1D/2D INTEGRATED MODELLING AND PERFORMANCE ASSESSMENT TO SUPPORT FLOODS MANAGEMENT. APPLICATION TO STORMWATER URBAN DRAINAGE SYSTEMS IN ESTUARINE AREAS.

Paula María García Beceiro

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Orientadores: Dra. Filipa Maria Santos Ferreira e Dra. Maria Adriana Canas Mendes de Almeida Cardoso

Júri

Presidente: Prof. António Alexandre Trigo Teixeira
Orientador: Dra. Maria Adriana Canas Mendes de Almeida Cardoso
Vogal: Prof. José Manuel de Saldanha Gonçalves Matos

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RESUMO

A ocorrência de inundações urbanas está associada a importantes impactos e efeitos negativos que requerem uma adequada avaliação, devendo ser consideradas as diversas consequências que lhes podem estar associadas.

A presente tese propõe uma metodologia fundamentada no desenvolvimento e utilização da modelação integrada 1D/2D e, posteriormente, a avaliação técnica de desempenho para o apoio à gestão de inundações em áreas estuarinas. A modelação integrada 1D/2D é desenvolvida com recurso à utilização combinada dos programas *Mike Flood* e *Mike Urban*, através da aplicação do modulo *Overland Flow*. A avaliação de desempenho em sistemas de águas pluviais é baseada na aplicação de indicadores de desempenho (PI) a partir da informação fornecida pela modelação 1D e 1D/2D. A avaliação de desempenho baseia-se nos PI propostos pela *International Water Association* (Matos *et al.*, 2003) para os serviços de águas residuais, sendo adaptados para a aplicação na gestão de inundações dos sistemas de águas pluviais, e em novos PI desenvolvidos com base nas capacidades da modelação (1D e 1D/2D). Na presente tese também se identificam as vantagens e desvantagens da utilização da informação obtida através da modelação 1D/2D em comparação com modelação 1D.

A metodologia foi testada e validada para o caso de estudo do Dafundo, onde o risco de ocorrência de inundações se foca na zona baixa da bacia. Foi identificado que as condições operacionais apresentam um impacto significativo na ocorrência inundações no sistema de drenagem de águas pluviais, sendo o seu efeito agravado devido aos elevados níveis de maré no estuário do Tejo.

Palavras-chave: sistema de drenagem pluvial, gestão de inundações, modelação integrada 1D/2D, avaliação de desempenho, áreas estuarinas.

ABSTRACT

Urban flooding occurrence has associated significant impacts and negative effects that require an adequate assessment, taking in consideration the different consequences that can be associated with them.

This thesis proposes a methodology based on the development and use of a 1D/2D integrated mathematical modelling and, subsequently, the application of the technical performance assessment to support the flood management in estuarine areas. The 1D/2D integrated mathematical modelling is developed using the combination of Mike Urban and Mike Flood software through the application of the Overland Flow tool. The performance assessment in stormwater systems is based on the application of performance indicators (PI) using the information provided by 1D and 1D/2D integrated modelling. The set of PI was based on those from the International Water Association (Matos *et al*., 2003) for wastewater services, applicable to flooding management of stormwater systems, and some new PI proposed based on the modelling (1D and 1D/2D) capabilities. It is also assessed the advantages and disadvantages of the use of information obtained by 1D/2D modelling in comparison to 1D modelling.

The methodology was tested and validated for the case of study of Dafundo where the risk of flooding occurrence is focused on the downtown area. It was possible to identify a significant impact of the operational conditions in the flooding occurrence related to stormwater drainage system, being aggravated for high tide levels on the Tagus estuary.

Keywords: stormwater drainage system, flood management, 1D/2D integrated modelling, performance assessment, estuarine areas.

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NOTATION

Symbol	Description	Units
A	flow area	m^2
A_c	superficial area	$m.s^{-2}$
A_I	cross-sectional areal o inlet	$m.s^{-2}$
A_m	cross-sectional area of manhole	$m.s^{-2}$
A_s	transversal area	$m.s^{-2}$
C	coefficient for the Rational Method	[-]
C_D	discharge coefficient	[-]
D	diameter of the pipe	m
g	acceleration of gravity	ms^{-2}
h	water depth	m
H_g	ground level at coupling	m
H_M	average water level on the ground	m
H_U	water level in sewer system	m
I_f	friction slope	-
I_{max}	maximum rainfall intensity	$mm.h^{-1}$
I_o	bottom slope	-
K_{xx}	eddy viscosity in the x direction	-
K_{yy}	eddy viscosity in the y direction	-
P_{tot}	accumulated rainfall	mm
Q	discharge	m^3s^{-1}
Q_U	flow from sewer to grid point	m^3s^{-1}
S	water surface elevation	m
S	scaling factor	m
T	return period	year
t	time	s
tc	concentration time	min
U	depth-averaged velocities in the x direction	$m.s^{-1}$
U_s	velocity at the source, in x direction	$m.s^{-1}$
v	average flow velocities in pipes	ms^{-2}
V	depth-averaged velocities in the y direction	$m.s^{-1}$
V_s	velocity at the source, in y direction	$m.s^{-1}$
W_{crest}	crest width	m
x	distance in the flow direction	m
y	flow depth	m
Zp	Pomeroy parameter	-
α	velocity distribution coefficient	-

1. INTRODUCTION

Climates change, population growth, public health and safety and sustainability are the main challenges that should be considered in the urban drainage systems functioning (Upadhyaya, 2013). The urban infrastructures should be adequate and improved in order to cope with the significant effects associated to these factors, looking for a sustainable management of the urban water.

The inadequate capacity of the stormwater drainage systems, that have not been designed taking into consideration all the interactions with the population growth and the climate change, promote frequent occurrence of flooding, especially in urban areas. Most modern cities usually experience small scale local problems mainly due to the insufficient capacity of the stormwater drainage systems during heavy rainfall events (Mark *et al*., 2004). Some of the world most highly populated cities are located in estuarine low-lying areas facing a high risk of inundation with a potential for significant economic costs. Urban flooding occurrence has associated significant negative impacts and effects that require an adequate assessment, taking in consideration the different consequences that can be associated. Public health and safety, structural, functional and social-economic and environmental consequences are frequently related to flooding occurrence in urban areas.

The Directive 2007/60/EC on the assessment and management of flood risks, entered into force on 26 November 2007, emphasizes the flooding and the associate problems that can be posed to the population. The purpose of this Directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the community (Directive 2007/60/EG, 2007).

The population growth and accelerated urban expansion in the last decades in Portugal have significantly increased, especially in rural areas, creating serious alterations in the natural water cycle and motivating the occurrence of threatening situations for the stable development of human habitat (Matos, 2003). The population growth increases the pressure on the urban infrastructures, particularly in stormwater system. The large increase of impervious areas and the artificialization of water courses in urban areas associated, according to Matos (2003) increase the surface runoff and the frequency of flooding occurrence due to the inadequate capacity of the stormwater drainage systems. Other problems associated of population growth and urban expansion are the discharges and the increase of pollution in the receiving water due to the uncontrolled discharges from weirs; the sub-dimension of the surface water inlets and the related occurrence of flooding, being the transport capacity of network system not fully used; and pluvial discharges on paved areas.

Potential effects of climate dynamics on the urban water cycle can involve the aggravation of existing conditions as well as the occurrence of new hazards or risk factors (Cardoso *et al*., 2013). According to Zhu (2014), the effect of climate change and urbanization are converging to challenges in city drainage infrastructures due to their adverse impacts in rainfall extremes events and the environment of urban areas. The climate alterations, characterized by the modification in the spatial and temporal variations of the rainfall events and the increase of frequency and intensity of extreme climatic conditions, represent an important factor that should be considered to evaluate the occurrence and consequences of flooding.

In estuarine areas, urban drainage systems are subject to particular climatological conditions, as consequence of the combined effects of high water levels due to tide and storm surge. The tide effects may aggravate the occurrence of flooding and the associated effects can be intensified by human actions and inadequate drainage conditions, which can cause sediments accumulation or obstruction in the sewers. In estuarine urban areas, the relation between the estuary and the drainage system is essential to evaluate the flooding process, being required to analyse the causes and effects of their occurrence (Cardoso *et. al*, 2015).

The mathematical modelling of the stormwater drainage systems represents a useful tool to evaluate the susceptibility to flooding in estuarine areas, identifying the potential measures to be applied in order to reduce the risk. The improvements of the mathematical modelling capabilities and the advances in the computer technology promote the use of modelling tools to assess the complex interaction between the rainfall events and the flooding occurrence, assessing the potential effects of flooding. The results obtained by mathematical modelling of stormwater systems provide a level of detail that benefits from being post processed, using the technical performance assessment in order to support diagnosis and decision making in the flood risk management.

Stormwater systems constitute one important part of the urban water infrastructures, which value represents a major part of all public infrastructures. These systems should be adequately managed and performance assessment constitutes an adequate methodology to support their management. However, currently, a performance indicator system directed for stormwater drainage systems has not still been developed. In the well-known PI systems developed and implemented for water supply and wastewater systems, e.g. by IWA (Matos *et al.,* 2003) and by ERSAR (Matos *et al.,* 2004), there are not specific PI focusing stormwater systems, although some PI may also be applicable.

The improvement of the 1D/2D integrated modelling allows to achieve a level of detail of flooding occurrence that represents a significant opportunity to developed a methodology based on the 1D/2D integrated modelling and performance assessment to support floods management. This represents a significant contribution to validate and developed new performance indicators suitable for the diagnosis, control and support for the management of flooding occurrences in stormwater drainage system.

Despite several studies related to flooding occurrence based on 1D mathematical modelling are developed to date, the incorporation of 2D surface runoff modelling in a 1D/2D integrated modelling represent a significant improvement and an opportunity to contribute in the assessment of flood management.

2. OBJECTIVES AND OUTLINE OF THE THESIS

The present study aims to contribute for the improvement of urban flood management in estuarine marginal areas through the application of a proposed methodology based on 1D/2D integrated modelling of stormwater drainage systems and their performance assessment. It is fundamental to analyse and identify the causes and consequences of flooding occurrences to achieve an effective and efficient management of the urban drainage systems. These systems, particularly the stormwater systems, located in estuarine marginal areas are subject to particular climatological conditions, as consequence of the combined effects of high water levels due to tide and storm surge. The objective of this thesis is thus to support the flood management through the use of 1D/2D integrated modelling and performance assessment of the stormwater drainage systems. The study intends to identify the advantages and disadvantages of the 1D/2D integrated modelling towards the 1D modelling and to assess the causes and consequences of flooding occurrence.

Performance assessment of urban drainage systems is oriented by the objectives established for the systems functioning. It is based on the definition of the criteria or points of view, that have to be evaluated in an integrated way, informing about the objectives compliance and thus supporting not only the systems diagnosis but also decision making on prioritization of interventions or selection of solutions. The performance assessment of stormwater drainage system is proposed to be carried out based on modelling results, both 1D and 1D/2D. An analysis of the advantages and disadvantages provided by the use of each modelling type for flood management is carried out.

The specific objectives of the thesis are to:

- Identify the main capabilities, advantages and disadvantages of the surface runoff and network modelling using 1D, 2D and 1D/2D models and carry out a comparative analysis between the referred modelling types;
- Describe the relevance of using the performance assessment of stormwater drainage system as a tool to support floods management in estuarine areas. The importance of data uncertainty and quality is also emphasized;
- Describe the proposed methodology based in the 1D and 1D/2D integrated modelling of stormwater systems and in the performance assessment using these modelling results;
- Validate the proposed methodology by its application to a selected case study.

The thesis is divided into 7 chapters. Chapter 1 presents an introduction to the subject and the relevance of the theme. In Chapter 2 the objectives and an outline of the present thesis are detailed. In Chapter 3 a general description of stormwater drainage systems is presented, including the classification of urban drainage system and of special devices.

Chapter 4 presents a review of literature on important aspects related to the stormwater drainage modelling, focusing in the different characteristics and capabilities of the surface runoff and network model for 1D, 2D and 1D/2D integrated modelling. Geographic Information Systems and hydraulic performance assessment are described.

Chapter 5 describes the proposed methodology for the 1D/2D integrated mathematical modelling and for performance assessment. The definition of the objectives, model building, characterization and simulation of the stormwater drainage system (1D network model, 2D runoff model and 1D/2D coupling) are described. A comparative analysis between the 1D and 1D/2D modelling results is also carried out. The proposed methodology includes the hydraulic performance assessment, focusing in the advantages and disadvantages of the use of 1D and 1D/2D modelling results.

Chapter 6 describes the application of the proposed methodology to the case of study of the Dafundo stormwater drainage system. The system was evaluated in function of the hydraulic and hydrologic scenarios. The specifications of the surface runoff model, network model and 1D/2D coupling are detailed and a comparative analysis between the 1D and 1D/2D modelling results is carried out.

Chapter 7 remarks the conclusions of the study developed, presents recommendations for the application of the proposed methodology and suggestions for future research.

3. GENERAL DESCRIPTION OF STORMWATER DRAINAGE SYSTEMS

The urban drainage systems, wastewater, stormwater and combined systems, are composed by a set of infrastructural assets, equipment and installations, that provide the functions of collection and transport of wastewater and stormwater. A general overview of these systems is presented. The selection of the type of system mainly depends on national or local water management policies, the type of water collected, possible future changes in the catchment or in the system, the characteristic and quality of receiving waters, the nature of influents to the system, the need to prior treatment, the topography, the soil and ground characteristics, the treatment plant, economic considerations and other local conditions (EN 752, 2008).

In Portugal, the wastewater and stormwater drainage systems are classified in four types that are described as follows, based in the General Regulation of Public System and Building Service of Water Distribution and Wastewater Drainage (Regulatory Decree n° 23/95, Art. 116, 1995):

- Separate systems: sewer systems composed by two networks, being one designed for the drainage of domestic, commercial and industrial wastewater, and the other for the drainage of stormwater runoff or similar.
- Combined systems: sewer systems that collect domestic, commercial and industrial wastewater as well as stormwater runoff in a single network.
- Mixed systems: systems that are a combination of the two previous types, in which part of the network functions as a combined system and the other as separate system.
- Partial separate or pseudo-separate system: these systems are accepted in exceptional conditions, where the connection of stormwater courtyards to the domestic wastewater system is allowed.

The different nature of the water effluent transported by each type of system is subject to specific conditions for treatment and for final disposal with the objective of minimising the impact of discharges on the environment. Table 1 presents the main objectives for each type of urban drainage systems.

In urban areas, separate stormwater systems are in charge of transporting runoff from pavements, buildings cover and impervious areas. In the design of stormwater systems, both separate or combined systems, the high variability of the discharge is an important factor due to the rainfall events characteristics in terms of spatial and temporal distribution. The peak flows in stormwater systems are significantly higher when compared with the domestic flows, and it is required to take into account the use of the land and soil occupation. An improperly stormwater drainage may cause disturbances, damages, flooding and threatening health increasing risks.

Table 1 – Main objectives for each type of urban drainage systems (adapted from Duarte (2014))

System type	System type	Description	Flow conditions
Wastewater separate systems	Drainage systems with conventional sewers	Systems designed to transport domestic, commercial and industrial wastewater to treatment plants. Certainly, infiltrations and stormwater also transported through these sewers due to anomalies or undue connections.	Most part of sewer are in free surface; Pumping pipes are pressurized.
	Pressurized drainage systems of small diameters	Pressurized systems used when it becomes technically and economically unfeasible or unfavourable to use gravitational solutions with free surface flow.	Pressure flow, usually from manholes for the laterals using small diameter tubing.
	Vacuum drainage systems	The transport is biphasic (air and water) is ensured by conditions of under pressure in the pipes. In the vacuum drainage system, the risks of occurrence of septicity conditions is reduced and the infiltration is controlled..	Pressurized drainage, using vacuum drainage systems
Stormwater separate systems	Drainage systems with conventional sewers	Systems where water is transported resulting from rainfall on pavements, buildings coverage and impervious areas in urban environment. Domestic wastewater is not allowed although there are often undue connections.	Free surface flow, unusually pressurized.
Combined systems	Drainage systems with conventional sewers	Domestic, industrial and commercial wastewater and stormwater are transported by the same pipe. Currently, this type of solution is not allowed for new systems.	Free surface flow, unusually pressurized.
Partial separate or pseudo-separate system	Drainage systems with conventional sewers	These systems are accepted in exceptional conditions, where the connection of stormwater courtyards to the domestic wastewater system is allowed. Currently, this type of solution is not allowed for new systems.	Free surface flow, unusually pressurized.

Urban stormwater is characterized by high pollution levels, containing several substances such as heavy metals, hydrocarbons, suspended solids and organic matter. Numerous studies over the last twenty years have shown that urban stormwater can be heavily contaminated with a variety of polluting substances. These materials are incorporate into the drainage system from atmospheric sources and as a washed or eroded result from urban surfaces. In certain respects, stormwater can be as polluting as wastewater (Butler and Davies, 2004). The appropriate transport and treatment is an important aspect in the design, construction and maintenance of a stormwater drainage system.

Separate stormwater systems are constituted by a sewer network and additional devices, and, in some cases, special devices and installations can be incorporated. The sewer network is constituted by a set of pipes that ensure the runoff transport since the surface water inlets or manholes until the receiving water body.

The additional devices used in the stormwater drainage system are described (EN 752, 2008; Regulatory Decree n° 23/95, 1995) as follows:

- Manholes: chamber with a removable cover constructed on sewer to permit the access by personnel in the operation of inspection, cleaning and maintenance. The location of a manhole is required at the confluence of sewers, in sewer points of changes of direction, slope or diameter, and in straight line sewers, with a maximum distance of 60 or 100 m, respectively in function of the sewer man-entry allowance or not.
- Surface water inlets: theses inlets shall be designed in order to ensure an adequate transfer of runoff from impervious areas into the sewers, being located at lower points and in the intersection of public roads. The existing surface water inlets are the gullies, where the flow entry is carried out by the lateral or by the top and is located on the pavement surface.

The sewer system may have special devices or installations, the most common are referred as follow (Matos, 2003):

- Gully: auxiliary installations destined to promote the deposition of the sediment transported by the stormwater.
- Detention pounds: basin that regularizes the stormwater peak flows, discharging downstream flows compatible with the transport capacity of the drainage system.
- Infiltration chambers: devices promoting retention and infiltration of stormwater: This type of device can be incorporated in conventional sewers (buried sewer networks).
- Pumping systems: implementation of pumping stations should be avoided if possible due to the operation costs, the variability of influents flows, and the difficulties associated to maintain the optimum working conditions of the pumps equipment and in the pressurized conduit.

A stormwater drainage system must take into consideration any changes in flows over its design life ensuring that the system maintain the objectives and performance criteria compliance over its design life (CEN, 2008). The sewer pipes are usually designed to run full, without surcharge, for relatively frequent storms, providing protection against flooding from much larger storms, as is detailed in the Art. 8.4.3.3 of the EN 752 (CEN, 2008) standard. The recommended design and flood frequencies for stormwater drainage system are showed in Table 2.

Table 2 – Recommended design storm and flood frequencies (adapted from EN 752 (CEN, 2008))

Location	Design storm frequency (1 in “ ” years)	Design flood frequency (1 in “ ” years)
Rural areas	1 in 1	1 in 10
Residential areas	1 in 2	1 in 20
City centres /industrial / commercial areas	1 in 5	1 in 30
Underground railway / underpasses	1 in 10	1 in 50

In sensitive location, where public health or environmental risks are significant and a more complex method is required for drainage system design, the European Standard EN 752 requires to consider design flood frequencies.

4. LITERATURE REVIEW

4.1. INTRODUCTION

Population growth and the accelerated urban expansion in the last decades in Portugal have carried out significant changes in the natural hydrologic cycle, mainly due to the urbanization of rural areas, large increase of impervious areas and the artificialization of water courses in urban areas. The inadequate capacity of the stormwater drainage systems, which have not been designed taking in consideration the interaction with the population growth, promote the frequent occurrence of flooding, especially in urban areas. Most modern cities usually experience small scale local problems mainly due to the insufficient capacity of the stormwater drainage systems during heavy rainfall events (Mark *et al*., 2004).

The climate change occurred since the construction of most stormwater drainage systems, has aggravated the frequency of surcharge and flooding situations in sewers, being a recurrent situation in urban areas due to the combined effect of extreme rainfall events and insufficient drainage conditions. The climate alterations, characterized by the modification in the spatial and temporal variations of the rainfall events and the variation in the frequency and intensity of the extreme climatic conditions, represent an important factor that should be considered to evaluate the occurrence and consequences of flooding.

The urban drainage systems in estuarine areas are subject to particular climatological conditions, as consequence of the combined effects of high water levels due to tide and storm surge. The tide effects may aggravate the occurrence of flooding and the associated effects may be intensified by human actions and inadequate drainage conditions, which can cause sediments accumulation or obstruction in the sewers. In estuarine urban areas, the relation between the estuary and the drainage system is essential to evaluate the flooding process, being required to analyse the causes and effects of their occurrence (Cardoso *et. al*, 2015).

The negative impacts and effects of flooding occurrences require an adequate analysis and assessment in order to forecast and mitigate their consequences in urban areas, characterized by high population density and the presence of numerous infrastructures. Consequences of urban flooding can be divided into the categories that are described below, following the definition established in the project PREPARED for the Water Cycle Safety Planning regarding climate change (Cardoso *et al.* 2013).

- Public Health and safety, caused by flooding or other damages such as public streets or service interruptions;
- Structural consequences, which can affect the good performance of the system;
- Social-economic, as decrease of properties values or economic development, and negative long term effects associated with psychological consequences;
- Environmental consequences, such as the pollutant discharges to the receiving water.

Urban flooding may create considerable infrastructure problems and huge economic losses in term of production, as well as significant damage to property and goods (Mark *et al*. 2014). The mathematical modelling of the stormwater drainage systems represents a useful tool to evaluate the susceptibility to flooding and identify the potential measures in order to reduce the risk in estuarine areas. The advances in the computer technology have being promoting the use of mathematical modelling to assess the complex interaction between the rainfall events and the flooding occurrence, assessing the potential effects of flooding.

Over the last decades, the modelling software capabilities have been widely enhanced, especially through the facilities due to the advances in spatial data management and analysis tool of the geographic information system (GIS) that have been implemented in several software packages. The GIS combined with appropriate methodologies can represent an excellent tool in planning, decision making and flood management and control (Santos, 2015).

GIS are successfully used to visualize the flooding extension and also to estimate flood damage and risk, based on the development of maps (Demir, 2016). GIS were often used in the pre-processing of data to be incorporated in mathematical models. Nowadays, with the requirement of a more realistic overland modelling GIS is constituting an indispensable tool in the modelling and post-process phases, providing the opportunities of a real time forecast of flooding and the development of flooding risk maps. Terrain representation is increasingly used as input for overland flow model applications, such as 1D overland flow network delineation, 2D representation of surface runoff and in dual-drainage models (Johnson, 2009). The good quality of a Digital Elevation Model (DEM) is of paramount importance to perform advanced overland runoff analyses, such as urban pluvial flooding simulations (Leitão *et al.*2012).

In the urban drainage systems, performance evaluation is a widely used management tool and gradually more useful in the infrastructures asset management, particularly in planning the rehabilitation, operation and maintenance of the systems (Duarte, 2014). The technical performance assessment, based on performance indicators and indices, provides a systematic procedure to measure the system performance from the relevant points of view, under different loads and operation conditions (Alegre, 2008). The results obtained by mathematical modelling of stormwater systems provide a level of detail that benefits from being post processed, using the technical performance assessment in order to support diagnosis and decision making in the flood risk management.

4.2. STORMWATER DRAINAGE SYSTEMS MODELLING

A mathematical model can be used to simulate, reproducing the real behaviour of a drainage system or a system intervention solution, or to forecast, estimating future scenarios. The level of simplification adopted in a mathematical model depends on several factors, mainly the modelling objective and scope, the required and available data and the loading conditions of the system (Almeida and Cardoso, 2010). The simplifications adopted in the data, network and structures of the drainage system on study must guarantee the reproduction of the real system condition and functioning.

