

# Stochastic evaluation of the impact of sewer inlets' hydraulic capacity on urban pluvial flooding

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**Abstract** Sewer inlet structures are vital components of urban drainage systems and their operational conditions can largely affect the overall performance of the system. However, their hydraulic behaviour and the way in which it is affected by clogging is often overlooked in urban drainage models, thus leading to misrepresentation of system performance and, in particular, of flooding occurrence. In the present paper, a novel methodology is proposed to stochastically model stormwater urban drainage systems, taking the impact of sewer inlet operational conditions (e.g. clogging due to debris accumulation) on urban pluvial flooding into account. The proposed methodology comprises three main steps: (i) identification of sewer inlets

most prone to clogging based upon a spatial analysis of their proximity to trees and evaluation of sewer inlet locations; (ii) Monte Carlo simulation of the capacity of inlets prone to clogging and subsequent simulation of flooding for each sewer inlet capacity scenario, and (iii) delineation of stochastic flood hazard maps. The proposed methodology was demonstrated using as case study design storms as well as two real storm events observed in the city of Coimbra (Portugal), which reportedly led to flooding in different areas of the catchment. The results show that sewer inlet capacity can indeed have a large impact on the occurrence of urban pluvial flooding and that it is essential to account for variations in sewer inlet capacity in urban drainage models. Overall, the stochastic methodology proposed in this study constitutes a useful tool for dealing with uncertainties in sewer inlet operational conditions and, as compared to more traditional deterministic approaches, it allows a more comprehensive assessment of urban pluvial flood hazard, which in turn enables better-informed flood risk assessment and management decisions.

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## 1 Introduction

Urban storm water drainage systems are essential city infrastructure for the collection and conveyance of storm runoff away from critical areas, thus avoiding flooding and associated damage and health risks (Butler and Davies 2011; Leitão et al. 2013; Zhou 2014). These systems make up a big proportion of the constructed urban infrastructure, representing an invaluable asset that is expensive to operate and maintain. Reliable models of these systems are vital

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tools to understand and optimise their performance and form the basis of expensive and critical asset management and flood risk management decisions. In fact, the modelling of urban drainage systems and associated phenomena (e.g. urban pluvial flooding) has been an active topic of research for decades and nowadays models of varying levels of complexity are available (Yin et al. 2013; Salvatore et al. 2015; Pina et al. 2016). These models, however, are subject to multiple sources of uncertainty, including uncertainties in input and output data, model structure, model parameters and operational conditions (a review of the sources of uncertainty in urban drainage models can be found in Deletic et al. 2012). Novel stochastic approaches have been developed to account for some of these uncertainties (e.g. Del Giudice et al. 2013; Dotto et al. 2012; Löwe et al. 2014; Muleta et al. 2013; Tehrany et al. 2015; Thordarson et al. 2012; Yu et al. 2013). Nonetheless, as can be seen from the cited references, until now most of the work has focused on the first sources of uncertainty (i.e. input/output data, model structure and parameters) and the uncertainties related to the operational conditions of the urban drainage system are seldom explored. The present work aims at highlighting the importance of accounting for uncertainties in the operational conditions of sewer inlets and towards improving the understanding and representation of such uncertainties.

The performance of urban drainage systems can be substantially affected by the operational condition of its components (Dawson et al. 2008; National Audit Office 2004; Saegrov and Schilling 2002; ten Veldhuis et al. 2011; van Bijnen et al. 2012). Consequently, operational conditions constitute a large source of uncertainty which must be accounted for in urban drainage models if system performance and associated flood hazard are to be appropriately represented. One of the main components of urban drainage systems are inlet structures; this is, gullies, kerbs, slotted inlets, etc. through which surface storm-water runoff enters the sewer system and occasionally exits it when sewers surcharge (Djordjević et al. 2005). The operational conditions of inlet structures can largely affect the overall performance of the urban drainage system, with clogged inlets often leading to localised urban pluvial flooding, even before the internal capacity of the sewer system has been exceeded (Despotovic et al. 2005; National Audit Office 2004; Pina 2009; Pina et al. 2010; ten Veldhuis et al. 2011). Despite its importance, the discharge capacity of inlet structures and, in particular, its variability due to operational conditions is usually overlooked in urban drainage models and model-based assessment of urban pluvial flood hazard. Consequently, the level of serviceability is likely to be overestimated and models often fail to represent real urban pluvial flooding conditions.

A number of guidelines exist which describe the hydraulic behaviour and discharge capacity of inlet structures of different types. These guidelines, usually of national/municipal character, include recommendations about gully separation, geometry, type of cover, amongst others. Among the most popular guidelines are those by the US Federal Highway Administration—HEC-22 (Brown et al. 2009), which are often used in other countries outside the USA. In the case of Portugal, which is relevant for the present study, the Direção Geral de Recursos Naturais (National Directorate of Natural Resources; DGRN) published national guidelines for the design and construction of gullies (DGRN 1991). While these guidelines provide valuable information to design inlets and improve their representation in urban drainage models, the mathematical representations they present are usually limited to optimal operational conditions (i.e. fully clean inlets). However, blockage of inlet structures by accumulation of debris (Fig. 1) can occur depending on the type and location of inlets, calendar season (e.g. higher tree leaf fall-rate in late summer and autumn), antecedent weather conditions (e.g. higher transport of debris with first flush) and sewer inlet cleaning regimes (Gómez et al. 2013; Russo et al. 2013).

To take clogging conditions into account, several authors and local authorities suggest the assumption of constant reduction factors of inlet capacity in design projects. In the USA, municipalities suggest that a single gully should be sized with 50 % capacity reduction and kerb opening-inlet with 10 % capacity reduction (CCRFCD 1999; CDOT 2000). In Italy, the *Manual of Sewer Systems* (Artina et al. 2001) proposes a reduction of 25 % of the inlet efficiency to take into account clogging conditions. Guo (2006) recommends reducing the inlet capacity to take into account clogging; for single-units, he suggests reducing by 25 % the opening area of kerbs and by 50 % the length of gullies, and proposes a methodology to account for multiple inlet structures; Almedej et al. (2006) considered a clogging factor of 50 % to single-unit inlets located in terrain depressions and also suggested a 25 % reduction for double gully structures. Gómez et al. (2013) monitored one urban catchment in Barcelona, Spain, during one year and observed that clogging can reduce hydraulic capacity between 26.5 and 67.4 %. This highlights the importance of inlet clogging on the amount of surface runoff that can enter the sewer system; consequently, more runoff stays on the surface, eventually leading to surface flooding, even for relatively small rainfall events (Despotovic et al. 2005; Dawson et al. 2008; Pina 2009; ten Veldhuis et al. 2011). Given the frequent occurrence of inlet clogging and the large impact that these can have on the performance of the drainage system and on the occurrence of flooding, it is important to properly account for these circumstantial factors in urban drainage



**Fig. 1** Sewer inlet cleaning conditions. Images (b) and (c) were taken after a storm event on 15 April 2015 which caused flooding in the *Praça 8 de Maio* (Coimbra, Portugal). **a** Clean inlet grate, **b** partially

blocked inlet grate (after rainfall event), **c** fully blocked inlet grate (after rainfall event)

models, by considering their stochastic nature. To the authors' knowledge, little work has been done in this regard and methodologies for doing this stochastically have not yet been reported in the literature. In the present paper a methodology is proposed to stochastically model the consequences of a storm event, taking into account the impact of sewer inlet operational conditions (i.e. blockages due to debris accumulation) on urban pluvial flooding. The proposed methodology is demonstrated using as case study design storms of different return periods, as well as two storm events observed in the city of Coimbra, Portugal, which reportedly led to flooding in different areas of the catchment.

