discussions from the studies by analysing the modelling of overland flow and the results from the dual drainage network simulations on the software InfoWorks ICM, with a geographic information system (GIS) called ArcGIS.

The last chapter concludes this dissertation with the key points. Further studies and possible research topics are also listed in the last paragraph.

# 2 LITERATURE REVIEW

## 2.1 Introduction

According to the European Standart EN 752 (EN 752, 2008), the design of urban drainage should make them capable of withstanding periods of flooding of 10-50 years in range, considering the network of infrastructures and type of urbanized area. But, due to the recent climate changes and increasing urbanization, the response from traditional urban drainage systems often cannot prevent and mitigate the effects of floods adequately (Schmitt et al, 2004). As a result there is a need for a new approach on urban drainage management, in which the flood risks are quantified and displayed in maps, so the most vulnerable areas can be identified and intervened (Moel et al, 2009).

In this chapter, for a better understanding and contextualization of this dissertation, some key concepts of urban drainage will be addressed, such as rainfall and runoff models, dual drainage and 1D/1D, 1D/2D models. Some of the most used commercial softwares and data management tools will be briefly described. Finally, the concepts of flood risk and elaboration of the flood risk maps will be explained and demonstrated.

## 2.2 Urban drainage

The core purpose of urban drainage systems is to collect and re-direct the waste and storm water, and eliminate the excess surface runoff in the most efficient and rapid way possible through a close conveyance system, in the appropriate conditions (Sá Marques et al, 2013). Evidences of the most basic urban drainage systems (gutters and drains for the collection of surface runoff) have been dated as far as 2500 B.C., in the ancient cities of Ur and Babylon (Matos, 2003) (Figure 2.1).

Figure 2.1 – Sewer pipe in the ruins of Ancient Babylon (U.S. National Archives)

The first system of noticeable dimension was the *Coacla Maxima* in Rome: an underground sewer pipe connected to several different channels that drained the wastewater and surface runoff from the city, and re-directed the excess water coming from the aqueducts that supplied the inhabitants of Rome and their public baths (Hodge, 1992) (Figure 2.2).

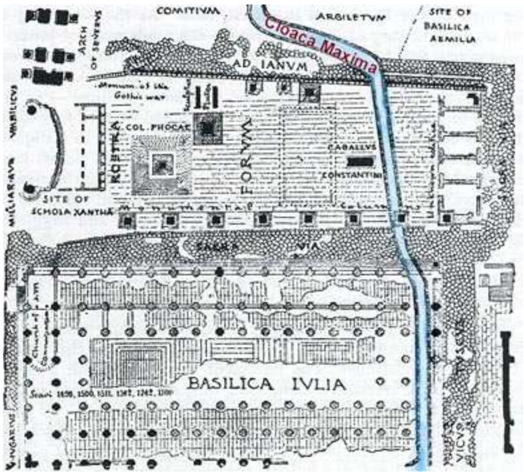


Figure 2.2 – Coacla Maxima (Hopkins, 2004)

According to Matos (2003), it was not until the XVII century that the urban drainage strategies came to any sort of breakthrough, and not before the XVIII century that the need of having a functional and efficient drainage system became one of the main concerns of the society. The main advances in urban drainage concepts and designs were only achieved during the XIX and XX centuries, as is showed in Burian et al (1999): (Figure 2.3):

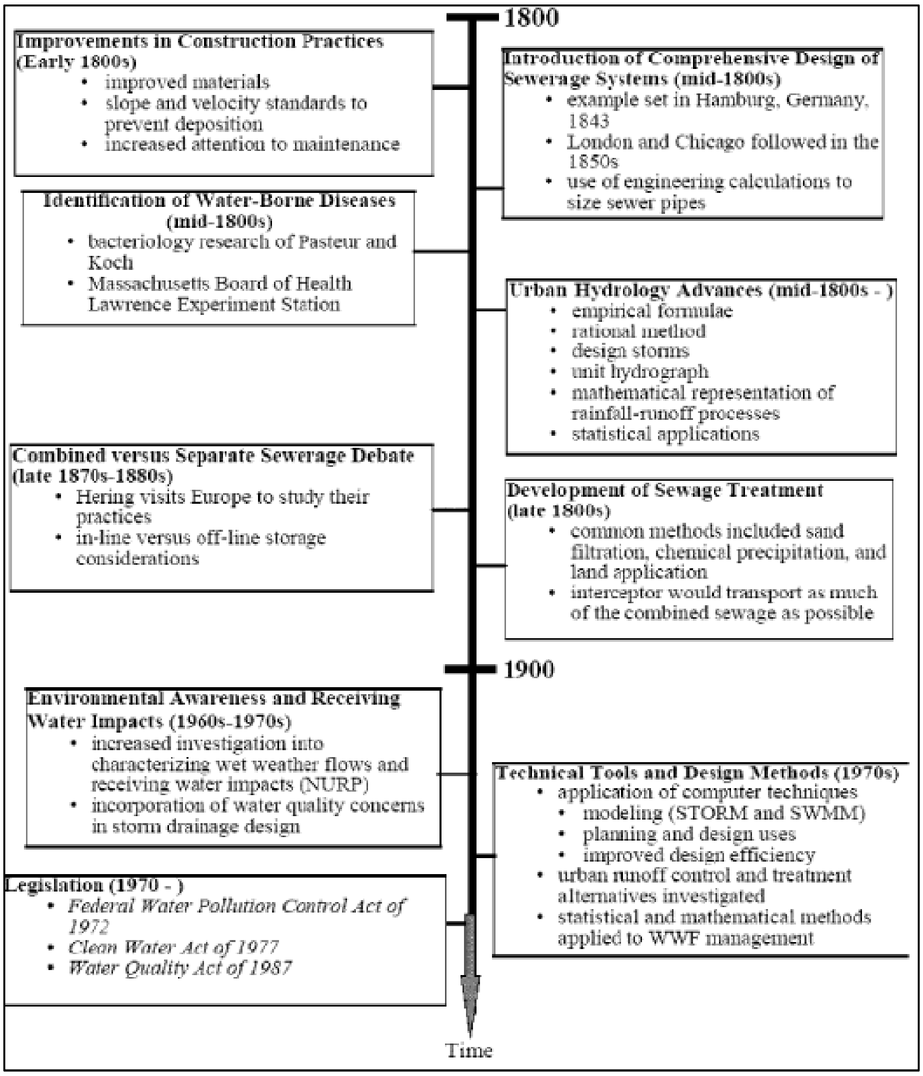


Figure 2.3 – Main advances on urban drainage in the 1800s and 1900s (Burian et al, 1999)

As it is possible to see in the Figure above, there were many important advances in the last century. This transformation was only achievable due to some key factors: the change of mentality regarding the importance of sanitation and basic hygiene, the technologic and computational advances, the new construction techniques and the raise of environmental and public health awareness in the society (Burian et al, 1999).

Two of the major benefits achieved by learning from past societies were the mitigation of the spread of diseases by preventing the exposure to stagnant and still water in open cesspools (Butler and Davies, 2011), and, as mentioned before, the prevention of floods by re-directing the excess surface runoff from the urban areas.

In general, the urban drainage systems can be separated into two different types: artificial where the storm water conveys to a closed piped system may or may not contain the wastewater from urban areas, and the more natural and water sensitive mean of drainage, consisting in soakaways, infiltration trenches, and other sustainable systems, that rely on infiltration and storage properties of semi-natural materials (Butler and Davies, 2011).

Following the line of thought of Lima et al (2013), the artificial urban drainage systems can be divided into 4 types, according to the origin of water:

- Fluvial Combined: a single pipe network in which the wastewater and stormwater flow together;
- Separated: two different and non-connected pipe network, so the wastewater and stormwater are kept separately;
- Hybrid or partially separated: a system where part of the pipe network is separated and the other is combined;
- Pseudo-separated: in which, due to the lack of stormwater collectors, the connection between the wastewater pipes and stormwater from courtyards and balconies is tolerated.

## 2.2 Flooding

According to the European Standart EN 752 (EN (752), 2008), the concept of flooding can be described as a ‘condition where wastewater and/or surface water escapes from or cannot enter a drain or sewer system and either remains on the surface or enters in buildings’. According to (EEA 2012) and the 2007/60/CE Directive, flood events can have different sources and occur in rural or urban areas, being the latter where the danger is higher, and can be divided into several different types. For this study it is important to highlight the three most relevant types of floods regarding the urban environment:

- Fluvial flooding, which happens when the water level of a channel or river rises above the crest elevation of the bank, causing the water to spread and cover nearby dry lands. Whilst varying in severity and pattern of flow, this type of flood can occur regularly through the yearly hydrological cycle, lasting for days or weeks (Figure 2.4).

Figure 2.4 – Fluvial flood in Coimbra (umpingodeluz@, 2013)

- Pluvial flooding is usually caused by a heavy localised storm where the drainage system has an insufficient capacity to deal with that volume of water, generating high levels of surface runoff, leading to an excess of water and possible damage to the drainage system. These floods are difficult to predict, usually have a higher impact than fluvial or coastal floods and last no more than a day (Figure 2.5).

Figure 2.5 – Pluvial flood in Coimbra (Simões et al, 2010)

- Coastal flooding occurs when the water's sea level is high enough to drive ocean water inland and flood the river's mouth or delta, thus causing damage to the drainage system. (Figure 2.6).

Figure 2.6 – Coastal Flood in North Devon, UK (telegraph@, 2010)

In this dissertation only the pluvial flooding event will be studied.

As mentioned before, one of the main factors that has led to an increase of frequency and intensity of floods is the continuous urbanization of the environment, due to public demand for living space in the cities and urban areas (Sá Marques et al, 2013). In the last decades it has become obvious that, while the growth of the more developed countries has slightly declined, the developing countries are expected to account for more than 80 % of the world's urban population by 2030, as it can be seen in Figure 2.7:

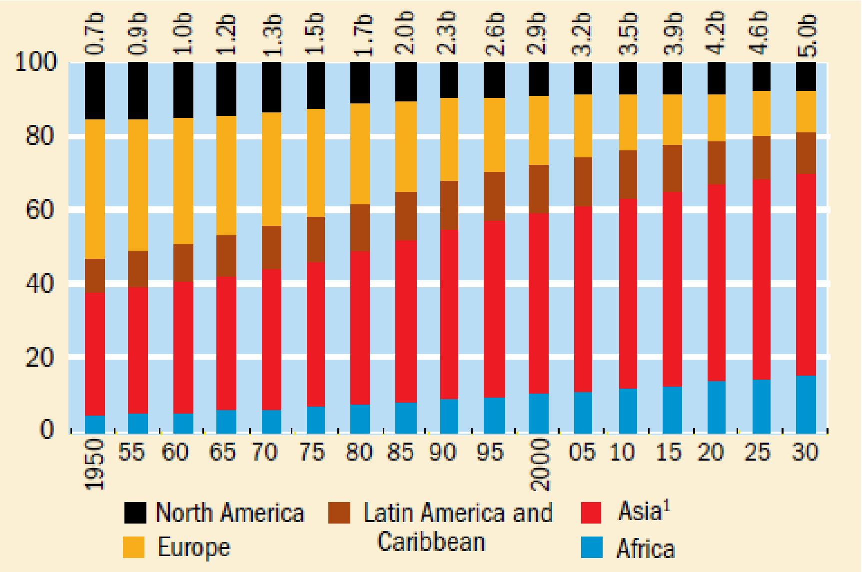


Figure 2.7 – Regional share of total world urban population percentage (United Nations, 2007)

It is also expected that in the coming years the urban population will surpass the rural population: according to Lima et al (2013), about 60% of the world's inhabitants will most likely be living in cities and highly urbanized areas.

It becomes clear, by looking at these results that, it is of extreme importance that the cities possess an efficient urban drainage system capable of dealing with this increase of population and urbanized areas. For a better understanding of the reason why the urbanization of areas leads to more flow in the drainage systems, it is necessary to explain some basic hydrological concepts.

When stormwater falls on the surface it can infiltrate the soil and become groundwater, return to the atmosphere by transpiration or evaporation, or run off the surface. The construction of building and streets leads to an increase of impermeable surface, therefore to a decrease of infiltration and raise of the amount of surface runoff (Butler and Davies, 2011). Since the run off travels much faster than the groundwater, and even faster on artificial surface and pipes, the flow will get to its destination sooner and will dissipate faster: the peak flow increases and reached faster, causing a higher probability of flood occurrence. In Figure 2.8 it is possible to visualize the evolution of the hydrograph of a rural area through several steps of urbanization: when the area is considered rural, when it has been urbanized and after mitigation procedures have been applied.

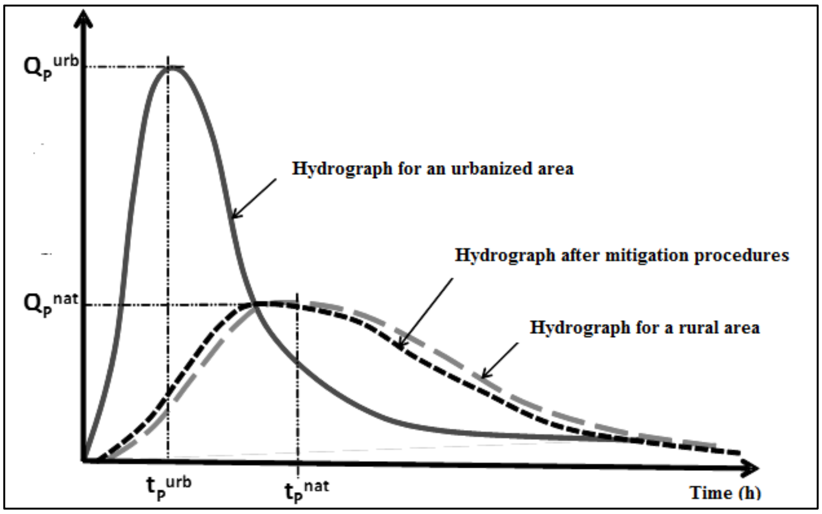


Figure 2.8 – Hydrograph for different steps of urbanization (adapted from Lima et al, 2013)

It is also more likely to have more pollutants and sediments on the catchment surface, which may lead to the deterioration of some elements of the drainage system, therefore to a decrease of the quality of water in its final destination.

The input elements can also become obstructed or clogged, causing the pipes to surcharge and increasing the intensity of floods in the low areas of the catchments (Lima et al, 2013) (Figure 2.9).

Figure 2.9 – Clogged inlet in Lake Wingra, USA (wingrawatershed@, 2012)

## 2.3 Data management

### 2.3.1 Overview

In order for the decision makers to have the necessary information to take the best decisions possible when attempting to plan, operate or maintain an urban drainage network, data must be collected, organized and analysed (Fletcher and Deletic, 2008). The data can be one of several characteristics of the urban water system: sewer pipe network data, water levels and flow rate, terrain elevation and land use, among others. Only when all of these data is obtained and looked through is it possible to understand the behaviour and interactions between the drainage systems and the environment (Price and Vojinovic, 2011). The data can be divided into two main distinct groups of information: spatial and temporal.

As the word suggests, spatial data is referred to the physical characteristics from both the drainage pipe network and the external environment features, like land use characteristics and terrain elevation. In addition, details from ancillary structures like weirs, pumping stations, storage tanks and inlets/outlets are also required for a proper spatial data collection.

According to Price and Vojinovic (2011), temporal data can be described as the measurement of a physical variable over time, in which the numerical value can be assigned by a sensor at specific time steps. Some examples of temporal data often collected to describe an urban drainage system are meteorological data, flow rates, velocity, depth and pressure of water, biological and pollution parameters, and pumping data. Meteorological data collected from urban areas often refers to temperature, precipitation, humidity and wind speed: these characteristics tend to be highly variable in time and space and dependant of the climate and topography of the localized areas (Fletcher and Deletic, 2008).

Apart from the spatial and temporal data, there is still relevant information that needs to be taken into to consideration that doesn't fit in the two groups like: economic and environmental indicators, geological data, infrastructure condition, maintenance and construction costs.

After all these data is collected it needs to be processed and analysed before being used by the decisions makers, otherwise the solutions might be inaccurate due to possible measuring errors. With the removal of biased and abnormalities in the data through statistical methods, it can then be stored in a database. The creation of databases whether using object-oriented technology or not, allows the data to be at hand for most users, cutting down on planning, design and maintenance costs (Price and Vojinovic, 2011).

### 2.3.2 Geographical Information Systems (GIS)

When all the data has been analysed and stored properly in databases, it can be manipulated and used through a system capable of such. This is typically done in a data management framework that allows the interactions between various types of databases: Geographical Information Systems (GIS).This tool is a versatile technology that has been developed in order to geo-reference the several types of data within a spatial framework, thus allowing the link between databases and property history, and becoming and efficient urban planning tool. It also allows to user to perform digital terrain models, slope maps and catchment delineations, among many other features.

Nowadays there are several commercial softwares that allow the use of the GIS framework, like ArcGIS, GeoMedia, SmallWorld GIS, which feature several plug-in applications for more specific spatial data procedures or data preparation procedures. There are also some open-source software choices that deserve mentioning, such as MapWindow and Quantum GIS. There is a great number of possible applications for the GIS tool: in Price and Vojinovic (2011) an extended list of uses for the tool is presented.

In the last years several models based on the GIS framework have been presented, like Lhomme et al (2005) and Boonya-aroonnet et al (2007). The development of this tool as provided a more accurate simulation of real world processes, more specifically, water events: as so, it is clear its importance when regarding the simulation of urban floods, and creation of flood and hazard maps (Leitão, 2009). But, for an accurate solution to be found, the GIS tool needs to be combined with a digital terrain model.