The modelling process is divided in several phases in which specific requirements must be respected. In figure 1 the phases in a mathematical model construction of a drainage system are detailed:

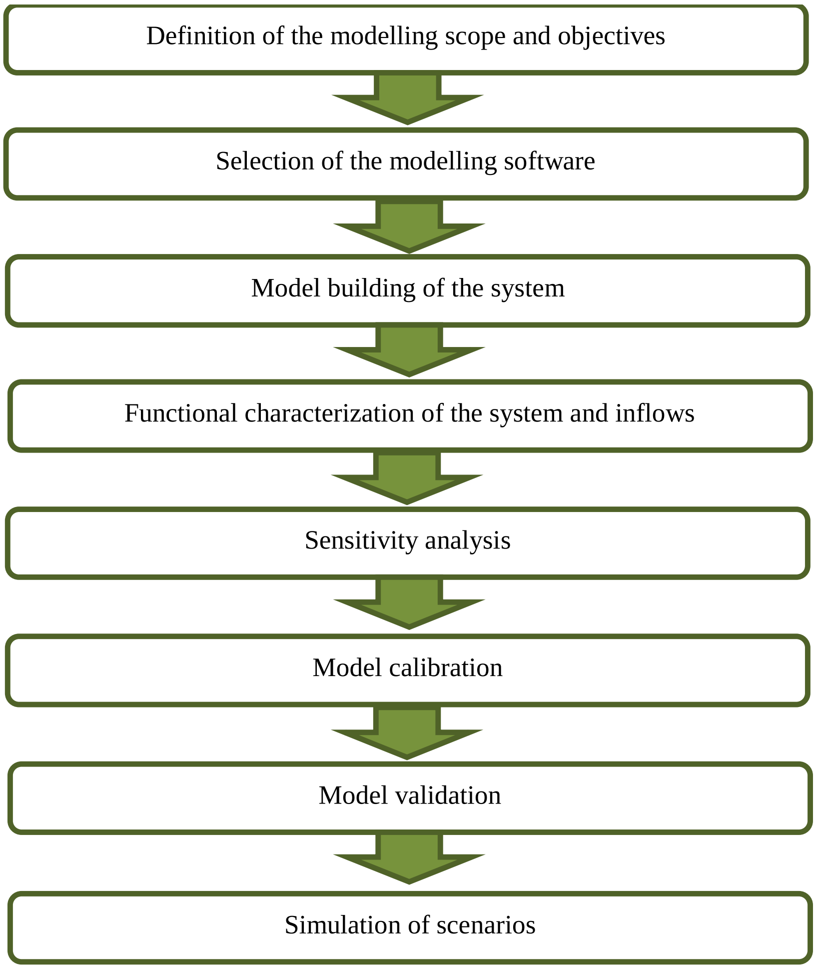


Figure 1 – Phases of mathematical modelling (adapted from Almeida and Cardoso, 2010)

A specific knowledge and experience in hydraulic of urban drainage networks and in urban hydrology, a sensitive perception of the variables involved in the process, are required for the adequate application of mathematical modelling in stormwater drainage systems.

Currently, several types of mathematical models are available to analyse the behaviour of the stormwater drainage system and the occurrence of flooding, being commonly classified in 1D and 1D/2D models. The main difference is based on the surface runoff modelling and the flow interaction between the hydrological and the network model.

The overflow modelling, which describes the flow interactions between the terrain surface and the drainage network, is an important issue integrated in the 1D/2D modelling, however, before the selection of the model it must be considered the significant requirements of input data (e.g. GIS data, Digital Elevation Model) and the high computational cost associated.

The mathematical models used for urban drainage system can be classified in the following types, according to Henonin *et al.* (2010):

- Catchment hydrological model
  These models are usually based on hydrological equations and the runoff is computed from the rainfall based on the catchment characteristics. The hydrological models are mostly conceptual models which depend on empirical parameters, being required the calibration from field measurements. The runoff hydrological model does not reproduce the runoff hydrodynamic behaviour and is basically used as input for the network model.
- 1D model – drainage network 1D model
  The model solves the Saint-Venant one-dimensional flow equation to simulate the behaviour of the flow in a drainage network, including complex devices such as pump, gates, among others. The model boundaries are usually the catchment runoff and the dry weather flow at the inlets and the water level at the outlets. Overland flow is not modelled using a drainage network 1D model. The excess of water is virtually stored and the flood depths in the inlets are overestimated. The quality of the model depends on the quality of input data and the calibration phase.
- 1D/1D model – drainage network 1D model coupled to 1D surface model
  The model is essentially a coupling between a 1D network system model and a 1D representation of the surface flow paths, usually the streets. The surface modelling is performed through a 1D hydrodynamic flow model of the streets with a storage function (Mark *et al*. 2004). The computed runoff can be distributed either directly into the drainage system or on the surface network, depending of the local framework. The exchange between the two networks is handled through coupling links, usually located at manholes.
- 1D/2D model – drainage network 1D model coupled to 2D surface model
  The flow in the network system is modelled in 1D and the surface flow is computed with a 2D engine solving the Saint-Venant 2D flow equations. The 2D model reproduces accurately the urban surface topography, including buildings, ponds, various structures, etc. The hydrodynamic flow computation with the 2D surface model allows the calculation of flow velocities with 2-directions components, among others variables. The overland flow models are able to describe the conditions in the surcharged drainage networks and the flooded area. The interaction of hydrology with the pipe network is modelled through flow exchange at identified linking points and segments through the two systems. The exchanges between the network system and the surface are still handled through coupling links as for the 1D/1D coupling, but the nodes of the collection system network are connected to cells of the 2D surface model.

The 1D/1D coupled models represent the first approach of the dual drainage concept, however, this can be a time-consuming procedure that requires a good knowledge of the overland flow pattern of the modelled area during intense rainfall events and can be carried out significant uncertainties associated the characterization of the storage nodes (Leitão, 2009).

Data requirements of a mathematical model are significant and should be complemented with field work to define and characterize the magnitude and relevant characteristics of the system (Almeida and Cardoso, 2010). There is a wide variety of software suitable for the mathematical modelling of stormwater drainage system such as SWMM, Mike Urban, Mike Flood, Info Sewer, Sewer Cad, among others. In the selection of the modelling software should be considered the aspects which are described as follows (Almeida and Cardoso, 2010):

- Modelling environment;
- Type of hydraulic simulation engine;
- Basic capabilities of the hydraulic simulation engine;
- Compatibility with the Geographic Information Systems;
- Easy connection with other Information Systems,
- Software support;
- Simulation engine compatibility with other engines in case of simulator change;
- Prices of acquisition, technical assistance and update to new versions.

4.2.1. 1D Modelling

4.2.1.1. Network modelling

The unsteady flow in open-channel is represented by the Saint Venant equations for the continuity and momentum (Quintela, 2005). The Saint Venant equations in drainage systems are adequate in situations where the following assumptions are appropriate:

- The pressure distribution is hydrostatic;
- The sewer bed slope is so small that flow depth measured vertically is almost the same as that normal to the bed;
- The velocity distribution at a channel cross-section is uniform;
- The channel is prismatic;
- Friction losses estimated by steady flow equations are valid in unsteady flow;
- Lateral flow is negligible.

The Saint-Venant one-dimensional flow equations, considering the previous assumptions, are represented as follows:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + v\,\frac{\partial\left(\alpha\,\frac{Q^2}{A}\right)}{\partial x} + gA\frac{\delta y}{\delta x} + g\,AI_f = g\,AI_0 \tag{2}$$

Where:

- Q: discharge [m3s^{-1}];
- A: flow area [m2];
- y: flow depth [m];
- g: acceleration of gravity [ms^{-2}];
- x: distance in the flow direction [m];
- t: time [s];
- α: velocity distribution coefficient [-];
- I_o: bottom slope [-];
- I_f: friction slope [-].

The Saint Venant equations are nonlinear hyperbolic partial differential equations and must be solved by numerical methods, being the analytical solution only possible in special cases. The high computational time required promotes the use of approaches models of the momentum equation, when the limitations of each approximation are respected. In many cases in urban drainage modelling, some terms of the momentum conservation equation of the Saint Venant equations can be neglected without a significant impact on model accuracy.

The kinematic wave, diffusive wave and dynamic wave models, in which the full dynamic description is considered, available for the urban drainage modelling are described in the following sections.

Kinematic wave model

The pressure gradient and the inertial terms are neglected in the kinematic wave approximation, being only considered the gravity and friction terms of the momentum equation. The model only allows the wave propagation to downstream, as the diffusive model. The kinematic approximation only can be used when the flow is independent of the downstream conditions (supercritical flow, Fr>1) or when the affluent hygrograms present sudden variation along the time, due to the inertial term must be considered.

The flow conditions in the partly full pipelines are mainly established by the balance between gravity forces and friction forces, the inertia and pressure terms in the momentum equations are less dominant. Accelerations are reasonably smalls and the flow is almost uniform, so the kinematic wave approximation is a reasonable approach (DHI, 2014).

The analysis of the characteristics of the kinematic wave approximation reveals that an improper use can carried out to incorrect results due to an unrealistic deformation of the propagation wave.

Diffusive wave model

The diffusive wave model considers the continuity equation and the momentum equation without the inertial terms, the local and convective acceleration. The storage, calculated through the continuity equation, and the wave delay due to the gravity and friction terms are considered in this approximation. The pressure gradient allows also represent the wave attenuation.

This approximation allows modelling the backwater due to the delay of the wave and attenuations deformations effects, despites the flow is only propagate to downstream. The results obtained through the diffusive wave are almost identical of the dynamic approach for supercritical flows, since there the hygrogram present slow variations.

Dynamic wave model

In this model the full momentum equation of the Saint Venant is considered, including all forces that affects the flow conditions. In this model the effects of storage of the continuity equation, the hydrodynamic effects of delay, attenuation and deformation in the discharge and the water depth variations, along the flow direction and the time, are considered.

This is the unique model that represents the wave propagation to upstream and downstream due to the local acceleration of the Saint Venant equations is considered, simulating the inverse flow and sudden variations of the hygrograms.

Summary

The dynamic wave description is applicable to be used in all cases, however, is recommended consider the application of the kinematic or diffusive wave models if the restrictions are satisfied due to the high computational load associated. The diffusive and kinematic wave approximations are simplifications of the fully dynamic descriptions that improve the computational efficiency but should only use when the omitted term have insignificant influence. A solid understanding of the influence of the different terms of the momentum equation is required to select the simplified model in order to achieve an adequate sewer flow modelling (DHI, 2014).

In table 3 the description and capabilities of models are presented.

Table 3 – Simplification and capabilities of the models

Model	**Terms of the momentum equation considered**	**Capabilities**
Kinematic wave	▪ Models only the bed friction and gravity forces.	▪ Adequate to simulate uniform flow and steady conditions; ▪ Does not simulate the influence of downstream conditions; ▪ Does not simulate backwater effects.
Diffusive wave	▪ Models only the bed friction, gravity forces and the hydrostatic gradient terms.	▪ Simulates the influence of downstream conditions; ▪ Simulates backwater effects, wave attenuation and surcharge condition.
Dynamic wave	▪ Uses the full momentum equation, including the acceleration forces.	▪ Adequate to simulate significant influence of downstream conditions; ▪ Adequate to simulate transient effects; ▪ Adequate to simulate significant changes in the inertia over time and space.

4.2.1.2. Surface runoff modelling

A significant knowledge of the runoff modelling and computation is required for the selection and development of surface runoff models, taking special attention on specific data and on definition of parameters required in each model type. The selection of a surface runoff model may imply significant differences in the computed runoff, being essential to take into consideration the following detailed aspects (Walsky *et al.*, 2007):

- Nature of the problem;
- Status of the system (existing or planned);
- Type of system (combined or separate);
- Availability of flow monitoring and rainfall data;
- Knowledge level of the modeller regarding the various methods;
- Available resources for the study.

The available methods for surface runoff computation used in urban drainage modelling are briefly described as follows, according to Butler and Davies (2004).

Kinematic wave or non-linear reservoir method

The non-linear reservoir method is based on the kinematic wave approximation of the Saint Venant equations. The surface runoff is simulated as a flow in an open channel, considering only the gravitational and friction forces of equation (2). Runoff is controlled by the several hydrological losses and by the dimension of the contributing area. The shape of the hydrograph depends on the length, slope and surface roughness of the catchment and the flow is obtained by the Manning-Strickler equation.

Linear reservoir method

This model considers that the catchment surface acts on the flow generated by an effective rainfall in analogy with one or more reservoirs connected in series. The storage volume is proportional to the flow rate in each downstream section. The model is based in the continuity and storage equations. The Nash model is based in the linear reservoir model and proposes that the overland process could be represented as a series of identical linear reservoirs, where the output from one reservoir is considered as the input to a second, and so on. This model can be applied in catchments of high dimensions (Ferreira, 2006).

Unit hydrograph model

The unit hydrograph is a widely used conceptual model in hydrology. It is based on the premise that a unique and time-variant hydrograph results from the effective rain falling over a particular catchment. The hydrograph can be used to construct the hydrograph response to any rainfall event based in the three principles: i) the time base of the unit hydrograph is constant; ii) the runoff flow-rate is directly proportional to the rainfall intensity; and iii) the response to successive effective rainfall events may be obtained by the aggregation of the individual runoff hydrograph starting at the corresponding times.

The unit hydrograph is calculated for each catchment based in the monitoring data, being usually used the simplified triangular form of the Dimensionless Unitary Hydrograph (DUH) presented by the U.S. Soil conservation Service (SCS). This hydrograph has a fixed geometry, defined in function of the peak of the flow rate and the duration of the rising phase of the hydrograph (Ferreira, 2006).

Time-area method

This model describes the evolution along the time of the catchment that contributes to the flow in the downstream section. The time-area curve area defined between the beginning of the rainfall event and the concentration time of the catchment, when the whole catchment is contributing to the runoff.

The runoff amount depends on the initial loss, the contributing area dimension and by the continuous hydrological loss. The shape of the runoff hydrograph is defined through the concentration time (t_c) and the time-area curve, which is selected in function of the catchment shape, rectangular, divergent or convergent (DHI, 2014).

4.2.1.3. Overland

The interaction between the drainage network and the overland flow is not considered in the 1D network modelling, being not suitable to analyse and asses the occurrence of flooding in urban areas, as is referred in 4.1. The traditional 1D urban drainage models should be used when the drainage capacity of the sewers is adequate, or in order carry out a first approach to localize and estimate the surcharged or flooding conditions in the area of study.

The manholes or surface water inlets (inlets) information about the surcharge conditions, water depth estimations of the exceeded flow, can be useful to get a first approximation of the affected network area in terms of surcharge and flooding conditions, to carried out qualitative assessments of the severity of the problem and intervention solutions response.

In the 1D modelling, when the flow into a junction exceeds the system capacity to transport it further downstream, usually the excess volume overflows the system and is lost. Modelling software may incorporate several options to take in consideration this situation through the virtual storage of the water volume. In the modelling software, the computation of the excess volume in the sewer system in case of insufficient drainage capacity is usually computed through the selection of the hydrodynamic simplified model.

For example, in the software SWMM (Storm Water Management Model) developed by the United Sates Environmental Protection Agency (USEPA), when the kinematic wave flow model is selected, the excess volume is stored in the junction and reintroduced into the system as long as the capacity permits. In case of selection of the dynamic wave routing, the water depths are maintained at nodes, and the excess volume is assumed to pond over the node with a constant surface area, being defined the surface area as an input parameter for each modelling junction (EPA, 2015).

The overland flow computed using the virtual storage overestimates the flood depth at the inlets because the attenuation effect and ponding in the terrain surface are not considered, according to Henonin *et al.* (2010).

A fist approach of the dual concept used in the 1D/2D modelling was the drainage network 1D model coupled to 1D surface model, which represented an important advance in the overland modelling process. The 1D/1D models improve the overland capabilities in the 1D model, however only represent an adequate approach in case of confined overland flow patterns (Leitão, 2009).

A methodology for simulation for urban flooding 1D/1D modelling was carried out by Mark *et al.* (2004), in which the urban drainage was carried out by two networks, one representing the free surface flow in the streets and one for the pipe network. This study shows that the 1D/1D is an adequate method in confined flow conditions, the surface flow in streets can be approximated using rectangular channels, and the potential limitations associated are the lack of representation of the pervious area.

4.2.2. 2D Modelling

4.2.2.1. Surface runoff modelling

The surface runoff modelling in the 1D/2D coupled model in urban drainage system is computed using 2D Saint Venant equations for the shallow water. The system of 2D shallow-water equations consists in a continuity equation and two equations for the conservation of momentum (Vojinovik *et al*., 2009). The general equations, which represent the hydrodynamic flow in shallow water, are described as follows:

$$\frac{\partial s}{\partial t}+\frac{\partial A}{\partial x}Uh+\frac{\partial A}{\partial x}Vh=0 \tag{3}$$

$$\frac{\partial U}{\partial t}+U\,\frac{\partial U}{\partial x}+V\,\frac{\partial U}{\partial x}+g\,\frac{\delta s}{\delta x}+\frac{g}{C^2 d}U\sqrt{U^2+V^2}+\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial U}{\partial y}\right)=F_s U_s \tag{4}$$

$$\frac{\partial V}{\partial t}+U\,\frac{\partial V}{\partial x}+V\,\frac{\partial V}{\partial x}+g\,\frac{\delta s}{\delta y}+\frac{g}{C^2 d}V\sqrt{U^2+V^2}+\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial x}\left(K_{yy}\frac{\partial V}{\partial x}\right)=F_s V_s \tag{5}$$

Where:

- S: water surface elevation [m];
- U: depth-averaged velocities in the x direction [m.s-1];
- V: depth-averaged velocities in the y direction [m.s-1];
- K_{xx}: eddy viscosity in the x direction [-];
- K_{yy}: eddy viscosity in the y direction [-];
- U_s: velocity at the source, in x direction [m.s-1];
- V_s: velocity at source, in y direction [m.s-1].

In the modelling software, the shallow water equations are discretized for the numerical method application, being the volume control used defined by the cell size. The surface model simulates vertically integrated two dimensional unsteady flows given the relevant boundary conditions and bathymetry, as provided by a digital terrain model of the catchment area (DHI, 2014). The hydrodynamic flow computation with 2D surface model allows to calculate the 2 directions components of the flow velocity and the water level in each one of the cells of the urban area discretization.

4.2.3. 1D/2D Modelling

The coupled model between 1D network model and 2D surface runoff modelling represents a significant improvement in the overland flow modelling due to the incorporation a detailed representation of the terrain and the existing features (e.g. buildings, walls) that controls the hydraulic dynamic in urban environments. The simulation process in the case of coupled 1D/2D modelling is slightly complex and computationally very demanding. The main factor that provided the improvement of the application of the dual-drainage concept, 1D/1D or 1D/2D models, has been the high development of Geographic Information Systems (Leitão, 2009).

In the coupled 1D/2D models, the network flow is modelled applying the 1D Saint Venant equations and available approximations (kinematic wave, diffusive and dynamic wave), described in 4.2.1.1, and the surface runoff is modelled applying the 2D Saint Venant equation. The 1D network and 2D surface runoff models are coupled through the inlets of the sewer system (manhole or surface water inlets) and the 2D surface elements, being the flow interactions carried out in these components. The coupling of the shallow water equation model of the surface flow with the dynamic network flow model is a crucial step in from a mathematical point of view (Smith, 2004).

The 1D/2D models are based on the division of the surface in small individual elements, denominated as cells. Each element should have associated information such as elevation, cover type, soil properties and roughness coefficient. The simulation method consists in the application of the flow equation to each element or mesh node, such as the Saint Venant equation or one of its simplifications (Leitão, 2009)

In the available 1D/2D modelling software, the computation and requirements to define and to characterize the flow interaction between the 2D hydrological model and the 1D network model are slightly different from the other models. In figure 2 the flow interactions between the network and the surface model considered in 1D/2D models are represented.

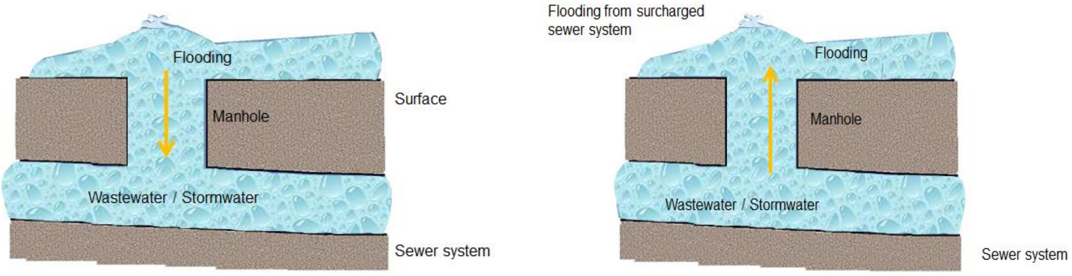


Figure 2– Simplified representation of the water exchanges in 1D/2D models

In the modelling software Mike Flood, developed by DHI, the 1D/2D urban drainage model must be handled through the definition of the urban links. The urban link is designed to describe the interaction of water when a manhole is overtopped or when overland flow enters a network. This link may be used for network outlets within the overland topography and where the system is discharging into the surrounding area through a pump or over a weir.

In table 4 the available functions in the Mike Flood software to model the exchange of water at the inlet is described. The weir equation application depends on the existing flooding in the surface and calculates the flow exchange between the surface and the network such as free weir or submerged weir, respectively.

Table 4 – Link water exchanges methods available in Mike Flood (DHI, 2014)

Method	Equations	Variables
Orifice equation	$Q_U = sign(H_U - H_M)C_D Min(A_m, A_I)\sqrt{2g\lvert H_U - H_M\rvert}$ For $\lvert Q_{UM}\rvert < Q_{max}$	▪ Q_U: flow from sewer to grid point ▪ H_U: water level in sewer system ▪ H_M: average water level on the ground ▪ A_m: cross-sectional area of manhole ▪ A_I: cross-sectional areal o inlet; ▪ C_D: discharge coefficient.
Weir equation	No flooding conditions: $Q_U = C_D\ (H_U - H_M)\ W_{crest}\ \sqrt{2g\lvert H_U - H_M\rvert}$ For $\lvert Q_{UM}\rvert < Q_{max}$ Flooding conditions: $Q_U =$ $C_D\ (H_U - H_M)\ W_{crest}\ \sqrt{2g\lvert H_U - H_M\rvert}\ \left(\frac{\lvert H_U - H_M\rvert}{\max(H_U, H_M) - H_g}\right)$	▪ Q_U: flow from sewer to grid point; ▪ H_U: water level in sewer system; ▪ H_M: average water level on the ground; ▪ C_D: discharge coefficient: ▪ W_{crest}: crest width; ▪ H_g: ground level at coupling.
Exponential equation	$Q_U = sign(H_U - H_M)\ S\left(\left\lvert max(H_m, H_G) - max(H_U, H_g)\right\rvert\right)^{Exp}$ For $\lvert Q_{UM}\rvert < Q_{max}$	▪ Q_U: flow from sewer to grid point; ▪ H_U: water level in sewer system; ▪ H_M: average water level on the ground; ▪ H_g: ground level at coupling; ▪ S: scaling factor.

A suitable grid size must be selected for the surface model and computational grid in order to achieve the required level of detail to reproduce the overland phenomenon. In the 2D surface model it can be used a structured or unstructured mesh, depending of the selected software capabilities, which have a specific 2D model solver.

The use of rectangular mesh provides some limitations such as less accuracy in the representation of the existing urban features in the terrain surface (e.g. building, streets levels) and in the localization of the coupled nodes. Additionally, the mesh is not flexible to the inlets and may originate problems of accuracy in the representation of the flood extension and in the computation of the values of flood depth. However, the rectangular mesh is widely used in the urban drainage modelling in comparison with the flexible mesh due to the lower computational cost and the difficulties associated of the mesh generation. This requires a high knowledge level and is a more time consuming and laborious process. In the major part of the urban drainage modelling, the disadvantages associated to rectangular mesh use may be neglected without a significant impact on model accuracy.

The types of available mesh and the main differences in 1D/2D modelling software, based on Mike Flood capabilities, are the following:

- Single Grid: uses a rectangular cell solver. The 2D model area is covered by square calculation cells.
- Single grid uses a rectangular multi-cell solver. The 2D model area is covered by a grid of square cells. This is referred to as the coarse grid. Each coarse grid cell is further subdivided into N by N cells called the fine grid.
- Flexible mesh solver: the 2D model area is covered by a grid consisting of a combination of triangular and quadrangular cells.

4.3. GEOGRAPHIC INFORMATION SYSTEMS AND DIGITAL ELEVATION MODEL

4.3.1. Geographic Information Systems

A Geographic Information System can be defined as the manipulation of the geo-referenced spatial data within a computational system. As already referred, the GIS in conjunction with appropriate methodologies can be an excellent tool in planning, decision making and flood management and control (Santos, 2015). Its development brought a new perspective to science helping to spatially relate different phenomena, as a basis to support and implement mathematical and theory concepts, and simplifying the process of map creation (Johnson, 2009; Leitão, 2009).

The GIS have become an increasingly important mean for understanding and dealing with the water problems and resource management, being the databases, analysis functions, and coupled simulation models widely used in wastewater and stormwater system design and management. GIS represent an integrated tool in several modelling software (e.g. HEC-RAS, MIKE FLOOD, Infoworks) due to the powerful capabilities, being also successfully used to visualize the flooding extension and to analyse the flood maps in order to produce flood damage estimation maps and flood risk maps (Demir, 2016).