The paper is organised as follows: in Sect. 2, a description is provided of the geo-spatial and stochastic methods employed to investigate the impact of sewer inlet capacity on urban pluvial flooding. In Sect. 3 the pilot catchment and the dataset used to test the proposed methodology are presented. The results of the testing are presented and discussed in Sect. 4. Lastly, in Sect. 5 the main conclusions and contributions of the study are presented and future work is discussed.

## 2 Methodology

The proposed methodology to define stochastic flood hazard maps is based on three main steps (Fig. 2):

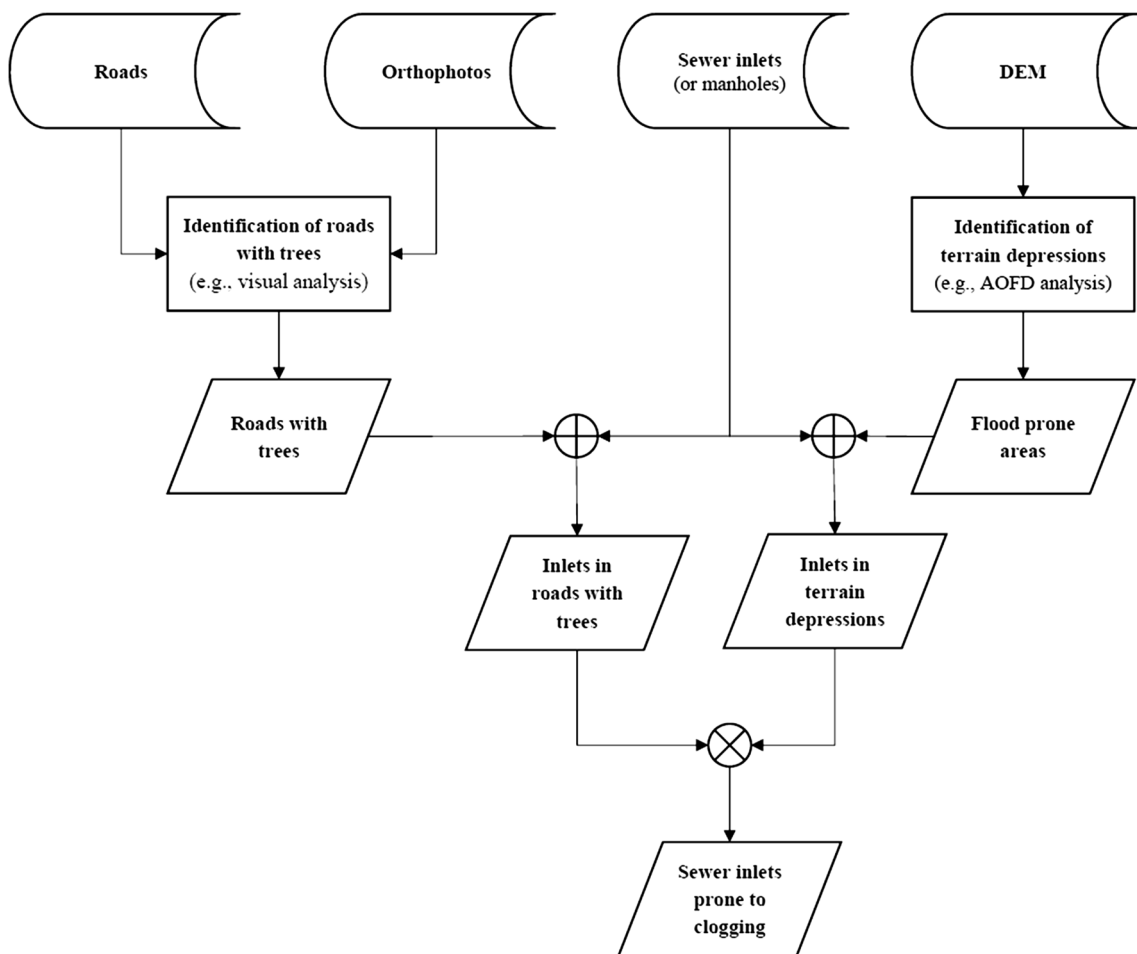
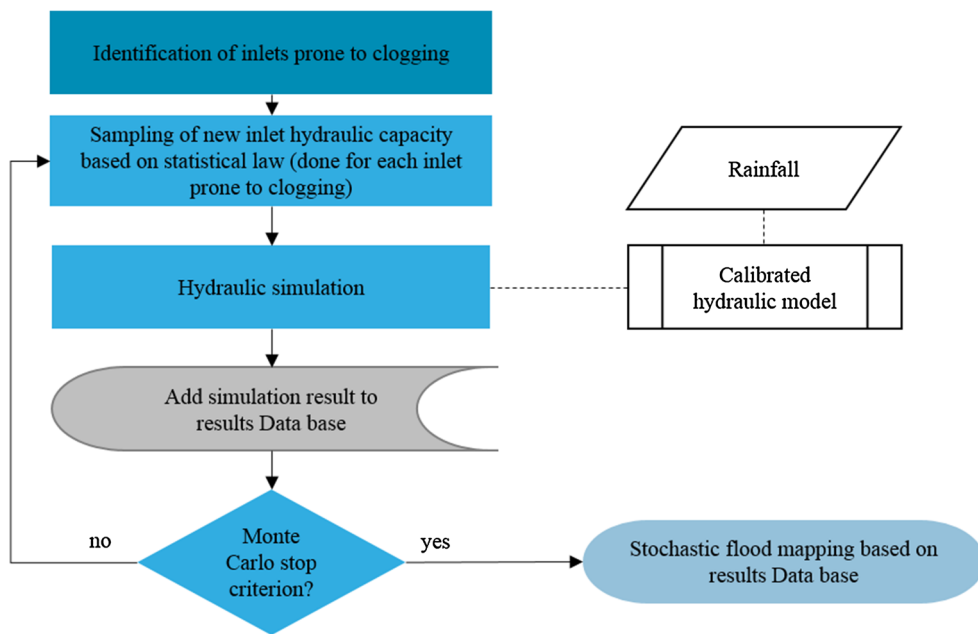
- A. Identification of sewer inlets prone to clogging;
- B. Monte Carlo simulation of the capacity of inlets prone to clogging and subsequent simulation of flooding for each scenario; and
- C. Delineation of flood hazard maps.

Each of these steps is explained in more detail in the following sub-sections.

### 2.1 Identification of sewer inlets prone to clogging

The identification of sewer inlets prone to clogging was studied by Gómez et al. (2013) based on a monitored urban catchment. They concluded that clogging patterns of sewer inlets can be associated to debris mobilised by runoff and are usually independent of road slope and of the position of inlets in the catchment. Hence, in this study, the sewer inlets most prone to clogging were considered to be those near trees or located in terrain depressions. Considering this, the selection of sewer inlets prone to clogging (see Fig. 3) was done based on the identification of roads with trees alongside and of terrain depressions. Roads with trees alongside were identified in this study based upon visual analysis of orthophotos covering the case-study catchment. A simple “binary” (yes/no) approach for the tree coverage was followed in this study; nevertheless, in the future, other factors such as tree density, tree species and associated properties (e.g. average size of leaves) may also be incorporated. The identification of terrain depressions was done based upon geospatial analysis of the high resolution digital elevation model (DEM) of the study area. For this purpose the automatic overland flow delineation (AOFD) tool (Maksimović et al. 2009) was used. The sewer inlets located in the identified streets with trees and/or in terrain depressions were considered prone to clogging. Ideally, information about the location of all inlet structures should be used as input for this analysis. However, when information at this level is not available, as is the case of the present study, manhole location can be used as a proxy to sewer inlets. Conversely, when information about sewer inlets is available with a high level of detail (e.g. exact location and a thorough description of their features) a different Beta-PERT distribution (i.e. with different parameters) could be assigned to each individual inlet in order to characterise its likelihood of clogging.