### 2.3.3 Digital terrain models

All modelling needs precise and up-to-date terrain information in order to provide accurate responses to the problems at hand: for that digital terrain models (DTM) and digital elevation models (DEM) need to the deployed (Fletcher and Deletic, 2008). A DTM refers to a topographic map used to represent the terrain's surface and properties that contains terrain elevations, whereas a DEM refers to any type of surface elevation (Figure_2.10). There are multiple ways of structuring a DEM such as line models, triangular irregular networks and grid networks (Price and Vojinovic, 2011).

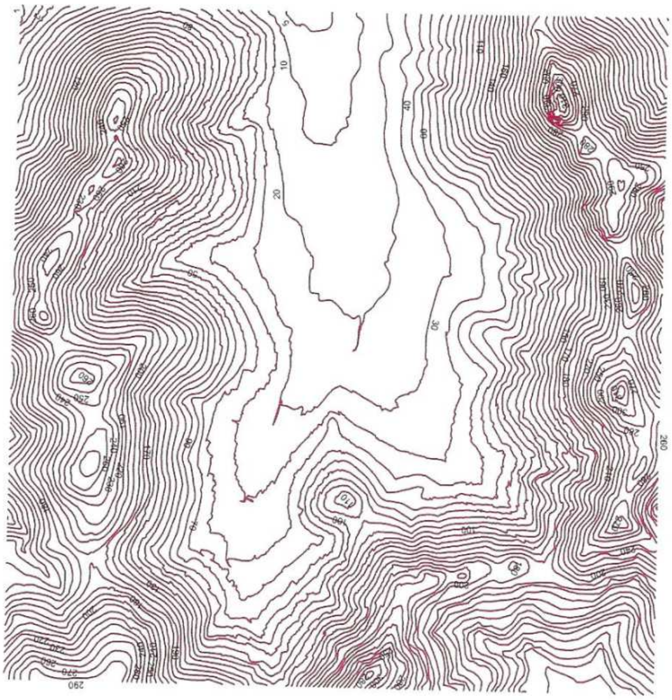


Figure 2.10 – Example of a DEM (Price and Vojinovic, 2011)

Some of the possible ways to obtain the data required for a DTM model are through:

- Digitalization of points/lines of contour from an analogue format;
- Ground surveys;
- Aerial or satellite stereo imagery;
- Airborne laser scanning.

Whereas the digitalization of points and ground surveys is the most time consuming method and usual way of getting terrain data, there have been several important advances in technology in this area (Leitão, 2009). One of the most recent breakthrough was the use of airborne laser scanning or Light Detection and Ranging (LiDAR), which provides a more economically efficient and accurate solution (Price and Vojinovic, 2011).

A scanner is deployed in an aircraft also with GPS positioning devices and an inertial navigation system to capture the data: the laser emits a pulse of light along a vector that scans from side to side as the plane flies. As a remainder of the pulse is returned to the device the distance is calculated by measuring the time it took to return, and the spot is identify and pin pointed through the GPS positioning system. The points obtained are usually spaced of 0.5 to 0.5 m with an accuracy of 0.3 m horizontally and 0.15 m vertically (Figure 2.11).

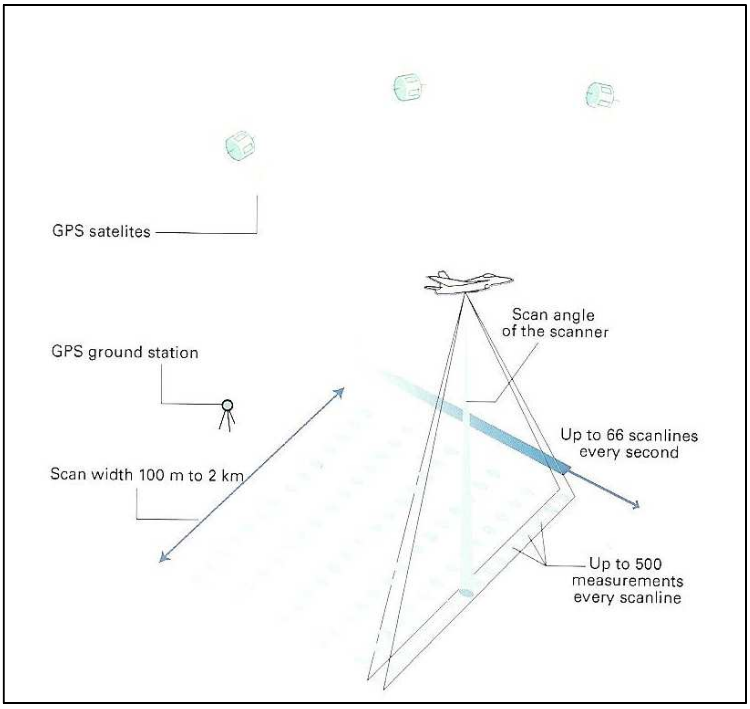


Figure 2.11 – LiDAR scanning (Price and Vojinovic, 2011)

The post-processing of these data produces a large amount of topographic data that needs to be thinned, filtered and interpolated so it can provide a manageable set of points. The thinning is usually done by removing neighbouring points within a defined level of tolerance, whereas the filtering is done through the use of algorithms and some od the interpolation methods normally used are the inverse spline, natural neighbour and kriging (Price and Vojinovic, 2011) (Figure 2.12).

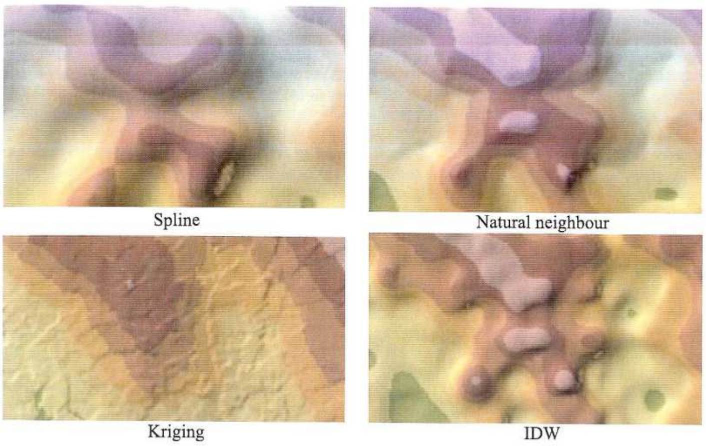


Figure 2.12 – Interpolation techniques to create DTM (Price and Vojinovic, 2011)

## 2.4 Modelling

### 2.4.1 Overview

The main purpose of urban drainage models is to simulate real-life rainfall/runoff processes and the drainage system behaviour, allowing the analysis of different scenarios under normal or extreme rainfall circumstances (Lima et al, 2013). Within the topic urban drainage, two distinct types of models can be found: hydraulic and hydrological models that serve to test the behaviour of the drainage system, and water quality models. In this dissertation only the hydraulic and hydrological models will be described and then applied to a case study.

The breakthrough caused by the appearance of computational modelling of urban drainage systems, in the 1970s, lead to the need to improve the rainfall and geographical data collection systems, since these models need up to date and precise information to provide reliable simulation results (Butler and Davies, 2011).

Models, as stated in Tucci (1998) regarding the usable approaches, can be classified as:

- Continuum when the phenomenon is unchanged over the course of time, or discrete if there are changes of state through non-continuum periods of time;
- Conceptual if the equations used to create the model take into consideration physical processes, or empiric when the calculated values are adjusted to the ones observed without the influence of physical processes;

- Concentrate models do not take into consideration the spatial and temporal distribution, whereas the variables and parameters of the distributed models depend on time and space;
- Stochastic models programs, for several simulations, generate different outputs for the same input, while the results generated from deterministic models programs are constant for the same input, independently of the number of simulations;

Another type of model described in Butler and Davies (2011) is the deterministic models, which are considered by Butler and Davies (2011)as the most commonly used approach for commercial softwares, since it allows the simplification of the treatment of relevant information for the programs. The fact that these types of models do not take into consideration the randomness enables the user to reach a concrete solution instead of a broad spectre of answers to a problem (Butler and Davies, 2011).

As stated in Estellés (2010) deterministic models can be divided into two distinct types: empiric models (as explained before), and physically based models where a numerical solution of equations describes the physical processes of the fluid in the environment that is mapped and deconstructed into cells and elements.

Within the simulation modelling of urban drainage systems, the hydrological and hydraulic processes need to be separated, because of the excessive amount of data required to recreate realistically the situation (Butler and Davies, 2011). Hydrological models allow the simplification of the conversion of rainfall to runoff, and try to estimate the quantity of water that reaches the drainage network. One of its objectives is to obtain the runoff hydrograph, by crossing the rainfall information (duration, intensity and variability) with geographical data (areas, permeability, and land use). This can be carried out by standart surface runoff models like the linear reservoir models and others that will be more extensively described in the next chapters.

Hydraulic models deal with the way that the water flow generated by the hydrological models travels along all the pipe network's elements into its final destination, formally described as flow routing. According to Mark et al (2004), there are two distinct areas that can be found within hydraulic models:

- Surface model that deals with the water flow in the surface, taking into consideration street systems, alternative flow paths and localized areas of water accumulation;
- Pipe flow model where the inlets, manholes, gutters and pipes are also simulated through elements that lead the water to the pipe drainage network.

In the Figure 2.13 it is possible to get a better understanding of how the models and its different phases are connected, from the rainfall to the discharge of water in the final destination.

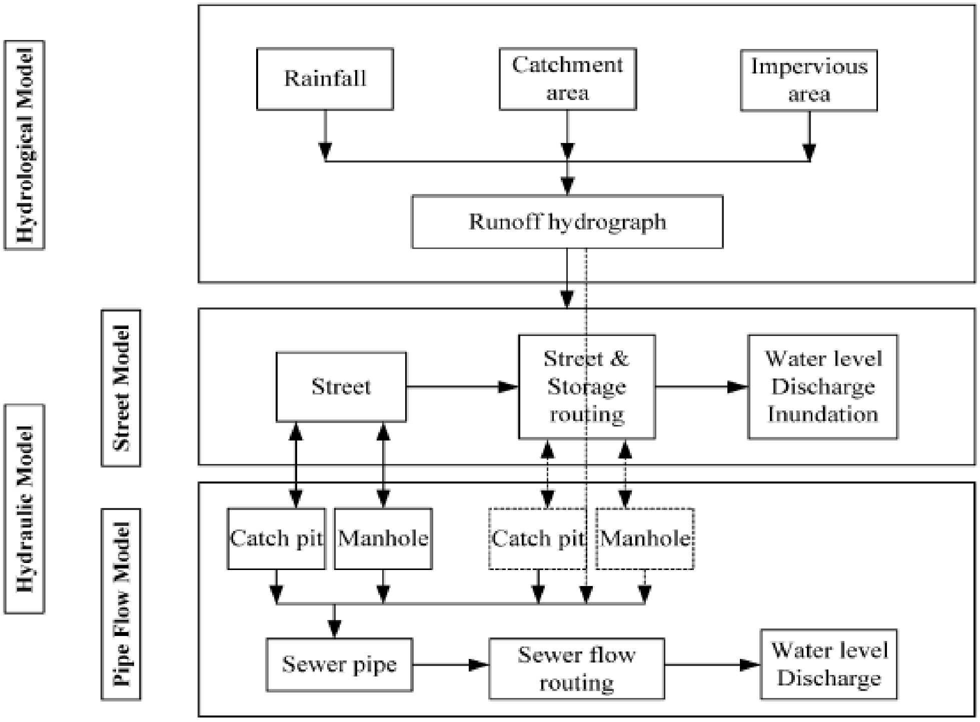


Figure 2.13 – Interactions between various stages of modelling an urban drainage system (Mark, 2004)

### 2.4.2 Rainfall:

As mentioned in the previous chapters, rainfall generates flow in an urban drainage network. Therefore, before any type of more detailed description of hydrological/hydraulic models, it is best to properly characterize what a rainfall event really is.

A rainfall event occurs over a time period (rainfall duration) with a life-spend preceded and followed by periods of unmeasurable rainfall, and is characterized by its variable temporal and spatial distribution. Its nature is also variable along the year, since the rainfall events tend to intensify in the winter and diminish in the summer (Dunkerley, 2008). The rainfall is most of the times described through a mass curve (where the rainfall depth is cumulated in relation to time) or by a hyetograph, in which the rainfall is presented in a histogram form.

According to Chow et al (1998), the rainfall is normally classified into three different types, regarding the processes of air mass elevation that lead to rain:

- Orographic rain: caused by the presence of high ground when the air passes through a ridge;
- Cyclonic rain: through the large-scale vertical motion associated with depressions and fronts;
- Convective rain: by the vertical ascending motion of a mass of air, since its temperature is warmer than the environment.

Price and Vojinovic (2011) states that rainfall can be defined typically by the following parameters:

- Intensity: the rate if rainfall (usually expressed in mm/h);
- Duration: a period of rainfall event (usually expressed in min or h);
- Depth: thickness of the water layer in the surface (usually expressed in mm);
- Area: geographical extent of the rainfall (usually expressed in $km^2$);
- Frequency: the number of repetitions of a particular rainfall event per unit of time (usually expressed in return period values).

In urban drainage system modelling it is to the frequency in which a rainfall event can occur is where most of the attention is turned to (Price and Vojinovic 2011), since a design of urban drainage systems needs to properly prevent and mitigate the effects of an extreme rainfall events. This makes the analysis and treatment of rainfall data a key factor whilst designing a drainage system, whether by using synthetic data (intensity-duration-frequency curves, hyetographs and stochastic time series), times series rainfall or forecast rainfall.

### 2.4.3 Rainfall to runoff

In order to better understand the concepts regarding the hydrological and hydraulic models, it is necessary to first explain some important aspects of the conversion of rainfall to runoff. When the rainfall reaches the urban surface it undergoes a series of transformations: some of it is retained in building or vegetation before it hits the ground, other reaches the surface and infiltrates the ground through cracks in the pavement or directly in the soil, and of the amount of water that reaches the ground exceeds the rate of reception of the drainage systems and infiltration it generates the so called overland flow.

The rainfall loss that proceeds from the interception, infiltration, retention of water can be described in different ways. Since the initial loss can be directly removed from the effective rainfall volume, it is possible to use a runoff coefficient that I used to determine the percentage of water volume that actually reaches runs off. However, since the surface is not always homogenous with the same properties (the rainfall can hit roofs, gardens, streets), a continuing loss model may need to be taken into consideration, where the most impervious areas are considered as a constant loss and the more permeable might vary according to its infiltration rate (Price and Vojinovic, 2011).

The empirical equation provided by Horton to calculate the infiltration parameter is one of the most used options (Dunkerley, 2008):

$$f_{capac} = f_c + (f_0 - f_c) \cdot e^{-kt} \tag{1}$$

Where:

$f_{capac}$ – Maximum infiltration capacity of the soil at the time t;

$f_c$ – Initial infiltration capacity of soil at initial time $t_{0;}$

$f_0$ – Final constant infiltration capacity of infinite time t;

k – Decay time constant.

The equation describes that the infiltration capacity ($f_{capac}$) starts at a constant rate ($f_0$) that decreases exponentially over time (t), and when the soil saturation reaches a certain level, its rate of decline will level off to the rate ($f_c$).

The rainfall/runoff routing models present in commercial softwares are, in most cases, conceptual and empiric: they simulate the processes of rainfall transformation in the catchment based in physical processes (Adeyemo, 2007).

The most used methods are:

- **Rational method**: The simplest hydrological model possible to express is the rational method, which is usually used to estimate the peak flow in small catchments, as it is stated in Sá Marques e Sousa (2008). The expression that translates the rational method is shown below :

$$Q = C \cdot I \cdot A \tag{2}$$

The expression above represents the method, in which the variable Q is the peak flow (ls$^{-1}$), C a non-dimensional coefficient related to rainfall losses and runoff diffusions (varying from 0 to 1), I to the rainfall average intensity (mm h$^{-1}$) and A the area of the catchment (ha). Some of the limitations of this method are the fact that the rainfall is not considered as a spatial and temporal variable, the transformation from rainfall to runoff is considered as linear, and that the peak flow is only possible when all of the catchment is contributing to the surface runoff, as it is stated in Sá Marques and Sousa (2008).

- **Time-Area method**: Considers that the surface runoff is influenced by 3 main factors: initial losses, the catchment area and the hydrological continuous loss. The time-area diagram assumes the plot of each individual pipe sub-catchment as linear, and is made of lines of flow travel time to the final outfall, named isochrones (Adeyemo, 2007). By adding up all of the isochrones of local sub-catchments (since the method allows the overlaps of plots), the response of the whole catchment is easily visualised in the diagram. The maximum travel time of the flow is the catchment's concentration time. An example of time-area diagrams for three different types of catchments is shown below (Figure 2.14):

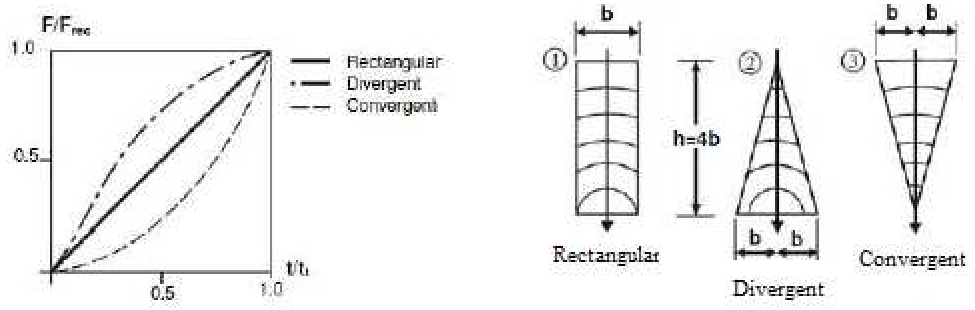


Figure 2.14 – Time-area method according to the catchment's area (Leitão et al, 2008)

According to Butler and Davies (2011), this method is an improvement over the rational method, since the shape of the catchment is taken into some account, making it possible to create an output hyetograph that considers some aspects of a rainfall time's variability. Despite this, it still doesn't account for storage effects in the catchment and the flood wave is still considered as linear.