The GIS is a data-management system which provides a more comprehensive environment for data integration and analysis through the use of geo-referenced information. The main capabilities of the GIS are described as follows, according to Johnson (2009).

- GIS data and databases: the data is organized by layers, which contain a theme of map information that is logically related by its location. The aim is proposing a multipurpose inventory data that was incorporated as part of a municipal GIS, providing a fully integrated database to support administrative and decision-making functions across all levels of the municipality. The layers are registered through a standardized reference system, and the information displayed on the different layers that can be compared and analysed in combination.

  The databases can be incorporated such as spatial database, defined as a vector structure composed of features (points, lines and polygons), or as associated attribute database, which are handled as images, or *rasters*.
- GIS analysis: the analysis tool allows the use of graphical and logical procedures to identify the correspondence between several data layers, being incorporated functions such as the terrain analysis,

statistical interpolation as well as functions for spatial database development and maintenance. An important tool is the surface operations that include a wide variety of functions. The surface is commonly represented using DEMs or TINs.

- GIS management: the implementation and management of a GIS is a difficult challenge due to the several technical issues involved. GIS analysis capabilities provide ways for modelling and synthesizing information that contributes to supporting decisions for resource management across a wide range of scales, from local to global.

The utilization of a 1D/2D model requires significant specific data, especially when the aim of the model development is to reproduce and asses the occurrence of flooding, being particularly relevant the topography, existing buildings and available urban features in the area of study.

An adequate GIS inventory data requires network data, including the specific dimensions and characteristic of each element that will be incorporate in the model, and surface data, such as the detailed characterization of the land and elevation data with significant accuracy. Data requirements are the main limitation of the 1D/2D modelling, especially concerning the density of elevation points in the area of study and the accuracy level required to reproduce adequately the overland flow in urban areas. The availability of good quality terrain data, such as LiDAR, at a reasonable cost has allowed further development and application of the dual-drainage concept (Schmitt *et al*., 2004; Leitão, 2009).

4.3.2. Digital Elevation Model

The Digital Elevation Model (DEM) represents the terrain elevation data, which is essential for a detailed assessment of the occurrence of flooding in urban areas, promoting the representation and the 1D/2D modelling of flood inundation processes. The resolution and accuracy of DEMs are important issues in land modelling driven processes. Several generation techniques have been developed in the recent years (Leitão, 2009). The present study is focused in the 1D/2D modelling and in the performance assessment, based on their results, to support the flood risk management. Thus, the main focus is in the information and requirements to build the DEM and the existing techniques are not detailed. However, it should be noted that the DEM generated by different acquisition and techniques have different properties in terms of spatial resolution, accuracy, and geographic coordinate system.

The level of detail of DEM is important to achieve an adequate reproduction of the interactions between the network and the surface model, and the overland flow extension and magnitude. The DEM should reproduce the land surface, including streets, available features, land uses (pervious level and roughness) with a high accuracy in terms of spatial and elevation resolution. The Digital Elevation Models created by LiDAR (light detection and ranging) data are adequate to use in flood modelling applications, where sufficiently detailed an accurate representation of the topography represents a key role (Vojinovic *et al.*, 2009).

The required data that should be incorporated in a DEM for the flood modelling purposes are detailed as follows (Mark *et al.*, 2004):

- Elevation of bottom and curb level of road system;

- Elevation and general topography of the catchment or sub-catchments;
- Elevation of low and high areas.

The resolution of DEM should be fine enough to cover important details, and accurately reproduce the elevation in the urban area, especially along the streets, roads and green areas. The exact correspondence between the ground level and the existing levels described in the network model, in the manholes and surface water inlets, is an important constraint in modelling applications.

In order to obtain a DEM with an adequate accuracy and representative of the terrain in the area of the study, special attention is required when several data sources are used or when the aim is merging DEMs to combine one or more elevation data. According to Leitão (2009), the main types of problems when merging two DEMs are: the lack of information in common areas, the overlapping between DEMs is only performed in the boundary line, the existence of partial or complete overlapping between DEMs, in which the different DEM resolution may carry out significant problems.

In Portugal, a DEM developed by the *Direção Geral do Territorio* (DGT) is available for the continental area with a spatial resolution of 50m. In the elaboration of the DEM elevation curves with an equidistance of 25m have been used. Despite the availability of this DEM, for the mathematical modelling of flooding occurrence in urban areas a higher spatial resolution is required. It was necessary to develop a specific DEM of the area of study. The LiDAR technique is the most widely used for DEM construction in urban drainage system modelling.

4.4. PERFORMANCE ASSESSMENT OF STORMWATER DRAINAGE SYSTEMS

4.4.1. Overview

In the urban drainage systems, the performance evaluation is a widely used management tool and gradually more useful in infrastructure asset management, particularly in planning the rehabilitation, operation and maintenance of the systems (Duarte, 2014). Performance assessment is therefore an approach that allows evaluation of the efficiency and the effectiveness of a process or activity through the production of performance metrics (Alegre and Covas, 2015). The increase of the performance assessment utilization by the water supply and wastewater utilities has been motivated by the increase of the requirements to a more transparent, adequate and sustainable management of the systems and of the service to the users, also promoted by the regulatory agents (Cardoso, 2008).

As already referred to, performance assessment of urban drainage systems is oriented by the objectives established for the systems functioning. It is based on the definition of the criteria or points of view, that have to be evaluated in an integrated way, informing about the objectives compliance, and thus supporting not only the systems diagnosis but also decision making on prioritization of interventions or selection of solutions. Performance is assessed by using performance metrics, that can be quantitative or qualitative. The metrics should provide a clear and explicit method to verify the compliance of the objectives that can be established by the utility or by the regulator, or the level of customer satisfaction, and allow to identify if improvements are required (Cardoso, 2008).

Performance evaluation determines, through the use of metrics and of a systematic analysis of the results, the level achieved for the intended purposes in a specific organization, activity or system, providing a measure of efficiency and effectiveness (Cardoso, 2008).

The metrics are represented by a unit of measure, which represents the meaning, and a number, that represents the magnitude of the measure, and should consider the following aspects (PBM SIG, 1995):

- Effectiveness: a process characteristic indicating the degree to which the process output (work product) conforms to requirements.
- Efficiency: a process characteristic indicating the degree to which the process produces the required output at minimum resource cost.
- Quality: the degree to which a product or service meets customer requirements and expectations.
- Timeliness: measures whether a unit of work was done correctly and on time. Criteria must be established to define what constitutes timeliness for a given unit of work. The criterion is usually based on customer requirements.
- Productivity: the value added by the process divided by the value of the labour and capital consumed.
- Safety: measures the overall health of the organization and the working environment of its employees.

Usually, the performance metrics can be classified into performances indicators (PI), performance indices and performance levels. Performance indicators may be converted into performance indices through the application of a performance function, or into performance levels when they are compared with reference levels (Alegre and Covas, 2015).

The classification of the performance metrics is described as follows, based on Sjovold *et al.* (2008):

- Performance indicators are quantitative efficiency or effectiveness metrics for the activity of a utility. A performance indicator consists of a value expressed in specific units, and a confidence grade which indicates the quality of the data represented by the indicator.
- Performance indices are standardized and commensurable metrics that may result from the combination of more disaggregated performance metrics or from analysis tools.
- Performance levels are performance metrics of a qualitative nature, expressed in discrete categories.

The performance indicators are usually expressed as ratios between variables that may be commensurate or non-commensurate. In the last cases the denominator represents a dimension of the system in order to allow the comparison. The use of performance indices present advantages due to represent an aggregated metric and can be used in the assessment of future scenarios, however, should be considered that are more subjective and less auditable.

4.4.2. Performance indicators (PI)

The application of performance indicators (PI) has been intensified in the last decades and extended in a wide range of domains, including the water industry. The concern of the utilities in charge of the water supply and urban drainage systems in order to provide a service with a high level of effectiveness and efficiency has been increasing.

The Technical Committee ISO/TC 224 - Service activities relating to drinking water supply and wastewater systems – quality criteria of service and performance indicators was created due to the high relevance of the performance assessment in the recent years. The scope of ISO /TC 224 is the standardization of a framework for the definition and measurement of service activities relating to drinking water supply and wastewater systems, including: the definition of the characteristics of the elements of the service according to customer expectation, definition the requirements for the management of drinking water supply and wastewater systems, service quality criteria and related system of performance indicators, without setting any target values or thresholds (Matos *et al.*, 2003). The ISO standards series for service activities relating to drinking water supply and wastewater system are mentioned as follows.

- ISO 24510: service activities relating to drinking water and wastewater – Guidelines for the improvement and for the assessment of the service to users (service-oriented standard);
- ISO 24511: service activities relating to drinking water and wastewater – Guidelines for the management of wastewater utilities and for the assessment of wastewater services (management-oriented standard);
- ISO 24512: service activities relating to drinking water and wastewater – Guidelines for the management of drinking water utilities and for the assessment of drinking water services (management-oriented standard).

According to the ISO 24510 (2007), the performance indicators described in these standards are presented only as example, and the service assessment to users cannot be reduced to a single or universal set of performance indicators. The International Water Association (IWA) contributed directly to the Technical Committee work, providing and supporting the definition of the standard and procedures through the publication of the water supply and wastewater PI manuals (Matos *et al*., 2003).

There are several performance indicator systems focused in the evaluation of the service provided of the water and wastewater utilities or in more specific evaluations (OFWAT in OFWAT, 2012; CARE-S in Cardoso *et al.,* 2006; USEPA in Stone *et al.,* 2002). The CARE-S - “Computer-Aided Rehabilitation of Sewer networks” was a project focused in the performances assessment of the urban drainage system to support the rehabilitation, being applied in wastewater and stormwater systems. CARE-S promoted the performance assessment based on the utilization of performance indicators an integrated computational system to support rehabilitation decision making. Most of PI were adopted from the IWA system and other relevant PI were also developed.

A key performance indicator system for the wastewater systems was developed by the IWA (Matos *et al*., 2003) and Water and Waste Services Regulation Authority in Portugal (ERSAR) (Matos *et al.*, 2004), based in the principles presented in the ISO 24510:2007 and ISO 24510:2007 (Duarte, 2014). The IWA published a Best Practice Manual for the wastewater systems with the aim to create a reference framework for the performance indicators to support the commons requirements of wastewater utilities. The IWA performance indicator system has six categories: environmental, physical, personnel, operational, quality of service, and, economic and financial. The performance indicators of this system are independent of the objectives and the characteristics of the utility. Thus, each utility should select the adequate performance indicators to be used in function of the objectives established.

Table 5 – Structure of the PI framework, adapted to IWA (Matos et al., 2003)

	Code	**Number of PI for category**	**Category**
Performance indicators	wEn	15	Environmental indicators
	WPe	25	Personnel indicators
	Wph	12	Physical indicators
	wOp	56	Operational indicators
	wQS	29	Quality of services indicators
	wFi	45	Economic and financial indicators

A correct assessment and interpretation of the performance should be carried out taking into account the context in which the system is operating, the characteristics of the infrastructure and of the resources system, and the characteristics of the region in which the service is provided.

The system proposed by ERSAR is based in the IWA PI system and aims assuring the quality of service to the users through definition of 16 PI for each service of drinking water supply and of wastewater and 12 PI for waste management. These quality of service assessment system allows ERSAR to regulate the water utilities and to perform benchmarking. The assessment procedure is established by the regulatory authority, through the definition of the information to be obtained, the computation and interpretation of the PI, and the comparative assessment. Reference values are proposed by the regulatory authority and the values achieved by the utilities are reported. The performance indicators for quality of service provide assessment of the three objectives: Adequacy of the service provided, Sustainability of service provision and Environmental sustainability.

Stormwater systems constitute one important part of the urban water infrastructures, which value represents a major part of all public infrastructures. The high investments as well as the risk associated to urban stormwater systems justify the need to implement technically appropriate and economically viable solutions and to manage them assuring their sustainability. Currently, a performance indicator system directed for stormwater drainage systems has not still been developed. In the PI systems developed and implemented for water supply and wastewater systems, e.g. by IWA and by ERSAR, stormwater systems are not included, although some PI may also be applicable. However, several studies focused in the performance assessment for stormwater drainage system have been carried out to date, being the application by the utilities more specific or more extended in certain countries (Griggs, 2012; Dechesne *et al.*, 2004).

4.4.3. Performance indices

Performances indices are metrics used in the technical performance assessment that provide a systematic procedure to measure the systems' performance from the relevant points of view, under different system loads and operational conditions (Alegre, 2008). Performance indices are an aggregated metric and can be used in the assessment of future scenarios.

The technical performance assessment consists in the selection, definition, computation, graphic representation and interpretation of the technical performances indicators or indices. The performance indicators allow a global evaluation of the behaviour of the system comparing it with the reference values, regarding the selected points of view such as hydraulic, environmental, structural, among others (Almeida and Cardoso, 2008). The performance indices allow a component evaluation that, when aggregated, translate the system behaviour, regarding the different domains such as hydraulic, environmental, structural, among others (Almeida and Cardoso, 2008).

Cardoso (2008) developed a methodology for the technical performance assessment in urban drainage systems focusing on the hydraulic and environmental domains. The aim of this methodology is to provide a systematic and standardised procedure to measure objectively the global performance of the systems and of each component of the system in the present, past or in the future. It is noticed that the assessment result must be interpreted from an integrated point of view and not be considered as an individual interpretation of each metric.

In urban drainage systems, for the domains proposed for performance assessment, the points of view or criteria considered were the hydraulic capacity, self-cleaning condition, directs discharges to receiving waters, inflow, infiltration and septicity. The methodology was tested and validated through the application and analysis of 26 proposed performance metric in several case studies with different characteristics.

The methodology proposed by Cardoso (2008) consists in the selection and development of three components, for each aspect to be analysed:

- A performance metric represented by a state variable or a property of the system;
- A performance assessment function that classifies the metric value into a classification, for each element of the system or globally, as applicable;
- In the case of the elemental analysis level, an operator of the network which generalizes and aggregates the elemental performance values for the entire system.

For example, for the hydraulic capacity, self-cleaning and septicity condition assessments, Cardoso (2008) proposed the use of the variables of water depth (h), average flow velocity in pipes (v) and the Pomeroy parameter (Zp), respectively, being developed performance functions for each variable.

In figure 3 the performance function proposed by Cardoso (2008) for the performance index water depth is presented (h), applicable in separate stormwater and combined systems. The performance function establishes a classification between 0 to 4 for this performance index, corresponding 0 to the minimum performance value, associated to a service failure, and 4 to optimum value of performance. It must be noticed, for water depths below the diameter of the pipe (D) the performance is optimum, and there is a failure of service when the water depth is higher than the ground level.

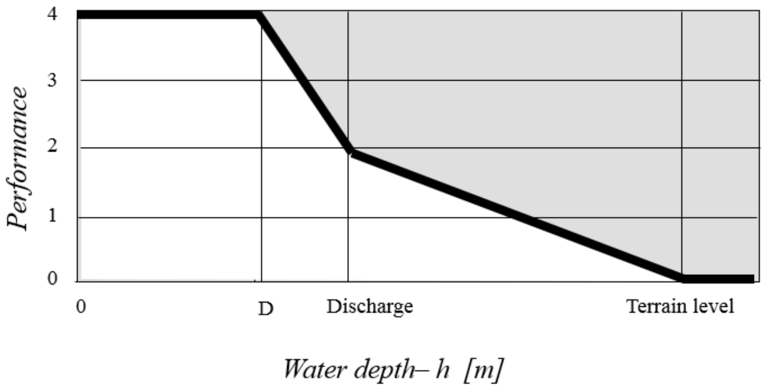


Figure 3 – Example of performance assessment function for the water depth in separative stormwater or combined systems (Cardoso, 2008)

In the technical performance the interpretation of the result should be considered each performance indices, taking into consideration the performance assessment classification, the performance function, and, in the case of analyse at the component level, the generalizing function.

The tools available for the analysis, diagnosis and evaluation of the wastewater drainage systems performance include the inspection and the use of monitoring and mathematical modelling, being essential to achieve a detailed characterization of the system for the technical assessment evaluation (Ferreira, 2006).

Monitoring and modelling are essential tools for the technical assessment evaluation. It should be noticed the different characteristics of the monitoring or modelling information and the different analyse that can be carried out in function of the available information and the information type, according to Cardoso (2008). The information obtained by monitoring allows to the performance assessment at the scale of the sub-catchment, system or subsystem, and, the information of modelling allows the assessment at level of the component.

The available data to carry out the technical performance assessment determines the level of detail of the assessment and the performance metric to be used. Monitoring information is adequate to the macro-analyse through PI assessment, however, the more extensive information of the mathematical modelling allows to get a higher level of detail of the case of study and the attainment of performance indices, which represent an aggregate measure of the system performance.

In the present study entitled "1D/2D integrated modelling and performance assessment to support floods management. Application to stormwater urban drainage system in estuarine areas" the technical performance assessment will be carried out from of point of view of the hydraulic domain focused in the stormwater systems using performances indicators.

4.4.4. Uncertainty and quality associated of the data

The reliability of the performance assessment depends of the quality of the information used. It is essential to know the reliability and accuracy of the data in order to obtain information about the quality of the performance assessment and to understand the associated uncertainty. The measurement of a physical variable is associated to an imperfect measurement due to several reasons, for example, the model does not reproduce perfectly the conceptual model or the instrumentation and the measurement system have intrinsic limitations.

In the JCGM 100:2008 standard the uncertainty is defined as a parameter, associated with the measurement result that characterizes the dispersion of the values that could reasonably be attributed to the measurand, and results of the contribution random components, such as the repeatability. The JCGM 100:2008 standard establishes general rules for evaluating and expressing uncertainty in measurement that are intended to be applicable to a broad spectrum of measurements.

Since the publication of the guide ISO - GUM (1993), the expression of a measurement result is only complete when is defined the value for the measurand and the respective uncertainty of the measurement (Henriques *et al.*, 2006). Recently, the ISO-GUM (2008) establishes general rules for evaluating and expressing uncertainty in measurement and the various levels of accuracy in many fields, being the principles applicable to a broad spectrum of measurements. The Monte Carlo simulation is a widely used technique to quantify the uncertainty through the estimation of the error associated of the monitoring data and the modelling results, as is applied in Yoo *et al.* (2012) to estimate the uncertainty associated to rainfall monitoring. The uncertainty associated to modelling results is mainly due to the input data, the adopted parameters in the calibration and the model structure (Ferreira, 2006). The model calibration intends to reduce the uncertainty due to the referred causes but does not quantify the uncertainty.

Performance metrics should always be associated with the quality of the data used to calculate them and should be assessed in terms of the source and of the accuracy of data (Alegre and Covas, 2015). The confidence grades scheme method, developed by the Office of Water Services, provides a rational method for undertakings to qualify the reliability and accuracy of information provided for the performance indicator. Alegre *et al.* (2006) presented an evolution in the analyses of the confidence grades scheme for water supply systems, based on the field application of the IWA performances indicators.

The confidence grades scheme, combining the reliability and accuracy bands of the data, can establish a basis for the water supply and wastewater utilities to validate the information. The accuracy is defined such as the approximation between the result of the measurement and the correct value of the variable to be measured. The accuracy takes into account the relative error in the acquisition and processing of data, including the error due to the eventual extrapolation between specific measurements and the global value (Cardoso, 2008).

The reliability and accuracy bands are described in table 6 and table 7, based on Alegre *et al.* (2006). Recommendation to establish the confidences grades are included in the IWA and ERSAR performance assessment system.

Table 6 – Reliability bands of data (adapted from Alegre et al. (2006))

Reliability bands of source data	Associate concept
★	Data based on estimations or extrapolation from a limited sample.
★★	Generically as the previous one, but with some not significant gaps in the data, such as part of the documentation is missing, the calculations are old, or to have relied on unconfirmed records, or that there have included some data extrapolation.
★★★	Data based on extensive measurements, reliable records, procedures, investigations and analyses adequately documented and recognized as the best method of calculation.

Table 7 – Accuracy bands of data (adapted from Alegre et al. (2006))

Accuracy bands of data	Associated error of data
0 - 5%	Better or equal than a ± 5%.
5 - 20%	Worse than ± 5%, but better or equal than a ± 20%.
20 - 50%	Worse than ± 20%, but better or equal than a ± 50%.
> 50%	Worse than ± 50%.

5. METHODOLOGY FOR INTEGRATED MATHEMATICAL MODELLING OF STORMWATER URBAN DRAINAGE SYSTEMS AND FOR PERFORMANCE ASSESSMENT

5.1. DESCRIPTION OF METHODOLOGY

The methodology for 1D/2D integrated modelling in stormwater urban drainage system, proposed in this dissertation, consists in the building of the separate surface runoff and buried network model, coupling of models, calibration and simulation of scenarios. The performance assessment is based on the concepts developed and applied by Cardoso (2008) in urban drainage systems, focusing in the selection of a set of performance indicators (PI) appropriated for an objective assessment and management of flooding occurrence.

The methodology is based on the development and use of a 1D/2D integrated mathematical modelling and, subsequently, application of the technical performance assessment to support the flood management in estuarine areas. The 1D/2D integrated mathematical modelling is developed using the combination of Mike Urban and Mike Flood software through the application of Overland Flow tool. The performance assessment in stormwater systems is based on the PI application using the information provided by 1D and 1D/2D integrated modelling. Is also verified the advantages and disadvantages of the utilization of information obtained though 1D/2D modelling in comparison to 1D modelling.

In the present study, the proposed methodology is divided into 4 parts, as presented in figure 4, that are detailed as follows.

- Part 1: Definition of the modelling objectives;
- Part 2: Building, characterization and simulation of the stormwater drainage system (network model, runoff model and coupling between the 1D surface runoff model and the 1D network model);
- Part 3: Comparison between the 1D and 1D/2D modelling results;
- Part 4: Performance assessment of the stormwater drainage system through the application of existing and proposed performances indicators (PI) and comparison of the assessment results by using the 1D and the 1D/2D model.

In Part 1 the specific modelling objectives to be analysed in the stormwater drainage system from the point of view of the flood occurrence and management are identified.

In Part 2 the 1D/2D model building takes into consideration the objectives and requirements of the modelling process and the available and required information for the established purpose. The models building, network and surface runoff model, and the coupling between them are carried out. The incorporation of data for the models building (characterization of the manholes, pipes and surface water inlets, including the dimension, shape and another required specification in the network, and the description of catchments and DEM development) are performed. The model is calibrated and simulated using scenarios regarding rainfall events, tide level and obstruction level in the network system.

In the Part 3 a comparative analysis between the results obtained through the 1D and 1D/2D modelling is presented. The advantages and disadvantages of 1D and 1D/2D modelling are also detailed, taking into consideration the objective of the present study.

In the Part 4 the performance assessment at system level based both on the 1D and 1D/2D mathematical modelling results (Mike Urban and Mike Flood) using the performances indicators proposed by IWA (Matos *et al.*, 2003) for wastewater services, being adapted to stormwater drainage system. Additional PI are also proposed, taking into consideration the aim of the study.

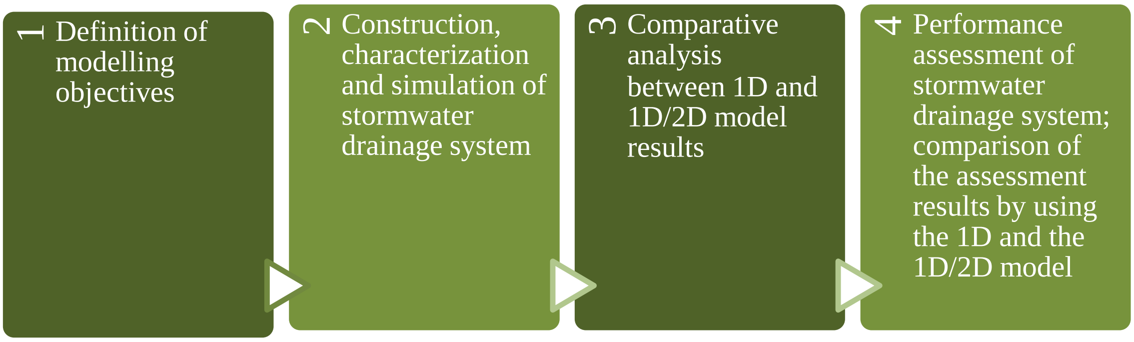


Figure 4 – Proposed methodology

5.2. DEFINITION OF MODELLING OBJECTIVES

The main objectives of the 1D/2D integrated modelling are to assess the flooding occurrence in stormwater drainage systems and to provide a support tool for flood management in estuarine areas. The specific objectives are detailed as follows:

- Assessing the hydraulic capacity of the sewer network system and the surcharging or flooding conditions in the manholes and surface water inlets. An important aspect is evaluating the effects of tide and obstruction conditions in the system performance.
- Assessing the catchment hydrological response in function of the rainfall event characteristics.
- Assessing the overland flow conditions, being essential to determine the causes that leads to the flow exchanges in the manholes or surface water inlets (*inlets*).
- Assessing the limitations of the sewer network system for different scenarios, which depend on the characteristic of the rainfall events, estuarine water level and obstruction level of in sewers and at the outfall.
- Assessing the performance of the stormwater system based on the IWA PI for wastewater services (Matos *et al.*, 2003), those focused in flooding assessment and applicable to stormwater system.
- Develop additional PI to complement the stormwater system performance assessment from 1D/2D modelling.
- Identify and demonstrate advantages and disadvantages of 1D versus 1D/2D modelling.