**Fig. 2** Schematic representation of the steps of the proposed methodology



**Fig. 3** Used methodology to identify sewer inlets most prone to clogging

## 2.2 Stochastic representation of sewer inlet capacity

### 2.2.1 Modelling sewer inlet capacity

There are several types of sewer inlets: grate inlets; curb-opening inlets, and combination inlets have a grate and a lateral curb-opening. Each of these types has different inlet capacity that can be defined according to its dimensions, intersected flow and connections to the sewer network. There are several guidelines that define their capacity and the most popular are those by the US Federal Highway Administration—HEC-22 (Brown et al. 2009), which formulations are implemented in most commonly used urban drainage software. In the case of Portugal, the Direção Geral de Recursos Naturais (National Directorate of Natural Resources; DGRN) published national guidelines for the design and construction of gullies (DGRN 1991), which leads to similar results to those of the American guidelines (Sá Marques et al. 2013). Besides these guidelines, several laboratory and numerical studies have been conducted in recent years which have further investigated the discharge capacity of different inlet structures (e.g. Almedej et al. 2006; Ally 2011; Gómez and Russo 2009; Guo et al. 2009; Russo and Gómez 2011; Russo et al. 2013; Comport and Thornton 2012; Saul 2012; Martins et al. 2014). In general, sewer inlets can behave as a weir until a certain water depth limit, from which they can be considered an orifice. Their maximum discharge limit depends on the opening's geometry and dimensions that define the weir and orifice equations, and also on the capacity of the connection to the sewer system. In the case of combined systems, inlets are installed with traps to stop releasing odours which hardly limit the inlet capacity. For typical UK inlet structures with traps, Ally (2011) proposes a discharge limit of  $10 \text{ l s}^{-1}$ ; in a field study conducted by Pina et al. (2010) in Coimbra (Portugal), a maximum discharge limit of  $20 \text{ l s}^{-1}$  is proposed to common inlet structures found in Portugal, such as the ones presented in Fig. 1.

To represent the sewer inflow process more realistically, a concept model based on virtual nodes was developed by Pina et al. (2016) and is implemented in the urban drainage model used in this study. Traditionally in urban drainage modelling, the runoff is routed directly into the sewer system, not taking into account the inlet capacity. As a consequence, flooding would only happen when the sewer system becomes surcharged, irrespectively of the hydraulic capacity of the sewer inlets.

The above mentioned concept for accounting for the sewer inlet capacity makes use of a virtual node in the 2D overland mesh that also represents the discharge point of each subcatchment. This node acts as intermediate connection between the subcatchment outlet node, a node of the sewer system and the 2D mesh of the surface. Each

virtual node has infinitesimal volume and has the following hydraulic connections: a link that discharges to a network node according to a weir and orifice definition and a maximum limit that represents the capacity of the sewer inlet; and a flap valve in the opposite direction of the link that allows runoff to flow from the sewers onto the 2D surface model once sewer surcharge occurs. In this way, whenever the capacity of the sewer inlet is exceeded, runoff discharged from subcatchments or on the 2D mesh remains in the overland surface and can directly flow into the 2D overland model, thus adequately representing flooding due to insufficient inlet capacity. The link with the weir and orifice is defined by an orifice element, which works as a weir until water depth exceeds the orifice diameter, and as an orifice when water depth exceed orifice diameter.

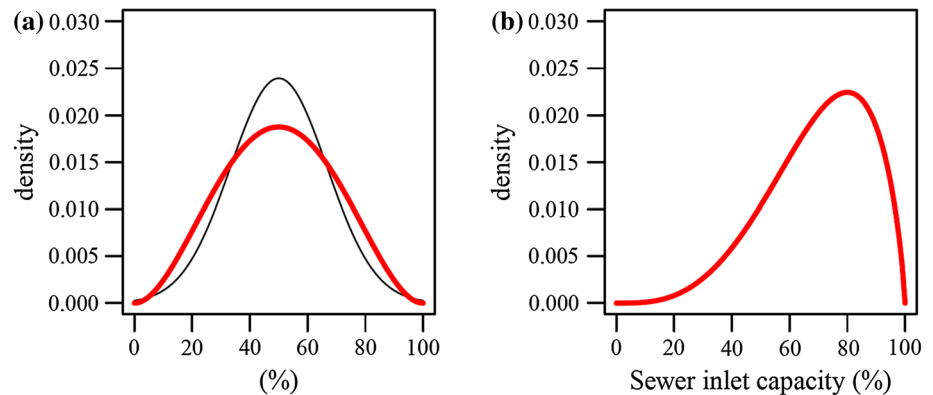
Based on previous studies carried out in the case study catchment (Pina et al. 2010), the maximum capacity for the sewer inlet was validated by comparing flooded areas generated with the hydraulic model against photographic records for the largest flooding event recorded in *Praça 8 de Maio* (09 June 2006). Since the exact location and type (e.g. different size, inlet grate, with or without water seal, etc.) of the sewer inlets is usually not available, sewer inlets are aggregated and represented in the model network nodes. As a simplification, each node considers an average number of inlets, with the maximum limit of inlets capacity defined after calibration. Several software, including Infoworks ICM (Innovyze 2013), define the sewer inlet capacity as a tabular relation between water depth and inlet flow (an adaptation of weir and orifice equations), thus defining a maximum inlet flow based on the water depth in each node; these values can be changed to mimic sewer inlet clogging conditions, and were used in the present study.

### 2.2.2 Stochastic representation of clogging conditions

The mathematical representations of sewer inlets presented in the last section are limited to optimal operational conditions (i.e. fully clean inlets). However, blockage of inlet structures by accumulation of debris (Fig. 4) can occur depending on the type and location of inlets, calendar season (e.g. higher tree leaf fall-rate in late summer and autumn), antecedent weather conditions (e.g. higher transport of debris with first flush), and maintenance regimes. The accumulation of debris and subsequent blockage can lead to further reduction of their maximum discharge. However, this limit is seldom considered in urban drainage models. Recent studies (e.g. Russo et al. 2015) considered clogging factors to reduce inlet capacity on a 1D/2D urban drainage model; however, they did not consider the clogging variability as suggested in the present



**Fig. 4** Probability density functions. **a** Normal (black line) and PERT (red line) distributions with the same mean and standard deviation:  $\mu = 50\%$ ;  $\sigma = 16.667$ , **b** PERT distribution used in this study with parameters min: 0%; max: 100% and mode: 80%



paper. This is partly due to the fact that currently available urban drainage software tools provide little flexibility for representing the different flow conditions that occur at inlets. To overcome this problem, a novel methodology was developed and is presented in this paper.

One way to study the impact of model parameters on model outputs is through Monte Carlo simulations in which the given parameter is assigned different values, randomly sampled from a probability distribution. In many cases, this requires a few hundreds or thousands of simulations. In order to study the effect of the hydraulic capacity of the sewer inlets on urban pluvial flooding, the level of inlet blockage was allowed to vary stochastically between 0 and 100% using the Beta-PERT probability distribution. This distribution is a useful tool for modelling expert data, and is frequently used for the construction of an approximate probability distribution representing the outcome of future events, based on very limited information (Coates and Rahimifard 2009; Lake et al. 2010). It is a three-point estimation technique that is easy to define and based on prior experience or best-guesses, such as the minimum (or best-case) estimate ( $a$ ), the maximum (or worst-case) estimate ( $b$ ), and the mode (or most likely) estimate ( $m$ ). Unlike the uniform distribution, three-point distributions, like the Beta-PERT, emphasise the most likely value. In practice, this means that we “trust” the estimate for the most likely value, and we believe that even if it is not exactly accurate, as estimates seldom are, we have an expectation that the resulting value will be close to that estimate. Another significant difference from the normal distribution is that events that are far from the most likely value (mode), have larger probability than they would have under a normal distribution (Hubbard 2009); this is an important feature that should be considered for stochastic (flood) risk assessment (as can be seen in Fig. 4a). The Beta-PERT probability distribution has been applied in various risk probability assessment studies in different fields; these include, for example: infrastructure design and decision-making (Salling and Leleur 2012; Thorhallsson and Sveinbjornsson 2012), software project management

(Barros de et al. 2000), food quality control and risk analysis (Straver et al. 2007; Lake et al. 2010) and pollution risk assessment (Carroll and Harms 1999; Jing et al. 2013).