- **Unit hydrograph method**: Defines a resulting unique and time-invariant hydrograph from effective rainfall over a catchment, in which the outflow from a unit depth of a uniform effective rainfall over a catchment at a constant rate for a unitary duration is represented: as it can be seen below in Figure 2.15:

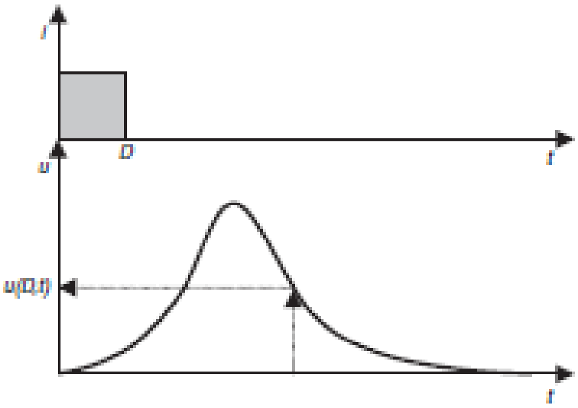


Figure 2.15 – Unit hydrograph of a catchment (Butler and Davies, 2011)

The construction of the catchment’s response to any rainfall event, whilst using the unit hydrograph, is based on three guiding principles (Adeyemo, 2007):

1. Constancy: independently of the rain’s intensity, the time base of the unit hydrograph is constant;
2. Proportionality: the volume of effective rainfall is directly proportional to the ordinate of the hydrograph;
3. Superposition: by adding up the runoff hydrographs of individual effective rainfalls, each starting at particular times, it is possible to obtain the response of the accumulated rainfalls in a single hydrograph.

- **Reservoir models**: The flow routing is modelled as a series of consecutive linear reservoirs: it considers the mass conservation law, but not the conservation of momentum law, thus the response of the catchment is assumed as instantaneous. The simplification to linear reservoir allows a rapid simulation, but prevents backwater and pressurized flows from being directly simulated. Figure 2.16 illustrates the cascade of reservoirs methodology:

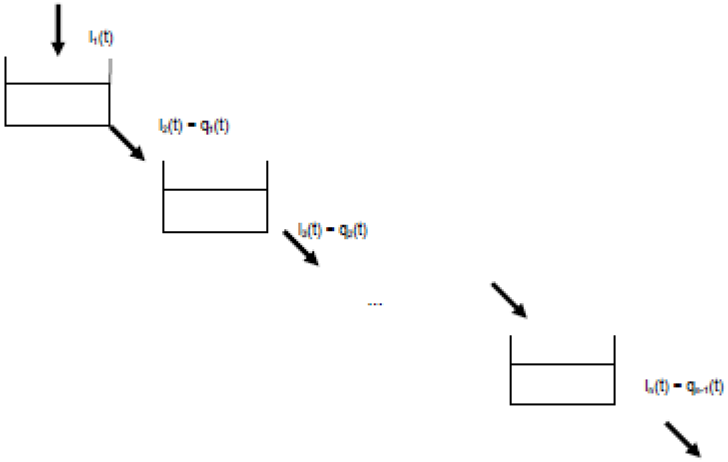


Figure 2.16 – Depiction of the reservoir cascade method (Adeyemo, 2007)

Despite the fact that these and others similar methods that were originally applied for river flow modelling, like the Muskingum-Cunge (Chow et al 1988), are still used nowadays, they do not provide the modelling capabilities to accurately represent the rainfall/runoff flow dynamic interactions in urban catchments (Leitão, 2009). This becomes even clearer in extreme rainfall conditions, when the flow rate is faster and more intensified and the sewer system is caused into surcharge, as it is described in Sá Marques et al (2013).

### 2.4.3 Hydraulic models

As mentioned before, when there are extreme rainfall conditions, there is a need for a more advanced way of representation of the overland flow. The more traditional approach to represent the overland flow it is the Manning-Strickler formula, but it is only valid for steady and uniform flow. When there are sudden variations of flow rate, and thus unsteady flow, the hydrodynamic models portrait a more realistic view. They are based on the conservation of momentum and mass laws.

The Saint-Venant equations are the mathematical equations that better describe the behaviour of overland unsteady flow, whether it is in one (1D) or two dimensions (2D). They originate from the depth-integration of the Navier-Stokes equations and, according to Butler and Davies (2011), are based on the following assumptions:

- The distribution of pressure is hydrostatic;
- The average channel slope is small and fixed, thus for flow routing the effects of scour and deposition are negligible;

- The channel is considered as prismatic and its longitudinal axis as a straight line: any variation is represented as a series of prismatic reaches;
- At any cross-section the distribution of velocity is uniform;
- Friction losses are only valid if they are estimated by steady flow equations, like the Manning-Strickler equation;
- Lateral flow is negligible.

The 1D model can be applied if the direction of runoff is well defined and the cross-section is constant along the pipes. The Saint-Venant equations portraying the 1D model are described in the following way, according to Lima et al (2013):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{3}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\frac{\partial h}{\partial x}=g(S_0-S_f) \tag{4}$$

Where:

A - cross-sectional area of channel segment [$m^2$];

Q - flow rate [$m^3s^{-1}$];

x - longitudinal distance [m];

t - time [s];

g - acceleration due to gravity [$ms^{-2}$];

$S_0$ - bottom slope [-];

$S_f$ - friction slope [-];

$\frac{\partial h}{\partial x}$ - pressure force term;

$\frac{1}{A}\frac{\partial Q}{\partial t}$ - local acceleration term;

$\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)$ - convective acceleration term.

On the other hand, when the conditions mentioned before are not applicable, the 2D Saint-Venant equations have to be used:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \tag{5}$$

$$\frac{\partial uh}{\partial t} + \frac{\partial}{\partial x}(\mathrm{hu}^2 + \tfrac{1}{2}\mathrm{g}h^2) + \frac{\partial}{\partial y}(\mathrm{huv}) = \mathrm{gh}(S_{ox} - S_{fx}) \tag{6}$$

$$\frac{\partial vh}{\partial t} + \frac{\partial}{\partial x}(\mathrm{huv}) + \frac{\partial}{\partial x}(\mathrm{h}v^2 + \tfrac{1}{2}\mathrm{g}h^2) = \mathrm{gh}(S_{oy} - S_{fy}) \tag{7}$$

Where:

u – velocity in x direction [ms$^{-1}$];

v - velocity in y direction [ms$^{-1}$];

x – primary flow direction [m];

y – perpendicular flow direction to x [m];

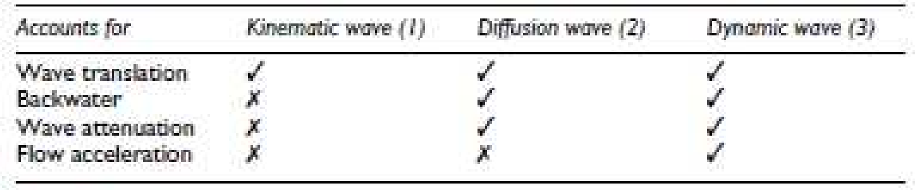
$S_{ox}$ – bed slope in x direction [-];

$S_{oy}$ – bed slope in y direction [-];

$S_{fx}$ – friction slope in x direction [-];

$S_{fy}$ -friction slope in y direction [-];

The Figure (2.17), from Mark (2004), summarizes the simplifications and application range of the equations mentioned above:



| Accounts for | Kinematic wave (1) | Diffusion wave (2) | Dynamic wave (3) |
|---|---|---|---|
| Wave translation | ✓ | ✓ | ✓ |
| Backwater | ✗ | ✓ | ✓ |
| Wave attenuation | ✗ | ✓ | ✓ |
| Flow acceleration | ✗ | ✗ | ✓ |

Figure 2.17 – Hydraulic conditions by simplifications of wave equations (Mark, 2004)

### 2.4.5 Dual Drainage

Occasionally, under extreme rainfall circumstances, the system may surcharge and spill on to the urban surface, causing the appearance of overland flow. It is then possible to occur two types of flow inside the pipes: pressurized in some parts and flow in open channels in another. In order for the Saint-Venant equations to be applied to pressurize flow in pipes, the concept of the Preissman slot needs to be considered (Butler and Davies, 2011).

It translates as an imaginary slot in the top of the conduit that allows the flow to exceed the diameter of the pipe, simulating the effect of pressurized flow. When this phenomenon occurs, the excess flow may spill into the surface, causing problems related to floods: the solution to this problem was to admit the loss of volume of water when it reaches the surface or the unlimited rise of the water level in the pipe (Figure 2.18):

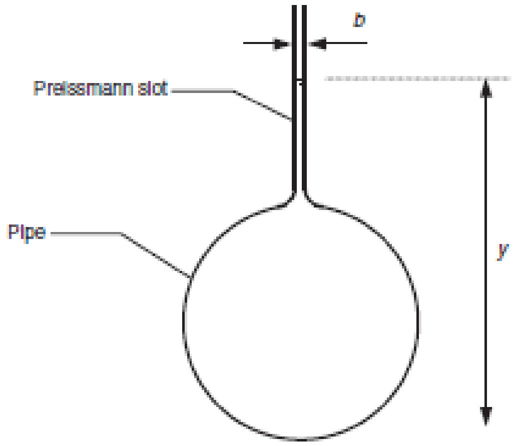


Figure 2.18 – Preissman slot (Butler and Davies, 2011)

But recently, a more precise solution to this problem was found: in the 1990s, by resorting to new urban drainage modelling tools, the connection between geographical data and drainage models lead to a new concept known as dual drainage (Butler and Davies, 2011). According to Djordjevic et al (2005) the concept was first introduced in North America in the eighties, but Smith (2006) refers that it may have been in use some years previously.

According to the AMK Associates, International, Ltd (2004) the concept of dual drainage states that an urban drainage system is divided into two different and separate components:

- A major system (surface), consisting of streets, ditches and others natural and artificial channels;
- A minor system composed by the actual storm sewer pipe network.

The concept of dual drainage gives a more realistic way of modelling the process of urban drainage, especially when it is required to deal with situations of possible flooding events, by enabling the simulation of the sewer and overland flow and its interaction by a link of weir-orifice-type elements, such as inlets and manholes (Mark et al, 2004): the Figure 2.19 below depicts the interaction between the two systems.

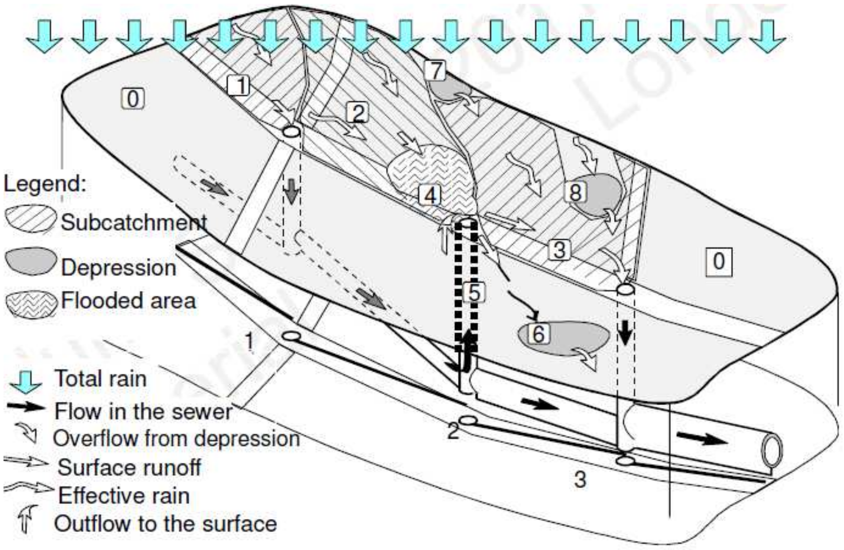


Figure 2.19 – Dual drainage concept (Simões, 2011)

As present by Djordevic et al (1999) the simulation of the two groups of systems (major and minor), is very time-variable and spatially distributed, and so it requires the combination of three basic tools to deal with the interaction of the two systems:

- Advanced hydraulic models capable of modelling free surface and its transition to surcharge state, and surcharge flow with proper interactions between all the phases of flow (surface and sewer pipe flow);
- Computer-based information support tools that can process data on land use (terrain depressions and flow paths), surface flow patterns, and the links between the pipe network and storage units;
- Tools that enable the presentation of the dynamic processes and the statistics of the results.

### 2.4.5 1D/1D and 1D/2D models

Currently there are two distinct ways of approaching dual drainage models: despite both having a one-dimensional (1D) for the sewer network, one represents the overland flow as 1D and the other as a two-dimensional surface (2D) (and Sá Marques et al, 2013). The drainage network 1D model coupled to a 1D surface model (1D/1D model) can distribute the runoff directly into to the drainage system or on the surface network, and the exchange between the two system (major and minor) is made through localized links, like manholes or gullies (Hénonin et al, 2010).

One of the issues of the 1D/1D model is the fact that the flow exchange between the two systems needs to be considered bi-directional, to properly simulate the drainage of water and cases of surcharge and spilling. According to Mark et al (2004), the 1D surface model consists normally in a 1D hydrodynamic model of the surface pathways with a storage function attached to handle situations of floods. The development of this type of model requires a large amount of terrain and land use data.

One solution to the creation of 1D/1D models was developed by the Urban Water Research Group (UWRG) of the Imperial College: the Automatic Overland Flow Delineation (AOFD) (Maksimovic et al, 2009).The tool generates an overland flow model, by automatically delineating several possible surface pathways, based on terrain slope that interacts with the underground drainage system. The quantification and analysis of the overland network is done through several GIS routines, which search the entire DTM for low terrain points. According to Simões (2012) the analysis of the DTM can be divided into four steps: (1) pond delineation; (2) pathway delineation; (3) pathway geometry; and (4) generation of input files for the urban drainage models (Figure 2.20).

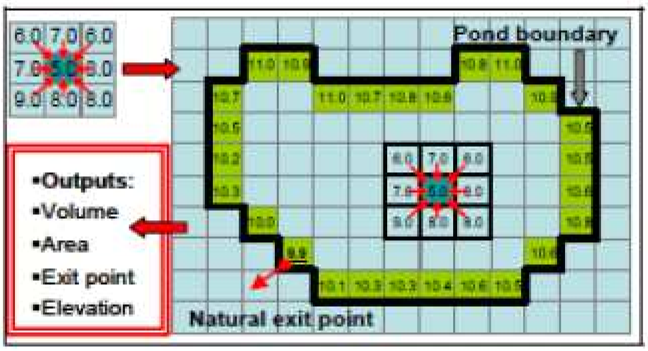


Figure 2.20 – Pond delineation in the AOFD methodology (Simões, 2011)

Studies like Boonya-aroonnet et al (2007), Mark et al (2004), Allitt et al (2009), have demonstrated that 1D surface modelling while being faster to simulate than the 2D surface models, its results are only acceptable if the uncertainty in relation with alternative surface flow pathways is small (when the water overflows the streets it is unreliable, because the flow becomes multi-directional). Studies like Leandro (2008) and Simões et al (2011) have also been made where the results of improved 1D/1D models are compared with 1D/2D model. Nevertheless, it provides a good solution when the flow channels are well delimitated (Figure 2.21)

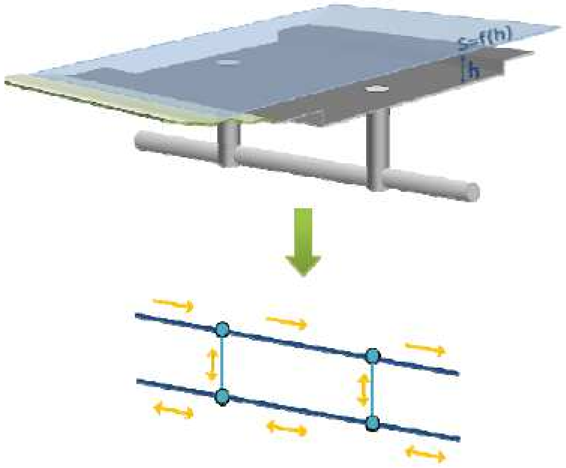


Figure 2.21 – Example of 1D/1D modelling principle (Henónin, 2010)

The drainage network 1D model coupled to a 2D surface model (1D/2D model), whilst still modelling the sewer flow in 1D, it models the overland flow as a 2D problem, and so reproduces in a more accurate way the urban topography (buildings, street crossings, ponds) (Leitão, 2009), since the 2D surface model enables calculations using the flow velocity in two directions components (Hénonin et al, 2010). An issue of the 1D/2D models is the high dependence on the accuracy of the terrain data resolution, requiring a pre-treatment of data, as it will be explained in the chapters below.

While the 1D/2D model provides a more realistic surface flow behaviour when compared with the 1D/1D, it requires a much longer amount of calculation time, which leads to the use of small catchments or a lower resolution of the terrain data in order to have an acceptable period of calculation (Simões et al, 2011). (Figure 2.22).

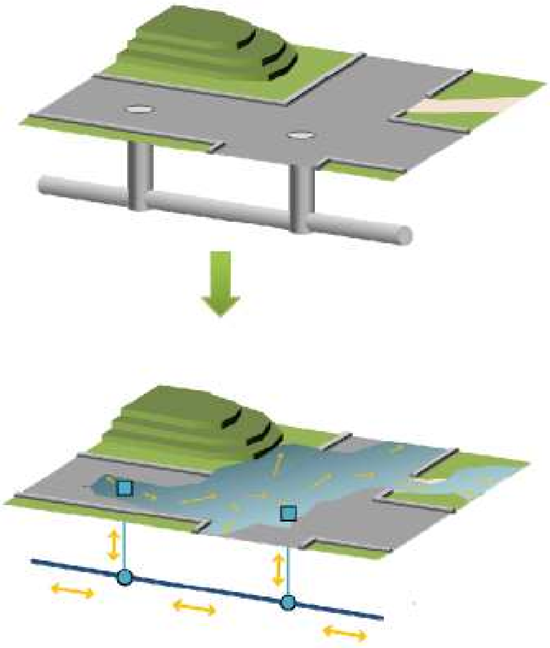


Figure 2.22 – Example of 1D/2D modelling principle (Henónin, 2010)

The 1D/1D and 1D/2D models are available in most commercial softwares, such as InfoWorks (Wallington, 2003) and MIKE FLOOD and MIKE URBAN (DHI, 2005).

