Semi-distributed or fully distributed rainfall-runoff models for urban pluvial flood modelling?

Rui PINA[1]*, Susana OCHOA[1], Nuno SIMÕES[2], Ana MIJIC[1], Alfeu SÁ MARQUES[2] and Čedo MAKSIMOVIĆ[1]

[1]*Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom*
[2] *IMAR-CMA, Department of Civil Engineering, University of Coimbra, 3030-790 Coimbra, Portugal*
**Corresponding author's e-mail: r.pina13@imperial.ac.uk*

ABSTRACT
Urban drainage models comprise four main components: rainfall, rainfall-runoff, overland flow and sewer flow modules. The rainfall-runoff module can be either semi-distributed (i.e. based upon sub-catchments units through which rainfall is applied to the model and at which runoff volumes are estimated), or fully distributed (with rainfall inputs applied and runoff flow directly on a 2D model of the surface).
This paper presents a comparison of semi-distributed and fully distributed rainfall-runoff modules coupled with 1D2D urban drainage model (one-dimensional sewer flow and two-dimensional overland flow modules). A real case study is analysed and modelling results are compared against water depth records in sewers and photographic records from a flood event. The differences between the models are outlined and the results are discussed. In general, fully distributed models require more detailed data than is normally available. Nerveless, the connections between the four modules, the hydrological characterisation and the calibration of the inlet structures and hydrological parameters are the questions where further research is needed for FD models.

KEYWORDS
Urban drainage models, urban flooding, fully distributed models, semi-distributed models, rainfall-runoff modelling

INTRODUCTION

Urban pluvial flooding can be defined as an event that occurs when the drainage system capacity is exceeded and/or water remains on the surface, posing risks for the economy, environment and human health. Exceedance of the drainage capacity can happen on the surface (before water reached underground sewers), in the sewer system (surcharging when water flow out of the sewers back on the surface) or as a combination of these two cases. The physical processes involved in this type of flooding can be divided into four main components: rainfall, rainfall-runoff, overland flow and sewer flow. Overland and sewer flow simulation modules have been greatly improved in recent years (Djordjević et al., 2005; Hunter, et al., 2008; Maksimović et at (2009), Giangola-Murzin et al., 2012); however, with the advances in technology (e.g. remote sensing, digital map, weather radar data, computing techniques (Cea, et al., 2010)) and the development of urban drainage methodologies such as Sustainable Urban Drainage Systems (SUDS), Water Sensitive urban design (WSUD) and Blue Green Dream (BGD) project solutions further research is needed to study rainfall-runoff transformation and its link with other processes.

Two main types of rainfall-runoff models are semi-distributed (SD) and fully distributed (FD) models. SD models are based on defining sub-catchments units (by delineation using some simple or more sophisticated method), each of which has uniform characteristics and a unique discharge point that can be either a node or another sub-catchment. Each sub-catchment can have its own physical and hydrologic characterisation, such as area, slope, impervious area, soil characteristics of pervious area, etc., and generates runoff from a spatially uniform rainfall input. FD are physically based models defined by a more detailed discretisation of a grid or a mesh of regular or irregular elements. In FD models the rainfall is directly applied to each grid element, generating grid-point runoff. The movement of surface runoff is then simulated by the overland flow module, thus this type of model should be applied for two-dimensional (2D) modelling of overland flow (Beven 2012).

This paper discusses the differences between SD and FD rainfall-runoff models applied to 1D2D urban drainage models (one-dimensional (1D) sewer flow model and two-dimensional (2D) surface overland flow model). SD and FD models were coupled with a 1D2D model of a real case study at Coimbra, Portugal. The input dataset is presented and the particularities of these models are shown. Results are compared against registered data and the differences observed between the SD and FD models are outlined in a discussion for further developments.

CASE STUDY

The case study used in this paper is the "Zona Central" catchment, located in the downtown area of Coimbra, Portugal (Figure 1). It has a total area of approximately 1.5 km^2 and an average slope of 0.24 m/m. The sewer system is nearly 35 km long, most of which is combined.

The steep topography of the catchment plays a major role in exacerbating urban pluvial flood hazard. Surface runoff cannot enter the minor sewer system due to the steep slopes during intense rainfall events. Therefore, it stays on the surface and flows through preferential pathways (e.g. roads) or accumulates in natural and man-made ponds, such as the 8 MaySquare, where important services and historical buildings are located (e.g. City Council, Monastery of Santa Cruz).

Dataset

The SD and FD models of the "Zona Central" catchment were built with the same input data in order to make them comparable.