The Beta-PERT distribution is a special case of the Beta distribution. The probability density function of the Beta-PERT distribution is calculated using Eq. 1.

$$f(x) = \frac{1}{B(\alpha_1, \alpha_2)} \frac{(x-a)^{\alpha_1-1} (b-x)^{\alpha_2-1}}{(b-a)^{\alpha_1+\alpha_2-1}} \quad (1)$$

where  $a$  is the minimum,  $b$  is the maximum and  $m$  is the mode parameter;  $B$  is the Beta function,  $\alpha_1 = \frac{4m+b-5a}{b-a}$  and  $\alpha_2 = \frac{5b-a-4m}{b-a}$ . For more details about the Beta-PERT distribution the reader may refer to Vose (2000).

Figure 4b presents the negatively skewed probability density function of the Beta-PERT distribution adopted in this study. The minimum, maximum and mode (i.e. most likely occurrence) parameters adopted were, respectively, 0, 100 and 80% of the maximum inlet discharge. These parameters were chosen based upon the experience of the company in charge of the drainage system of the pilot catchment, which are in agreement with the reduction factors suggested by several authors (Guo 2006; Almedeij et al. 2006; Gómez et al. 2013) to account for inlet clogging conditions. The proposed methodology was developed to take sewer inlet hydraulic capacity uncertainty into account. If more detailed and better quality data are available other distribution parameters may then be used. The hydraulic capacity can vary between 0 and 100% of the theoretical value ( $Q = \beta f_{(h)}$ , where  $Q$  is the sewer inlet hydraulic capacity,  $\beta$  varies between 0 and 100% with 0% meaning a fully blocked inlet and 100% a blockage free inlet, and  $f_{(h)}$  is a function of the water level and the hydraulic capacity of the inlet) and, in most of the cases, sewer inlets are assumed to be relatively clean. The inlets prone to clogging are considered to have 80% of their full hydraulic capacity during most of the time, as the performance of annual cleaning process of the inlets is not 100% effective and the accumulation of debris can make the clogging process more acute (Gómez et al. 2013).

### 2.3 Delineation of stochastic flood hazard maps

For each hydraulic model used in the Monte Carlo simulation, the inlets identified as prone to clogging were assigned a hydraulic capacity factor, sampled from the Beta-PERT distribution. Hydraulic simulations for each of the resulting urban drainage models, i.e. for different sewer inlet hydraulic conditions, were conducted. After the convergence of the Monte Carlo simulation, the entire set of runs is analysed to assign a flooding probability to each element of the 2D overland mesh. The output is a more comprehensive map rather than a deterministic floodplain.

At catchment scale, the various sewer inlet types that can be found and their local conditions (construction conditions and clogging conditions) can significantly influence their hydraulic capacity. Therefore, the definition of the inlet capacities for an urban catchment in urban stormwater models can introduce a large source of uncertainty (Pina et al. 2010, 2016). The proposed methodology reduces this uncertainty with the introduction of the stochastic variation of their capacity to represent clogging conditions.

## 3 Pilot catchment, datasets and hydraulic model

### 3.1 General

The methodology proposed in this paper was demonstrated using as pilot location the *Zona Central* catchment (Fig. 5), located in Coimbra (Portugal), for which a recently calibrated urban drainage model as well as other datasets,

including flood records, were available (Pina et al. 2016 Simões 2012). A description of the catchment and of the available model and datasets is provided in what follows.

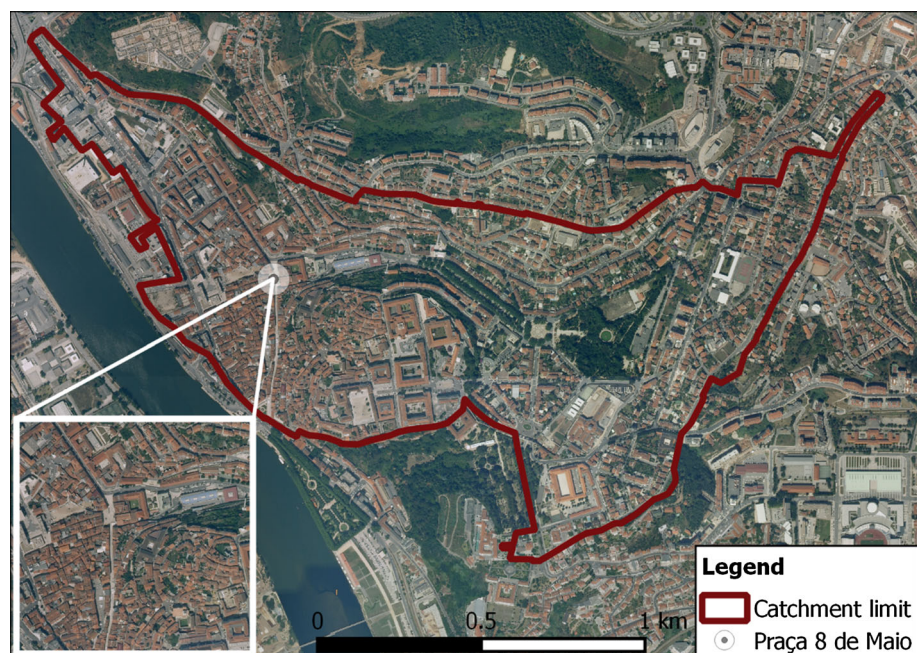
### 3.2 Catchment description and flooding history

As its name suggests, the *Zona Central* catchment is located in the downtown area of the city of Coimbra. It stretches over an area of 1.5 km<sup>2</sup> and has an average slope of 24 %. The sewer system of this area is mainly combined and comprises nearly 35 km of pipes. The time of concentration of the catchment is estimated to be approximately 45 min (Pina 2009).

Pluvial flooding events have been reported frequently in this catchment. In fact, at least six pluvial flood events have occurred in the last 10 years (see Table 1). The most critical area within the catchment is *Praça 8 de Maio* (see inset in Fig. 5). This area is located at a low point and has a high density of historical and cultural buildings, including the town hall and several museums. It also hosts numerous shops and is one of the main tourist attractions of the city.

The role of sewer inlet capacity and cleaning conditions in the occurrence of pluvial flooding in the *Zona Central* catchment has been discussed in previous studies (Pina et al. 2010, 2016). According to these studies and existing records (see Table 1), some of the rainfall events that have caused flooding often have a relatively small return period ( $\leq 5$  years) and during these events no surcharge in the upstream or downstream sewer pipes, nor backwater effects were reported. In contrast, other storm events with larger return period ( $\sim 10$  years) have not resulted in

**Fig. 5** Case study area (Coimbra, Portugal); *Zona central* catchment



**Table 1** Rainfall events and flooding in *Praça 8 de Maio*

Date	Flooding in Praça 8 de Maio?	Return period of the storm event		
		30 min duration	45 min duration	60 min duration
09/06/2006	Yes	100	100	50
25/10/2006	Yes	50	50	50
<b>20/04/2007</b>	<b>No</b>	<b>5</b>	<b>2</b>	<b>2</b>
<b>21/09/2008</b>	<b>Yes</b>	<b>5</b>	<b>5</b>	<b>5</b>
29/04/2011	No	10	10	5
24/12/2013	Yes	5	5	5

The events in bold are the ones used for testing in the present study

flooding. One potential explanation for this could be the spatial variability of rainfall fields (Segond et al. 2007; Leitão et al. 2009; Gires et al. 2012; Simões et al. 2015); however, given the small size of the pilot catchment, the impact of spatial rainfall variability is likely to be small. Thus, the source of flooding must be explained by other factors than the precipitation. In situ observations suggest that the limited hydraulic capacity of sewer inlets may be a key factor which exacerbates flooding in this area.