## 2.5 Softwares

### 2.5.1 SWMM

The software Storm Water Management Model (SWMM) was developed by the Environmental Protection Agency (EPA) in 1971, and has been through several improvements since then. It is considered a dynamic rainfall-runoff simulation model, as it allows the simulation of quantity and quality of surface runoff in single or long-term events, for urban and non-urban areas. According to the software's manual (Rossman, 2010) the primary use of this software is to plan, analyse and design existing or non-existing drainage systems that may include pumps, regulators, pipes and storage elements. It can also be applied for flood control and water quality protection issues.

Ultimately, the software SWMM can not be utilised to solve problems requiring the use of 1D/2D models, since the surface model (2D model) simulates two-dimensional unsteady flow on the urban morphology that can not be simulated in the software.

In reality, 1D model overflow is considered as a virtual storage on top of the manholes, not being able to reproduce a realistic behaviour of surface overflow. Thus it is needed to call upon more advanced simulation models like Infoworks, MIKE, or SOBEK.

### 2.5.2 Infoworks ICM

In the 1990s the company Wallington Software released Infoworks: a commercial package of softwares capable of dealing with the different aspects of the water cycle. The component most relevant for this dissertation is Infoworks ICM, since it refers to the urban drainage systems modelling (Wallingford, 2003).

The software provides a database to store networks and hydraulic data by combining a relation database with a geographic analysis, becoming a practical method for operation and real-time control of urban drainage networks. It provides a fully integrated solution to backwater and reverse flow modelling, as well as open channels and complex pipe networks and connections modelling issues. allows the analysis and prediction It has several tools that allow it to deal with data integration and model building problems, fully integrate 1D and 2D modelling environments, optimization of multiple surfaces meshes designs, and, among all of the many visualisation tools, a 3D terrain view that allows the viewing of ground surface for a more complete picture of the networks performance.

It is a very powerful hydraulic simulation tool that provides a fully integrated and real time control of water quality, whilst supporting sustainable urban drainage systems (SUDS) structures and infiltration modules for groundwater influences. It can also provide a sediment modelling and a real life modelling of complex pumps and network behaviours. One of its applications is the ability to assess the impact of climate changes, flood and pollution prediction on urban drainage systems.

### 2.5.3 Other available softwares

Another widely used software is the commercial package MIKE developed by the Danish Hydraulic Institute: beyond the several components, the most important to highlight are the MIKE URBAN CS (for urban drainage network modelling) and MIKE FLOOD (for urban, coastal and riverine flood modelling).

The software SOBEK developed by the research institute WL/Delft Hydraulics, is also a powerful comprehensive modelling package of tools for design and optimization of drainage systems, flood and surface water quality prediction, and control of irrigation systems. It provides an integrated approach to the simulation of management issues along the several aspects of the water cycle. It has a powerful hydrodynamic 1D/2D simulation engine that can simulate pipe, river and overland flow through an implicit coupling of 1D and 2D flow equations.

## 2.6 Flood management

### 2.6.1 Introduction

According to the Global Water Partnership Technical Advisory Committee (2000), an effective management of water resources requires an approach that provides a link between land and water use, and socio-economic development with the protection of the environment. As mentioned in the first chapters, the social awareness towards floods as increased in the last years, since floods may cause the loss of lives and assets, environmental damages and forced dislocation of population (Directive 2007/60/CE), and therefore play an important role on defining the sustainable solution for a location.

The Hyogo Framework for Action 2005-2015: Building the Resilience of Communities and Nations (UNISDR, 2005) is a response from the world to this serious issue. As this crucial topic needs to be considered while managing the water resources of a river basin or urban area, the need for a more integrated solution rose, leading to the instatement of the Integrated Flood Management (IFM) framework (WMO, 2009a).

The IFM approach aims to integrate the land and water resources of a catchment, whilst maximizing the net benefits from the use of floodplains, minimizing loss of life from flooding, and lowering flood risk and vulnerability (concepts explained in the next chapters). The approach must take into consideration the connection between all the components of the catchment, from the coastal aspect, to risk assessment and water resource managing: the Figure 2.23 below demonstrates an IFM model.

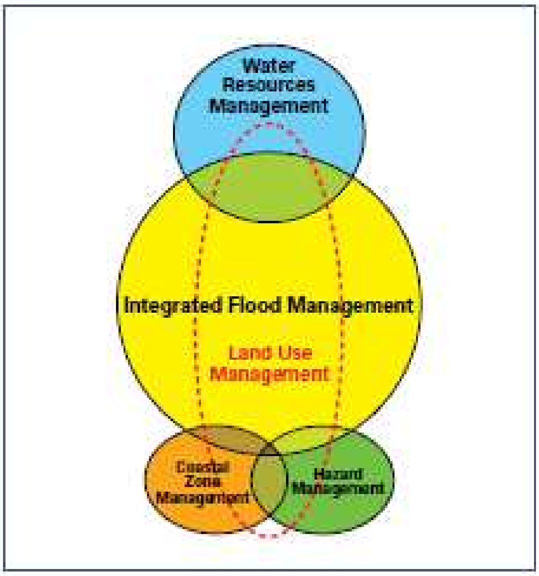
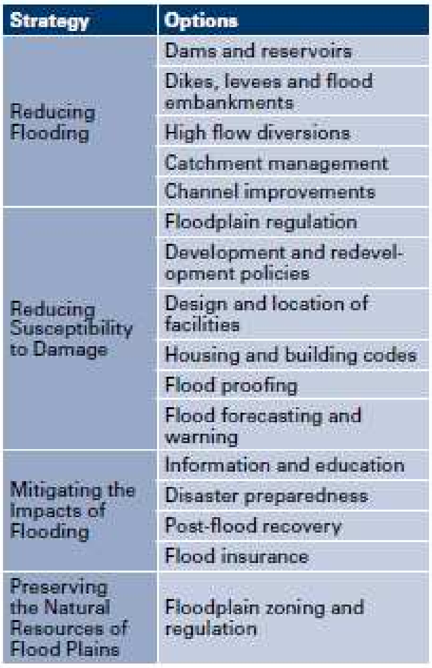


Figure 2.23 – Depiction of a IFM model (WMO, 2009a)

As discussed in several World Meteorological Organization (WMO) documents, the IFM must address certain key elements in order to manage floods in an integrated manner (WMO, 2009b):

- Managing the water cycle as a whole;
- Integrate land and water management;
- Managing risk and uncertainty;
- Adopt a best mix of strategies;
- Ensure a participatory approach;
- Adopt integrate hazard management approaches.

In the concept paper on Integrated Flood Management (WMO, 2009a) a more extensive explanation of the six elements presented above is given: it is also important to highlight in this document the table showing the possible strategies and solutions for flood management, as it is shown below (Figure 2.24). Within the framework of an IFM plan, Rocha (1998) presents also similar measures to be implemented in order to perform a better flood management.

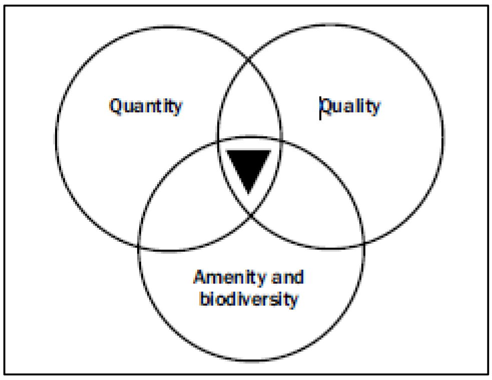


| Strategy | Options |
|---|---|
| Reducing Flooding | Dams and reservoirs |
| | Dikes, levees and flood embankments |
| | High flow diversions |
| | Catchment management |
| | Channel improvements |
| Reducing Susceptibility to Damage | Floodplain regulation |
| | Development and redevelopment policies |
| | Design and location of facilities |
| | Housing and building codes |
| | Flood proofing |
| | Flood forecasting and warning |
| Mitigating the Impacts of Flooding | Information and education |
| | Disaster preparedness |
| | Post-flood recovery |
| | Flood insurance |
| Preserving the Natural Resources of Flood Plains | Floodplain zoning and regulation |

Figure 2.24 – Strategies and options for flood management (WMO, 2009a)

Another key feature in the flood mitigation and prevention, which needs to be referred is SUDS (Sustainable Urban Drainage Systems), which form an important role within the integrated drainage design framework (Balmforth et al, 2006): examples of SUDS are the artificial ditches, infiltration drenches, permeable pavements and retention storage tanks (Butler and Davies, 2011).

Their main objective is to reduce the surface runoff from rainfall by controlling the flow of water, and thereby diminishing the negative effects of urbanization: more permeable areas, storage and retention elements lead to much smaller flood event, since the excess runoff is lower (Butler and Davies, 2011). According to Balmforth et al (2006) the SUDS approach follows three main principles: sustainable management of environmental risks, minimization of the impact of flow quantity and quality development, and maximization of biodiversity (Figure 2.25)



(16)

Figure 2.25 – SUDS objectives (Woods et al, 2007)

But, in order for all this measures, strategies and plans to be applied, certain issues and topics need to be properly explained: such as flood risk assessment.

### 2.6.2 Flood Risk

Since the European Directive 2007/60/EC called for its Member States to prepare preliminary flood risk assessment plans and flood risk, many countries have already flood risk management plans in action, as it is mentioned in Meyer and Messer (2005). The management of an urban flood risk plan has to start with the assessment of present and future flood risks, and therefore can not be static and need to be continually revised and updated (Rocha, 1998).

But what is risk? Risk is both a scientific and social concept: it is the combination of the probability of an event and its negative consequences (WMO, 2009b). Betâmio de Almeida (2004) presents a more theoretical definition and explains the development of the concept. According to WMO (2009b), mathematically speaking, risk is expressed as:

$$Risk\ (probable\ loss) = probability\ \cdot consequence\ (=)$$

$$(=)\ p(h) = v(d) * s(h, d)$$

Where:

p(h) - probability of occurrence of the hazard;

v(d) - value of the elements at risk, which is a function of the development in the exposed areas, the land use and the probability of presence (exposure);

s(h,d) - the susceptibility of the elements at risk, which is a function of the magnitude of the hazard as well as the socio-economic construct of the exposed elements (vulnerability).

The concept can be explained by words as the combination of the magnitude of the hazard (in terms of frequency and severity), the exposure of the elements to floods and the vulnerability of the elements at risk (Figure 2.26).

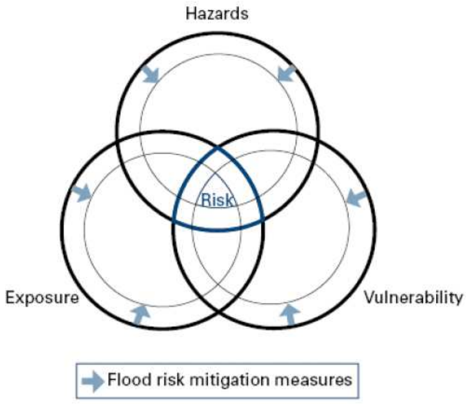


Figure 2.26 – Concept of flood risk (WMO, 2008)

This definition of risk is also made by the United Nations International Strategy for Disaster Reduction (UNISDR), as it is stated in Hora and Gomes (2009), that classifies risk as the probability of harmful consequences or expected losses that result from natural or social hazards in vulnerable circumstances.

The probability is associated with the return period of the rainfall event, whilst the consequences are obtained through the quantification of the flood impact. In addition to the concept of risk, it is also important to highlight the existence of various types of damages that floods might cause: damage can be categorized into two possible distinct flood losses situations, as shown below (WMO, 2008):

- Direct losses: resultant from direct contact of infrastructures with flood water;
- Indirect losses: caused by the event but not directly influenced, like transportation disruption due to closure of flooded roads;
- Tangible losses: the loss of something with a monetary or replacement value;
- Intangible losses: loss of things that can be measured or transacted, like lives and memorabilia;

The aim of an IFM, as mentioned before, is to minimize these losses, whilst making sustainable and beneficial choices for the people and the environment. However as the damage can never be completely avoided, there is a need for management of the risk of flood events, a process that, according to the WMO (2009a), can be summarized into three stages:

- Risk assessment;
- Planning and implementation;
- Evaluation and reassessment.

### 2.6.3 Flood risk assessment and management

According to WMO (2008), the main basis for a flood management plan is a extensive assessment of the current and future flood risks that can identify all the possible hazards, their future development due to an increase of urbanization, climate change or land use changes. In order for that to happen, the hydrologic and hydraulic characteristics of the hazards need to be modelled in the context of the river basin, and as such, the assessment should begin with the analysis of the meteorological data.

The surface flow pathways within an urban area are highly modified due to day-to-day activities (dumping of waste in the drainage system), and have a direct impact on the carrying capacity of surface runoff drainage, therefore the determination of the likely flood areas is complicated and difficult to estimate. The use of GIS tools enables an early assessment of the flood endangered areas, and its combination with survey of the economic value of the infrastructures on the areas and flood frequency and magnitude data, allows an economic risk can be calculate.

In addition with the identification of floodable areas and the damages caused, a quantitative comparison of the components of risk can be done: one of the products resulted from a flood risk assessment that enables such is the flood risk maps.

### 2.6.4 Flood risk maps

Flood risk maps are a great tool for risk assessment and planning, that allow the users to see accurately where and how the impact of flood water processes, and to possibility to identify where the most vulnerable locations to flooding. According to the Decreto-lei nº115/2010, in each hydrographic and managed area, the flood risk and corresponding mitigation measures have to be evaluated. The flood maps made in this study will be classified in a quantitative manner, as each zone of a determined area with the corresponding flood risk (Figure 2.27).

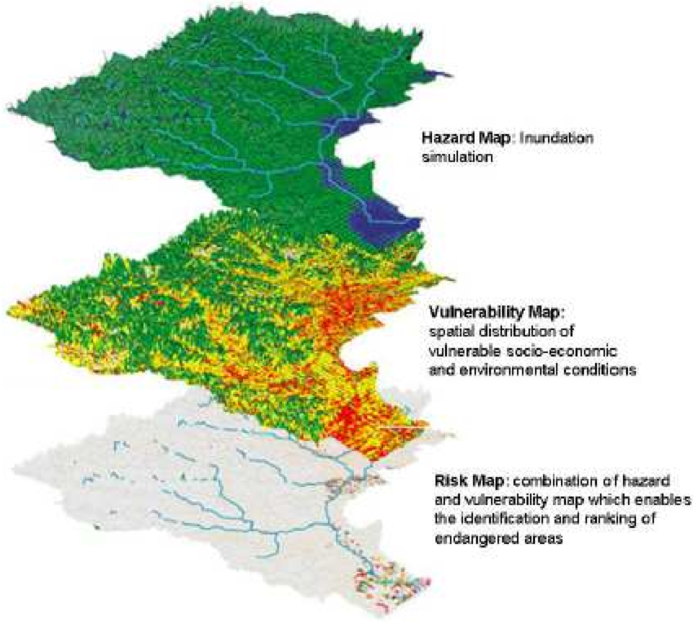
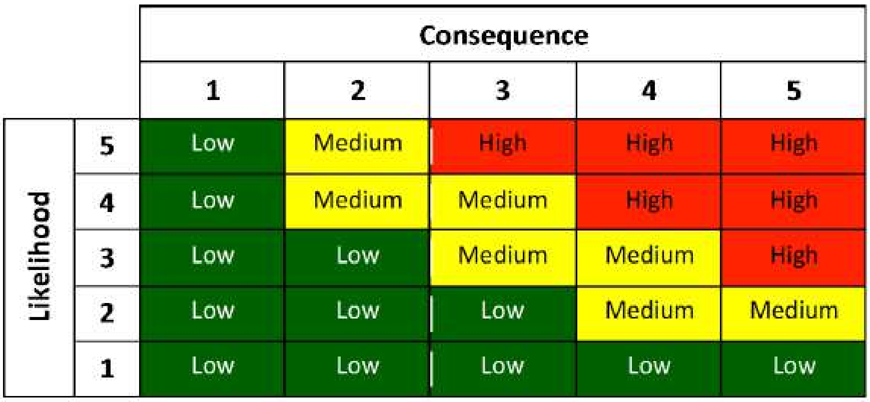


Figure 2.27 – Risk map with geographical information (WMO, 2008)

In order for that to be possible, it was necessary to take into consideration the probability and consequence of a specific flood: therefore there is a need to clarify in regard of the probability levels (rare, unlikely, probable, likely, and very likely to happen) and the consequences considered in the analysis. Also, the elaboration of flood maps involves a hydrological and hydraulic analysis. Through the study of a rainfall with different return period times it is possible to obtain an indication of the probable floodable zones when a precipitation event with a determined probability is checked. As said before, the consequences of the flood taken into consideration in this study also need to be defined. According to the European Directive 2007/60/CE the issues that can be quantified for potential consequences, can be the following:

- Number of potential affected population (directly or indirectly) by the flood;
- Type of potential affected economic activities in the area;
- Infrastructures that may cause accidental pollution in case of flood;
- Areas where there is a high probability of a high volume of debris or soil being dragged.

