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

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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.

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, that have not been designed taking in consideration all the interactions with the population growth and the climate changes, promote frequent occurrence of flooding, especially in urban areas. 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 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. Currently, several types of mathematical models are available. The main difference is based on the runoff and overland modelling. The overflow modelling is an important issue integrated in the 1D/2D modelling. The results obtained by modelling provide a level of detail that benefits the use of the technical performance assessment to support diagnosis and decision making in the flood risk management.

Currently, a performance indicator system directed for stormwater drainage systems has not still been developed. In the performance indicators (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), stormwater systems are not included, although some PI may also be applicable.

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

2.1. Description of methodology

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 methodology for 1D/2D integrated modelling in stormwater urban drainage system, proposed, consists in the building of the separate surface runoff and buried network model, coupling of models, calibration and simulation of scenarios. The 1D/2D integrated modelling is developed using the combination of Mike Urban and Mike Flood software through the Overland Flow tool. 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 PI appropriated for an objective assessment and management of flooding occurrence. Is also verified the advantages and disadvantages of the utilization of information obtained though 1D/2D modelling in comparison to 1D modelling.

2.2. Integrated modelling 1D/2D of stormwater drainage systems

The 1D/2D integrated modelling of stormwater drainage systems is a laborious and complex process that requires a high availability of specific information. In figure 1 the main phases of 1D/2D modelling are detailed.

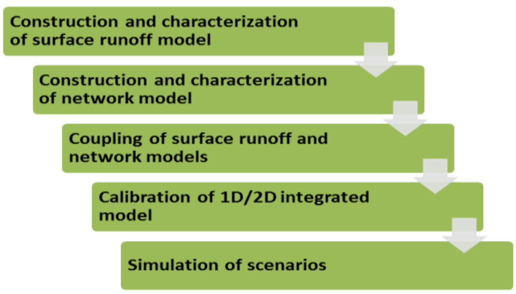

Figure 1 – Phase of the 1D/2D integrated modelling

2.2.1 Surface runoff modelling

The surface runoff model is built using Mike Urban (DHI, 2014), by applying the 2D Overland Flow. In the 2D runoff model the geometrical and hydrological characteristics for the sub-catchments 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. In the surface runoff modelling the time-area method is selected. By default, the sub-catchments were considered rectangular. This parameter and the concentration time should be determined in the calibration phase.

2.2.2 Network modelling

The 1D network model building is carried out using the Mike Urban (DHI, 2014). This 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. 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 (regular and sealed), pipes and surface water inlets. The manholes are defined as regular manholes if the flow entrance and exit through the manhole cover to the system is allowed, and sealed manholes if is not allowed. The geometric characterization of the water inlets is carried out through the predefined curves.

The downstream final section of the 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.

2.2.3 Surface runoff and networks models coupling

Once the 1D network model and the 2D surface runoff models were developed, the incorporation of a Digital Elevation Model (DEM), definition of the computational mesh, coupling between the 1D network model and 2D surface runoff model, and incorporation of the boundary conditions (tide level and rainfall event) should be carried out. The coupling is handled by inlets, represented by the surface water inlets and normal manholes. In each inlet an *urban link* should be defined.

The characteristics of the tide and the rainfall events have to be inserted in the 1D/2D coupled model.

2.2.4 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. The model accuracy depends on the level of calibration accomplished. Modelling results should be validated through the historical information regarding existing floods.

2.2.5 Definition of scenarios

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

The rainfall events are defined in function of the hietogram shape. 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 (Decree-Law 23/95) for Portugal. The shape of the rainfall event is defined by a design rainfall pattern for the maximum intensity in function of the return period. For the corresponding rainfall volume, an additional uniform hietogram is defined.

2.3. 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, information requirements 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 water inlet, flooding extension estimated in function of the registered maximum water depth, and 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 2D. Subsequently, the flooding extension is delimitated, using GIS application.

2.4. Performance assessment

2.4.1. Assessment procedure

The performance assessment follows the methodology developed in Cardoso (2008). 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. The methodology can be applied to a system using the detailed information provided by the 1D and 1D/2D integrated modelling. In figure 2 the methodology followed is detailed.

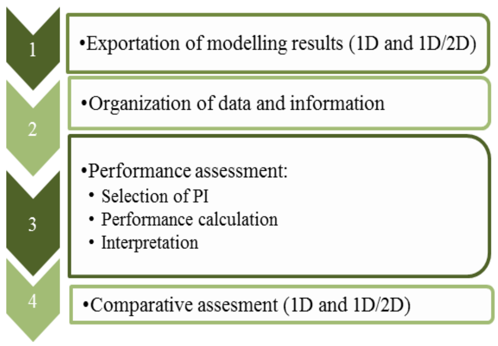

Figure 2– Performance assessment procedure

The performance assessment was based on the PI from the International Water Association (Matos *et al*., 2003) for wastewater services and on some new PI developed in the present thesis, based on modelling (1D and 1D/2D) capabilities. The process consists in determine the PI to assess the hydraulic capacity, flooding occurrence, affected properties, number of flooding incidents and network elements affected, service interruption and traffic impact.