- Contribute to support the flood management through the 1D/2D integrated modelling of the urban stormwater system, including the GIS representation of results helping in the identification of the flooding occurrence (location, water depths) and the possible causes.

5.3. INTEGRATED MODELLING 1D/2D OF STORMWATER DRAINAGE SYSTEMS

Mathematical modelling is a widely used tool for assisting with flood risk management due to its efficiency and reliability (Kokas *et al*., 2016). The 1D/2D integrated mathematical modelling of stormwater drainage systems is a laborious and complex process that requires a high availability of specific information for the model building, calibration and simulation. However, if justified by the modelling objectives, it is worthwhile their development since they provide added information regarding the 1D models. In Figure 5 the main phases of 1D/2D integrated modelling developed in the framework of the present thesis are detailed..

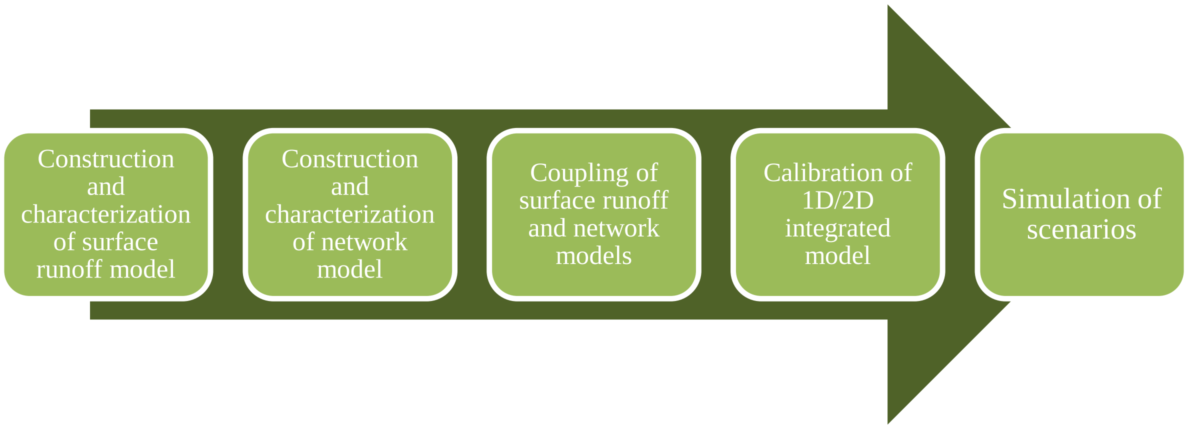


Figure 5 – Phase of the 1D/2D integrated modelling

5.3.1. Surface runoff modelling

The surface runoff model is built using Mike Urban (DHI, 2014), by applying the 2D Overland Flow tool. Overland Flow tool allows definition of a 2D surface runoff model, based on the Mike Flood software, through the Mike Urban interface.

In the 2D runoff model the geometrical and hydrological characteristics for the sub-catchments, in the area to be modelled, should be defined. The delimitation of the drainage sub-catchments and their characterization (length, total, pervious and impervious areas) is required for the runoff modelling. The sub-catchments are divided into three categories: roads, buildings or green areas. The selected runoff method should be defined, being specified the parameters to be applied in each sub-catchment.

In the surface runoff modelling the time-area method is selected, taking into consideration the catchments shape in each sub-catchment. By default, the sub-catchments were considered rectangular. This parameter and the concentration time of the sub-catchments should be determined in the calibration phase.

5.3.2. Network modelling

The 1D network model building is carried out using the Mike Urban (DHI, 2014). This is suitable to simulate urban drainage systems and provides the opportunity to develop an integrated 1D/2D model. The urban stormwater system must incorporate the available information on the mapping and inventory data, which should be validated and, in specific cases, modified through the information obtained in field works. The available data should be verified in order to ensure an adequate accuracy and representation of the stormwater drainage system.

The type of elements to incorporate in the network model building are manholes, pipes and surface water inlets. All elements of the urban drainage system are geo-referenced, based on the available inventory data. The pipes are defined through the specification of the upstream and downstream manholes (ID, bottom level, offsets), type of material, cross section (type and dimensions) and length.

The manholes are defined as normal manholes if the flow entrance and exit through the manhole cover to the system is allowed, and sealed manholes if the entrance and exit of flow is not allowed. The sealed manholes are incorporated in auxiliary nodes of the network model, for connection in intermediate sections of the pipes. In the incorporation of the manholes the following properties should be also defined: ID, cross section (type and dimensions), depth, top level, bottom level, terrain level and the section.

The geometric characterization of the surface water inlets is carried out through the selection of predefined curves which are previously incorporated to the network model. Each curve defines the relation between the superficial area and the transversal area for each component. In the incorporation of surface water inlets, the following properties should be also specified: bottom level, terrain level and predefined curve.

The downstream final section of the stormwater drainage system should be defined as outfalls and allow the incorporation of temporal series, being required for scenarios simulation. Additional elements should be incorporated in the network model to reproduce correctly the upstream boundary condition and to simulate the degree of obstruction in sewers and at the outfalls, that can be considered in the scenarios.

5.3.3. Surface runoff and networks models coupling

The coupling between the runoff model and the network model is carried out using the Overland Flow tool. Once the 1D network model and the 2D surface runoff models were developed, the incorporation of a Digital Elevation Model (DEM), the definition of the computational mesh, the coupling between the 1D network model and 2D surface runoff model, and the incorporation of the boundary conditions (tide level and rainfall event) should be carried out.

The incorporation of the DEM should be performed in *raster* format and its extension should be higher than that of the modelling area. It is expected that flooding areas are included into the mesh extension, avoiding convergence problems.

The coupling is handled by inlets that are represented by the surface water inlets and normal manholes. In each inlet an *urban link* should be defined, which are the elements in charge for flow exchanges between the DEM and the buried drainage network in case of flooding or when surface runoff enters the network. An essential requirement to carry out the coupling of the surface runoff model (2D) and the stormwater network model (1D) is that the difference between the terrain level in the DEM and in the inlets should be lower than 0.10m. The validation of the introduced data and specific adjustments based on the information collected in the field work must be realized.

The characteristics of the tide and the rainfall events have to be inserted in the 1D/2D coupled model. The boundaries conditions that reproduce the tide effect should be defined in the outfalls of the 1D/2D models The water level is established as a downstream boundary condition to the sewer network outfalls. The values were obtained through the coupled waves-currents hydrodynamic modelling of the Tagus estuary (Fortunato *et al*., 2014). The scenarios for the estuarine water levels and rainfall events considered are detailed in 5.3.5.

5.3.4. Model calibration

The calibration is an essential phase in the modelling process and is supported by the available field data and historical information provided by the entities in charge for the stormwater drainage system. Calibration involves the changes in model parameters until the modelling results achieve a consistent match with the observed set of data (Kuoka *et al*., 2016). The model accuracy depends on the level of calibration accomplished. Modelling results should be validated through the historical information regarding existing floods.

5.3.5. Definition of scenarios

The scenarios are defined in order to assess the consequences in terms of the flooding extension and water depths over the surface and to create a set of simulations that reproduce the typical conditions of the local flooding in the area. The aim is to reproduce flooding conditions in the catchment in function of the estuarine water levels and rainfall characteristics. The rainfall events are determined for a period–duration of four hours and different hietogram configurations for the same accumulated rainfall volume. The estuarine water level is adopted from the coupled waves-currents hydrodynamic modelling of the Tagus estuary, developed by Fortunato *et al.* (2014).

The rainfall events are defined in function of the hietogram shape, i.e., in terms of previous dry weather period, maximum rainfall intensity and variation of the intensity before and after the peak. Return periods (T) of 10, 20, and 50 years are considered, being the maximum intensity of the rainfall event calculated through the IDF (intensity-duration-frequency) curves, defined by the national Decree-Law 23/95 for Portugal. The shape of the rainfall event is defined by a design rainfall pattern (figure 6) for the maximum intensity previously calculated in function of the return period. The corresponding maximum intensities are, respectively, 56mm/h, 63mm/h and 73mm/h.

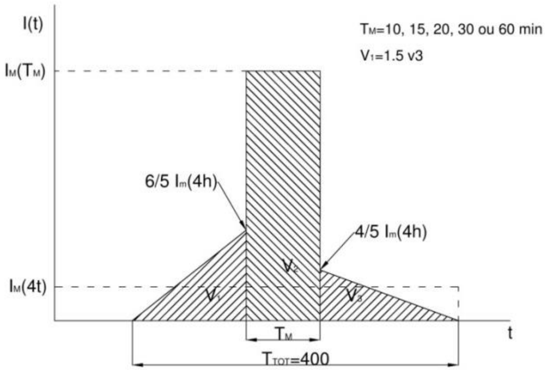


Figure 6 – Design rainfall patterns (Matos, 1987)

For the corresponding generated rainfall volume, an additional uniform hietogram is defined, during the pre-established duration of four hours, according to the design rainfall event.

5.4. COMPARATIVE ANALYSIS BETWEEN 1D AND 1D/2D MODELLING RESULTS

The comparative analysis between 1D and 1D/2D modelling results is focused in the flooding occurrence assessment, showing the advantages and disadvantages associated to the 1D or 1D/2D modelling in terms of results, quality of information and level of detail. Comparative analysis is based on the maximum water depth, flooding extension and maximum duration variables.

The 1D modelling results are analysed trough the maximum water depth registered in the manhole or surface water inlet, the flooding extension estimated in function of the registered maximum water depth, and the maximum duration of the flooding occurrence.

In 1D/2D modelling, the flooding is defined in term of maximum water depth and duration for each computational cell, providing a mesh of results in two dimensions. Subsequently, the flooding extension is delimitated based on the maximum water depth results, using GIS application. The 1D/2D model is simulated by scenarios in function of the rainfall event, tide level and the degree of obstruction.

5.5. PERFORMANCE ASSESSMENT

5.5.1. Assessment procedure

The performance assessment follows the methodology developed in Cardoso (2008) and presented in 4.4. It is based on the selection of a set of relevant performances indicators suitable for the diagnosis, control and support for the management of flooding occurrences in stormwater drainage system. It focuses mainly on indicators to measure the hydraulic performance of the stormwater drainage systems. Some PI related to the quality of service, such as associated to roads interruption, are also included.

The selection of the PI is an important issue in order to provide adequate information for an objective assessment. Then the performance functions are defined in order to classify performance. The methodology can be applied to a system using the detailed information provided by the 1D and 1D/2D integrated modelling. In figure 7 the methodology followed is detailed.

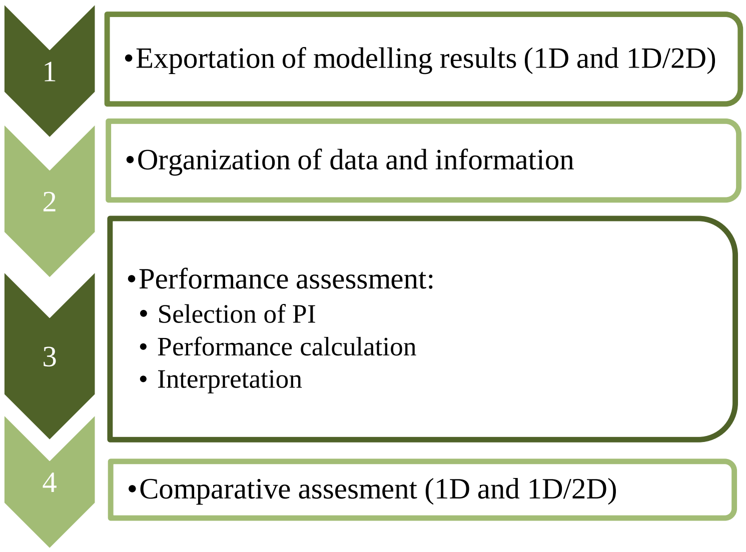


Figure 7– Performance assessment procedure

Based on the modelling results, a comparative assessment to determine the advantages and disadvantages of the performance assessment in each case (1D and 1D/2D) is carried out.

The performance assessment was based on the PI from the International Water Association (Matos *et al.*, 2003) for wastewater services, described in the present chapter, and on some new PI developed in the present thesis. In the present study the PI adequate to be applied in the stormwater systems for flood management are selected. Some new PI are proposed based on the modelling (1D and 1D/2D) capabilities. The set of selected PI include indicators from the physical, operational and quality of services assessment categories. The process consists in determine the PI to assess the hydraulic capacity, flooding occurrence in terms of extension, affected properties, number of flooding incidents and network elements affected, interruption of service and the impact on traffic.

5.5.2. Selection and interpretation of existing performances indicators

In the present thesis the existing PI from the International Water Association defined by combined sewer system will be applied to stormwater drainage systems. In Table 8 the existing PI from International Water Association are detailed:

Table 8 – Definition of existing PI from International Water Association (Matos et al., 2003)

Performance Indicator	Unit	Definition
WPh6	[%]	Length of gravity sewers where surcharging has occurred in wet weather during the assessment period / total sewer length at the reference date x 100
WPh7	[%]	Length of sewer where a high degree of surcharging has occurred in wet weather during the assessment period / total sewer length at the reference date x 100
WOp38	[No./100 km sewer / year]	Number of flooding incidents related to combined sewers during the assessment period x 365 / assessment period) / total sewer length at the reference date x 100

Surcharging in gravity sewers in wet whether (WPh6)

According to Matos *et al*. (2003) this PI is classified as a physical indicator and may be assessed for periods shorter than one year. The required information may be obtained by monitoring or by hydraulic modelling using rainfall data. This PI is applicable to stormwater drainage system.

High sewer surcharging (WPh7)

The high degree of surcharging means water level at least 0.5 m above the pipe crown. This PI is included in the physical indicators proposed by the IWA for wastewater services. According to Matos *et al*. (2003), this PI may be assessed for periods shorter than one year. This PI can be applied in stormwater drainage system.

Flooding from combined sewers (WOp38)

This PI is included in the operational indicators proposed by the IWA for wastewater services. The PI was indicated for combined sewer, being possible its utilization in stormwater drainage systems without additional modification or requirements. In the definition is indicated that only are included incidents related to combined sewers that are the responsibility of the wastewater undertaking, being in the present study adapted for stormwater services.

According to Matos *et al*. (2003), this PI may be assessed for periods shorter than one year. This PI can be applied to stormwater drainage system.

5.5.3. Proposal of new performances indicators for stormwater systems

In the present study some new PI adequate to be applied in the stormwater systems for flood management are proposed, based on the modelling (1D and 1D/2D) capabilities. The proposed PI are focused in the flooding occurrence in terms of extension, properties affected, number of flooding incidents and network elements affected, interruption of service and the impact on traffic.

Table 9 – Definition of proposed new PI

Performance Indicator	Unit	Definition
PI-1	[No./100 km sewer / year]	Number of manholes or surface water inlets affected by flooding related to stormwater sewers during the assessment period x 365 / assessment period) / total sewer length at the reference date x 100
PI-2	[%]	Flooding area extension, for the assessment period, related to stormwater sewers / Impervious area of urban catchment x 100
PI-3	[Nº / ha]	Number of flooding incidents, areas affected by flooding, related to stormwater sewers during the assessment period / Area of urban catchment
PI-4	[No./1000 critical locations /year]	(Number of critical locations affected by surface flooding in wet weather, during the assessment period x 365 / assessment period) / number of connected locations at the reference date x 1000
PI-5	[%]	Maximum duration of flooding in a manhole or surface inlet in hours in the assessment rainfall event / Total duration of the assessment rainfall event x 100
PI-6	[m]	Maximum extension, for the assessment period, of the roads affected by flooding incidents multiplied by the respective duration of interruptions in hours / duration of the rainfall event in hours

Flooding per manholes from stormwater sewer (PI-1)

Based on the operational indicator WOp38 defined by the IWA for wastewater services, in the present study a modification of this indicator is proposed. This PI intends to take advantages of the more detailed information provided by modelling data, focusing in the number of elements in charge for the runoff collection that are affected by flooding incidents.

Flooding extension from stormwater system (PI-2)

The proposed PI intends to determine the importance of the area extension of the stormwater system affect by flooding in the impervious urban catchment under assessment. The PI may be assessed for shorter period than one year, nonetheless is important take into consideration when is used for internal or external benchmarking.

Flooding incidence per catchment (PI-3)

The proposed PI intends to determine the importance of the number of flooding incidents related to stormwater sewers in the urban catchment that is in assessment. The PI may be assessed for shorter period than one year, nonetheless is important take into consideration when is used for internal or external benchmarking.

Surface water flooding of critical locations in wet weather (PI-4)

Based on the quality of service indicator WQS14 defined by the IWA for wastewater services, in the present study a modification of this indicator is proposed. The proposed PI intends to determine the critical locals affected by flooding related to stormwater sewers in the urban catchment that is in assessment. The PI may be assessed for shorter period than one year, nonetheless is important take into consideration when is used for internal or external benchmarking.

Interruption of stormwater services (PI-5)

Based on the operational indicators WQS15 defined by the IWA for wastewater services, in the present study a modification of this indicator is proposed. This PI intends to help in the assessment of the flooding relevance in the element in charge for the runoff collection, identifying the severity of the flooding occurrence. The PI may be assessed for shorter period than one year, nonetheless is important take into consideration when is used for internal or external benchmarking.

Traffic disturbances (PI-6)

Based on the operational indicators WQS29 defined by the IWA for wastewater services, in the present study a modification of this indicator is proposed. The PI is focuses in the assessment of the traffic disturbances associated to the occurrence of flooding, and identification of the relevance of the incidence. The PI may be assessed for shorter period than one year, nonetheless is important take into consideration when is used for internal or external benchmarking.

6. CASE STUDY APPLICATION

6.1. GENERAL CONSIDERATIONS

The case study of the present thesis is the Dafundo estuarine catchment located in Oeiras, in the Lisbon district. The wastewater and stormwater drainage networks of Dafundo are managed in terms of construction, operation and maintenance by the SIMAS OA (the local water utility) and by the Oeiras Municipal Council (CMO). The National Authority for Civil Protection (SPC), in cooperation with the Humanitarian Association of Volunteers Firefighters (BVD), provides support to the population in the event of serious flooding occurrence or imminent disasters in the urban area.

The historical information about flooding occurrences and recurrent obstructions at the system outfall was provided by the referred entities. This information allowed to delimitate the expected area to be affected by floods, being essential in the 1D/2D modelling in terms of network selection and model building. The urban drainage system was studied in the framework of the FCT “MOLINES – Modelling floods in estuaries. From the hazard to the critical management”, where several *in situ* inspection and monitoring field surveys took place.

Based on the referred field works, it was possible to identify an independent behaviour of the Dafundo downtown drainage network from the network system located upstream. Consequently, it is possible to analyse these two networks separately. The location of the monitoring sections was selected in function of the differentiated behaviour between the upper and lower area, taking into consideration the adequate condition for installation and assessment of the hydraulic and hydrologic behaviour of the upper area.

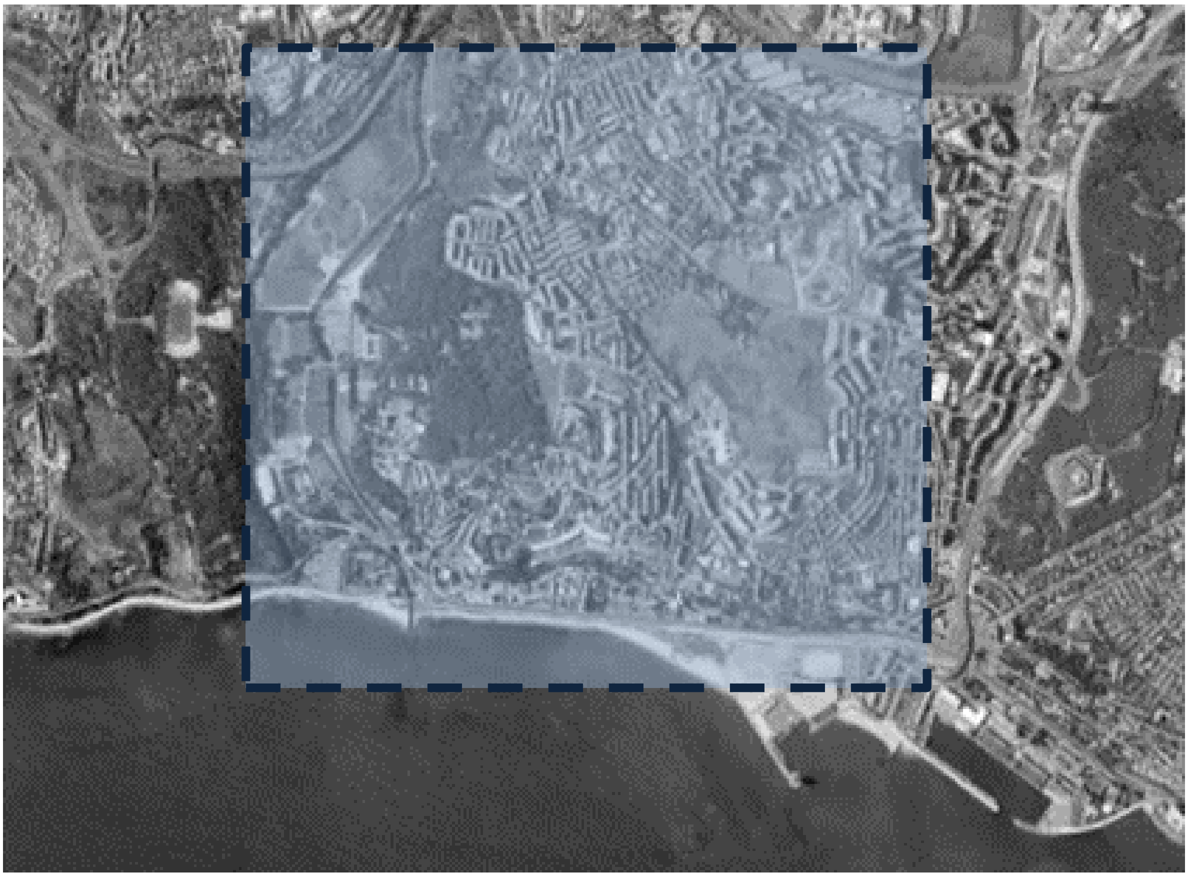
The integrated model was carried out combining the Mike Urban, for the buried network, and Mike Flood, for the surface runoff, applying the Overland Flood tool. Mike Urban represents an adequate tool specialized in the hydrodynamic modelling of drainage systems for different rainfall events and boundary conditions. This software allows the runoff computation, however, is not suitable to reproduce the two-dimensional behaviour over the terrain surface, which represents an objective of the present study. Mike Flood was used to achieve the modelling results in term of flooding extension in the Digital Elevation Model, previously developed, since the model is coupled. An adequate solution to decrease the great computational effort associated to 1D/2D modelling, the Overland Flow available in Mike urban was selected due to the significant number of scenarios to simulate and the high computation time of the Mike Flood.

Once the 1D/2D model was constructed and coupled, the boundary conditions must be defined. The upper area of Dafundo catchment was previously analysed to be incorporated as upstream boundary condition. The estuarine water level was imposed as a downstream boundary conditions, in order to assess the tide effect in the urban area. The upstream boundary condition, which establishes the surface runoff that drains to the network system located in Dafundo downtown, was obtained through the application of a lumped model, based on David (2006). The downstream boundary condition that reproduce the tide effect in the stormwater drainage system are defined through the coupled waves-currents hydrodynamic modelling of the Tagus estuary developed by Fortunato *et al*. (2014).

6.2. DESCRIPTION OF DAFUNDO URBAN DRAINAGE CATCHMENT

The Dafundo catchment is located in Oeiras, in the Lisbon district, on the right marginal area of Tagus estuary, within the Junça River catchment. Dafundo catchment is characterized by a significant extension and a high density population, which represents a common situation in urban areas placed in estuarine marginal areas. In figure 8 the locations of Dafundo area and Junça River are presented.

a) Junça River



b) Dafundo area (Google Maps)

Figure 8 – Location of the a) Junça River and b) Dafundo area

The urban drainage network is characterized by the occurrence of flooding and undue inflows from the wastewater to the stormwater drainage system, being the flow discharged into the Tagus estuary through two main sewers, the canalized Junça River and a parallel duplication of the canalized Junça River. In figure 9 the representation of the confined area with frequent flooding occurrences, based on historical information, is presented.