Another important aspect in the flood map procedure is a risk matrix, which translates the interconnection of the probability and consequences, providing a classification for each area accordingly to the flood risk map. As such, after having both the issues needed, the matrix can be made, as it is shown below in Figure 2.28.



| | | Consequence | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Likelihood | 5 | Low | Medium | High | High | High |
| | 4 | Low | Medium | Medium | High | High |
| | 3 | Low | Low | Medium | Medium | High |
| | 2 | Low | Low | Low | Medium | Medium |
| | 1 | Low | Low | Low | Low | Low |

Figure 2.28 – Example of a risk matrix (Leitão et al, 2012)

Since the qualitative approach can be very subjective and requires a great deal of information and data to be properly used (Leitão et al, 2012), a more clear approach that revolves around quantifying the monetary costs caused by floods was chosen.

The analysis of the flood impact can be made through the quantification of the resulting cost of the damages caused by it. Normally the costs are directly associated to height of the water and the velocity of the flow in a flood event: higher heights and velocities lead to bigger costs and impacts on infrastructures and people’s lives.

In spite of the fact that it is a more narrowed approach in terms of quantity of information needed, it still depends on a number of factor and parameters to quantify the different monetary losses caused (direct-indirect and tangible-intangible).

Several studies like Leitão (2009) and HR Wallingford (2006), focused in the direct losses, while other like Penning-Rowsell (2005) and Balmforth et al (2006) made a more generalised quantification of costs, including both cultural-social and demographical influences (Figure 2.29).

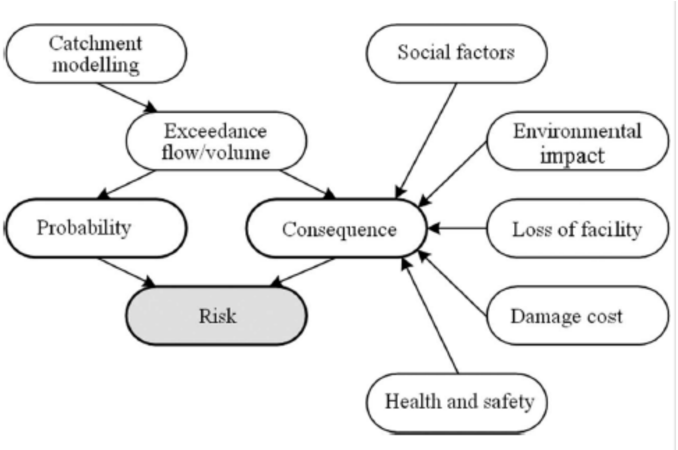


Figure 2.29 – Flood risk assessment (Balmforth et al (2006)

Leitão et al (2009) and Balmforth et al (2006) also confirmed that there are several influential factors to the resulting losses, from the duration and intensity of the precipitation, to the depth and speed of the overland flow, to the use and type of buildings, and to the occupation, density and social classes of the inhabitants of the urban catchment.

But, when a faster and more generic idea of the damages caused is needed, a more simplified approach for the quantification of costs can be adopted: some studies such as Hammond et al (2012), Cançado et al (2008) and Machado et al (2005) considered the damage cost per meter of height of water (Figure 2.30).

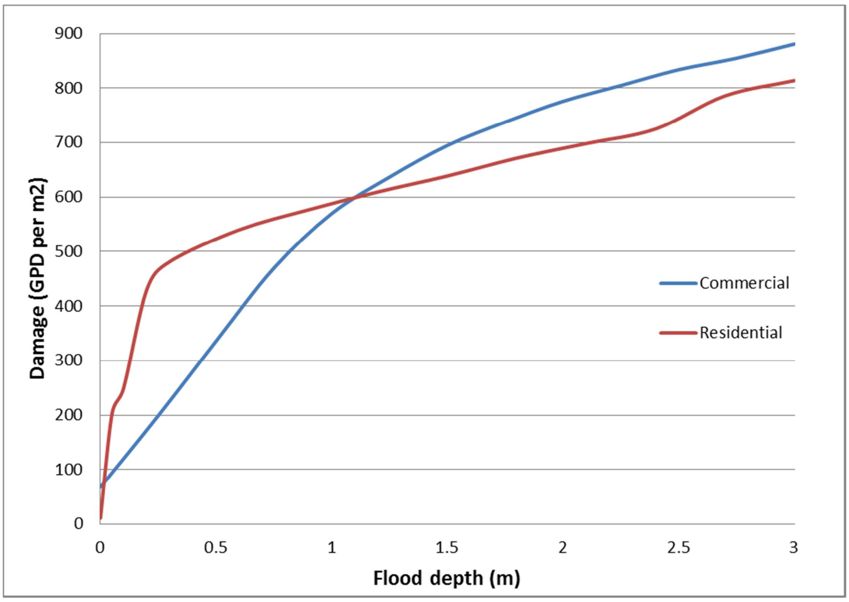


Figure 2.30 – Depth-damage curves regarding the usage of buildings (adapted from Hammond et al, 2012)

# 3 CASE STUDY / METHODOLOGY

## 3.1 Introduction

Concluded the literature review needed to enlighten and obtained the required knowledge about the subject, it is possible to present the methodology adopted as well as a brief description of the case study.

## 3.2 Case study: Coimbra

The catchment studied in order to approve this methodology is the medium sized city of Coimbra, which has been recently affected by several urban floods, for instance in 2006, 2008 and 2013 as it can be seen in the figures below (Figures 3.1 and 3.2), therefore reinforcing the fact that more precise study needed to be done in the area. It has a total area of 1.5 km2 approximately, with a sewer system 34.8 km long, of which only 1.2 km are exclusively towards storm water drainage. The time of concentration of the catchment, according to studies already made (Simões, 2012), is estimated to be 45 minutes.

Figure 3.1 – Praça 8 de Maio in the 09/06/2006 (Sá Marques and Pina, 2013)

Figure 3.2 – Praça 8 de Maio in the 21/09/2008 (Simões et al, 2010) and 24/02/2013 (D.C.@, 2013) floods, respectively

According to Sá Marques et al (2013), the catchment area of the city of Coimbra can be divided into three distinct zones:

- “Baixa”: referred to the low ground area with an area of 0.4 km2, that contains mostly services and local commerce infrastructures, with a combined drainage system;
- “Alta”: a high ground and steep slopes area that contains the highly urbanized area with an area of 0.2 km2;
- The remaining area: which is also a highly urbanised area of the city with approximately 0.9 km2, where most of the flood problems arise.

As such, the quantification of flood risk will be mainly focused in a more restrict area that has shown to be more prone to the influence extreme rainfall events: the area in question is highlighted below (Figure 3.3), which concerns the so called “Zona Central” of Coimbra that envelops the Praça 8 de Maio and Câmara Municipal, where some of the most noticeable flooding events have happened (Figures 3.1 and 3.2).

Figure 3.3 – Zona Central of Coimbra highlighted in blue (adapted from Sá Marques et al, 2013)

## 3.3 Rainfall

The rainfall events considered we're obtained through the alternating block method described in Chow et al (1988), where the standart IDF curves are used to obtain the intensity of precipitation.

According to Sá Marques et al (2013) the estimated concentration time for the Coimbra's urban catchment is 45 minutes. Despite this fact, the simulations we're carried out for a duration of 135 minutes, 3 times the concentration time of the catchment: Portela et al (2000) conducted a study that concluded that a rainfall event with thrice the duration of the concentration time could lead to a peak flow higher than by using a duration equal to the concentration time. Therefore, a safer approach for the catchment was chosen where the duration of the rainfall event is 3 times the concentration time.

The return periods chosen for the simulations were 20, 50 and 100 years, as shown below (Figure 3.4). Since the urban drainage systems are usually dimensioned for a return period of 5 to 10 years, but can be increased so far as 20 to 25 years for catchments with a high level of urbanization (Sá Marques et al, 2013), as is the case of the catchment in this study. Another reason is the fact that any value of return period lower would not cause any noticeable disturbances that could be of interest in this study, since the depth and speed of the overland flow would be too small in comparison with the other cases.

Sá Marques et al (2013) suggests that for projects of great economic significance return periods of 100 and 50 years have already been used before. The return period of 100 years was also chosen as a maximum limit because any value higher for a rainfall event would have a very low probability of happening in an urban catchment. The 50 years were chosen as a middle ranged value that could represent well a midway situation.

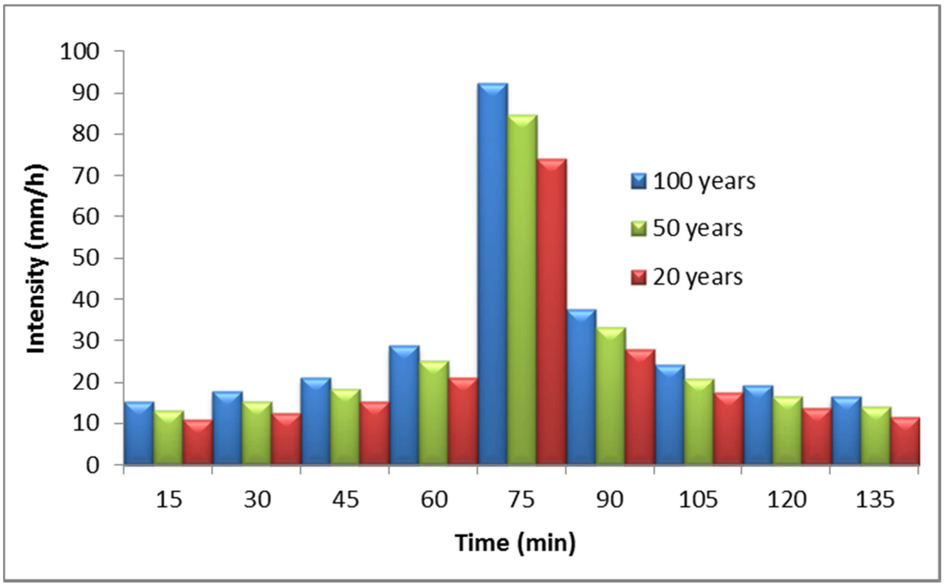


Figure 3.4 – Precipitation by the alternating block method for return periods of 100, 50 and 20 years

## 3.4 Modelling and dual drainage

In order to obtain the results for the elaboration of the flood risk maps a modelling approach had to be chosen: in this situation a 1D/2D dual drainage model was used to get to the necessary results (Figure 3.5). The model had been used before in Simões (2012) and Pina et al (2014) through the softwares InfoWorks CS (for urban flood forecasting) and Infoworks ICM (to compare urban flood models: semi-distributed and fully-distributed) respectively. The digital terrain model was obtained through the technology LiDAR, the sewer data obtained from AC, Águas de Coimbra E.E.M, and the surface network from the 1D/2D model was modelled as a 2D surface using a mesh of triangular elements.

The software Infoworks ICM was used to perform the simulations in the 3 distinct rainfall events chosen. The results were then exported to the Geographical Information System ArcGIS, where the analysis and elaboration of the flood risk maps was made.

Figure 3.5 – 1D/2D semi-distributed dual drainage model used for the elaboration of the flood risk map

## 3.5 Flood damage estimation

In this study, the cost damage function used connects the depth of water with the monetary losses, according to the type of usage of the building, as shown in the Figure mentioned before (Figure 2.30). Since in the area in question for this study, the majority of the buildings are of commercial usage on the ground floor, the curve used was the non-residential.

Since the expression that better describes the curve did not take into consideration the local currency exchange rate, and are displayed in UK Pounds Sterling (GBD) regarding the gross domestic product (GDP), some adjustment had to be made in order for the expression to be relevant for a Portuguese city.

A relation made between the value of the GDP of Portugal and the UK was made: according to the World Bank, in 2014 the GDP per capita of Portugal was 26.759 US dollars and the UK's was 38.452 US dollars, and so the relation between them is of approximately 1.437 (WorldBank@2015). The currency exchange rate of UK Pounds Sterling to Euros, in the 5th of January 2015, is 1 UK Pound Sterling to 1.310 Euros (BancodePortugal@2015).

Therefore, the depth-damage function used to obtain the monetary losses is:

$$Cost\ (€/m^2) = \frac{-16.072 \cdot h^5 + 130.2 \cdot h^4 - 347.74 \cdot h^3 + 227.29 \cdot h^2 + 504.95 \cdot h + 66.337}{1.431} \cdot 1.310 \quad (17)$$

Where:

h – Water depth [m];

## 3.6 Elaboration of flood risk maps

### 3.6.1 Depth-damage flood risk maps

Before any flood risk maps could be made, a methodology for the classification of the actual flood risk had to be established. Taking into consideration the time available to perform this study, only the direct costs were quantified, since the indirect and intangible losses required a more detailed set of information regarding the population density and demographic of the city of Coimbra, and a clear distinction between the different types of buildings and occupations. Therefore, a quantitative approach was implemented in this study to quantify the direct costs. The following sequence of steps was used:

- Identification of the floodable areas;
- Identification of the affected infrastructures;
- Estimate of the depth of water for each floodable area;
- Estimate of the damages caused by the flood, by taking into consideration water depth-cost functions;
- Registration of the results and creation of the flood risk maps.

### 3.6.2 Depth-velocity flood risk maps

Another type of flood risk maps created took into consideration both the depth of the overland flow as well as the speed of the flow, in order to better understand the risks, since they provide a more complex view of the situation by considering depth and water velocity.

These maps allow the user to evaluate other risks besides monetary losses, such as risk to pedestrians, vehicles or the impact on public transports (topics that will be addressed later on) (HR Wallingford 2006). The sequence of step for their creation is similar to the one before, except both parameters are estimated (depth and velocity), and the risk was estimated by using different depth-velocity risk functions: the figure below as used to extrapolate the equations needed (Figure 3.6).

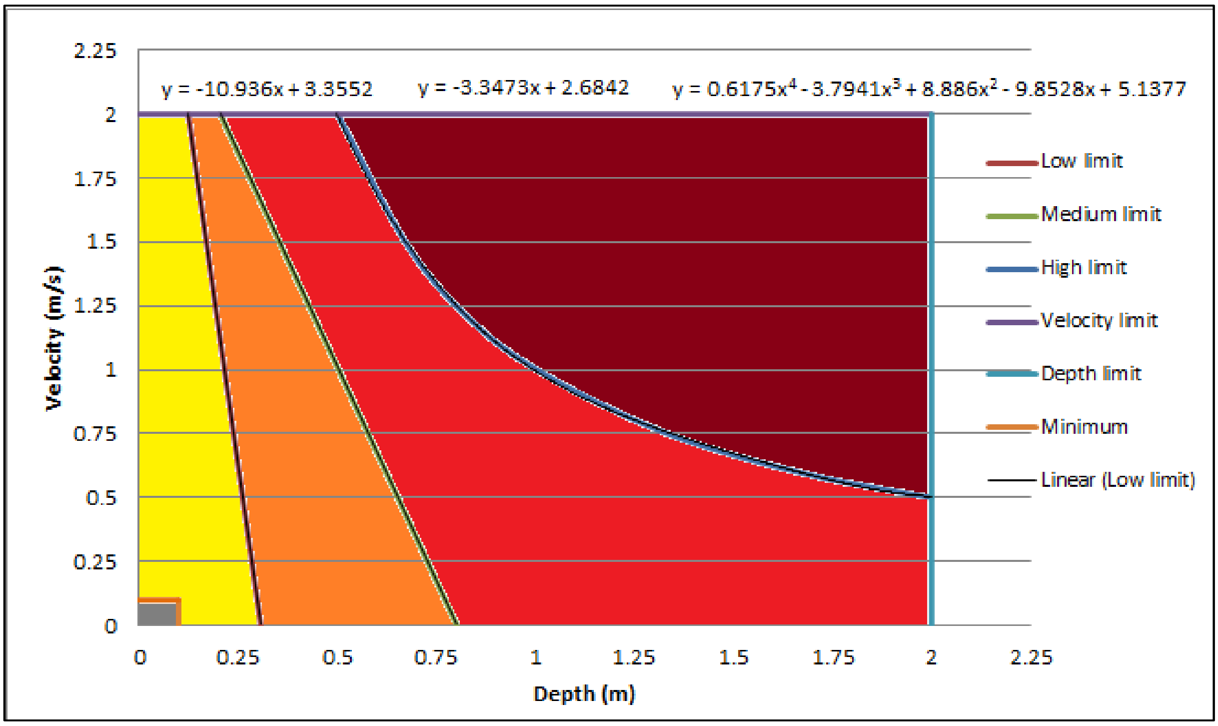


Figure 3.6 – Depth-velocity risk curves (adapted from ProjectsUmwelt@2014)

With the equations obtained, zones of classes of risk were created (from Low to Very High), whilst a minimum was assumed as 0.1m of depth and 0.1 m/s of velocity: any value below these limits were considered as insignificant, since they would not affect the pedestrians or vehicles present, as the risk towards building irrelevant. This reason of choice of this minimum limit derived from other studies that used the same value, like Cançado et al (2008).

### 3.6.3 Transports impact flood risk maps

With these depth-velocity maps created, there are some analyses that can be made: one of which is the influence of flood events to the public transports of the city of Coimbra (more specifically the bus lines, presented in Figure 3.7). In Leitão et al (2012), it defined that a route is considered as affected to the level of stalling the bus line when the water depth is above 0.3 meters for over an hour.

Figure 3.7 – Map of bus lines of part of the city of Coimbra (SMTUC@2014)

# 4 RESULTS AND DISCUSSION

## 4.1 Floodable area maps

As mentioned before, only a specific area of the catchment of Coimbra was chosen due to higher probability of flood events occurring, especially in the surroundings of the Praça 8 de Maio (Figure 4.1), and because in order to analyse the whole catchment more time would be necessary and the limit of pages would be greatly exceeded to contain all the relevant information. For the same reason only the results of two rainfall events will be displayed: 20 and 100 years.