The network data was provided by the water utility company AC, Águas de Coimbra, EM and digital terrain model (DTM) data was defined by a LIDAR model with 1 m regular cell resolution (Figure 1.a).

Open Street Maps (OSM) data and buildings polygons were used to obtain the land use information required for the hydrological characterisation of both rainfall-runoff models and for the overland flow model characterisation (Figure 1.b).

A monitoring campaign was carried out during the period between 2010-2012 by Simões (2012) to estimate rainfall in the catchment and measure water depth in main points of the sewer network (Figure 1.a). This data was used to adjust both models and to compare their results. In addition, recorded rainfall and photographs of one flood event (9 June 2006) were used to compare flood results of both models.

The system is combined and the waste water inflows and their pattern were defined based upon water demands data from 2012 for each geolocated client.

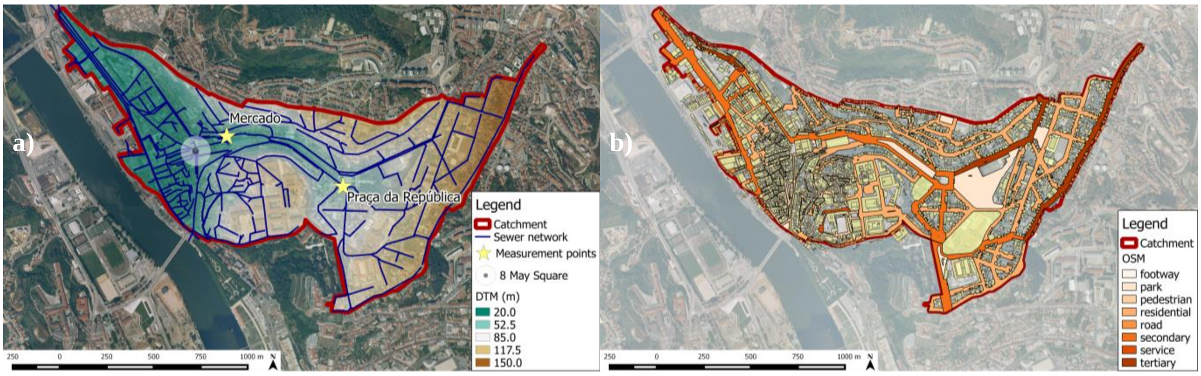

Figure 1. a) Sewer network, DTM and monitoring point locations; b) Land use data in the "Zona Central" catchment in Coimbra

SEMI AND FULLY DISTRIBUTED MODELS BUILDING

The 1D2D dual drainage models with rainfall inputs applied respectively through sub-catchments (i.e. semi-distributed model, SD) and directly on the 2D surface model (i.e. fully-distributed model, FD) were implemented using the dataset described above. The two models share the same 1D sewer model and 2D surface model; the only differences are:

- the way in which rainfall is inputted (through sub-catchments vs. directly on 2D surface model),
- the way in which runoff volume is estimated (at sub-catchment scale vs. at grid or mesh element of the 2D surface model)
- the way in which runoff volumes are inputted to the model (in SD models the estimated runoff at each sub-catchment is directly inputted into the nodes of the 1D sewer model, whereas in the FD model the runoff generated at each grid/mesh element is routed through the 2D surface and, depending on topography and on the location of sewer gullies, it may or may not enter the sewer system

In what follows the way in which each component of the 1D2D SD and FD models was setup is described.

Sewer and overland flow models

The 1D sewer flow model was built using the topology and geometry network data provided by the water utility company. The 2D overland flow model was created based upon the DTM, the buildings polygons and the land use characteristics. The resolution of the overland mesh is 50 - 300 m^2 in the overall area and 150-900 m^2 in green areas, such as parks. In both models flows are routed by solving the full shallow water equations, respectively in 1D (i.e. de Saint-Venant equation) and 2D.

Rainfall-runoff models

The rainfall-runoff model was based on sub-catchments units for the SD model and on the surface overland mesh and building polygons for the FD model. The Horton method was chosen to model the infiltration of pervious areas, with parameters based on Butler and Davies (2011), and fixed runoff coefficients were adopted for impervious surfaces. A calibration procedure was applied to adjust these infiltration parameters in both models.

The SD model is split into sub-catchments covering the entire catchment area, with sub-catchment areas ranging from 50.0 m^2 to 4.8 ha with an average of 0.17 ha and standard deviation of 0.28 ha. Each sub-catchment has its own uniform hydrological characterisation, namely initial losses, impervious area, width, surface roughness and infiltration parameters. Width was defined by sub-catchments geometry and the other parameters were based on covered land use zones percentages for each sub-catchment. The SWMM hydrological model was applied for the surface runoff routing (single non-linear reservoir with routing dependent on surface roughness, surface area, ground slope and catchment width (Rossman, 2010)).