Over the catchment, and especially in the area upstream of the *Praça 8 de Maio*, there is a significant number of deciduous trees planted along the streets. The water utility responsible for the operation and maintenance of the drainage system, AC, *Águas de Coimbra, E.M.*, (AC) has a maintenance plan for the sewer network of this catchment, which includes cleaning the inlets four to five times per month. The cleaning procedure is focused on removing solids from the inlets' sandbox and replacing the water of inlets traps, in order to ensure that sewer inlets have adequate hydraulic capacity and that odours are not released from the combined sewer system. However, during heavy rainfall events debris is dragged along the roads and accumulates on top of sewer inlets, blocking these structures and potentially leading to localised flooding in subsequent storm events.

### 3.3 Geo-data used for model building and identification of inlets prone to clogging

The following geo-datasets were used for the implementation of the urban drainage model of the Zona Central catchment, as well as for the identification of inlets prone to clogging, following the methodology described in Sect. 2:

- *Orthophotos* with a pixel resolution of 0.5 m (used to identify roads with trees);
- *LiDAR-generated Digital Elevation Model (DEM)* with 1 m horizontal resolution (used to identify terrain depressions) (Fig. 6a);
- *Land use and buildings data* in vector format (Fig. 6b);

- *Sewer network topology and geometry information* in vector format, including location of manholes (used to identify clogging prone inlets and set up the hydraulic model) (Fig. 6a).

### 3.4 Storm events selected for analysis

Three design storms and two real rainfall events were used to test the proposed methodology. The design storms were used to conduct a sensitivity analysis and to gain a better understanding of flooding mechanisms in the catchment and of the impact of sewer inlet capacity on these (Fig. 7a).

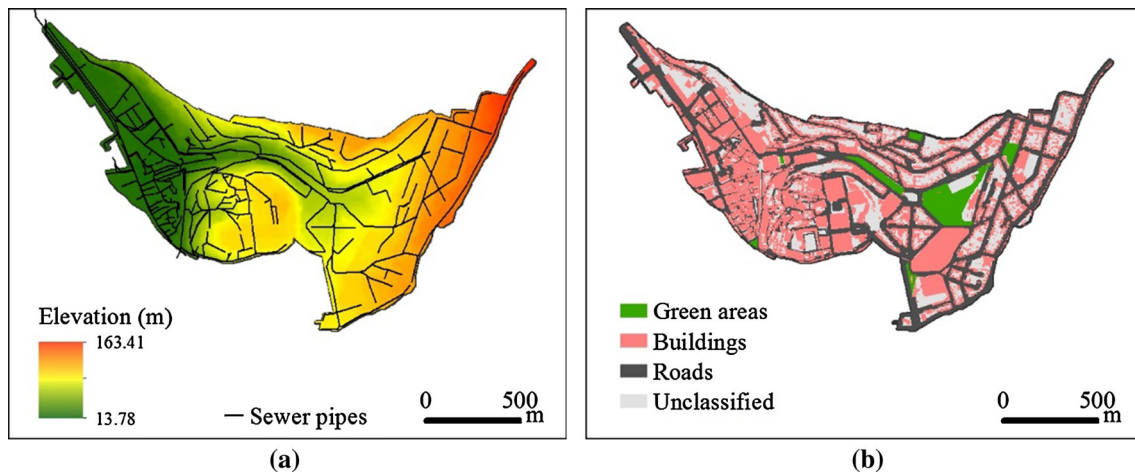
The design storm events used in the analysis correspond to return periods of 5, 10 and 20 years. The Intensity–Duration–Frequency (IDF) curves for Coimbra, along with the alternate block method were used to generate the 5-, 10- and 20-year design rainfall hyetographs with a duration of 45 min (~the *Zona Central* catchment concentration time) (Fig. 7a).

The recorded storm events were those of 20 April 2007 and 21 September 2008 (Table 1; Fig. 7b, c). Both events had a similar return period (~5 years); however, only the 2008 event caused flooding in *Praça 8 de Maio*. The fact that both events were similar in terms of rainfall rates and depths (as indicated by their similar return periods), but led to different consequences (i.e. flooding/no flooding) makes for a good case to demonstrate the benefit of the proposed stochastic approach to account for the operational condition of sewer inlets. During these events rainfall was recorded using one tipping-bucket rain gauge located near the catchment. This gauge is operated and maintained by the water utility of Coimbra (AC). It continuously records rainfall data with a temporal resolution of 10 min.

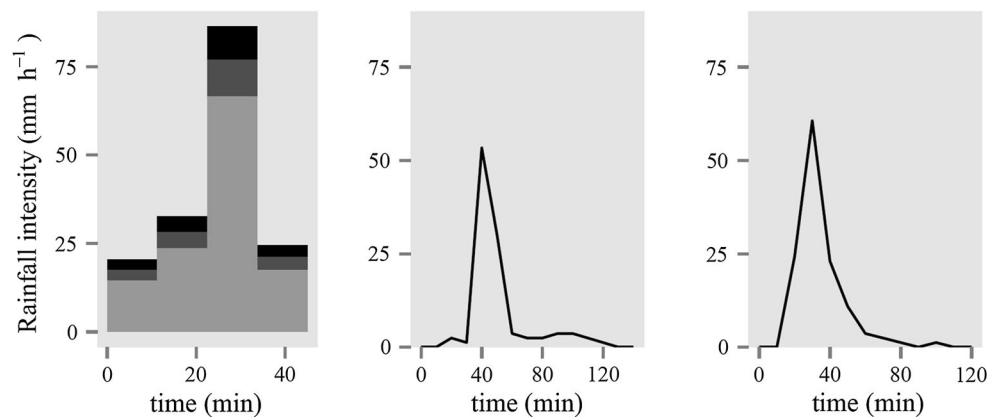
### 3.5 Urban drainage model

The analyses presented in this paper are based on a semi-distributed 1D/2D urban drainage model (see Sect. 2.2.1 for a description of this modelling approach) of the *Zona*





**Fig. 6** Data sets used in this study. **a** DEM and sewer system datasets, **b** land use dataset



**Fig. 7** Hyetographs of storm events. **a** Design storms (*black*  $T = 20$  years; *dark grey*  $T = 10$  years; *light grey*  $T = 5$  years), **b** storm event of 20 Apr 2007, **c** storm event of 21 Sep 2008

Central catchment, implemented in Infoworks ICM v.5.5 (Innovyze 2013). Rainfall is assigned to the model through 911 subcatchment units, with areas ranging from 50 to 48,000 m<sup>2</sup> (mean subcatchment area of 1722 m<sup>2</sup>) and slopes ranging from 0.00 to 1.13 m m<sup>-1</sup> (mean slope of 0.24 m m<sup>-1</sup>). Runoff hydrographs are modelled within each subcatchment; Horton's (1940) model is employed for pervious areas, whereas for impervious areas a fixed runoff coefficient is used. The resulting runoff volume is routed to the subcatchment's outlet (i.e. a sewer inlet) based upon the single non-linear reservoir routing model defined as in EPA SWMM (Rossman 2010). The one-dimensional (1D) model of the sewer network comprises 1016 conduits and 1014 manhole nodes. The conduits have a total length of 34.8 km, an average slope of 5 % and different cross-sections (circular and closed-rectangular cross-sections), with dimensions ranging from 0.2 to 3.5 × 1.7 m. The urban surface is represented with a two-dimensional (2D) mesh comprising 10,741 irregular elements with areas

ranging from 25 to 678 m<sup>2</sup> (mean area of 89 m<sup>2</sup>). The flow in the 1D sewer model and in the 2D overland model is simulated based upon the Dynamic Wave equations.