Figure 4.1 – Highlight of the area of the Coimbra's catchment studied

After the analysis and exportation of the most relevant results had been made to ArcGIS, the elaboration of the flood risk maps could initiate. By performing a spatial intersection between the shapefile of the buildings and the shapefile of the mesh zone's pond areas where the rainfall event has caused overland flow, the depth of water affecting each building could be estimated (Figure 4.2).

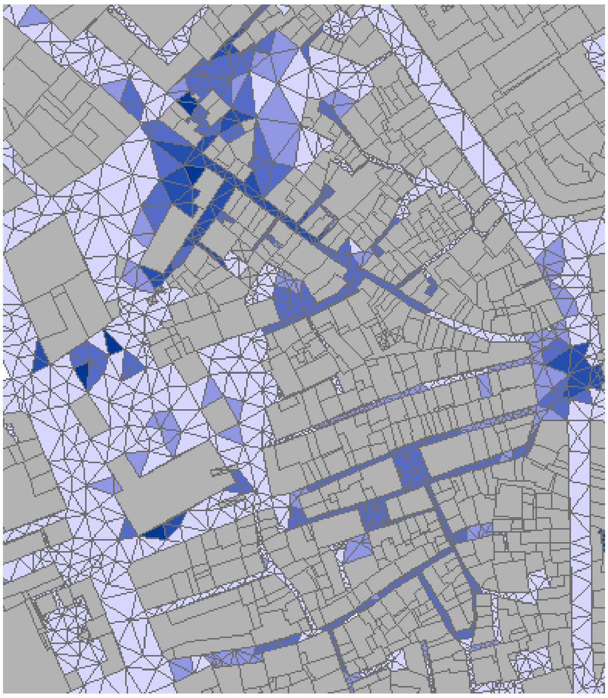


Figure 4.2 – Example of a spatial intersection between the two shapefiles: buildings and pond areas

This was only made possible by performing a filtering of the results, because a number of pond areas surround each building and it had to be taken into account only the maximum value of water depth, for that value is the one that creates a bigger impact on the infrastructure. Also a minimum of water depth had to be established: it was considered as relevant water depth to affect negatively a building the value of 0.12m, since any value below would be lower than the usual Portuguese sidewalk height (Euroacessibilidade@2001), and therefore the water would not reach the ground floor of the infrastructure or cause significant damages. To consider the buildings unaffected by the overland flow it was considered that any value below 0.02m, which is a normal height for the doorstep of buildings (Euroacessibilidade@2001), would be discriminated.

With the intersection of shapefiles done, a division of water depth into distinctly coloured classes was made: yellow for the lower values of water depth (0.12 to 0.25m), orange and red for intermediate and dark red for the highest value (> 0.75m). The unaffected buildings were portrayed in the colour grey. Regarding the pond areas of the mesh zone a colouring of light to dark blue was chosen (lower to higher values). Below, the resulting floodable area maps are displayed for two distinct rainfall events with return periods of 20 and 100 years, respectively (Figures 4.3 and  4.4):

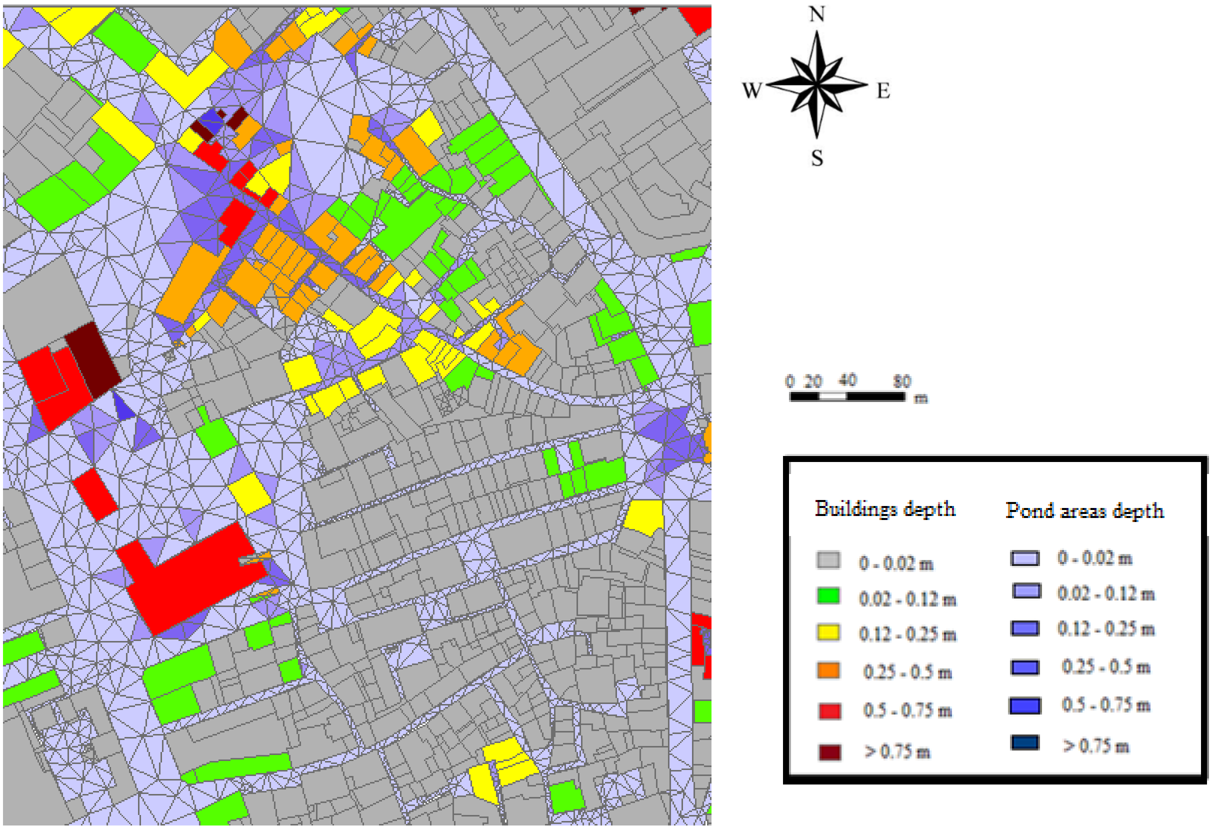


Figure 4.3 – Floodable area map for a return period of 20 years

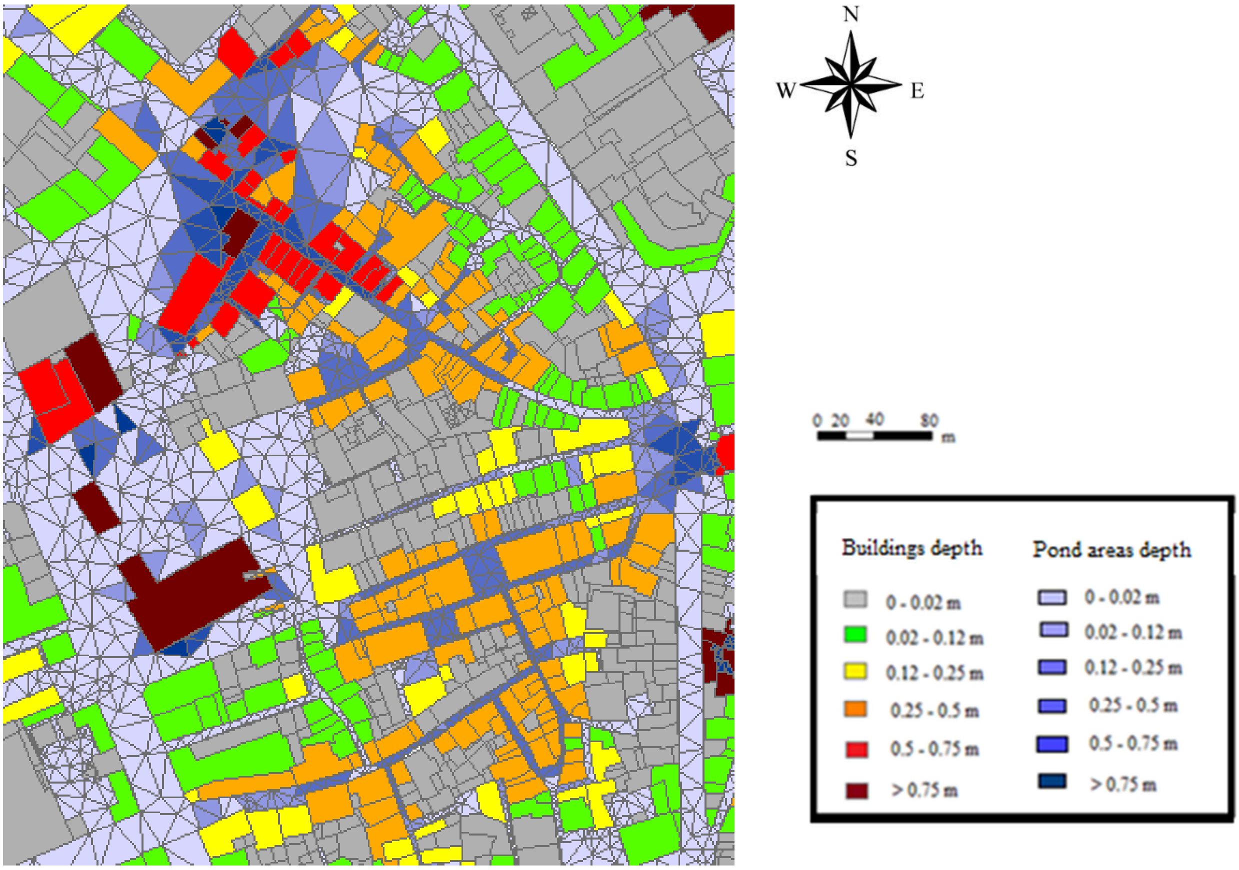


Figure 4.4 – Floodable area map for a return period of 100 years

By observing the resulting maps, it can be easily seen that from the return period of 20 to 100 years, that the water depth increases towards the higher value of return period, which means that the higher the intensity of precipitation is (higher return period=higher intensity of precipitation due to the lower probability of happening in a time period), a more negative impact it will have upon the infrastructures (buildings and urban drainage system). Despite the gradual increase, the majority of the buildings is affected by small water heights (0 – 0.12 m), but in the situation of 100 years of return period the class of 0.25 – 0.5 m presents a respectable number of affected buildings.

It is also visible that there are two area where the water depth levels are higher: one located in the upper part of map at the end of the Rua Direita, and the other zone in the opposite end of that street (Praça 8 de Maio) .Since they are relatively plain zones with elevated surroundings and streets connected to it, the water tends to accumulate there. Below the increase of water depth classes can be seen through two resulting maps (Figure 4.5) where the number of buildings in each water depth class for each return period is displayed:

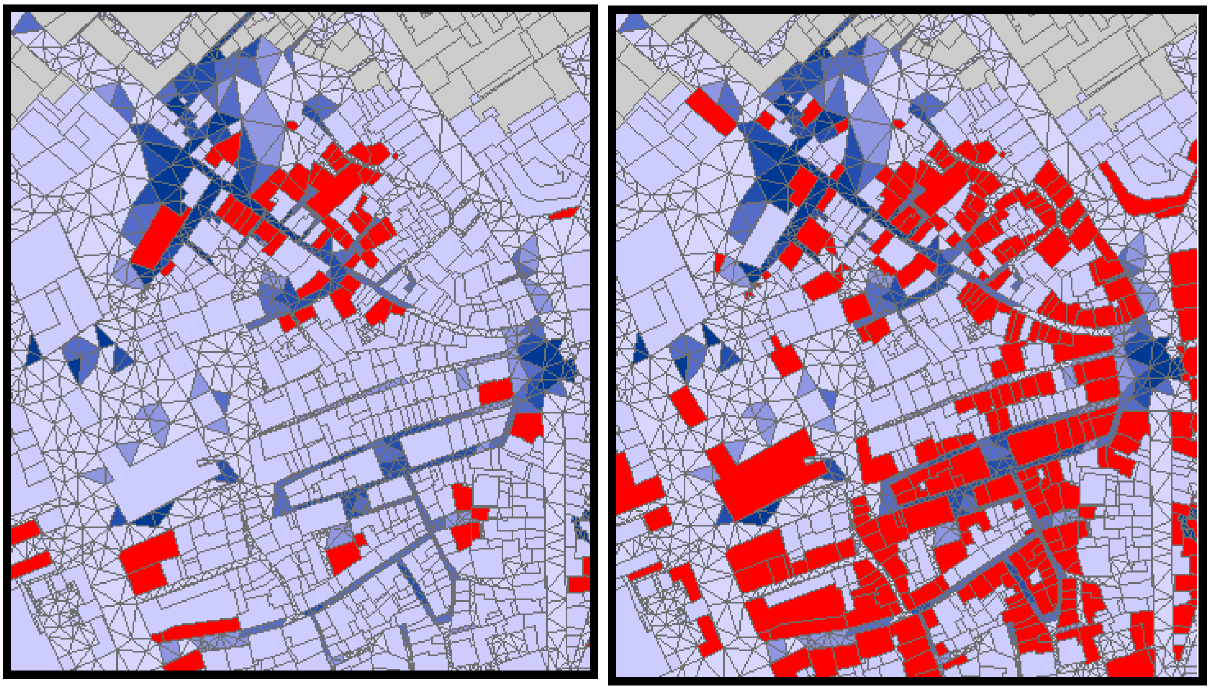


Figure 4.5 – Increase of buildings water depth classes, from return period of 20 to 50 years, and 50 to 100 years, respectively

By looking at the maps it is possible to conclude that the increase of classes is much more noticeable in the transition from the rainfall event of 50 to 100 years of return period than from the 20 to 50 years of return period: it reinforces the idea of increase in water depth and negative impact towards the buildings as rainfall event tends to be less likely to occur (higher return period = smaller probability of occurring).

## 4.2 Flood risk maps for monetary losses

With the floodable area maps already made, the sequence of steps towards the flood risk maps can advance, and for that the depth-damage equation obtained in the chapter before was used. By replacing the variable height with the values for each building, two maps that represented the monetary damage per $m^2$ were created regarding the return period situations (Figures 4.6 and 4.7).

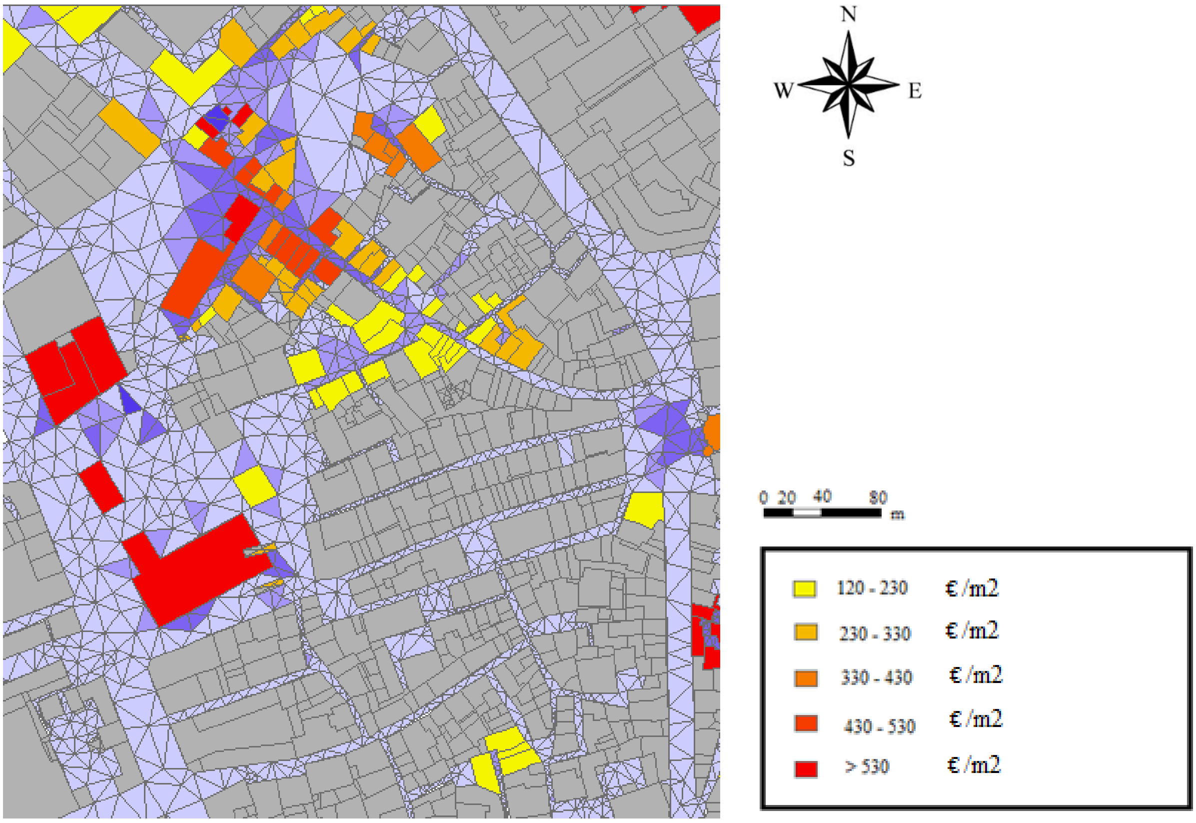


Figure 4.6 – Depth-damage flood risk map (return period of 20 years), expressed in €/m$^2$ per building