Figure 9 – Flooding area delimitation based on provided historical information

The main stormwater sewer corresponds to the local stream, the Junça River, which has been canalized for decades. In the lower area of the catchment, downtown area of Dafundo, a parallel duplication of the canalized Junça River was constructed, to solve flooding problems. After the construction, the surface water inlets of the canalized Junça River were connected to the parallel duplication to reduce the stormwater collected in the main sewer. Flooding in the estuarine marginal area was significantly reduced in terms of frequency, severity and flooded area. However, after the construction of the parallel sewer flooding still occurs and it was studied using the 1D/2D coupled modelling.

6.3. SELECTION AND DESCRIPTION OF A SUB-SYSTEM IN THE DOWNTOWN AREA OF THE DAFUNDO CATCHMENT

The historical information provided by the SIMAS OA and the BVD focuses on the risk of flooding occurrence in the Dafundo downtown. The flooding occurrences in the upper area of the stormwater drainage system are not recurrent due to the canalization of the Junça River through manholes with high depth and storage capacity, decreasing the floods frequency.

In the *in situ* inspections a vertical drop was detected between two branches of the stormwater system. The network located upstream of the downtown area is linked through a vertical drop with a significant height. This condition allowed to consider the Dafundo catchment segmented into an upper and a lower hydraulic areas, being the hydraulic behaviour of the network almost independent in each of them. The vertical drop controls the flow from its upstream to its downstream branches, and reduces the possibility of sewer surcharge in the lower area.

In terms of urban drainage modelling, the presence of the vertical drop allowed the segmentation of the network, using a simplified, conceptual and lumped model developed by David (2006) for the upper area, whereas the lower area was modelled using a 1D/2D integrated Mike Flood model (DHI, 2014), by applying the 2D Overland Flow. The segmentation of the Dafundo catchment was carried out in a manhole with an adequate location to be monitored and to evaluate the hydrologic and hydraulic behaviour of the upper catchment.

In order to achieve an adequate 2D runoff modelling, the representation of the terrain surface through the construction of a Digital Elevation Model (DEM) was carried out and the required level of accuracy was taken into consideration in function of the upstream catchment and the sub-catchments characterization. The representation of the terrain surface was developed using a (DEM) based on the elevation curves, each 1 m, provided by SIMAS OA for the whole catchment, including the upper and lower areas of catchment.

In the estuarine marginal area, the lowest area of catchment, the use of elevation points acquired through LiDAR technique was required in order to achieve an adequate accuracy to allow the representation of local roads, streets and of existing urban features and singularities in the urban surface. This is essential for the surface runoff assessment and for the 1D/2D model construction. This technology represents an adequate technique to achieve a higher accuracy due to higher density of elevation points attained.

Previously to the runoff model construction, the characterization of the upper area of the catchment was carried out. The simplified model represents the urban catchment as a few number of catchments disposed in series or parallel and replicates the lumped catchment response to rainfall events, by generating the response of hydrographs considering initial hydrological losses, continuous losses through a hydrologic reduction coefficient and flow propagation using the linear reservoir method. The model allows to incorporate another contribution to the computed runoff hygrogram such as infiltration hydrograph.

In the simplified model, the upper area of the catchment was defined, using the developed DEM, with a total area of 87.15ha and a percentage of impervious areas of 78.2%. It was identified a different behaviour of the catchment under study in function of the characteristics of the rainfall event. In the case of rainfall events with lower intensities, the simplified model shows an adequate representation for a C value of 0.23. The low value of C obtained can be explained by the fact that some impervious areas do not contribute for this catchment under study for low rainfall intensities.

For rainfall events with higher intensities, generating flows higher than 350l/s, an additional flow discharge was detected. This different behaviour of the catchment under study could be explained by inflow contributions from adjacent catchments, that only take place for higher discharges. In figure 10 the delimitation of the upper area of Dafundo catchment over the DEM surface is detailed.

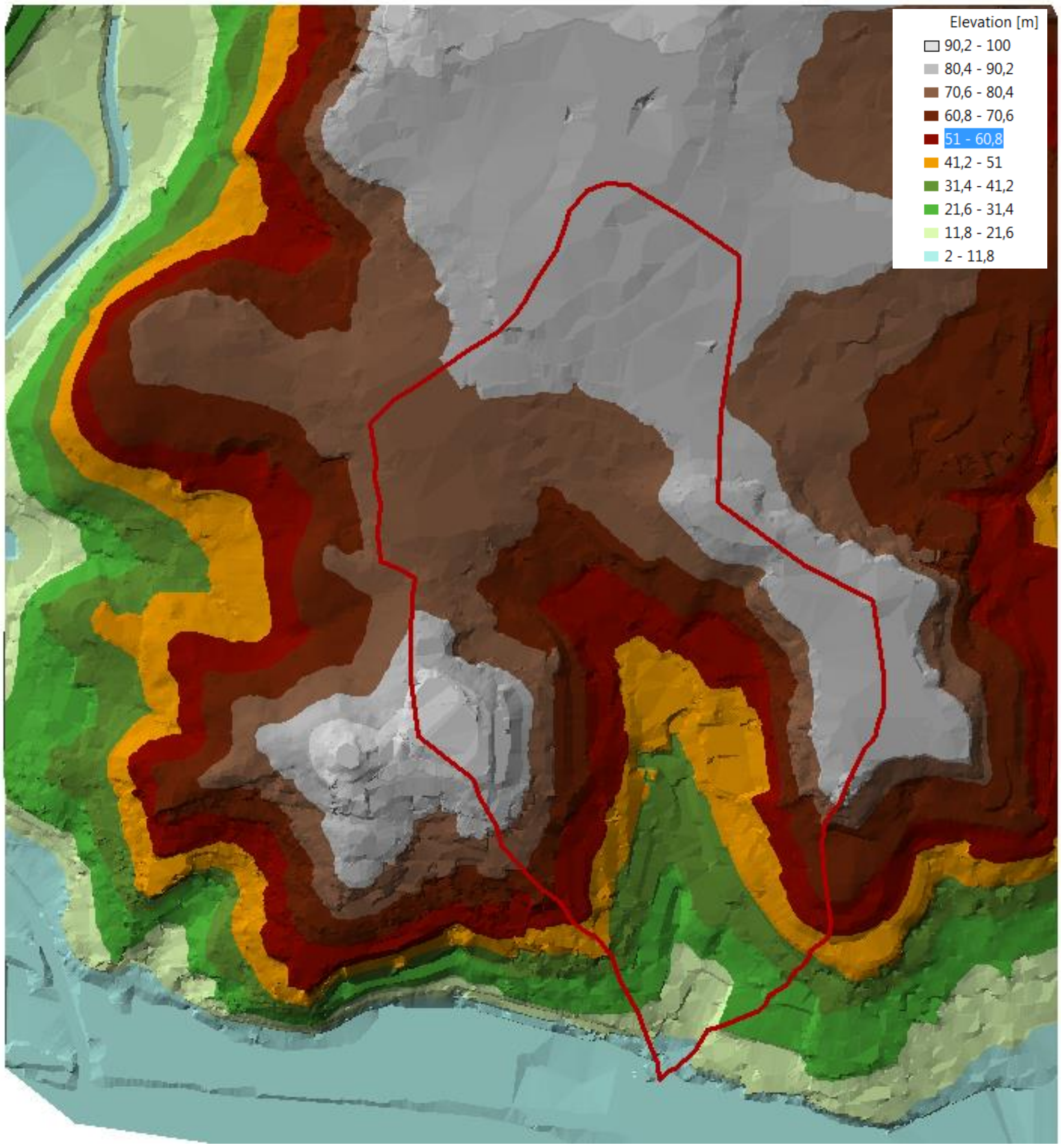


Figure 10 – Delimitation of the upper area of Dafundo catchment over the developed DEM

6.4. INTEGRATED MODELLING 1D/2D OF SUB-SYSTEM IN THE DOWNTOWN AREA OF THE DAFUNDO CATCHMENT

6.4.1. 1D/2D integrated model

The urban drainage flooding occurrence of sub-system in the downtown area of the Dafundo catchment was assessed based on a coupled 1D/2D Mike Flood model (DHI, 2014), by applying the 2D Overland Flow to the surface runoff modelling and the 1D mathematical model to drainage buried network modelling.

In the 1D/2D integrated model two catchments, a main catchment and an adjacent catchment, were defined to simulate the upper area of Dafundo catchment as already described. The contribution of the adjacent catchment to the lower area of Dafundo catchment is regulated.

The upstream catchment that was characterized through the model developed by David (2006), was incorporated in the runoff model by defining the coefficient for the Rational Method (C), total area and the percentage of impervious area. For rainfall events with higher intensities, the additional inflow was represented through the incorporation of an additional upper catchment, with the same characteristics of the upstream catchment, but that only contributes to the lower area drainage system if the flow is higher than 350l/s. The regulation of the adjacent catchment was assured by considering a rectangular weir, allowing simulating catchment behaviour in case of higher rainfall events, being the controlled through the water depth over the weir crest. Runoff from the adjacent catchment only flows into the stormwater system of the lower area whenever the water depth over the crest is higher than a pre-established value, defined in the calibration phase.

A total area of 87.15ha and a percentage of impervious areas of 78.2% were defined both for the main and for the adjacent catchment. The concentration time for each catchment (t_c), the parameter C for the adjacent catchment and the water depth over the weir crest were determinate in the calibration phase.

In the lower area of the Dafundo catchment, the delimitation of the drainage sub-catchments was required for the surface runoff model building, being each sub-catchment characterized in terms of length, total area, pervious and impervious areas. The whole lower area of the Dafundo catchment is 2.7ha and the percentage of impervious area is 84.3%. The lower area the sub-catchments were separated into three categories: local roads, buildings and green areas. The determination of impervious area percentages in each sub-catchment was carried out using the developed DEM, considering for local roads and buildings an imperviousness of 100%.

Each sub-catchment was connected to the corresponding surface water inlet or manholes. In figure 11 the delimitation of the sub-catchments in the lower area is detailed, being the characterization of each sub-catchment described in the Appendix I.

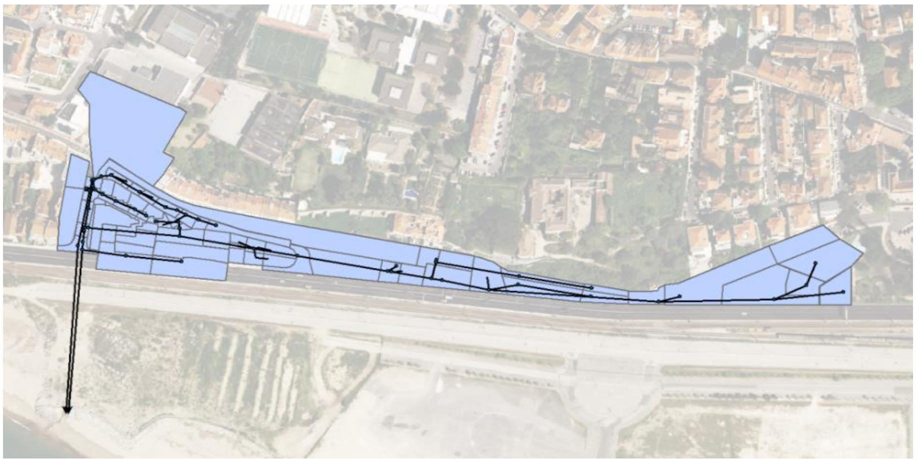


Figure 11 – Delimitation of sub-catchments in the downtown area of Dafundo

The time-area method was selected in the runoff model which takes into consideration the catchments shape. By default, it was considered rectangular. Initially the concentration time for the sub-catchments was defined as 7min, being verified in the calibration phase as well as the shape.

The stormwater drainage system defined in the 1D network model was developed based on the available inventory data provided by the water utility, being validated and, in specific cases, modified through the information obtained in the field works. The network model is composed by manholes (normal and sealed), basin (surface water inlets elements), pipes and additional weirs, inserted to regulate the additional catchments contribution and the obstruction scenarios.

The terrain level defined in manholes and surface water inlets was validated through the elevation points used in the DEM construction, as this information was recently collected to update the urban drainage information. In figure 12 the existing stormwater drainage system in the Dafundo downtown is presented.

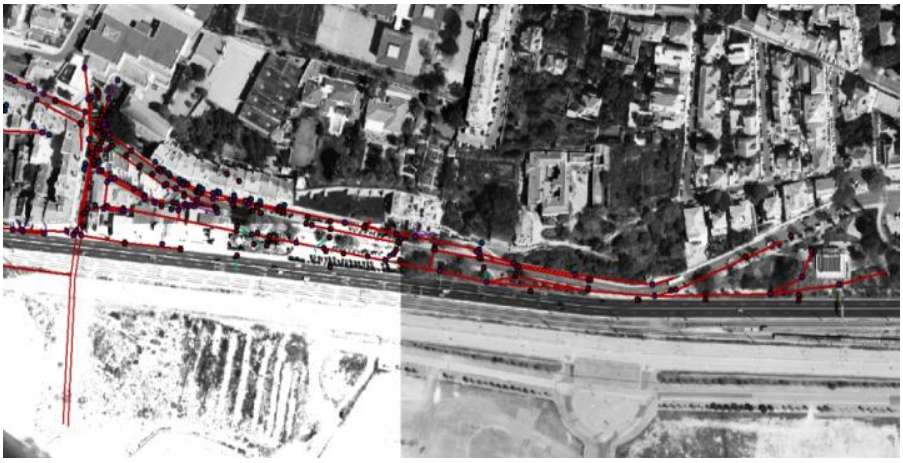


Figure 12 – Stormwater drainage system of the Dafundo downtown area

In certain cases, for example in the Junça river, when it is required to reproduce the pipe junctions detailed in the inventory data, incorporate additional elements or report 1D modelling results in these sections, sealed manholes were defined in the network model.

The geometric representation of surface water inlets was carried out through the selection of predefined curves which are defined in table 10. Each curve defines the relation between the superficial area (As) and the transversal area (Ac) for each component.

Table 10 – Predefined curves defined in the 1D network model

Curve ID	**Ac** **[m^2]**	**As** **[m^2]**
Curve- 1	0.01	0.10
Curve 2	0.02	0.10
Curve 3	0.03	0.10
Curve 4	0.03	0.40
Curve 5	0.03	0.70
Curve 6	0.12	0.12

The boundaries conditions in the 1D/2D model included the definition of the water level in the Tagus estuary and the rainfall events defined for the simulation scenarios. The rainfall events were assigned as a boundary condition in the catchment and sub-catchments. The estuarine water level in the Tagus estuary were defined as time series and were established as downstream condition at the two outfalls, the canalized Junça River and the parallel duplication of the canalized Junça River. In the figure 13 the network model and the delimitate sub-catchment are represented.

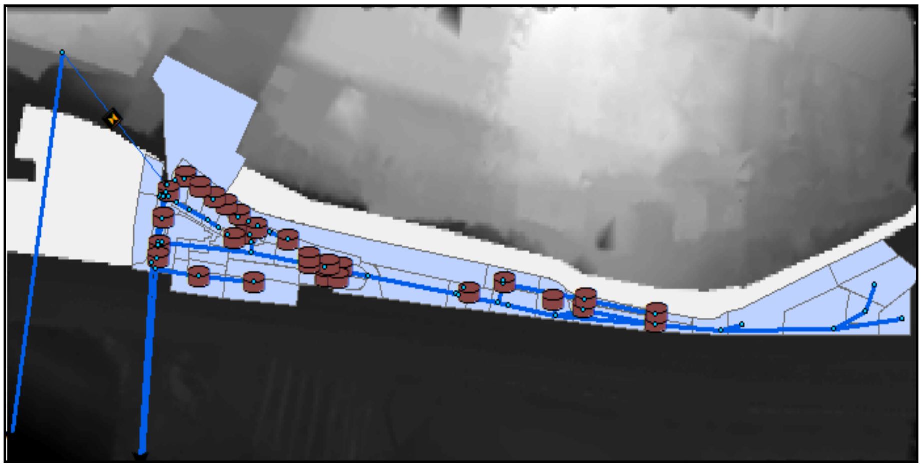


Figure 13 – Representation of 1D/2D model

As result from the field works, it was identified several levels of sediments in some sewers and it was observed that the natural tidal dynamics at the Dafundo beach promotes the obstruction of the outfalls, reducing their cross sections approximately until 10%. After sand removal operations, sediments were naturally replaced two or three weeks after. To represent these restriction, a standard situation was defined in order to consider obstruction conditions that corresponds to specific levels of sediments in the sewers. In the standard situation, the outfalls obstruction was also considered. Despites a level of sediments was imposed in the canalized Junça River and the parallel duplication of the canalized Junça River, two additional weirs were defined in order to reproduce accurately the frequent obstruction at the outfalls.

Once the 1D network and the 2D surface runoff models were built, the 1D/2D coupling between them was carried out through the devices that collect the runoff, being defined an urban link in each connection. The stormwater devices are regular manholes and surface water inlets. The criteria established for the coupling between the computational cells and the inlets was that the difference between the terrain level in the cell and in the inlet should be less than 0.10m

In the 1D/2D model, a square and uniform mesh with a cell size of 1.0m was adopted. The dimension of the mesh was established as a solution between the required accuracy and an adequate computational effort, taking into consideration the high number of simulation scenarios established.

In a reduced number of scenarios, corresponding to scenarios with obstruction and higher tide levels, it was required to reduce the cell size until 0.05m to ensure convergence achievement. In figure 14 the 1D/2D integrated model with the computational mesh adopted is represented.

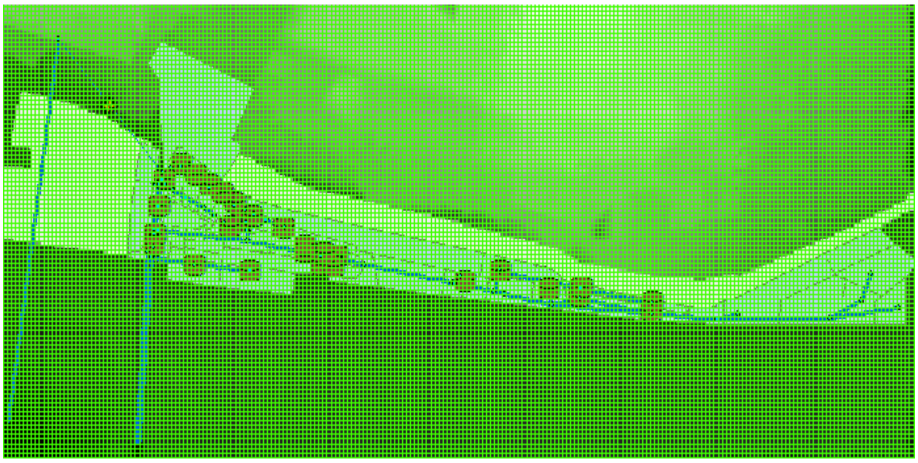


Figure 14 – Representation of the adopted mesh in the 1D/2D integrated model of the case of study

6.4.2. Results of calibration phase

Model calibration was based on the hydrograph provided by the simplified model of the upper catchments and the water depths obtained in the monitoring sites. Modelling results were validated through the historical information regarding flood occurrences reported, provided by local authorities.

In the calibration phase it was determined: i) the parameter required to achieve and adequate hydrological behaviour for the main and adjacent catchments of the upper area; ii) the shape and the concentration time in the sub-catchments; iii) the degree of obstruction in sewers that reproduces the historical flooding occurrences based on the historical information provided by the responsible entities.

The hydraulic and hydrological behaviour of the 1D/2D drainage system model was calibrated considering selected rainfall events, with different rainfall intensities, and the water level monitored in several sections, during the monitoring phase. Table 11 presents the rainfall events considered in the calibration phase, specifying the type of event, the period and the considered flow meter.

Table 11 – Rainfall events used in the calibration phase

Rainfall event	Event Type	Initial date	Final date	Flow meter designation
1	Wet weather	06-09-2014, 06:00	06-09-2014, 15:00	LNEC 2
2	Wet weather	06-/09-2014, 21:00	07-09-2014, 03:00	LNEC 2
3	Wet weather	10-09-2014, 09:00	10-09-2014, 15:00	LNEC 2
4	Wet weather	15-01-2015, 12:00	15-01-2015, 21:00	SIMAS 3
5	Wet weather	15-01-2015, 21:00	16-01-2015, 06:00	SIMAS 3
6	Wet weather	16-01-2015, 06:00	16-01-2015, 15:00	SIMAS 3
7	Wet weather	17-01-2015, 15:00	18-01-2015, 09:00	SIMAS 3
8	Dry weather	18-01-2015, 15:00	19-01-2015, 00:00	SIMAS 3
9	Wet weather	20-01-2015, 00:00	20-01-2015, 09:00	SIMAS 3
10	Dry weather	20-01-2015, 09:00	20-01-2015, 18:00	SIMAS 3

In the calibration of 1D/2D model, for the upper catchment a time concentration of 10min and a base flow discharge of 20l/s was determined. For the additional catchment, with the same characteristics, the parameter of the Rational Method (C) with the same value of the upper catchment (C=0.23) was verified to be adequate. It was determined that the contribution of the additional catchment to the 1D/2D modelling network, for higher rainfall events, occurs when the water depth over the crest is higher than 0.15m.

Figure 15 and figure 16 shows a significant agreement between the flow discharge modelled by 1D/2D and the estimated provided by the simplified model, either for reduced or for higher intensity rainfall events. However, the peak flow is under calculated by the 1D/2D model regarding the estimated value.

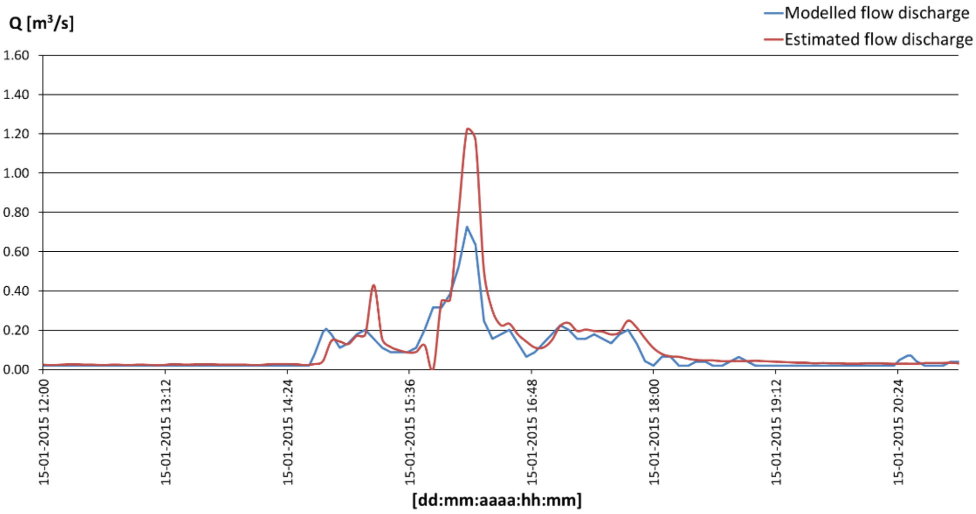


Figure 15 – Comparison between the 1D/2D modelled and estimated flow discharge, based on the simplified model, for the rainfall event registered since 15-01-2015(12:00) to 15-01-2015 (09:00)

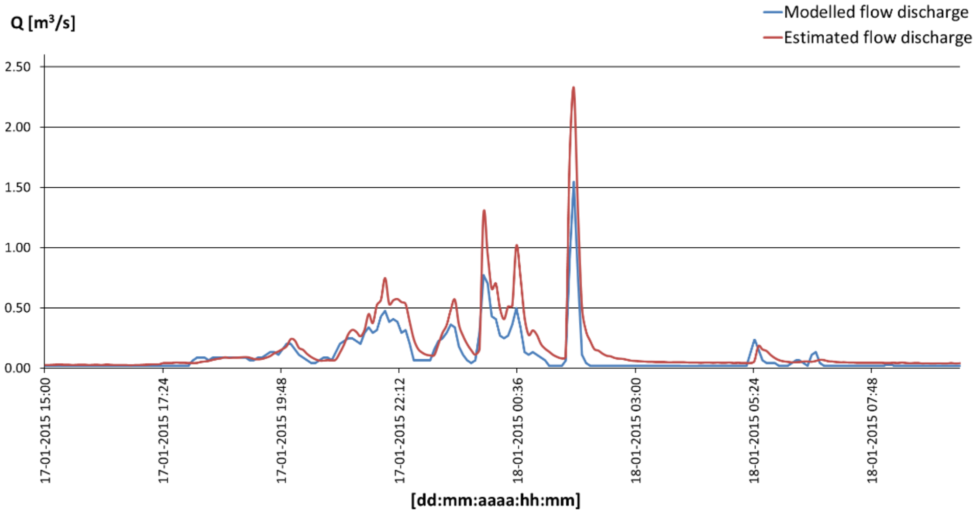


Figure 16 – Comparison between the 1D/2D modelled and estimated flow discharge, based on the simplified model, for the rainfall event registered since 17-01-2015 (15:00) to 18-01-2015 (09:00)

In figure 17 and figure 18 the water depth obtained by 1D/2D and monitored are detailed for the same rainfall events (Figure 15 and Figure 16). The results are presented for the manhole that corresponds to the section in which the upper and lower area of Dafundo catchment were segmented.