## 4 Results and discussion

### 4.1 Identification of sewer inlets prone to clogging

As described in Sect. 2, inlets prone to clogging were identified based upon their relative location to trees and/or terrain depressions. Inlets located in roads with trees are shown in Fig. 8a. Moreover, the terrain depressions identified with the AOFD tool, as well as the inlets located within these depressions are shown in Fig. 8b. The results of this analysis were verified based upon photographic records of road gullies, which revealed that the inlets identified as prone to clogging were indeed amongst those most often obstructed.

## 4.2 Convergence of the Monte Carlo analysis

The convergence of the Monte Carlo method was validated based upon simulations conducted with the 20-year return period storm as input. For each of the runs, sewer inlet orifice parameters, for clogging-prone inlets, were sampled from the Beta-PERT distribution, as described in Sect. 2.2.

A water depth threshold of 0.1 m over the elements of the 2D overland model was adopted to determine flooding occurrence. Based upon this, the following flooding indicators, which are directly related to the aim of the proposed methodology, were estimated:

- i. number of flooded 2D mesh elements;
- ii. total flooded area, estimated as the sum of the individual area of each of the flooded 2D elements ( $A_{2D\ element}$ );
- iii. total flood volume, estimated as the sum of the maximum flood volume at each flooded 2D element. The individual flood volume of a 2D element ( $V_{2D\ element}$ ) is estimated as  $V_{2D\ element} = A_{2D\ element} \times D_{2D\ element}$ , where  $D_{2D\ element}$  is the maximum water depth over a given 2D element, for each simulation.

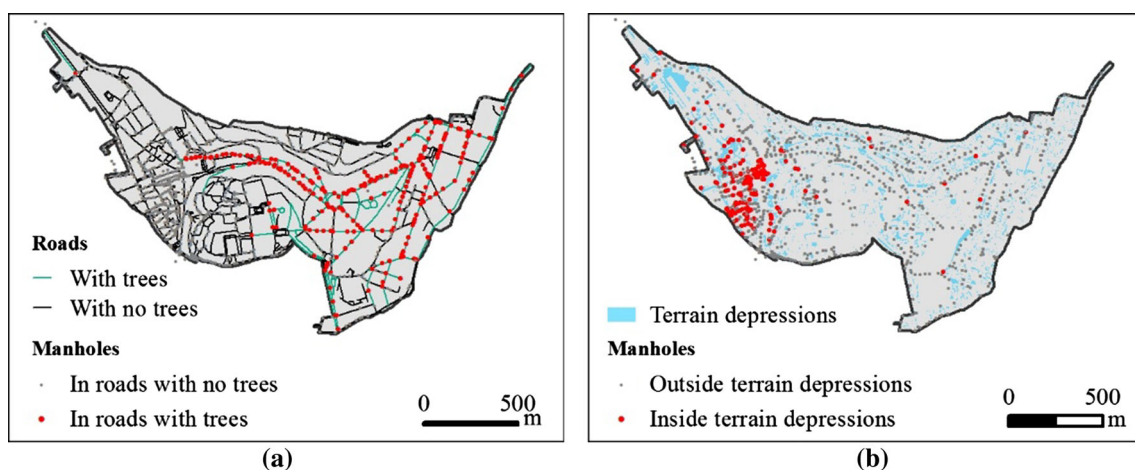
As expected, as the number of model runs increases, variations in the distribution of the outputs (determined based upon the above mentioned indicators) are likely to reduce, until convergence is achieved. From the performed convergence analysis, 200 runs produce variations (errors) of less than 0.001 %, which was used as the acceptance (convergence) criterion for the minimum number of Monte Carlo simulation runs. Based upon this, it was decided to conduct 200 simulations for all Monte Carlo analyses carried out in this study. Each simulation took approximately two minutes to run (136 s for the case of 20-year return period storm, using a computer equipped with a Intel® Core™ i7-3770 (3.40 GHz) processor unit; 16 GB

RAM and a 64 bits Windows 7); simulation times showed some variation due to the different model conditions, e.g. sewer inlet capacity and storm events.

## 4.3 Stochastic flood hydrographs and hazard maps

In this section, the results of the stochastic analysis, including stochastic flood hydrographs and hazard maps are presented. In order to highlight the benefits of accounting for variations in sewer inlet capacity, the results of the stochastic analysis are compared against deterministic flood simulations. The deterministic simulations consider the inlets prone to clogging with 80 % of the theoretical hydraulic capacity. This value was adopted as it was considered the most likely value in the Beta-PERT distribution adopted in this study to represent variations in sewer inlet capacity (Sect. 2). The stochastic simulations comprise a set of 200 runs per storm event, each run with variable inlet capacity sampled from the Beta-PERT distribution, as described in Sect. 2. The deterministic flood hazard maps correspond to the unique floodplain resulting by running the hydraulic model once (with fixed inlet capacity) for a given rainfall input. The stochastic flood maps, on the other hand, display the probability of a given 2D element being flooded; this is estimated as the ratio of the number of times a 2D element is flooded, in relation to the total number of simulations under consideration (i.e. 200).

In what follows the results for the design storms are first presented; these are used to examine the sensitivity of the catchment to sewer inlet capacity, as well as to better understand flooding mechanisms in the area. Afterwards, the results of the real (observed) storm events are presented; these are used to further prove the importance of accounting for sewer inlet capacity in urban drainage models.



**Fig. 8** Identification of sewer inlets prone to clogging. **a** Manholes located in roads with trees, **b** manholes located in terrain depressions

### 4.3.1 Design storms

All simulations resulting from the 20-year return period design rainfall, with variation in the hydraulic capacity of clogging-prone inlets, showed flooding in *Praça 8 de Maio* (Fig. 9a). As can be seen, when the hydraulic capacity of the inlets is limited, more water stays onto the surface, increasing the water depth over the 2D model and causing delays in the entrance of runoff into the sewer system. Despite the visible variations, most of the water depth results were within a 0.05 m range (notice interquartile range between approximately 0.45 and 0.5 m). The time to water depth = 0 m also showed a significant variation (more than 3600 s), however most of events vary within a range of 10 min (600 s).

As a consequence of the variation of water entering into the sewer system, the flow in the pipes also varies. Figure 9b shows the flow in the sewer pipe upstream *Praça 8 de Maio*. Besides the variation of flow due to variations in inlet capacity, this figure also shows that the maximum water depth of the sewer (1.7 m) was never achieved. This clearly indicates that the flooding problem in this catchment, and in particular in *Praça 8 de Maio*, is related to the limited hydraulic capacity of inlets and consequent inability of surface water to enter to the sewer pipe system.

Figure 10 shows (a) the probabilistic distribution of inlet hydraulic capacity and (b) the associated distribution of water depth in *Praça 8 de Maio* for the design storm of 20 years; both distributions have ten classes, sewer inlet capacity varies between 0 and 100 %, while water depth varies between 0.40 and 0.76 m. Most of the obtained water depth results are concentrated in the lower classes, from 0.4 to 0.5 m (Fig. 10b). The water depth values showed a smaller variability than the sewer inlet hydraulic capacity distribution used (Fig. 10a). This clearly shows that the relation between the inlet hydraulic capacity and simulated water depth is not linear and direct.

Figures 11 and 12 present the stochastic and deterministic flood extent for the whole catchment using the design rainfall with a return period of 20 years. As can be seen,

some areas which are identified as prone to flooding in the stochastic map (Fig. 11) are not identified as such in the deterministic map (Fig. 12).