In contrast, the FD model uses sub-catchment units only to estimate runoff from the buildings' roofs; the runoff estimated at each building sub-catchment is then connected directly to the sewer system. The remaining areas (i.e. non buildings) are divided into overland mesh elements, each of which is assigned infiltration parameters based upon the land use data above. In these areas surface runoff is calculated at each mesh element and it is then routed using the shallow water equations, as described in the previous section. Surface runoff will only enter the sewer system once it reaches a sewer network node.

Connections with the sewer network

The amount of water entering the sewer system is, in reality, limited by the capacity of the inlet structures; nonetheless, this fact is not always considered in urban drainage models. Given the flooding mechanisms in the study area, accounting for such limitation is essential. Therefore, a concept based on virtual nodes (hypothetical connections) was adopted as represented in Figure 2. These virtual nodes have an infinitesimal volume (in opposite to usual manholes, defined by chamber area and level) and are directly connected with the overland surface and with the sub-catchments. They are also connected with the sewer network manholes through orifices with the limited capacity of inlet structures. Therefore, the inlet flow to the sewer system from the sub-catchments discharges and from the runoff on the surface overland is limited to the inlet capacity of gullies (defined by the orifices). Since these orifices only allow flow in one direction, flap valves were adopted in the opposite direction to enable stormwater from the surcharged sewer network to run to the surface. The definition of the inlet structures capacity was based on experiences presented by Pina (2010).

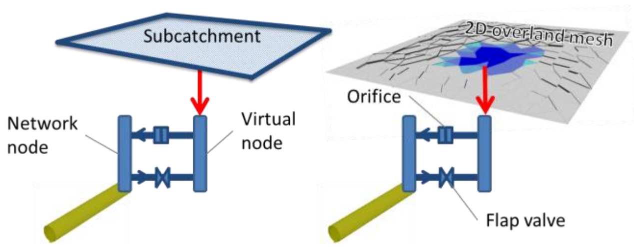

Figure 2. Hypothetical connections of sub-catchments (left) and surface overland (right) with the sewer network used in the model to better model flooding mechanism.

RESULTS

The SD and FD models were tested using several storm events for which water depths records in sewers were available. In this section, three storm events are presented and the recorded water depths at two main points (Figure 1.a) are compared against model results. In addition, photographs of a flood event at the 8 May Square are compared with the floodplains produced by the models.

Analysis of events with measured water depths

The water balances shown in Table 1 reveal that SD and FD models are producing the same overall runoff volumes, but the maximum water volume on the 2D surface is higher in the FD model. In addition, the water depths in the sewer system (Figures 3-5) are lower in the FD model. This can be explained by the connections of the overland network to the sewer system. In the SD model runoff is directly applied to the nodes of the sewer network and it only reaches the surface in case of sewer surcharge or if the capacity of the inlet structures is exceeded. In contrast, in the FD model runoff remains on the surface until it reaches a manhole (and it can also come back to the surface once if sewers surcharge). Because of this, higher water volumes are generally retained on the surface of the FD model, due to overland singularities which would normally be drained by private network sewers. The sewer flow model used in this study only includes the public sewer network and not considers any private network connections. The absence of such connections in the sewer flow model is not critical in SD models, where all the water in a given sub-catchment is assumed to go straight to an associated node. But it is a problem in FD models, where water simply remains on the surface as it cannot be drained.

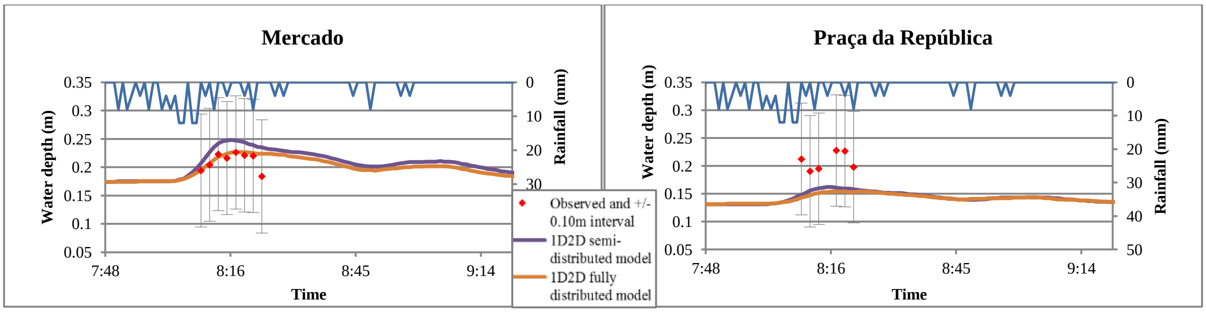

Figure 3. Observed data and model results – 2011/01/29.