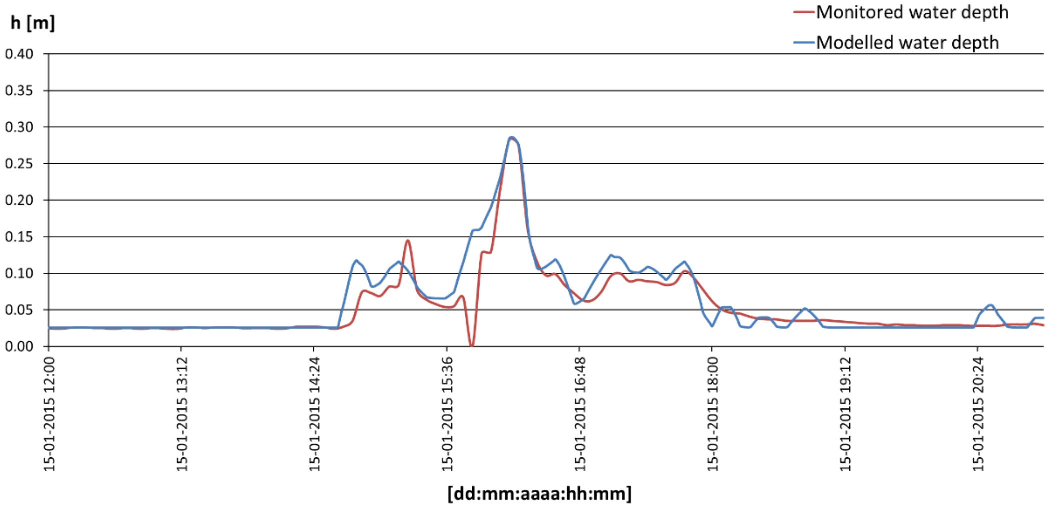


Figure 17 – Comparison between the 1D/2D modelled and monitored water depth for the rainfall event registered since 17-01-2015 (15:00) to 18-01-2015 (09:00)

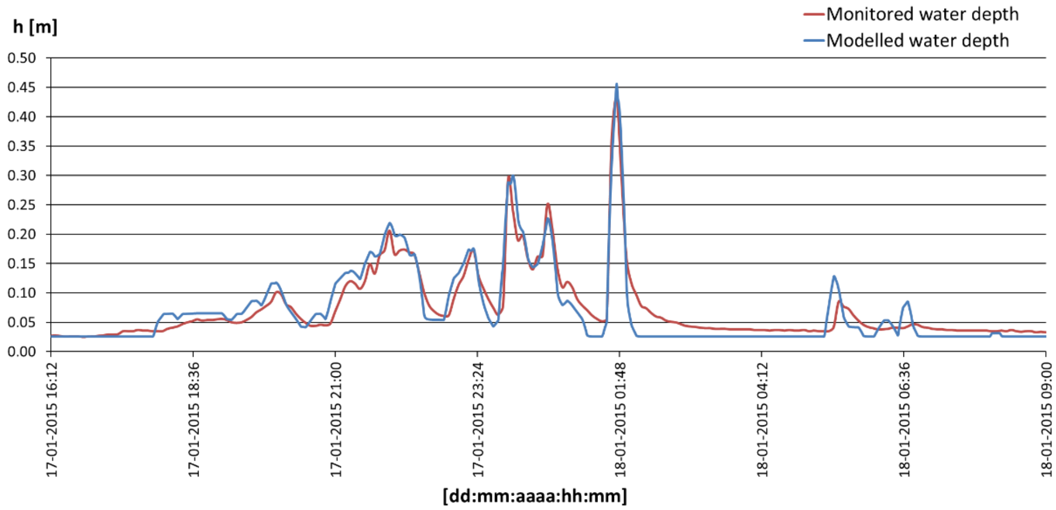


Figure 18 – Comparison between the 1D/2D modelled and monitored water depth for the rainfall event registered since 17-01-2015 (15:00) to 18-01-2015 (09:00)

In the calibration it was observed an adequate adjustment between the results of the 1D/2D model and the available data based on the monitoring works (water depth, flow discharge). However, for the rainfall events with higher intensities the peaks of the flow discharge or water depths are slightly underestimated. Considering the selected rainfall event, the volume error varies between 5.5 and -24.5% while the flow discharge peak error ranges between -10.4 and -40.6%.

The concentration time of the sub-catchments was calibrated and all concentration time remained as 7 min except in the catchments that discharge to the canalized Junça River. The concentration time for this sub-catchments was defined as 10 min.

For the scenarios that correspond to “with obstruction” several degree of sediments in pipes were tested. The sediment deposition was defined corresponding to a height of 0.20m in sewers, among 25 and 30% of the pipe section, and a cross section obstruction at the outfalls of 90%, in which recurrent obstruction are described in the inventory data or was observed in field works.

6.4.3. Selection of scenarios

Design and uniform rainfall events were considered for the selected scenarios, which were calculate according to 5.3.5. Three monitored rainfall events, registered in the Dafundo catchment, are also simulated. In table 12 scenarios of rainfall events considered in the 1D/2D modelling are showed.

Table 12 – Scenarios of rainfall events defined in the 1D/2D modelling

Rainfall event type	Designation	T [years]	I_{max} [mm/h]	P_{tot} [mm]
Design rainfall	pp_1	10	56.12	57.38
	pp_2	20	63.40	66.62
	pp_3	50	72.74	79.13
Uniform rainfall	pu_1	-	14.34	57.38
	pu_2	-	16.65	66.62
	pu_3	-	19.78	79.13
Registered rainfall	pr_1	-	20.77	21.02
	pr_2	-	38.27	14.83
	pr_3	-	4.28	7.80

T: return period
I_{max}: maximum rainfall intensity
P_{tot}: accumulated rainfall

The tide scenarios of the estuarine water level estuary were established taking into consideration the tide amplitude and storm surge effects, which reflects the alteration of the tide level due to the atmospheric pressure. A maximum and a minimum variation of the water level of 0.5m and -0.3m are considered, respectively, to reflect the storm surge effects. The maximum and minimum limits for the amplitude value of the tide adopted are 4.2m and 0.8m, based in Fortunato *et al.* (2014). The worst and the best case scenarios are 2.74m and -2.26m, respectively, considering the maximum and minimum water level.

In the table 13 the estuarine water levels considered in the scenarios are detailed. The tide scenarios are referred at the topographical zero, considering a value of 2.08 m. The tide scenarios below 0.65m are not considered because the water level is located below the outfalls.

Table 13 – Scenarios of tide level defined in the 1D/2D modelling

Mean sea level MSL [m]	Storm surge [m]	Semi-Amplitude [m]	Simulated sea level [m]
0.14	0.50	2.10	2.74
			-1.46
		0.40	1.04
			0.24
	-0.30	2.10	1.94
			-2.26
		0.40	0.24
			-0.56

A degree of obstruction on the sewers and at the outfalls was also considered in the scenarios definition. A standard situation of network operational conditions (“with obstruction”) was defined to represent sediment deposition in sewers and a cross section obstruction at the outfalls of 90%. The operational condition standard values were established according with the field work conclusions. For each tide and rainfall scenarios the 1D/2D coupled model is simulated for the “without obstruction” and “with obstruction” operational conditions.

6.5. COMPARATIVE ANALYSIS BETWEEN 1D AND 1D/2D MODELLING

6.5.1. General remarks

In the present thesis, the objectives of the 1D/2D integrated modelling are to assess the flooding occurrence in the Dafundo stormwater drainage system and to contribute to support flood management in estuarine areas. The comparative analysis between 1D and 1D/2D modelling was carried out in order to evaluate the provided results, level of detail and information that can be achieved using each modelling method. This analysis allows to give some guidance on 1D or 1D/2D modelling use, taking into account the benefits and drawbacks of each model.

The 1D/2D model is simulated for all scenarios, referred in 6.4.3, in function of the rainfall event, tide level and the degree of obstruction, being the maximum water depths and surface extension for each scenario detailed in the Appendix II. For the comparative analysis between the 1D and 1D/2D modelling results some specific scenarios (12) are selected due to the significant number considered in the 1D/2D modelling. The scenarios for the rainfall event include a design rainfall, for a return period of 20 and 50 years, and two real rainfall events. For the tide level, the maximum and minimum values are selected for the comparative analysis of modelling results. The operational conditions "without" and "without obstruction" are also considered. This set of scenarios are adequate to assess the flooding occurrence in the drainage system. In table 14 the scenarios for the comparative analysis between 1D and 1D/2D modelling results are detailed.

Table 14 – Scenarios for comparative analysis between 1D and 1D/2D modelling results

	Simulation	Rainfall event	Return period [years]	Tide level [m]
Without obstruction	A1	pp_2	20	2.74
	A2	pp_2	20	0.64
	A3	pp_3	50	2.74
	A4	pp_3	50	0.64
	A5	pr_1	-	2.74
	A6	pr_2	-	2.74
With obstruction	B1	pp_2	20	2.74
	B2	pp_2	20	0.64
	B3	pp_3	50	2.74
	B4	pp_3	50	0.64
	B5	pr_1	-	2.74
	B6	pr_2	-	2.74

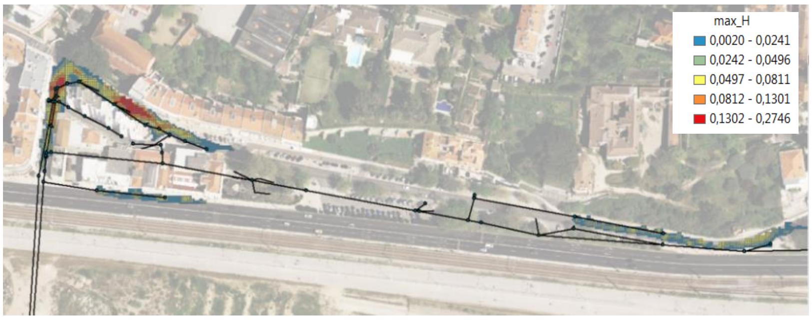
Flooding extension, maximum water depth and duration were the variables selected to perform the comparative analysis between 1D and 1D/2D results, according to 5.4. The surface velocities were not analysed in the present case study because the modelled area is characterized by a flat surface. In future research work, the surface velocities will be studied as they may represent an important issue in flooding occurrence assessment, particularly in areas characterized by an irregular orography, since may be responsible for serious injuries and damages.

The comparative analysis between 1D and 1D/2D modelling was carried out for the selected scenarios presented in 5.4. A detailed analysis is presented for the scenarios B3 and A3, corresponding to the worst simulated scenarios for the operational condition “with obstruction” and “without obstruction”, respectively, in term of area affected by flooding in Dafundo catchment, maximum water depth and number of flooded manholes and surface water inlets.

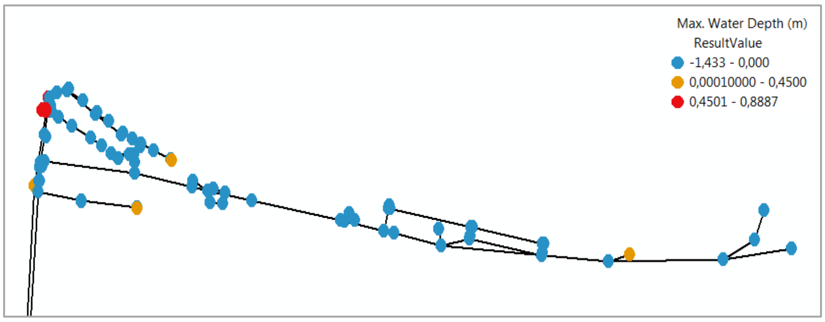
To conclude, a summary and discussion of 1D and 1D/2D modelling results for maximum water depth, flooding extension and maximum duration variables for all scenarios is carried out.

6.5.2. Worst scenario with obstruction (B3)

The worst scenario with obstruction (B3) corresponds to a design rainfall with a return period of 50 years, a tide level of 2.74m and the operational condition “with obstruction”. This scenario presents the highest maximum water depth and flooding extension. Figure 19 presents the maximum water depth calculated using 1D and 1D/2D modelling results for the scenario B3.



a) 1D/2D model

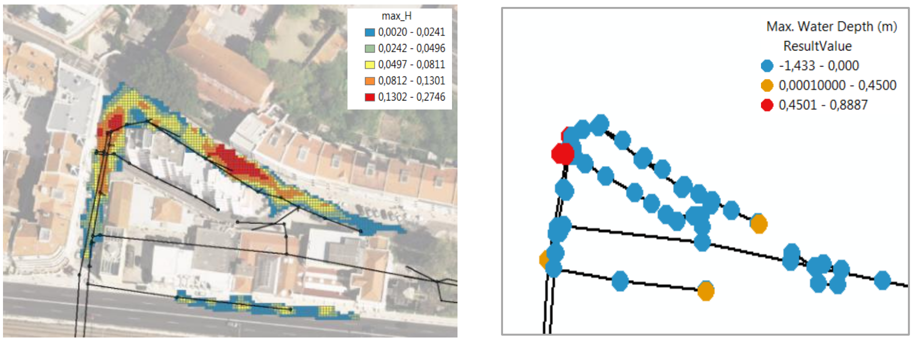


b) 1D model

Figure 19 – Maximum flood water depth (m) for scenario B3: a)1D/2D model, b) 1D model

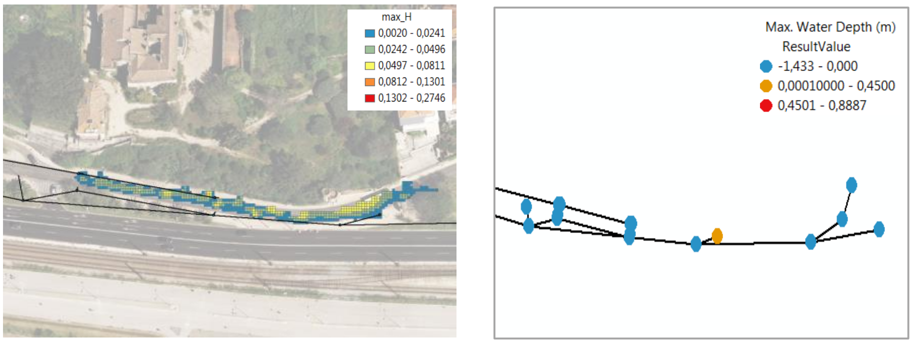
In this figure, according to 1D/2D modelling results, for scenario B3 flooding occurs in three area locations but present significant differences between maximum water depths. The maximum value at the Dafundo area is 0.27m, with a maximum duration of 2.03h, located in the upper west flooding extension. The maximum water depths in this area are significantly higher comparing with the other two areas. It is noted that the lowest west area presents lower maximum water depths. However, the flooding is located in a main road that represents a critical location in Dafundo catchment.

Referred to the same manhole, for the 1D modelling results the maximum value for maximum water depths is 0.89m, three times higher than the 1D/2D results, and flooding duration is 2.44h. Flooding occurrence is registered in nine manholes and surface water inlets. A detailed perspective of 1D and 1D/2D results for west and east area of Dafundo is showed in figure 20.



a) 1D/2D model - West area

b) 1D model - West area



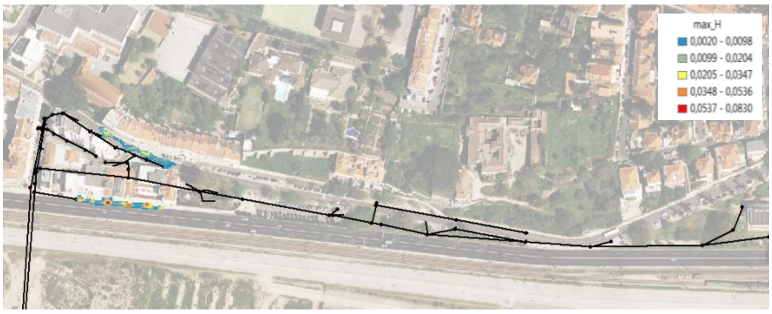
c) 1D/2D model - East area

d) 1D model - East area

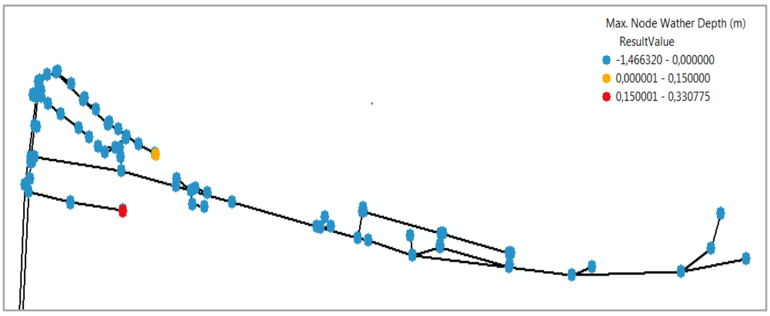
Figure 20 – Maximum flood water depth (m) for scenario B3 in the west and east areas

6.5.3. Worst scenario without obstruction (A3)

The worst scenario without obstruction (A3), corresponds to the same design rainfall (return period of 50 years) and a tide level (2.74m) as in 6.5.2 but the operational condition “without obstruction”. This scenario presents the highest maximum water depth and flooding extension for the operational condition “without obstruction”. figure 21 presents the maximum water depth calculated using 1D and 1D/2D modelling results for the scenario A3.



a) 1D/2D model



b) 1D model

Figure 21 – Maximum flood water depth (m) in the west and east area for scenario A3

In this figure, according to 1D/2D modelling results, for scenario A3 flooding occurs in two areas located in the west area of the Dafundo catchment. The maximum value for maximum water depth is 0.08m with a maximum duration of 2.20h. Maximum water depth are significantly lower for the operational condition "without obstruction". It is noted that the maximum value for this scenario is located in the lowest west area, which is placed in the main road.

Referred to the same manhole, for the 1D modelling results the maximum value for maximum water depths is 0.33m, four times higher than the 1D/2D results, and the flooding duration is 1.93h. Flooding occurrence is registered in two manholes and surface water inlets. A detailed perspective of 1D and 1D/2D results for the west area of Dafundo is showed in figure 22.

a) 1D/2D model - West area

b) 1D model - West area

Figure 22 – Maximum flood water depth (m) for scenario A3 in the west area

6.5.4. Comparative assessment analysis

The comparison between 1D and 1D/2D modelling was carried out considering the maximum duration of flooding, flooding extension and maximum water depths.

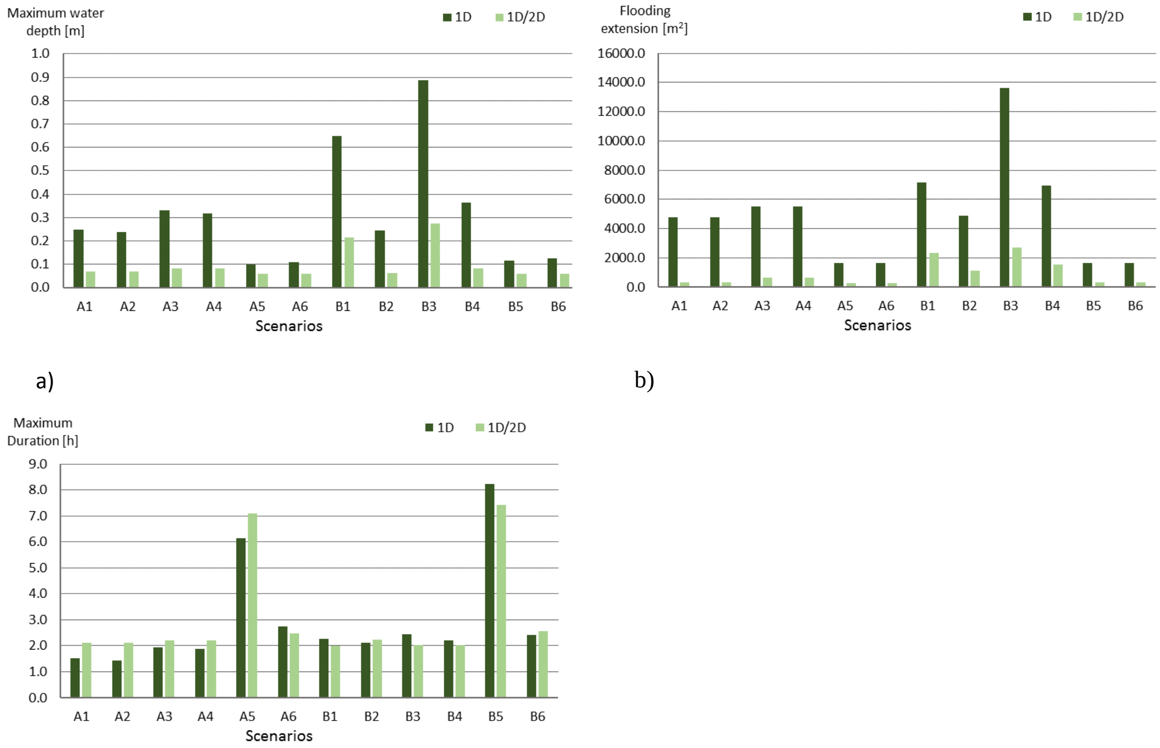
The maximum duration of flooding occurrence was calculated in the manhole or water surface inlet where the maximum value for maximum water depths was obtained. Flooding extension was estimated through GIS, based on the results obtained by each model for each scenario. It was obtained by representing the maximum water depth in the flooded surface elements over the DEM, which was previously developed for the 1D/2D model. To determine the flooding extension for 1D model result, it was required to evaluate each flooded manhole or surface water inlet. The flooding extension using 1D/2D modelling was delimited based in the computational flood. The 1D and 1D/2D results of maximum water depth, flooding extension and maximum duration for considered scenarios, referred in 5.4, are detailed table 15.

As can be observed, the maximum water depths and flooding extension results are highly overestimated in the 1D modelling for all the considered scenarios. In the case of the operational condition " with obstruction" and for the design rainfall events (B1, B2, B3 and B4) the difference between the 1D and 1D/2D modelling results are more pronounced. Despites the overestimation of 1D modelling, this model shows a better behaviour in terms of maximum water depth for the scenarios less serious, which correspond to the two real rainfall events (A5, A6, B5 and B6). A reasonable agreement is achieved for the maximum duration of flooding between the 1D and 1D/2D results, being the average error 3.9%.

In figure 23 the results for the maximum water depth, flooding extension and duration variables are presented.

Table 15 – 1D and 1D/2D model results for selected scenarios: maximum water depth, flooding extension and maximum duration

Scenario	Flooding extension [m^2]		Maximum water depth [m]		Maximum duration [h]	
	Type of model					
	1D	1D/2D	1D	1D/2D	1D	1D/2D
A1	4748.09	335.29	0.247	0.068	1.52	2.11
A2	4748.09	335.29	0.239	0.068	1.43	2.11
A3	5500.99	619.61	0.331	0.083	1.93	2.20
A4	5500.99	619.61	0.317	0.083	1.87	2.20
A5	1621.93	273.34	0.099	0.059	6.15	7.09
A6	1666.50	281.53	0.109	0.059	2.74	2.49
B1	7168.40	2319.45	0.647	0.215	2.28	2.01
B2	4902.45	1093.61	0.246	0.062	2.12	2.24
B3	13609.95	2714.61	0.889	0.275	2.44	2.03
B4	6969.85	1548.92	0.363	0.083	2.22	2.03
B5	1621.93	311.82	0.115	0.059	8.22	7.44
B6	1666.50	313.82	0.124	0.059	2.43	2.56



a)

b)

c)

Figure 23 – 1D and 1D/2D model results for selected scenarios: a) maximum water depth, b) flooding extension and c) maximum flood duration

The post processing of flooding extension results, in the case of 1D modelling, may incorporate a significant error due to the estimation based on the maximum water depths, without considering the respective decrease of water depth over the terrain surface. The 1D/2D modelling results show the importance of considering the influence of terrain and urban features of the urban catchment in the assessment of the consequences of flooding occurrences.