2.4.2. Selection and interpretation of existing PI

Table 1 present the definition of the selected PI from International Water Association (IWA).

Table 1 – Definition of PI from IWA (Matos et al., 2003)

PI	Unit	Definition
WPh6 *Surcharging in gravity sewers in wet whether*	[%]	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 *High sewer surcharging*	[%]	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 *Flooding from combined sewers*	[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

2.4.3. Proposal of new PI for stormwater drainage systems

Table 2 present the definition of the new proposed PI.

Table 2 – Definition of proposed new PI

PI	Unit	Definition
PI-1 *Flooding per manholes from stormwater sewer*	[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 extension from stormwater system*	[%]	Flooding area extension, for the assessment period, related to stormwater sewers /Area of urban catchment x 100
PI-3 *Flooding incidence per catchment*	[Nº / ha]	Number of flooding incidents, areas affected by flooding, related to stormwater sewers during the assessment period / Area of urban catchment
PI-4 *Surface water flooding of locations in wet weather critical*	[No./ 1000 critical location /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 *Interruption of stormwater services*	[%]	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 *Traffic disturbances*	[m]	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

3. CASE STUDY APPLICATION

3.1. General considerations

The case study is the Dafundo estuarine catchment located in Oeiras (Lisbon district). The wastewater and stormwater drainage networks of Dafundo are managed in terms of construction, operation and maintenance by the SIMAS OA and by the Oeiras Municipal Council (CMO). The historical information about flooding and obstructions at the system and outfall was provided by the referred entities.

Based on 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 integrated model was carried out combining the Mike Urban, for buried network, and Mike Flood, for surface runoff, applying the Overland Flood tool. The upper area of catchment was previously analysed, based on David (2006), to be incorporated as upstream boundary condition. The estuarine water level was imposed as a downstream boundary conditions.

3.2. Selection and description of a sub-system in the downtown area of the Dafundo catchment

The historical information provided by the referred entities focuses on the risk of flooding occurrence in Dafundo downtown. 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 connected through a vertical drop with a significant height. In terms of urban drainage modelling, the presence of the drop allowed the segmentation of the network, using a simplified, conceptual and lumped model developed by David (2006) for the upper area.

In order to achieve an adequate 2D runoff modelling, the representation of the terrain surface through the construction of DEM was carried out. In the estuarine marginal area, the use of elevation points acquired through LiDAR technique was required to achieve an adequate accuracy to allow the representation of local roads, streets and existing urban features.

In the simplified model, the upper area of the catchment was defined with a total area of 87.15ha, a percentage of impervious areas of 78.2% and the value of C established was 0.23. It was identified a different behaviour of the catchment under study. In the case of rainfall events with lower intensities, the simplified model shows an adequate representation. For rainfall events with higher intensities, flows higher than 350l/s, an additional flow discharge was detected.

3.3. Integrated modelling 1D/2D of sub-system in the downtown area of the Dafundo catchment

3.3.1. 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 model (DHI, 2014). In the 1D/2D integrated model two catchments, a main and an adjacent catchment, were defined to simulate the upper area of Dafundo as already described.

The upstream catchment, characterized through the simplified model, was incorporated in the runoff model by defining the coefficient C, total area and percentage of impervious area. For rainfall events with higher intensities, the additional inflow was represented through an additional upper catchment, with the same characteristics of the upstream catchment, but that only contributes if the flow is higher than 350l/s. The regulation was assured by a rectangular weir, being the controlled through the water depth over the weir crest. 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) and the parameter C for the adjacent catchment 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 runoff model building. The whole lower area of the Dafundo catchment is 2.7ha and the percentage of impervious area is 84.3%. The time-area method was selected which takes into consideration the catchments shape. By default, it was considered rectangular. Initially the t_c 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 inventory data, being validated and, in specific cases, modified through information obtained in the field works. 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.

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 until 10%. To represent these restriction, a standard situation was defined to consider obstruction conditions that corresponds to specific levels of sediments in sewers. In the standard situation, the outfalls obstruction was also considered.

The 1D/2D coupling was carried out through the regular manholes and water inlets through an urban link. In the 1D/2D model, a square and uniform mesh with a cell size of 1.0m was adopted. The dimension of mesh was established as a solution between the required accuracy and an adequate computational effort.

3.3.2. Calibration

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.