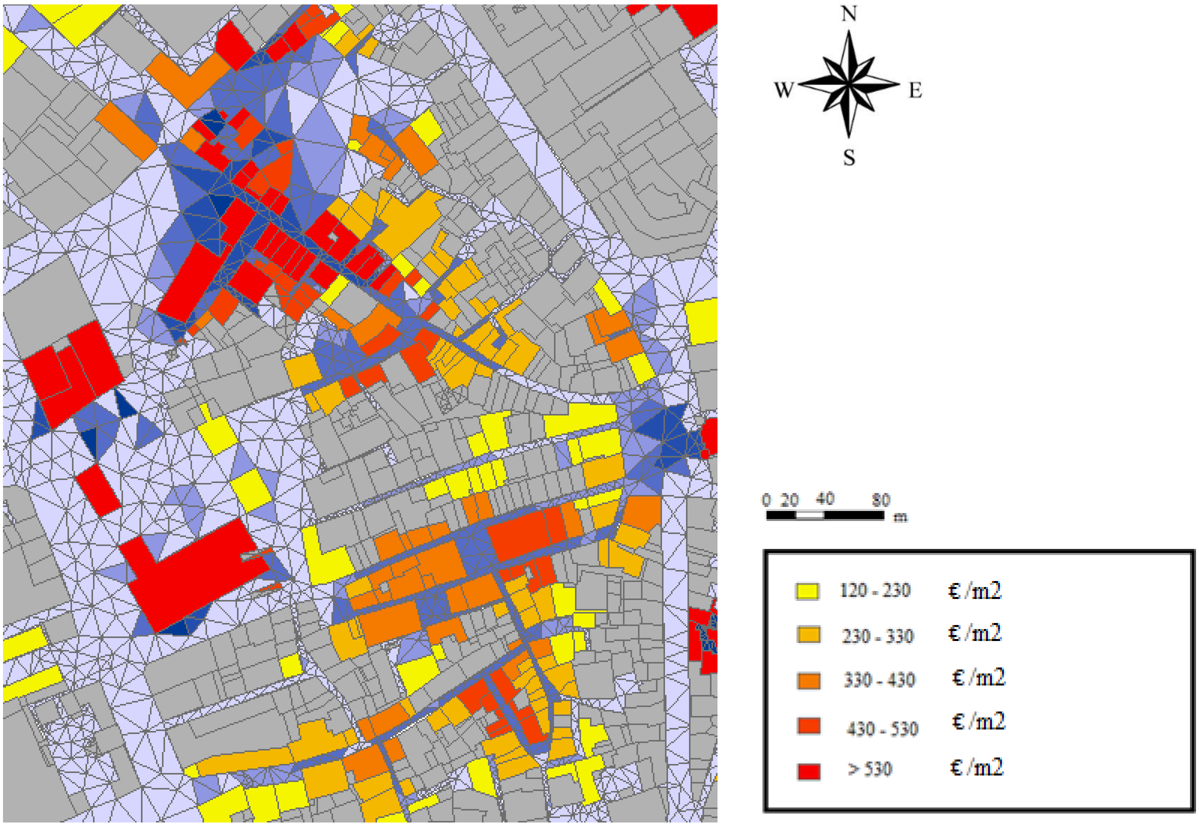


Figure 4.7 – Depth-damage flood risk map for a return period of 100 years, expressed in €/m$^2$ per building

Subsequently, the areas of every building were calculated using one of the commands of the software ArcGIS and multiplied with cost per m$^2$, providing the monetary damage to each building (Figures 4.9 and 4.9). The classes defined for the two sets of three maps considers 5 different categories coloured from the lightest in yellow (lowest monetary value) to the darkest in dark red (highest monetary value).

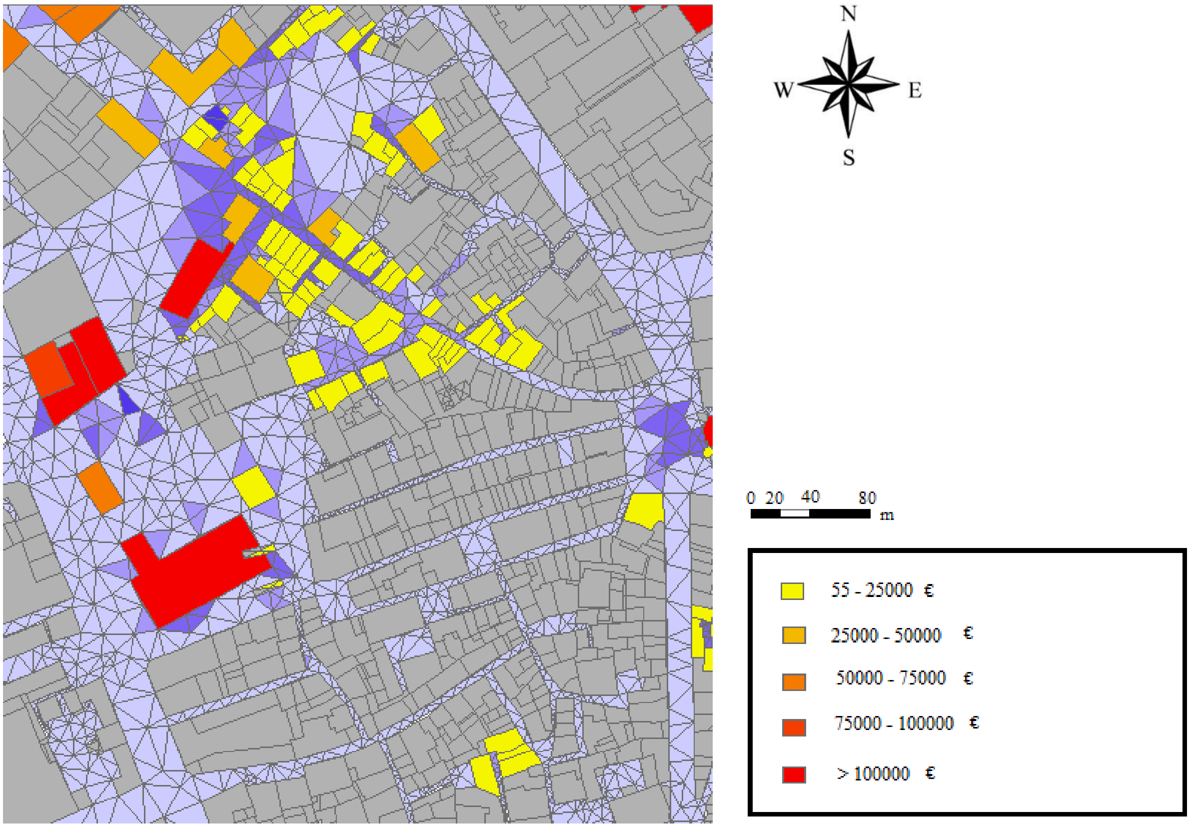


Figure 4.8 – Depth-damage flood risk map for a return period of 20 years, expressed in € per building

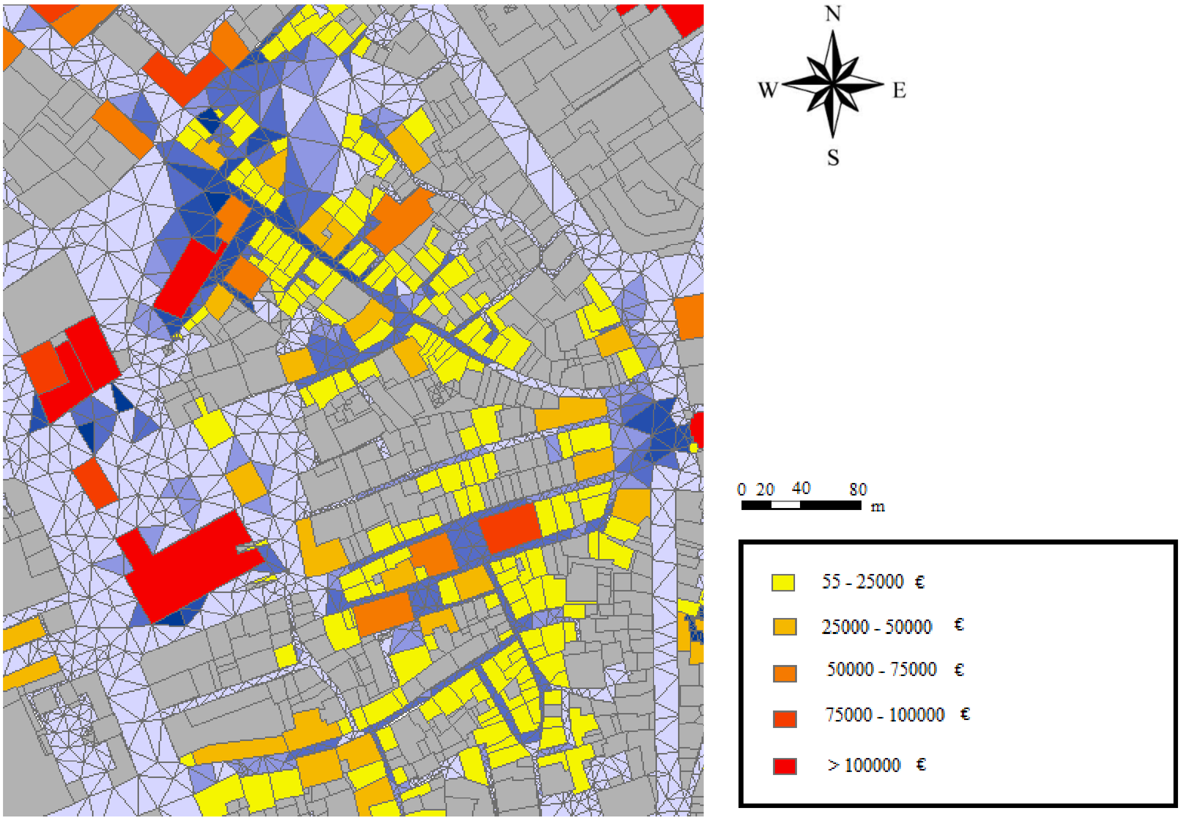


Figure 4.9 – Depth-damage flood risk map for a return period of 100 years, expressed in € per building

By analysing the resulting flood risk maps, a few remarks can be made: as expected (by having read others studies, like Leitão et al (2009) and Cançado et al (2008)), the higher the return period of a rainfall event is, the more monetary damages it causes on the building present in the catchment.

Since the water depth changes are not so accentuated, the classes of damage per building do not change because they stay in the same interval of cost per class: an example is shown below (Figure 4.13).

On the 100 years return period it is possible to see a substantial increase of costs in € per building, since the higher intensity of precipitation lead to higher water depths and consequently to more monetary losses. Another conclusion to be made is that, despite a building subjected to a high water depth, if its' area is small the cost associated to it is not high, since the depth-damage equation depends also of the building's area.

## 4.4 Flood risk maps for depth-velocity combination

The 1D/2D model, as stated before, allows the analysis of the velocity of the overland flow for a rainfall event. Therefore, maps of velocity per pond area of the mesh zone for the overland flow can be created: for that it was only needed to export the velocity parameter from Infoworks ICM to the software ArcGIS and the implementation of different coloured classes for lower to higher velocity values (light to deep blue, respectively). Below the maximum velocity per pond area maps for each return period are shown (Figure 4.10 and 4.11).

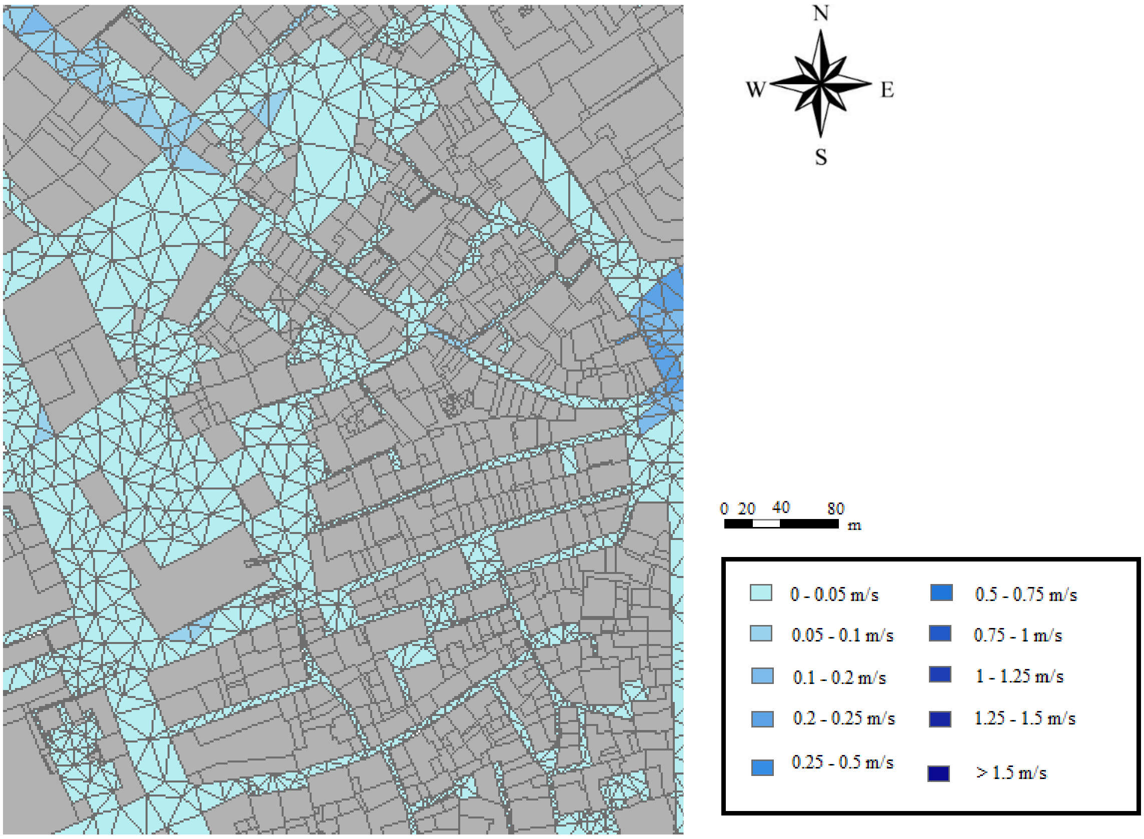


Figure 4.10 – Maximum velocity per pond area map for a return period of 20 years

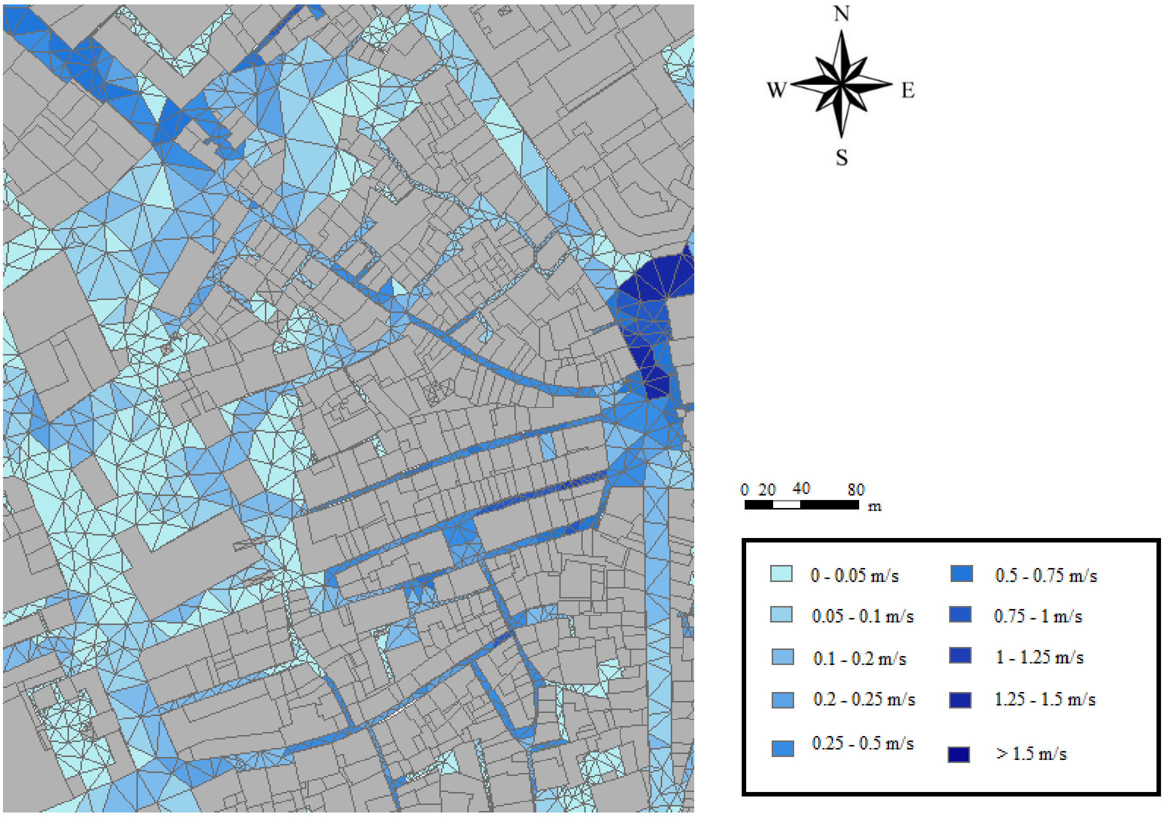


Figure 4.11 – Maximum velocity per pond area map for a return period of 100 years

As it was expected by viewing the orography of the zone in study, that velocity of the overland flow is the highest in the end of descending streets (in front of the bank Caixa Geral de Depósitos, near the Praça 8 de Maio) and in plain areas where the water from its' elevated surroundings flows to (at the end of the Rua Direita). As in the water depth maps, it is also clear the gradual rise of the velocity values along the three situations of rainfall events (20 and 100 years of return period).

By combining the floodable area and velocity per pond area maps and replacing the variables in the equations of depth-velocity risk that defined the intervals of classes of risk (Figure 3.6), three flood risk maps regarding the return period situations (20 and 100 years) were made.

It is important to note that the height and velocity represented in the maps above (Figure 4.3, 4.4, 4.10, and 4.11) are the values for the most unfavourable instant of the simulation, and so they are both related to the same instant (the 135 minute instant).