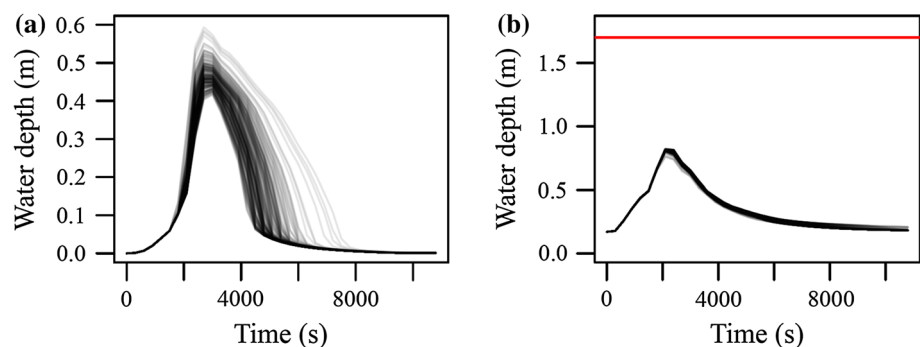
Uncertainty associated to rainfall return period was also investigated. Stochastic simulations using design storms with different return periods were conducted. Figure 13 shows the water depth variation for the stochastic simulations for three design storms with different return periods. It can be seen that, despite the increase of water depth with return period (as expected), the variation range reduces with increasing return period—this suggests that the uncertainty also decreases. Another interesting aspect that can also be seen in Fig. 13 is that the highest water depth values obtained using a rainfall with low return period can be higher than the lowest water depth values obtained using higher return period rainfall. This highlights the importance of correct estimation of the sewer inlet capacity and the importance of the developed stochastic approach presented in this paper.

### 4.3.2 Observed storm events

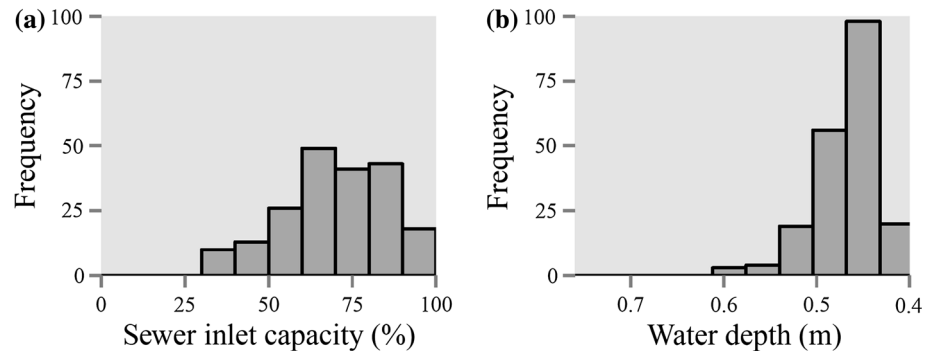
The rainfall event of 20 April 2007 has a return period that varies from 5 years in 30 min to 2 years in 45 min. It did not cause flooding in *Praça 8 de Maio* and this can be seen by the modelling results presented in Fig. 14. The results obtained with the stochastic simulation show a small likelihood of flooding of less than 10 % (Fig. 14a), while the deterministic simulation results show no flooding in this area (Fig. 14b). In fact, in 2007 no flooding was reported in *Praça 8 de Maio*.

The rainfall event of 21 September 2008 has a return period of 5 years for durations of 30 and 45 min. This rainfall event is similar to that of 20 April 2007 (see Fig. 7 in Sect. 3.4). News in a local newspaper (*Diário de Coimbra*) and photographic records provided by AC illustrate the flood occurred in *Praça 8 de Maio* caused by this event (Fig. 15). This result is captured by the stochastic simulations which attribute a flood probability higher than 50 % for this location (Fig. 16a), whereas the

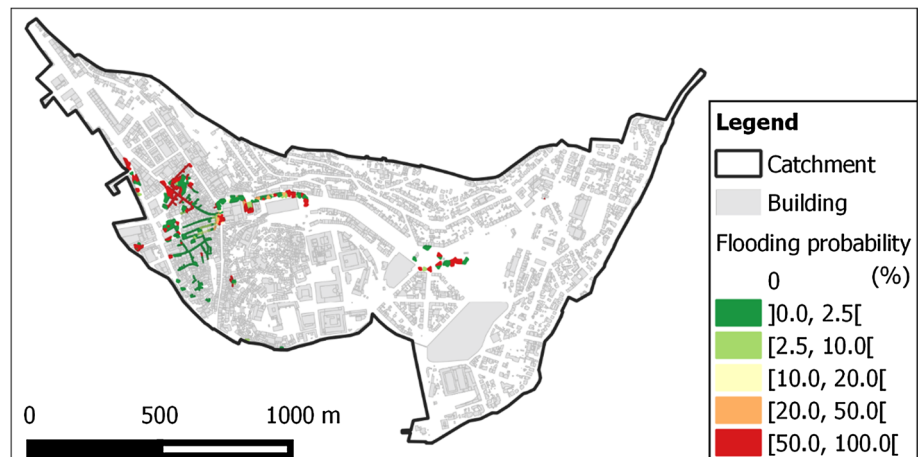
**Fig. 9** Hydrographs for different sewer inlet hydraulic capacities. **a** Water depth over the most critical element of the 2D mesh at *Praça 8 de Maio*, **b** water depth in the sewer pipe located upstream of *Praça 8 de Maio* (red line represents the maximum pipe depth)



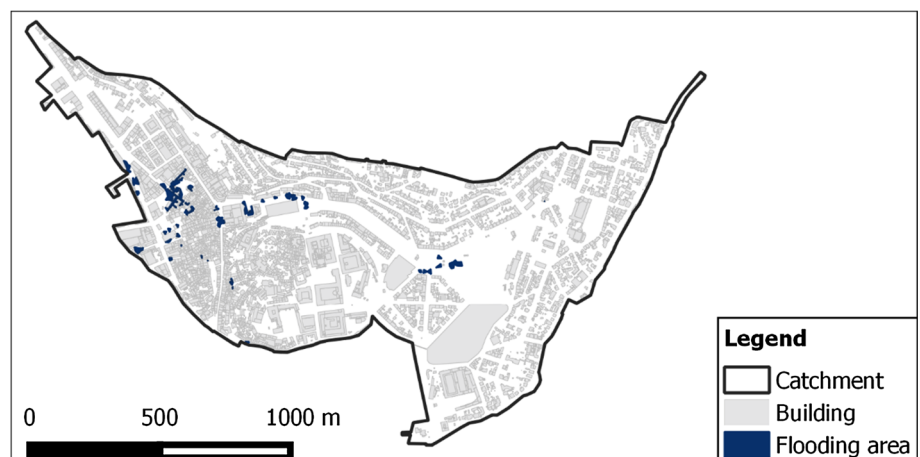
**Fig. 10** **a** Distribution of inlet hydraulic capacity; **b** distribution of maximum water depth in *Praça 8 de Maio* for the design storm of 20 years



**Fig. 11** Flood extent for a stochastic 20 years return period design storm simulation



**Fig. 12** Flood extent for a deterministic 20 years return period design storm simulation



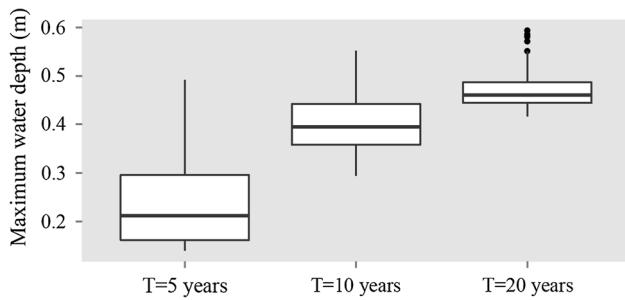
deterministic simulations show no flooding at *Praça 8 de Maio* (Fig. 16b).