In the calibration phase it was determined: i) the parameter required to achieve and adequate hydrological behaviour for the main and adjacent catchments; ii) the shape and concentration time in the sub-catchments; iii) the degree of obstruction in sewers. The hydraulic and hydrological behaviour of 1D/2D drainage system model was calibrated considering selected rainfall events, with different rainfall intensities, and the monitored water level, during the monitoring phase.

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, the parameter C (C=0.23) was verified to be adequate. It was determined that the contribution of the additional catchment, for higher rainfall events, occurs when the water depth over the crest is higher than 0.15m. A significant agreement between the flow discharge modelled by 1D/2D and the estimated provided by the simplified model was achieved, either for reduced or for higher intensity rainfall events.

3.3.3. Scenarios

Design and uniform rainfall events were considered for the selected scenarios. Three monitored rainfall events are also simulated.

The tide scenarios of the estuarine water level estuary were established taking into consideration the tide amplitude and storm surge effects. A maximum and a minimum variation of 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. The worst and best case scenarios are 2.74m and -2.26m, respectively. In table 3 the estuarine water levels considered in the scenarios are detailed. The tide scenarios are referred to the topographical zero, considering a value of 2.08 m.

Table 3 – Scenarios of tide level defined in the 1D/2D modelling

Mean sea level [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 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%.

3.4. Comparative analysis between 1D and 1D/2D modelling

The comparative analysis between 1D and 1D/2D modelling was carried out in order to evaluate the provided results, level of detail and information 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. Flooding extension, maximum water depth and duration were the variables selected to perform the comparative analysis. For the comparative analysis between the 1D and 1D/2D modelling results some specific scenarios (12) are selected. The scenarios for the rainfall event include a design rainfall (T of 20 and 50 years), and two real rainfall events. For tide level, the maximum and minimum values are selected. The operational conditions “without” and “without obstruction” are also considered. In table 4 the scenarios are detailed.

Table 4 – Scenarios for comparative analysis between 1D and 1D/2D modelling results

	Simulation	Rainfall event	T [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

The maximum duration was calculated in the manhole or surface inlet where the maximum water depths was obtained. Flooding extension was estimated through GIS, based on the results obtained by each model. 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 maximum water depths and flooding extension results are highly overestimated in the 1D modelling for all considered scenarios. In the case of the operational condition ”with obstruction” and for design rainfall events the difference between the 1D and 1D/2D results are more pronounced. A reasonable agreement is achieved for the maximum duration of flooding.

3.5. Performance assessment results

3.5.1. 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. The information required is: 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.

3.5.2. Interpretation of PI results from 1D and 1D/2D models

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.

Figure 3 and figure 4 present the PI WOp38 and PI-1 result for all scenarios from both 1D and 1D/2D. 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.

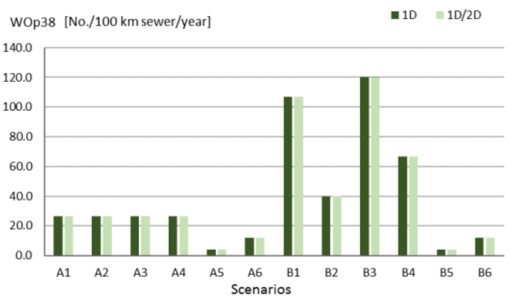

Figure 3 – Performance indicator WOp38:“Flooding from combined sewers”

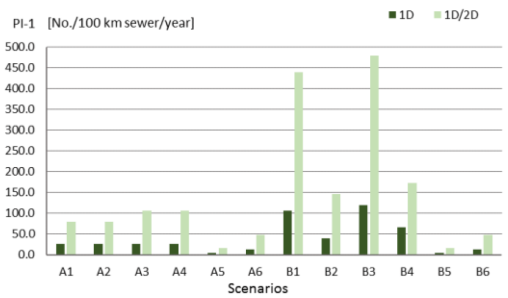

Figure 4 – Performance indicator PI-1: “Flooding per manholes from stormwater sewer”

The number of flooding incidents related to the urban catchment, though the PI-3 results, show the influence of the existing operational condition in the network, being the effect of the tide level attenuated.

The number of critical location affected by flooding and traffic disturbances (PI-4 and PI-6 results) 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 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.

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.

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

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 drainage network (Wph6 and Wph7), ii) flooding from combined sewers that only consider flooding drainage network surcharging (WOp38), iii) catchment flooding incidents (PI-3), and iv) 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 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 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 extension, and high differences are obtained for this variable, as is referred 3.4.

4. CONCLUSION AND NEW CONTRIBUTES

4.1. 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 performance assessment based on a set of performances indicators to support the flooding assessment and management in stormwater drainage systems.

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 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 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, 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 and it is suitable to be applied for other types of obstruction 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. 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.

4.2. New contributes

The present thesis contributes to the proposed methodology, through the development the following concepts:

- Building of a 1D/2D integrated modelling for flooding assessment, 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;
- 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.

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