The 1D/2D model provides a more representative and detailed information allowing to better evaluate the importance of the flooding occurrence in terms of consequence, considering: i) the maximum water depth; ii) number of flooded manholes and surface water inlets, that have flooded either by the drainage network surcharging or by the insufficient capacity of the element that collects surface runoff; iii) terrain surface and urban features that can be affected by the flooding extension.

The 1D model can be useful for a first assessment of the expectable maximum water depths, in case of flooding occurrence, for scenarios less serious as the real rainfall events. However, it should be considered that the maximum water depth in a 1D modelling is calculated through the storage of the exceed volume in a virtual storage unit, and will be overestimated due to the terrain surface is not consider.

6.6. PERFORMANCE ASSESSMENT RESULTS

6.6.1. Required information

The performance assessment of the stormwater system at the downtown area of Dafundo was performed based on both the 1D and 1D/2D modelling results for the scenarios selected in the comparative analysis (6.5). The objectives are: i) to apply to stormwater systems the methodology presented for performance assessment, based on performance indicators, ii) to validate the new PI proposed for stormwater systems; and iii) to identify, compare and analyse, in terms of benefits and drawbacks, the performance information provided by each type of model 1D or 1D/2D. The PI detailed in 5.5.2 include physical, operational and quality of services PI proposed in the IWA system (Matos *et al.*, 2003) as well as PI developed in the framework of this thesis, mainly focusing in the flooding occurrence assessment.

In order to apply the PI for each scenario, the model information required for their calculation was selected and exported. This information consists in: number of flooding manholes or surface water inlets, number of flooding incidences corresponding to locations affected by flooding, maximum water depth, maximum duration of flooding, surcharged pipes and level of surcharging in pipes.

The representation of modelling results in GIS was required to determine the flooding extension, critical locations and extension of roads affected by flooding occurrence. The duration of the interruption, needed for PI-4 calculation, was considered equal to the maximum flood duration obtained, from the simulations carried out, since the performance assessment is applied at the global catchment level.

6.6.2. Interpretation of performance indicators results from 1D and 1D/2D models

Table 16 presents the results of the performance indicators selected to assess the performance of the stormwater system of the Dafundo downtown. PI were obtained for all scenarios from both 1D and 1D/2D modelling.

Figure 24 and figure 25 present the PI Wph6 and Wph7 result for all scenarios from both 1D and 1D/2D modelling. Wph6 depends on the length of sewer in surcharge condition during the assessment period, while PI Wph7 refers to high degree of surcharging. Wph6 shows that a significant part of the network system is in surcharge condition for the scenarios corresponding to the maximum tide level and this condition is aggravated for the operational condition “with obstruction”. The higher values of Wph6 correspond to the scenarios for the operational condition “with obstruction”, design rainfall event and maximum tide level (B1 and B3), for both 1D and 1D/2D modelling results.

Table 16 – PI for selected scenarios from the 1D and 1D/2D modelling results

Scenario	Model type	**WPh6** (surcharge)	**WPh7** (high surcharge)	**WOp38** (flooding incidents)	**PI-1** (flooded manholes and inlets)	**PI-2** (flooded area extension)	**PI-3** (flooding incidents)	**PI-4** (critical locations affected)	**PI-5** (flooding duration)	**PI-6** (roads affected)
		[%]	[%]	[No./100 km sewer/year]	[No./100 km sewer/year]	[%]	[No./m2]	[No./1000 critical locations/ year]	[%]	[m]
A1	1D	0.41	0.37	26.67	26.67	24.42	0.74	0.47	37.99	120.96
	1D/2D	0.41	0.37	26.67	80.01	24.42	0.74	0.31	52.74	42.59
A2	1D	0.11	0.07	26.67	26.67	28.30	0.74	0.47	35.69	113.66
	1D/2D	0.11	0.09	26.67	80.01	28.30	0.74	0.31	52.74	42.59
A3	1D	0.44	0.37	26.67	26.67	8.34	0.74	0.47	48.13	153.33
	1D/2D	0.44	0.37	26.67	106.68	8.57	0.74	0.31	54.95	73.60
A4	1D	0.12	0.09	26.67	26.67	36.87	0.74	0.47	46.67	148.68
	1D/2D	0.12	0.09	26.67	106.68	25.22	0.74	0.31	54.95	73.60
A5	1D	0.37	0.34	3.88	3.88	70.01	0.37	0.09	44.75	143.77
	1D/2D	0.31	0.34	3.88	15.52	35.85	0.37	0.05	51.58	59.87
A6	1D	0.37	0.34	11.85	11.85	8.34	0.37	0.28	60.93	144.63
	1D/2D	0.37	0.33	11.85	47.41	8.57	0.37	0.14	54.72	60.23
B1	1D	0.47	0.28	106.68	106.68	1.72	1.11	0.94	56.94	356.58
	1D/2D	0.53	0.42	106.68	440.05	1.72	0.37	0.78	50.13	153.59
B2	1D	0.26	0.13	40.00	40.00	3.19	1.11	0.47	53.06	252.70
	1D/2D	0.26	0.13	40.00	146.68	3.19	1.11	0.31	56.04	114.98
B3	1D	0.48	0.28	120.01	120.01	1.41	1.11	1.41	60.97	478.23
	1D/2D	0.68	0.48	120.01	480.05	1.45	1.11	0.78	50.83	196.39
B4	1D	0.27	0.16	66.67	66.67	11.93	1.11	1.10	55.49	372.76
	1D/2D	0.27	0.15	66.67	173.35	5.63	1.11	0.47	50.83	137.91
B5	1D	0.39	0.20	3.88	3.88	13.96	0.37	0.05	59.78	149.73
	1D/2D	0.39	0.20	3.88	15.52	7.97	0.37	0.05	54.09	64.63
B6	1D	0.43	0.20	11.85	11.85	1.60	0.37	0.14	53.89	149.73
	1D/2D	0.43	0.20	11.85	47.41	1.61	0.37	0.14	56.80	66.62

The results obtained for Wph7 confirm the importance and the significant effect of the Tagus estuary tide level on the high degree of surcharging.

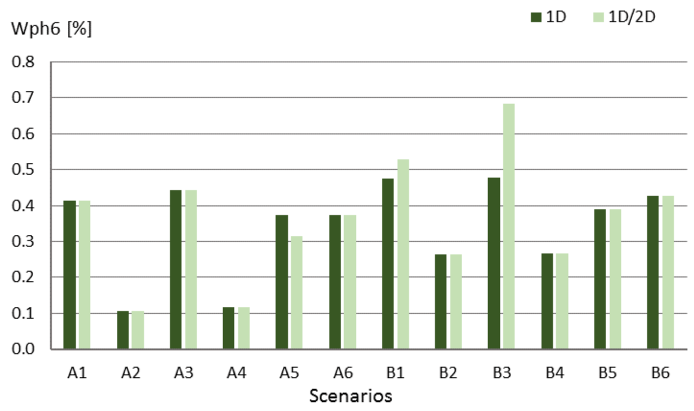


Figure 24 – Performance indicator Wph6: "Surcharging in gravity sewers in wet weather"

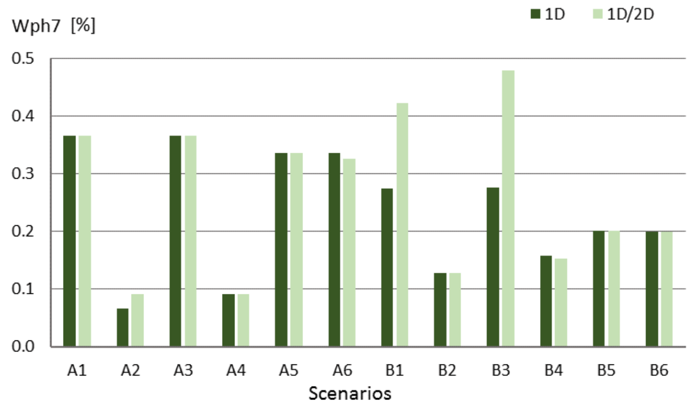


Figure 25 – Performance indicator Wph7: "High sewer surcharging"

The number of flooding incidents related to the stormwater drainage system is assessed through the performances indicator WOp38, in which the flooding incidents are the locations affected. In figure 26 the WOp38 is detailed for the selected scenarios for both 1D and 1D/2D modelling results. The results obtained show a significant increase of flooding incidents for the scenarios B1 and B3 that correspond to the operational condition "with obstruction", design rainfall event and maximum tide level. In Dafundo urban area the WOp38 results show the importance of the operational condition in the flooding occurrence for the scenarios more serious in terms of rainfall.

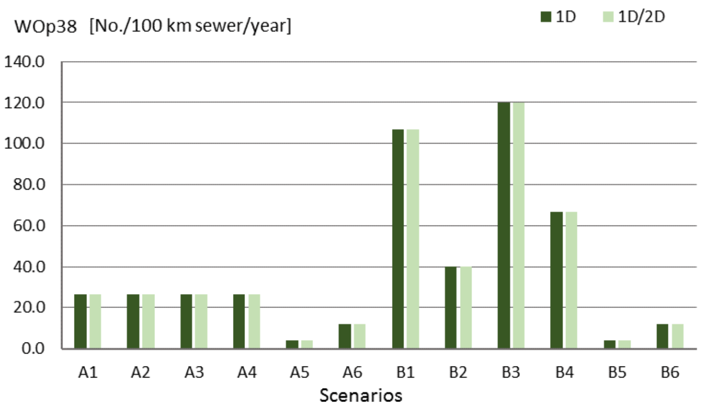


Figure 26 – Performance indicator WOp38: "Flooding from combined sewers"

The performance indicator PI-1 proposed in the present thesis focuses the analysis on the manholes or surface water inlets affected by flooding, providing a more detailed information of the flooding occurrence in the stormwater drainage system. It takes into consideration the flooding occurrence either due to insufficient capacity of drainage system or to insufficient capacity of the water inlets. In figure 27, PI-1 is presented for the selected scenarios for both 1D and 1D/2D modelling results.

Due to the limitations of the 1D modelling where the flooding occurrence due to the insufficient capacity of surface drainage is not considered, WOp38 and proposed PI-1 give equal results. The performance indicator PI-1 is useful as it considers a more detailed information from the 1D/2D model. For 1D/2D modelling results, the combined evaluation of the WOp38 and PI-1 allows to identify the causes of flooding and to select an adequate solution. The insufficient capacity of surface water inlets increases significantly the occurrence of flooding. The PI-1 result from 1D/2D modelling confirms that the influence of operational conditions in flooding occurrence are aggravated by the effect of the tide level in the case of operational condition "with obstruction".

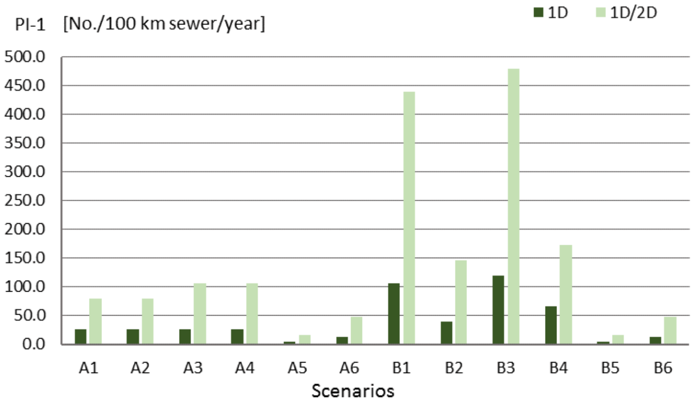


Figure 27 – Performance indicator PI-1: "Flooding per manholes from stormwater sewer"

The PI-2 calculated from 1D modelling results show high flooding extensions for the scenarios of rainfall design event, presenting an important addition to the operational condition, "obstruction". In Figure 28, IP-2 is presented for selected scenarios of both 1D and 1D / 2D modelling results. For 1D/2D model, the flooding extension presents a similar behaviour for all the scenarios having operational condition "without construction" and for the real rainfall events and operational condition "with obstruction". For this modelling type, the scenarios "with obstruction" and design rainfall events show a significant increase of the flooding extension.

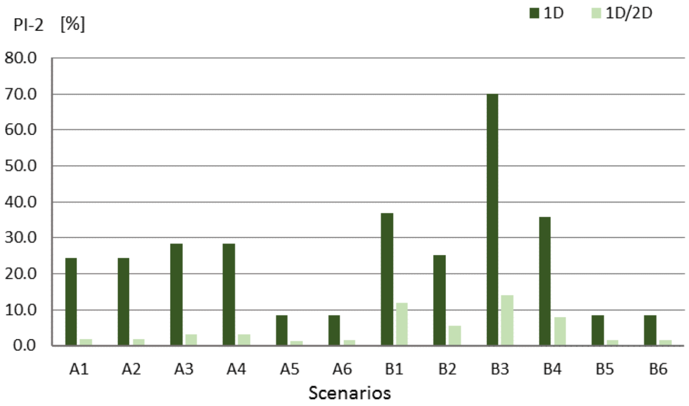


Figure 28 – Performance indicator PI-2: "Flooding extension from stormwater system"

Figure 29 presents the PI-3 for the selected scenarios from both 1D and 1D/2D modelling. The number of flooding incidents related to the urban catchment, detailed though the PI-3 results, show the influence of the existing operational condition in the network, being the effect of the tide level attenuated. For the most serious scenarios in term of rainfall event the PI-3 results confirm the importance to consider the operational condition.

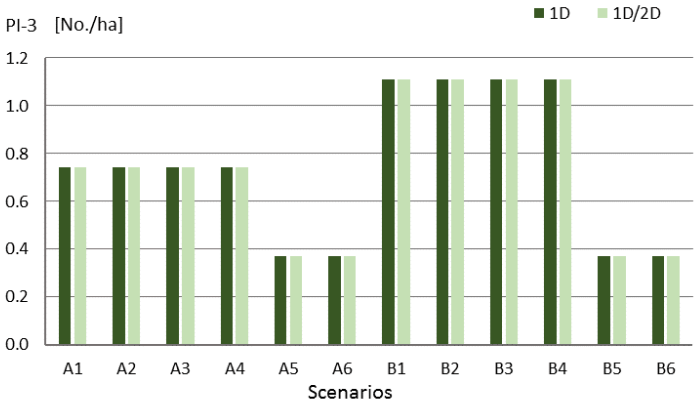


Figure 29 – Performance indicator PI-3:"Flooding incidence per catchment"

Figure 30 presents PI-4 results for the selected scenarios from both 1D and 1D/2D modelling. The number of critical locations affected by flooding, assessed through PI-4 results, is significant for almost all considered scenarios. Only the scenarios that correspond to real rainfall event present less critical locations affected by flooding. Dafundo is an estuarine urban area characterized by high number of locations, services and infrastructures that should be considered as critical locations due to the significant negatives consequences associated to flooding occurrence.

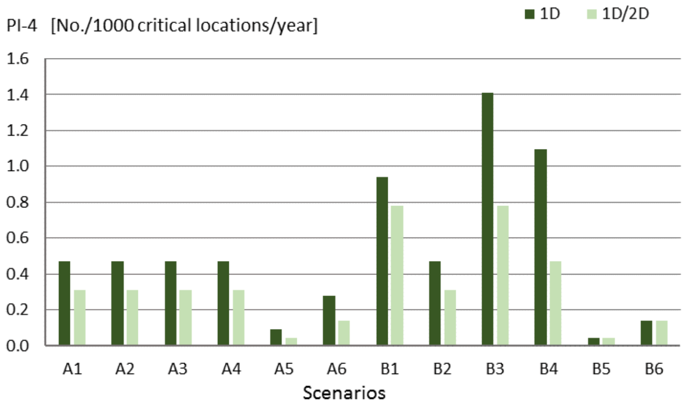


Figure 30 – Performance indicator PI-4: "Surface water flooding of critical locations in wet weather"

Figure 31 presents PI-5 results for selected scenarios from both 1D and 1D/2D modelling. The PI-5 results show that the stormwater system is affected by flooding during a significant period for each rainfall event. All scenarios show an interruption of stormwater service from 30 to 60% of rainfall event duration, averaging at 51% when both 1D and 1D/2D modelling are considered.

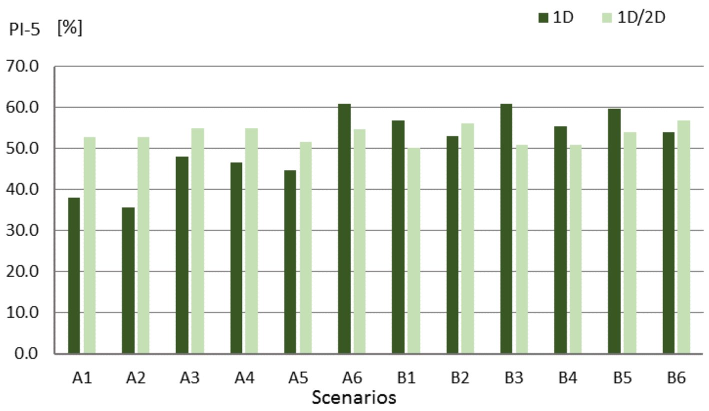


Figure 31 – Performance indicator PI-5: "Interruption of stormwater services"

The results obtained for PI-6 are presented in figure 32 for the selected scenarios from both 1D and 1D/2D modelling. The Dafundo urban area carries out substantial traffic disturbances for all considered scenarios. The results for PI-6 show that the most important factor for traffic disturbances is the operational condition of the drainage systems, being the effect exacerbated for the more serious scenarios in terms of rainfall. The traffic disturbances present similar behaviour for all scenarios of operational condition "without obstruction" and for the scenarios corresponding to real rainfall event for operational condition "with obstruction".

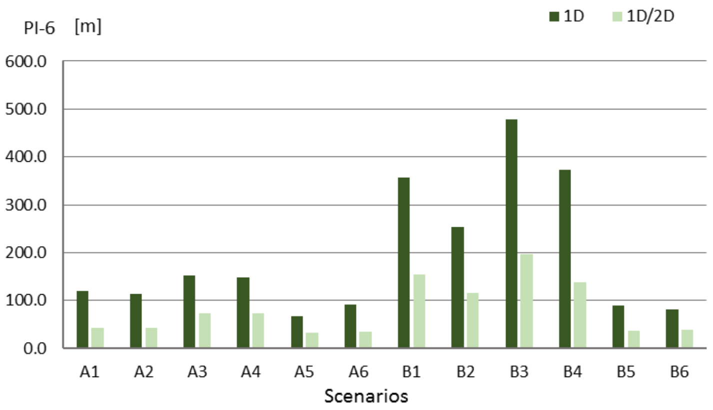


Figure 32 – Performance indicator PI-6: "Traffic disturbances"

6.6.3. Analysis of performance indicators results from 1D and 1D/2D models

Once the interpretation of performance indicators was developed a comparative analysis in terms of benefits and drawbacks of performance information provided by each type of model 1D or 1D/2D is presented.

The Wph6 and Wph7 are similar between from 1D and 1D/2D modelling results, particularly for the scenarios that correspond to the operational condition "without obstruction" (A1, A2, A3, A4, A5 and A6). In Wph6 the differences between the use of 1D and 1D/2D model are reduced. The surcharge condition of the network system can be evaluated through both type of modelling. The highest difference is obtained for the worst scenario (B3) for the operational condition "with obstruction" that corresponds to the design rainfall event (return period of 50 years) and maximum tide level. For the Wph7, in which the high degree of surcharging is assessed, the differences based on the provided information by each model type are higher, particularly for the operational condition "with obstruction".

Regarding WOp38, the use of 1D or 1D/2D modelling has no influence because PI only consider the flooding incidents related to the insufficient capacity of drainage system. The proposed PI-1 focus the analysis on the manholes or surface water inlets affected by flooding, providing a more detailed information of the flooding occurrence in the stormwater drainage system. For 1D modelling, WOp38 and PI-1 give equal results because the flooding occurrence for insufficiency capacity of surface water inlet is not considered. PI-1 shows significant difference between 1D and 1D/2D modelling results, increasing for the operational condition "with obstruction". PI-1 results present a significant increase of flooding occurrences when the insufficient capacity of the surface drainage system is considered.

PI-2 results show high differences in function of the modelling type. This PI is calculated in function of the flooding extension, being not adequate use 1D models to evaluate flooding extensions. In fact, high differences are observed in this variable, as presented in the comparative analysis between 1D and 1D/2D results (6.5).The PI-2 results reflect the importance to consider the terrain surface in the flooding occurrence assessment.

The PI-3 obtained from 1D and 1D/2D modelling give equals results because only consider the flooding incidents in terms of number of location affected by flooding related to the urban catchment.

For PI-4, the results present important differences between 1D and 1D/2D modelling. This PI, like PI-2, is calculated based on the flooding area extension that is highly overestimated from 1D modelling results. The critical locations affected by flooding, basis of the PI-4, are less overestimated from 1D modelling for the less serious scenarios, which correspond to all scenarios for the operational condition "without obstruction" and the real rainfall events for the operational condition "with obstruction".

For the interruption of service, a reasonable agreement between results from 1D and 1D/2D modelling is achieved. The interruption of service is calculated in function of the maximum duration of flooding occurrence. This variable presented a good adjustment as presented in the comparative analysis between 1D and 1D/2D results (6.5).

Traffic disturbances evaluated through PI-6 show significant differences between results from 1D and 1D/2D modelling, just like the results obtained for PI-2 and PI-4. The performance indicators that depend on flooding area extension present significant differences 1D and 1D/2D modelling. The higher differences for the traffic disturbance correspond to the operational condition "with obstruction" and design rainfall events.

6.7. SUMMARY AND DISCUSSION OF RESULTS

The comparative analysis between the 1D and 1D/2D modelling results was carried out based on the maximum water depth, flooding extension and maximum duration for the selected scenarios, in which different rainfall event, tide level and operational condition were considered. The most significant differences were obtained for the maximum water depth and flooding extension, when the results using 1D and 1D/2D modelling are analysed. However, in terms of maximum duration a reasonable agreement between the 1D and 1D/2D results was obtained. In a 1D mathematical model, the maximum water depth is calculated as the maximum water depth in a virtual storage unit, in function of the exceeded volume in case of flooding.

The maximum water depths and flooding extension results are highly overestimated on 1D mathematical results, when compared to 1D/2D, especially in the case of the operational condition" with obstruction" and for design rainfall events (B1, B2, B3 and B4). The result for the scenarios A5, A6, B5 and B6, which correspond to real rainfall events, present a better agreement, taking into consideration the limitations in the 1D mathematical modelling.

Flooding extension was obtained through GIS representation of maximum water depth, taking into consideration the provided information for each model. The flooding extension was delineated based on the result for maximum water depth, supplied in a 2D mesh by the 1D/2D model. In the case of 1D modelling, the flooding extension was estimated in function of the maximum water depth registered in the elements that collect the surface runoff. This process, applied to 1D modelling results, induces a significant error because the natural propagation over the terrain surface of the exceeded water volume, in case of flooding, is not incorporated.

The comparative analysis between the 1D and 1D/2D modelling results highlighted the importance of considering the influence of terrain and urban features existing in the urban catchment, as an important issue for the flooding assessment and management.

A detailed comparative analysis was performed for the scenarios A3 and B3, corresponding to a design rainfall event with return period of 50 years, the maximum tide level (2.7m) and the operational condition "without obstruction" and "with obstruction", respectively. Additional information about the location and maximum water depth in each flooded area, number of manholes and water surface inlets affected by flooding were analysed, providing more specific information of flooding occurrence assessment in the Dafundo downtown catchment. For the scenarios A3 and B3 the maximum water depth based on 1D modelling results is three times higher than the results using 1D/2D modelling. This was also verified for the flooding extension, where the differences are significantly amplified.

The scenario B3, corresponding to the operational condition "with obstruction", presented three flooding areas, and the maximum water depth was registered in the upper west area of the Dafundo downtown catchment. Despite the other two areas have a lower maximum water depth, they are located in the main road and street and can carry out significant disturbances and economical losses. For scenario A3, which corresponds to the operational condition "without obstruction", the number of flooding occurrences was reduced to two, located in the west area of the Dafundo downtown catchment. The maximum water depths are significantly lower than those obtained for the scenario B3. It is noticed that for these scenario the main road also flooded.

Performance assessment was based on 1D and 1D/2D modelling results for the scenarios selected in the comparative analysis between the modelling results. The proposed methodology considered a selected set of performances indicators, which includes PI from IWA (Matos *et al*., 2003), and PI developed in the present thesis, that focuses in the flooding occurrence assessment based on the 1D and 1D/2D modelling results.

The PI Wph6 and Wph7 assess surcharging in the sewer system, considering the length of sewer in surcharge condition and with a high degree of surcharging. This PI highlight the influence of the tide level in the surcharge condition, particularly for the operational condition "without obstruction" where differences are higher.