The 5 classes adopted went from Unaffected to High Hazard with light damage to infrastructures (grey to dark red). From the third risk level and above it is unsafe of pedestrians to walk in those areas, with the risk of falling and drowning, and vehicles start to become unstable to drive: the risk maps are displayed below (Figures 4.12 and 4.15).

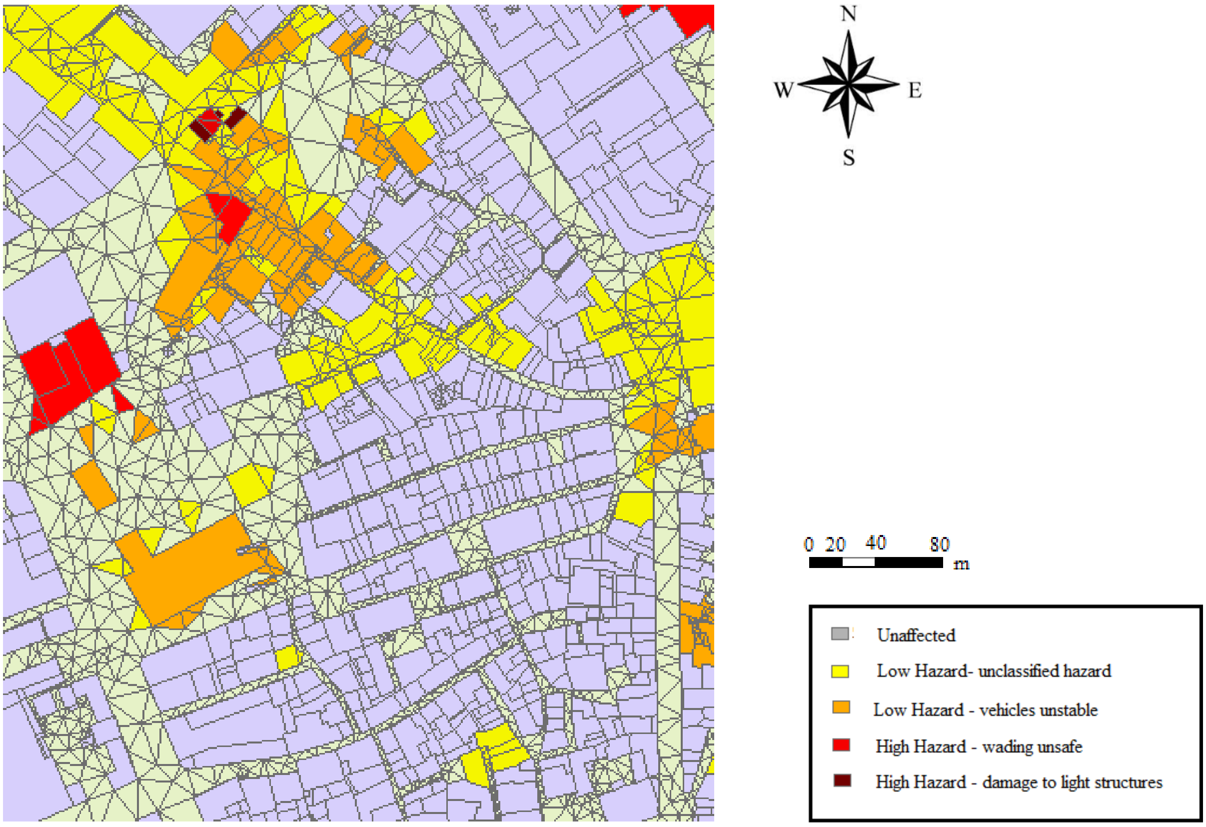


Figure 4.12 – Depth-velocity flood risk map for a return period of 20 years

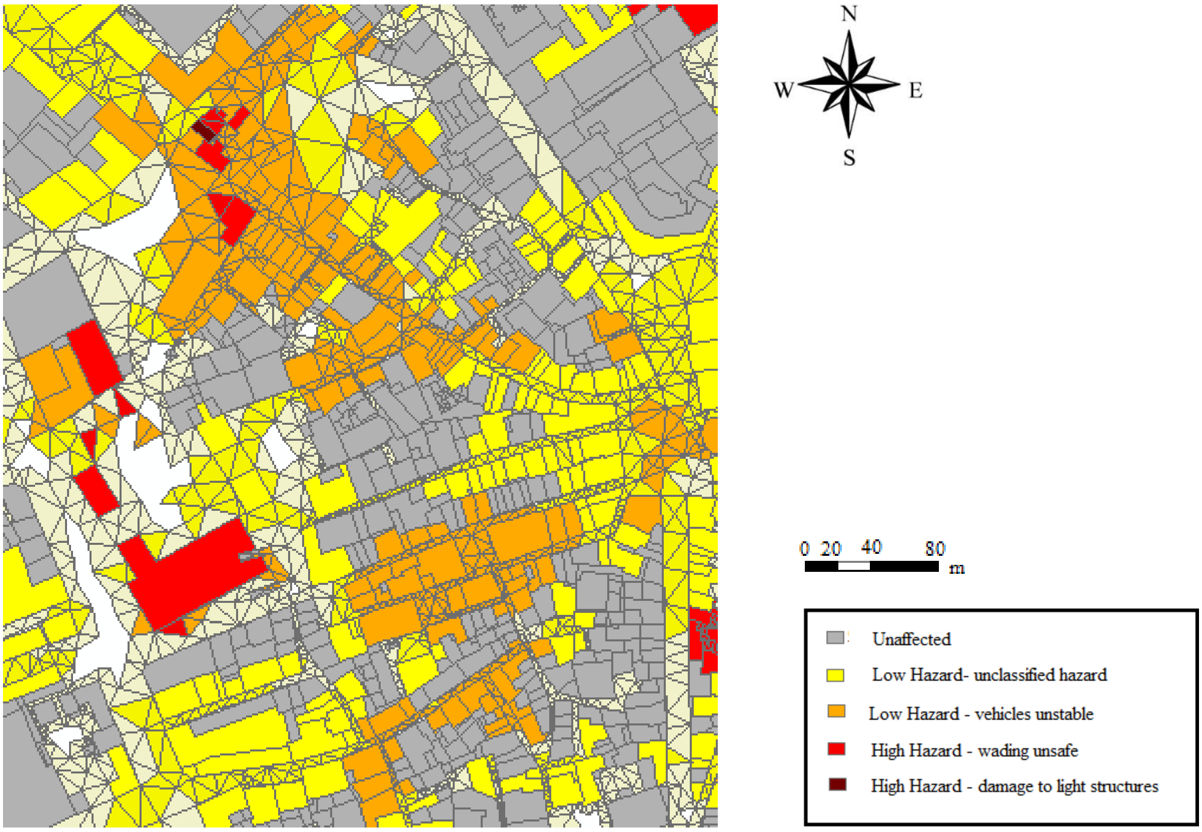


Figure 4.13 – Depth-velocity flood risk map for a return period of 100 years

By observing the three maps displayed above it is confirm what was expected by seeing the water depth and velocity maps: since the risk depends on these two parameters the two areas mentioned before (Rua Direita and Praça 8 de Maio), have some of the higher risk levels of the studied zone. Like the depth-damage risk maps, the difference in risk levels is much more significant in the transition from the rainfall event of 50 to 100 years of return period, due to the same facts stated before.

Passing to the flood impact maps, with the map of the bus lines of the city of Coimbra in mind (Figure 3.7), it is clear that there are only two streets, Rua da Sofia and Rua Visconde da Luz, where buses drive through, and one much more relevant that the other, because of the much higher number of bus lines that it involves (Rua da Sofia).With that in mind, calculations were made, by exporting the tables from ArcGIS to Excel and imported back to ArcGIS, to identify the areas where the stall situation occurred. The Figures below (4.14, 4.15 and 4.16) show the resulting maps for the rainfall situations described several times before:

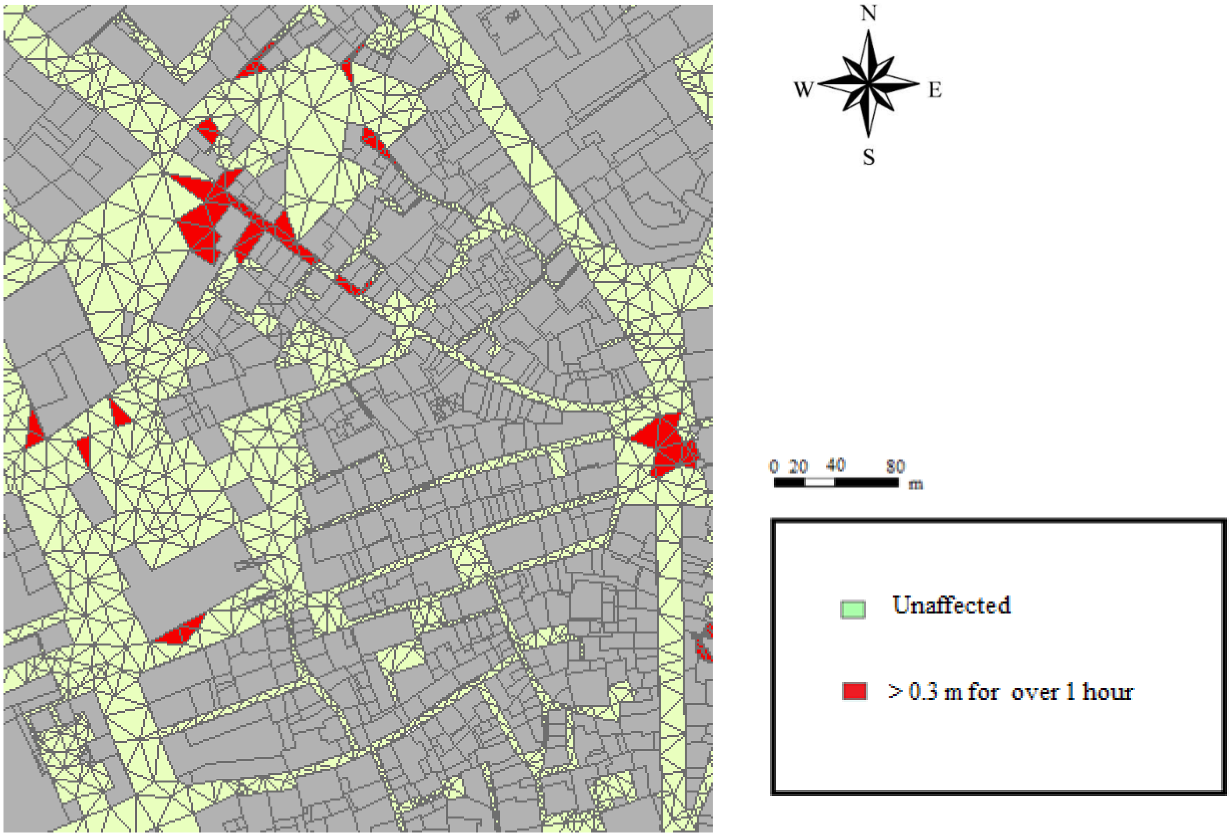


Figure 4.14 –Flood map for depths above 0.3 m for over 1 hour (return period of 20 years)

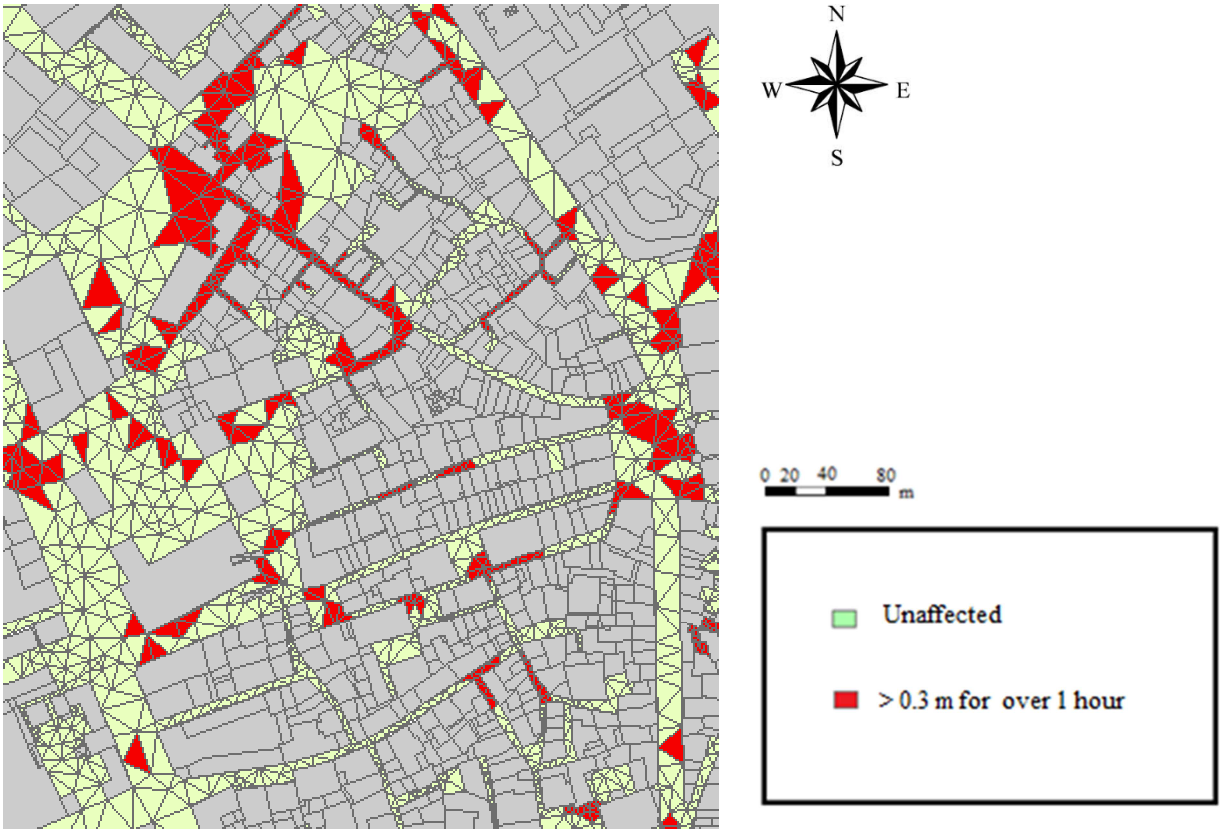


Figure 4.15 –Flood map for depths above 0.3 m for over 1 hour (return period of 100 years)

Figure 4.16 – Flood impact map towards the bus lines of the Zona Central catchment

It is visible that the Rua da Sofia only suffers from stalling of the bus lines in the rainfall event of 100 years of return: that’s because the water level and duration required for the situation to occur is difficult to attain (that water depth for the two other rainfall events is not high enough, or when it is, it does not stay above 0.3 meters for a whole hour). But with the stalling of the bus lines there is a serious negative impact towards the flow of traffic and the people riding the bus, with traffic delays occurring people arriving late at their destinations.

# 6 CONCLUSION

## 6.1 Concluding points

The cities growth through the urbanization of spaces and increase of extreme rainfall events through climate changes, have consequently led to a higher frequency of flood events. In this study a 1D/2D dual drainage model was used to perform computational simulations of rainfall events for different return periods, and with the results flood risk maps were created, in order to evaluate quantitatively the consequences of flood events.

The maps displayed are referred to an area of the Coimbra's urban catchment (the Zona Central of the Coimbra catchment) for rainfall events with return periods of 20 and 100 years. The return periods chosen represent an acceptable range of rainfall events that may occur in the catchment.

Three types of flood risk maps were created: depth-damage flood risk, depth-velocity flood risk, and flood impact on transports. Focusing on the first mentioned type of flood risk maps, it is possible to conclude that the monetary losses caused to buildings increase along with the value of the return period, as the probability of the rainfall event occurring decreases. It is also possible to visualise the areas where the water tends to accumulate.

Passing to the depth-velocity flood risk maps, where the risk associated to the flood events is displayed through classes of risk, it shows that there are concentrated areas with a high risk for pedestrians and vehicles even with rainfall events with lower return periods. The increase of risk is also evident, with some areas becoming unsafe to walk by and difficult to pass through in a vehicle.

The flood impact maps demonstrate that only for higher values of return period (100 years) are the bus lines affected by flood events, but nevertheless it involves a street where several lines pass through, and may cause traffic jams problems.

To sum up, the methodology adopted in this study demonstrated the importance of the elaboration of flood risk maps in growing urban cities, in order to prevent monetary losses and risk towards pedestrians and transports, caused by future flood events. It gave also a good insight on the fields of urban drainage, dual drainage and flood risk. This study may help the development of future studies in dual drainage modelling involving the 1D/2D model used.

## 6.2 Further Study

In the sequence of this study, further developments can be made within the field of flood risk map elaboration towards the quantification of the monetary losses in the remaining areas of the city of Coimbra, with the possibility of distinguishing the different occupation types of buildings in order to better use the depth-damage curves related to the types of buildings. Other depth-velocity risk curves could be used in order to make a comparison between the different approaches, and a more detailed analysis of the hazards caused by each risk class could show a more insightful view of the danger of flood events.

Another suggestion for future studies is the elaboration of the flood risk maps with more detailed dual drainage models which could provide more reliable results. A comparison between the results of rainfall events simulations in the case study area and the flood risk maps created by using the 1D/1D, 1D/2D and hybrid models could be made to demonstrate the differences in accuracy and reliability between the different types of models.

The impact upon transports and vehicles can also be more thoroughly studied by analysing the number of buses per day that pass through flooded areas, and quantifying the average number of people using that mean of transportation, that are affected by a flood event. Another aspect that may be studied is the combination between this study and prevention and mitigation measures of flood effects through the use of SUDS, by optimizing the localization of the SUDS through the quantification of construction costs and the level of risk reduction achieved.

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