## 5 Conclusions and outlook

In this paper, a methodology is proposed to stochastically model the consequences of a storm event, assessing the impact of sewer inlet operational conditions (i.e. clogging

due to debris accumulation) on urban pluvial flooding. The proposed methodology comprises three main steps: (i) identification of sewer inlets most prone to clogging based upon a spatial analysis of their proximity to trees and evaluation of their location in relation to terrain depressions; (ii) Monte Carlo simulation of the capacity of inlets prone to clogging and subsequent simulation of flooding for each scenario, and (iii) the delineation of stochastic flood hazard maps. The methodology was demonstrated

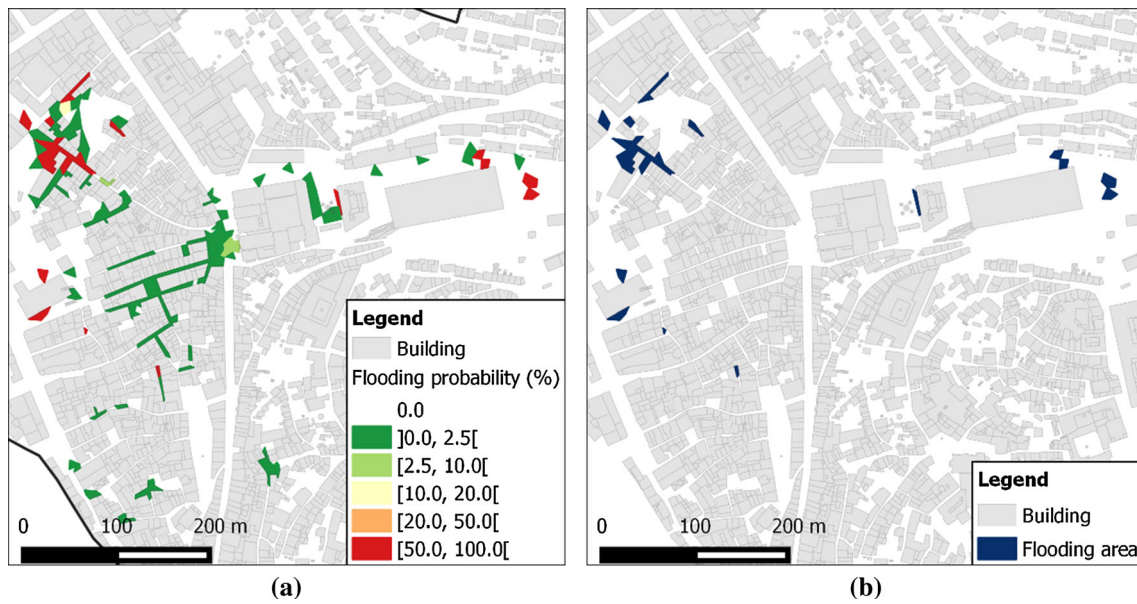




**Fig. 13** Water depth variation for rainfall events with different return periods (T)

using as case study design storms as well as two storm events observed in the city of Coimbra, which reportedly led to flooding in different areas of the catchment. The main findings of this study are the following:

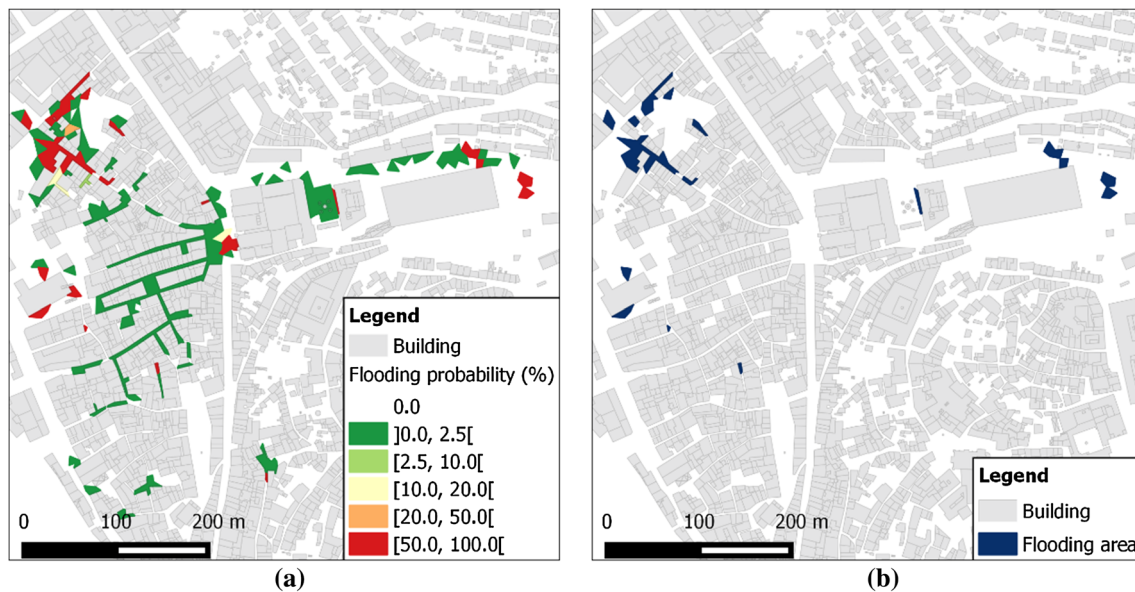
- The results show that variations in sewer inlet capacity can largely affect flooding occurrence and extent, and that considering such variations can lead to more accurate representation of urban pluvial flooding, as compared to traditional deterministic methods. For example, accounting for variations in inlet capacity can



**Fig. 14** **a** Detail of the flood extent for a stochastic simulation of the 20 April 2007 event; **b** detail of the flood extent for a deterministic simulation of the 20 April 2007 event



**Fig. 15** Flooding in *Praça 8 de Maio* caused by the rainfall event of 21 September 2008 *Diário de Coimbra*



**Fig. 16** **a** Detail of the flood extent for a stochastic simulation of the 21 September 2008 event; **b** detail of the flood extent for a deterministic simulation of the 21 September 2008 event

explain why, in some cases, relatively small rainfall events can lead to flooding, whereas larger storms may not. In addition, the stochastic flood evaluation can identify flood prone areas which traditional deterministic methods fail to identify.

- The stochastic approach proposed in this study establishes a useful tool for dealing with uncertainties in inlet operational conditions and allows a more comprehensive assessment of urban pluvial flood hazard, which in turn enables better informed flood risk management decisions.

Besides these main findings, other specific contributions and potential applications of the proposed analysis tools are the following:

- The geo-spatial analysis methodology employed to identify sewer inlets most prone to clogging with debris, tree leaves and branches could be used by utilities and/or local authorities as a simple stand-alone tool to optimise sewer inlet cleansing schedules. This could lead to reduced flooding likelihood and contribute to cost savings. More sophisticated cleansing schedules could be developed based upon the stochastic flood hazard maps.
- As mentioned above, the results of this study suggest that variations in the operational conditions of inlet structures constitute a significant source of uncertainty in urban drainage models. As such, it should be accounted for in the calibration of such models, and the methodology proposed herein could serve as starting point for doing so.

Future work should focus on further testing of the proposed method in more pilot catchments for which urban pluvial flooding records are available, on improving the characterisation of inlets and of the urban surface in general, and on improving the probability distribution that is employed to characterise the occurrence of inlet clogging. The characterisation of inlets and of the urban surface should include detailed mapping of road gullies and other inlet structures, and automation of the identification of roads with trees, in order to facilitate application of the current method in larger urban areas. This could be done with unmanned aerial vehicles, the use of which is increasing in urban hydrological applications (Tokarczyk et al. 2015; Leitão et al. 2016). As regards the probability distribution that is used to characterise the occurrence of inlet clogging, it could be extended to account for other factors that exacerbate or alleviate blockages, including seasons (i.e. blockage variations due to seasonal variation in the load of debris and tree leaves), specific characteristics of trees, specific inlet geometry and location factors, and impact of first flush effect. Moreover, one could also consider a distribution, e.g. the Beta-PERT, of which the parameters would be defined based on linear regressions dependent upon these factors.

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