A combined analyse of PI WOp38 and the proposed PI-1 allows to identify the importance of the information provided by the 1D/2D modelling, being the level of detail provided for PI calculation for the different scenarios a significant advantage for the flooding occurrence assessment. Flooding occurrence was evaluated in function of the number of incidents as well as the number of manholes and surface water inlets per sewer length. PI-1 results highlighted the importance to incorporate also flooding due to the insufficient capacity of the surface inlet and not only the cases for surcharged sewer. It is possible to identify operational condition as the most relevant factor in the flooding occurrence for this case study.

The number of flooding incidents related to the urban catchment, detailed though the PI-3 results, show the influence of the existing operational condition in the network, being the effect of the tide level attenuated. For the most serious scenarios in term of rainfall event the PI-3 results confirm the importance to consider the operational condition.

The number of critical location affected by flooding and traffic disturbances, assessed through PI-4 and PI-6 results, respectively, are significant for almost all considered scenarios The operational condition of the drainage system influence significantly the critical location affected by flooding and the traffic disturbances, increasing for the operational condition "with obstruction". The effects of the operational condition are exacerbated for the more serious scenarios in terms of rainfall. For the characteristics of Dafundo a high number of critical location affected by flooding and traffic disturbances are associated. Dafundo is a flat and high populated area, characterized by a significant number of services, buildings and infrastructures located in the downtown area.

The PI-5 results demonstrate that the stormwater system is affected by flooding during a significant period of each rainfall event. All scenarios show an interruption of stormwater service from 30 to 60% of rainfall event duration, averaging at 51% when both 1D and 1D/2D modelling are considered.

The comparative analysis between the 1D and 1D/2D results and the performance assessment based in the proposed methodology showed the significant importance of the operational condition of the stormwater drainage system, increasing flooding occurrences and the negative consequences associated. Flooding occurrence is aggravated due to the conjugated effect of the tide level on the Tagus estuary and operational condition "with obstruction", particularly for the design rainfall scenarios. Is it noticed that significant critical points and roads are affected in a high number of scenarios, what represents important negative impacts in term of public health, socio-economic and environmental consequences.

A comparative analysis in terms of benefits and drawbacks of performance information provided by each type of model 1D or 1D/2D was developed. An adequate agreement between the results obtained from 1D and 1D/2D modelling are observed for the selected PI to assess: i) the surcharging condition of the drainage network (Wph6 and Wph7), ii) flooding from combined sewers that only consider the flooding by drainage network surcharging (WOp38), iii) catchment flooding incidents (PI-3), and iv) the interruption of services (PI-5).

The higher differences between the use of the information provided by the 1D and 1D/2D modelling was identified for the PI that consider: i) the flooding incidents due to the insufficient capacity of water inlets (PI-1), ii) flooding area extension from stormwater system (PI-2), iii) critical location affected by flooding (PI-4) and iv) traffic disturbances (PI-6). The high differences between the PI-1 results from 1D and 1D/2D modelling can be explained by the limitation of the 1D modelling that does not allow to assess the flooding due to the insufficient capacity of the water inlets. For the PI-2, PI-4 and PI-6, the differences are due to the dependency of these PI on the determination of the flooding area extension, and high differences are obtained for this variable, as is referred in the comparative analysis between 1D and 1D/2D modelling (6.5).

7. CONCLUSIONS AND FUTURE WORK

7.1. GENERAL CONCLUSIONS

The methodology proposed in the present thesis includes the development of 1D/2D mathematical modelling, which incorporates the flow interactions between the overland flow and the drainage network, and the performances assessment based on a set of performances indicators to support the flooding assessment and management in stormwater drainage systems. A comparative analysis between the 1D and 1D/2D modelling in terms of results obtained, information requirements, advantages and disadvantages and level of detail is also included. Performances assessment is performed for both the 1D and 1D/2D modelling results in order to identify, compare and analyse the information provided by each type of model in terms of benefits and drawbacks. The PI include physical, operational and quality of services PI proposed in the IWA system (Matos *et al.*, 2003) as well as PI developed in the framework of this thesis, mainly focusing in the flooding occurrence assessment.

The 1D/2D mathematical modelling in estuarine urban areas represents an adequate tool that provides the required information to analyse the flooding occurrence and to contribute to support flood management. An adequate definition of scenarios to be studied is an important modelling step and should consider the objectives of the study. The set must include all relevant scenarios that reflect the conditions to be analysed but not more than that, since their simulation is highly demanding. The scenarios were defined in order to assess the consequences in terms of the flooding extension and water depths over the surface and to create a set of simulations that reproduce the typical conditions of the local flooding in the area. The conjugated assessment of the tide level, rainfall events and operational conditions provided a best knowledge of the mechanism that influence the flooding occurrence and existing limitations in the stormwater drainage systems.

The performance assessment based on the information provided by 1D/2D modelling allowed to identify the possible causes and negative impacts of flooding occurrence, considering the rainfall and tide, the operational condition of the sewer network, flooding incidents, area extension and duration as well as negative impacts on services, infrastructures and critical locations in urban areas. It can also be used to assess and compare solutions to implement or to support management decisions.

The incorporation of the operational conditions in 1D/2D mathematical modelling represents an important issue as it is a common situation in stormwater drainage systems, especially in estuarine areas, and it is suitable to be applied for other types of obstruction, such as the presence of roots, or for reduction in the network capacity. The obstructions lead to a high decrease of the hydraulic capacity of the system and intensify the flooding magnitude, frequency and duration associated. The incorporation of the operational conditions helps to improve the stormwater drainage management, contributing to a better understanding of the weaknesses of the network and of maintenance requirements.

Since the 1D/2D mathematical modelling allows to identify the hydraulic limitations of the surface water inlets, it may also be applied for planning surface maintenance practices that may be assessed and compared using the performance assessment methodology.

7.2. SPECIFIC CASE STUDY CONCLUSIONS

In the Dafundo catchment through the application of the proposed methodology it was identified a significant impact of the operational condition in the flooding occurrence related to stormwater drainage system, being aggravated for high tide levels on the Tagus estuary. In the Dafundo stormwater drainage system the following problems were identified: significant depositions of sediment and sand in sewers and at the outfalls, associated to the tide movement, and insufficient capacity of the water inlets. The conjugation of sediment deposition in the network system and high tide levels led to significant flooding occurrences with important negative impacts in the Dafundo urban area.

The comparative analysis between the 1D and 1D/2D modelling show that the maximum water depths and flooding extension results are highly overestimated in the 1D modelling for all the considered scenarios. However, a reasonable agreement between the 1D and 1D/2D in term of maximum duration results was obtained. The maximum water depths and flooding extension results are overestimated through 1D modelling, especially for the more serious scenarios that correspond to operational condition ”with obstruction” and design rainfall events. A better agreement, taking into consideration the limitations in the 1D mathematical modelling, was obtained for scenarios of real rainfall events.

Performance assessment highlighted the importance of the operational condition in the stormwater drainage system, being the effect aggravated by high tide levels. The performance assessment using the selected PI allows to identify the significant effect, in term of flooding occurrence, and the negatives impacts associated with the presence of sediments in sewers and with the obstruction at the outfalls condition “with obstruction”. The conjugated effect of the operational condition “with obstruction” with serious scenarios in terms of rainfall events results in important flooding occurrence, being the effects aggravated by high tide level on the Tagus estuary. Is it noticed that a significant number of critical locations and roads were affected in a high number of scenarios what could represent important negative impacts in term of health, public, socio-economic and environmental consequences.

Surcharged condition in the stormwater drainage system was analysed, considering the length of sewer in surcharge condition and with a high degree of surcharging for the assessment period. The application of these performance indicators exposed the influence of tide level for the surcharge condition of the network system, particularly for the operational condition “without obstruction”. The percentage of drainage network with a high degree of surcharge increase significantly for maximum tide level.

Flooding occurrence was evaluated in function of the number of incidents (WOp38) and number of element in charge for surface runoff collection (PI-1), manholes and surface water inlets, for the total sewer length. The proposed PI-1 considers the flooding due to the insufficient capacity of the surface inlet and not only the cases for insufficient capacity of the drainage system. The flooding occurrence in the Dafundo stormwater drainage system, when the insufficient capacity of surface inlet is considered, increase significantly for most serious scenarios in terms of rainfall.

Important negative impacts in the Dafundo catchment were identified in terms of critical locations affected by flooding occurrence and traffic interruption. Higher traffic disturbance associated to flooding occurrence was detected for the operational condition “with obstruction” and design rainfall events. In urban areas the negative impacts are exacerbated by the high density population, which represents a common situation in urban areas located in estuarine marginal areas.

The assessment of the interruption of stormwater services (PI-5) shows that the stormwater system is affected by flooding during a significant period of each rainfall event. All scenarios show an interruption of stormwater service from 30 to 60 % of rainfall event duration, averaging at 51% having no differences between 1D and 1D/2D modelling.

The comparative analysis in terms of benefits and drawbacks of performance information provided by each type of model 1D or 1D/2D showed the inadequate performance of the 1D model for the flooding area extension from stormwater system (PI-2), critical points affected by flooding (PI-4) and traffic disturbances (PI-6). These are overestimated when it is considered the 1D modelling information. These results emphasize the importance to consider the terrain surface in the flooding occurrence assessment.

An adequate agreement between the result obtained from 1D and 1D/2D modelling is observed for the PI selected to assess the surcharging condition of the drainage network (Wph6 and Wph7), flooding from combined sewers when it is only considered the flooding due to the insufficient capacity of drainage system (WOp38), catchment flooding incidents (PI-3), and interruption of services (PI-5). High differences between 1D and 1D/2D modelling for PI-1 are motivated due to the fact that 1D modelling overestimates the maximum water depth and, consequently, the flooding area extension. Besides, 1D model does not incorporate the overland modelling and, thus, the flooding occurrence due to the insufficient capacity of water inlet is not represented.

In the assessment of flooding occurrence for more serious scenarios, which correspond to the operational condition “with obstruction” and design rainfall events, the use of 1D/2D mathematical modelling is required due to the significant overestimation of maximum water level and flooding extension.

7.3. SUMMARY

The proposed methodology considers new aspects based on the combination of 1D/2D integrated modelling and performance assessment, providing an important improvement to assess flooding occurrence and contributing to an adequate support for an appropriate management of stormwater drainage systems, particularly in flat areas as the estuarine areas. The present thesis contributes to the proposed methodology, through the development the following concepts:

- Building of a 1D/2D integrated modelling for flooding assessment for Dafundo downtown catchment, considering the overland flow modelling and the effects of the terrain orography, infrastructures and urban features;
- Assessment of the conjugated effect of climacteric conditions, tide level and operational condition in estuarine urban areas;
- Incorporation of operational conditions, testing a standard obstruction that consider the deposition of sediments due to the tide effect and an inadequate maintenance of the network system;
- Identification of benefits and drawbacks of the two types of modelling

- Contribution to a performance assessment methodology for stormwater systems, focusing in flooding occurrence management in urban areas, applicable to 1D and 1D/2D modelling results;
- Development a set of new performance indicators (PI) to assess the flooding occurrence, considering the hydraulic condition, operational and quality of service aspects and incorporating important aspects related with the surface area.
- Comparing 1D and 1D/2D performance assessment results, identifying the main impacts of the two modelling types on decision making.

The most important limitation in the proposed methodology is the significant requirements of input data for the 1D/2D modelling building, in terms of inventory data, high density of elevation points, and detailed characterization of existing urban features in the urban catchment. These requirements result in a more demanding modelling.

7.4. FUTURE WORK

The methodology proposed in this thesis presents significant capabilities. However, there are still several aspects presenting opportunities for enhancement and for further work, that will contribute to improve the support to flood management. The future work to be developed is identified as follows:

- To test the proposed methodology of 1D/2D modelling for other case studies with different characteristics such as steep areas;
- To test different scenarios and operational conditions, e.g. considering higher sediment levels on the network system, above 50% of pipe cross section;
- To develop new performance indicators and indices for flooding assessment, including the analysis of surface runoff velocities, that are relevant in steep areas; tide level effects in stormwater systems; risk of flooding;
- To assess and quantify the effect of surface drainage on flooding occurrences;
- To apply the performance assessment methodology to compare flood management solutions;
- To define performance functions for each PI considered;
- To analyse quality of data and uncertainty;
- To develop a software tool to facilitate the application of the methodology by importing the model data, PI calculation, graphical representation, comparison and interpretation.

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APPENDIX I

Characterization of sub-catchment in the downtown area of Dafundo

Catchment ID	Area [ha]	Imperviousness [%]	Imperviousness area [ha]
Catchment_1	0.0112	100.00	0.0112
Catchment_2	0.0040	100.00	0.0040
Catchment_3	0.0079	100.00	0.0079
Catchment_4	0.0094	100.00	0.0094
Catchment_5	0.0164	100.00	0.0164
Catchment_6	0.0137	100.00	0.0137
Catchment_7	0.0089	100.00	0.0089
Catchment_8	0.4322	87.37	0.3776
Catchment_9	0.0107	100.00	0.0107
Catchment_10	0.0150	100.00	0.0150
Catchment_11	0.0133	100.00	0.0133
Catchment_12	0.0119	100.00	0.0119
Catchment_13	0.0070	100.00	0.0070
Catchment_14	0.0070	100.00	0.0070
Catchment_15	0.0036	100.00	0.0036
Catchment_16	0.0043	100.00	0.0043
Catchment_17	0.0036	100.00	0.0036
Catchment_18	0.0075	100.00	0.0075
Catchment_19	0.0067	100.00	0.0067
Catchment_20	0.0042	100.00	0.0042
Catchment_21	0.0111	100.00	0.0111
Catchment_22	0.0549	100.00	0.0549
Catchment_23	0.0151	100.00	0.0151
Catchment_24	0.0194	100.00	0.0194
Catchment_25	0.0083	100.00	0.0083
Catchment_26	0.0272	100.00	0.0272
Catchment_27	0.0206	100.00	0.0206
Catchment_28	0.0424	100.00	0.0424
Catchment_29	0.2794	100.00	0.2794
Catchment_30	0.0599	100.00	0.0599
Catchment_31	0.0260	100.00	0.0260
Catchment_32	0.0136	49.26	0.0067
Catchment_33	0.0045	100.00	0.0045
Catchment_34	0.0092	42.51	0.0039

Catchment_35	0.0154	73.86	0.0114
Catchment_36	0.0143	69.94	0.0100
Catchment_37	0.0204	68.54	0.0140
Catchment_38	0.0193	63.02	0.0121
Catchment_39	0.0351	100.00	0.0351
Catchment_40	0.0341	100.00	0.0341
Catchment_43	0.1012	73.59	0.0745
Catchment_44	0.0247	88.00	0.0217
Catchment_45	0.0282	44.58	0.0126
Catchment_46	0.0201	72.20	0.0145
Catchment_47	0.0324	69.33	0.0225
Catchment_48	0.0591	66.74	0.0395
Catchment_49	0.0602	71.35	0.0429
Catchment_50	0.0317	100.00	0.0317
Catchment_51	0.0685	65.77	0.0450
Catchment_52	0.0158	100.00	0.0158
Catchment_53	0.0279	88.83	0.0248
Catchment_54	0.0308	100.00	0.0308
Catchment_55	0.1590	87.09	0.1385
Catchment_56	0.0727	100.00	0.0727
Catchment_57	0.1097	66.85	0.0733
Catchment_58	0.0421	57.77	0.0243
Catchment_59	0.1391	17.47	0.0243
Catchment_60	0.0545	52.86	0.0288
Catchment_61	0.0857	100.00	0.0857
Catchment_62	0.0689	100.00	0.0689
Catchment_63	0.0351	100.00	0.0351
Catchment_64	0.0615	100.00	0.0615
Catchment_65	0.0100	100.00	0.0100
Catchment_66	0.0122	100.00	0.0122
Catchment_67	0.0170	100.00	0.0170
Catchment_68	0.0220	100.00	0.0220
Catchment_69	0.0102	100.00	0.0102

APPENDIX II

1D/2D modelling results of Dafundo drainage system

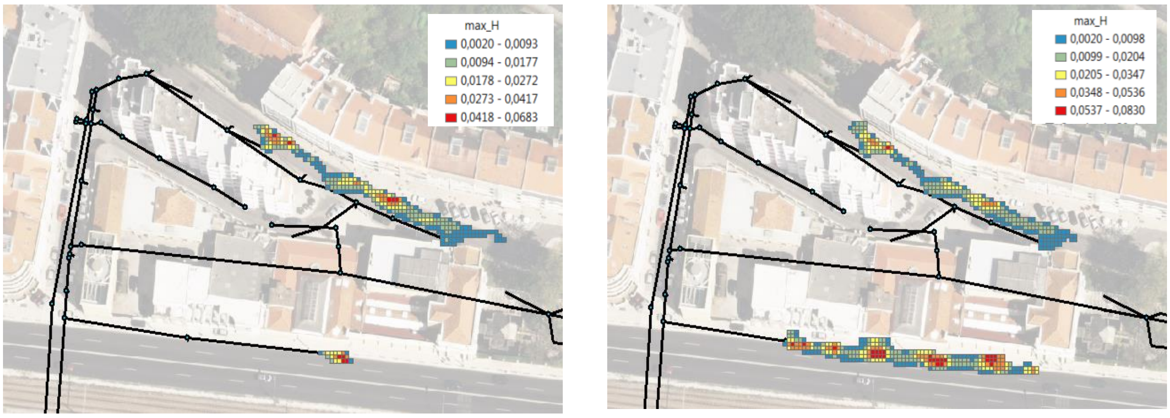
1D/2D modelling results of Dafundo drainage system

In the Appendix II the most significant results obtained using the 1D/2D model of the Dafundo downtown area for the operational condition of “without obstruction” and “with obstruction” are detailed.

Results for operational scenario “without obstruction”

a) pu_2 b) pu_3

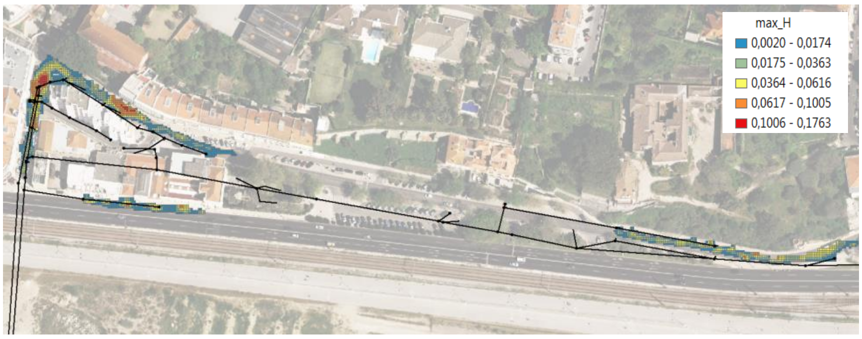
Figure A.I 1 – Maximum flood water depth (m) in the case “without obstruction”, for the uniform rainfall pu_2 and pu_3 and a tide level of 2.7m



c) pp_2 (T= 20 years) d) pp_3 (T= 50 years)

Figure A.I 2 – Maximum flood water depth (m) in the case “without obstruction”, for the design rainfall and a tide level of 2.7m

Results for operational scenario “with obstruction”

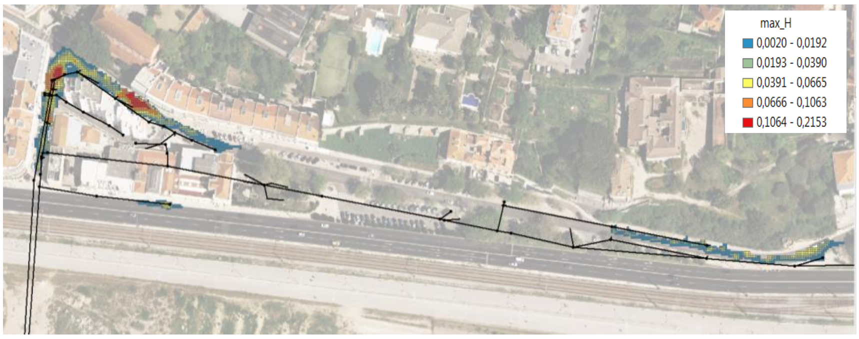


a) Overview of the area of study

b) West area

c) East area

Figure A.I 3 – Maximum flood water depth (m) in the case “with obstruction”, for the design rainfall (T=50 years)l and a tide level of 2.3m

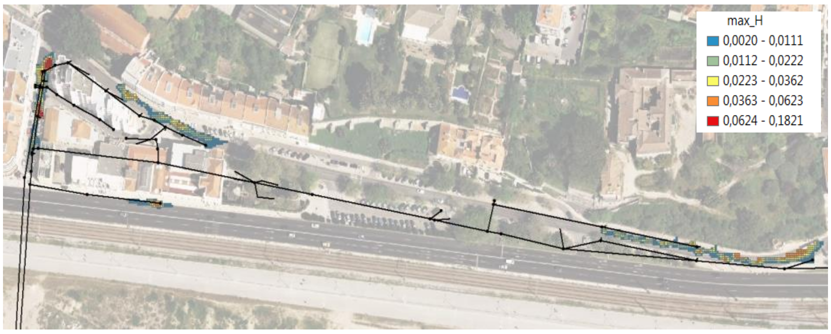


a) Overview of the area of study

b) West area

c) East area

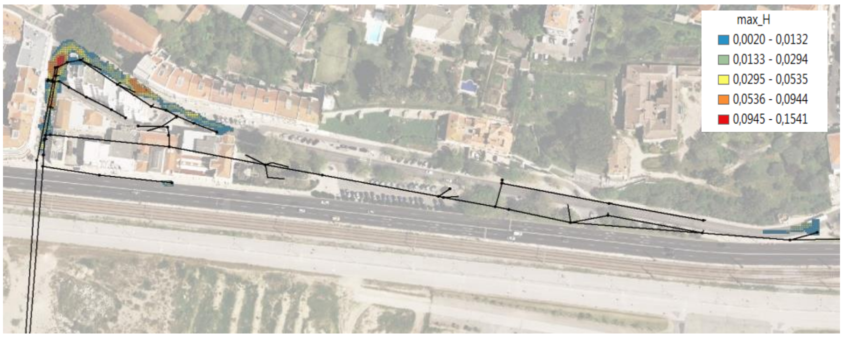
Figure A.I 4 – Maximum flood water depth (m) in the case “with obstruction”, for the design rainfall (T=20 years)l and a tide level of 2.7m



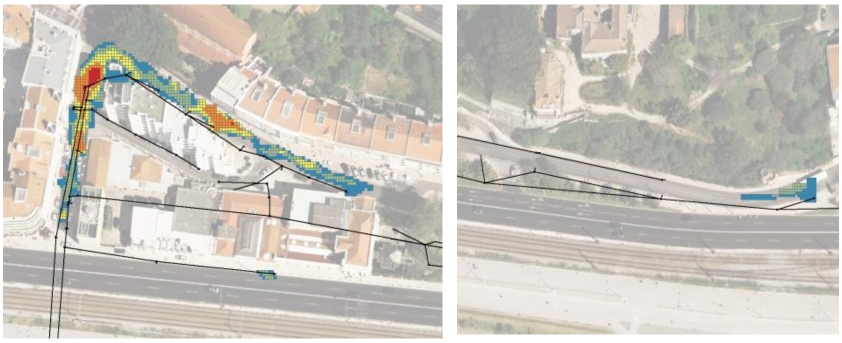
a) Overview of the area of study

b) West area c) East area

Figure A.I 5 – Maximum flood water depth (m) in the case "with obstruction", for the design rainfall (T=20 years)l and a tide level of 2.3m

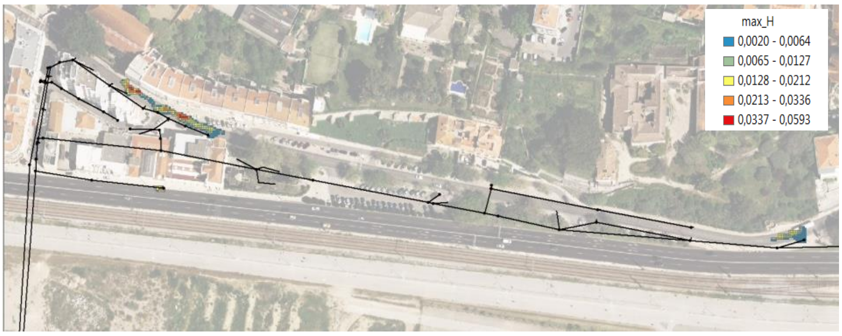


a) Overview of the area of study



b) West area c) East area

Figure A.I 6 – Maximum flood water depth (m) in the case "with obstruction", for the design rainfall (T=10 years)l and a tide level of 2.7m



a) Visão global da zona em estudo

b) West area

c) East area

Figure A.I 7 – Maximum flood water depth (m) in the case “with obstruction”, for the design rainfall (T=10 years)l and a tide level of 2.3m