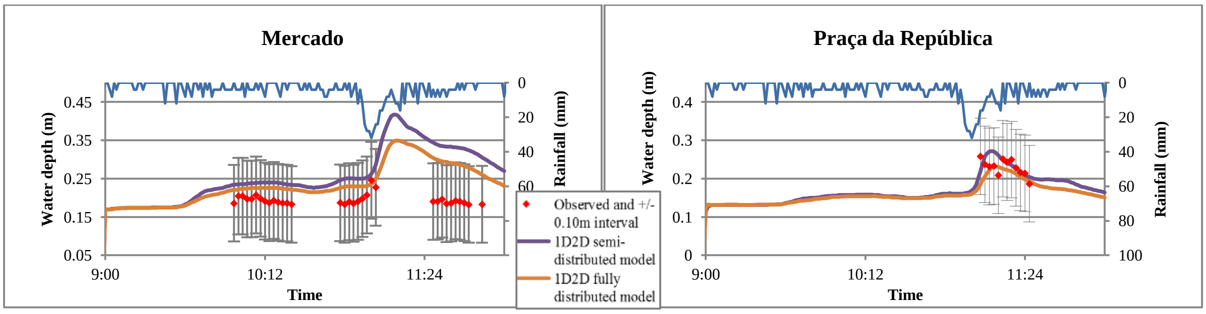

Figure 4. Observed data and model results – 2011/02/13.

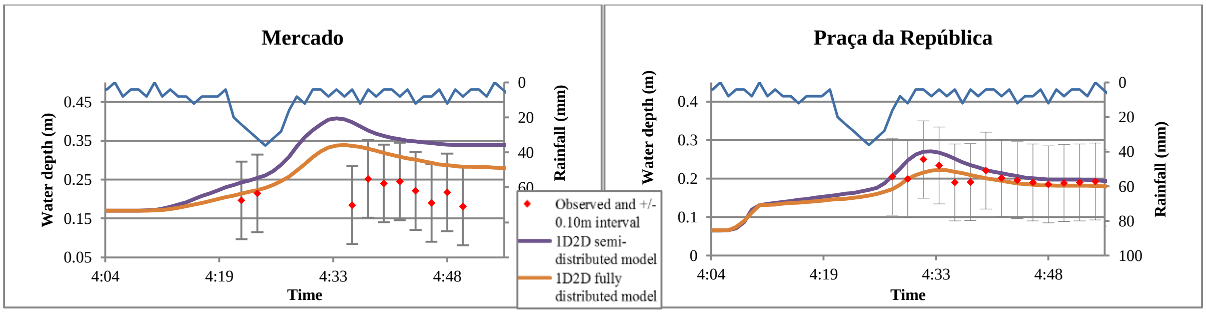

Figure 5. Observed data and model results – 2011/02/16.

Table 1. Water balance for each simulation.

Simulation	Model	Duration	Total rainfall	Total runoff	Max volume on the
2011-01-29	SD	120	4289.8	2289.7	1773.0
	FD	120	4471.8	2483.0	2156.8
2011-02-13	SD	180	19251.8	12843.0	8333.0
	FD	180	20068.6	12170.4	9934.9
2011-02-16	SD	60	13183.3	8879.3	6692.8
	FD	60	13742.7	8093.8	7269.5

Analysis of flood event with photographic evidence

The flood recorded on 9th June 2006 was caused by a rainfall with 50 years return period. Figure 6 presents photographs taken at 8 May Square during this flood event, as well the floodplains generated by the models with the registered rainfall. In this particular case, the floodplain produced at 8 May Square by the SD model covers a larger area and has higher water depths as compared to the FD results. This seems opposite to the conclusion in the previous section, but is justified because this is just a specific area. The overall results are in accordance to the previous conclusions, since the maximum volume on the 2D surface is higher in the FD than in the SD model (29808.1 m^3 and 26933.5 m^3, respectively). The observed results at 8 May Square can be explained by the fact that this area has the lowest elevation in the catchment and accumulates surface runoff that cannot enter the sewer system due to the limited capacity of inlet structures. Therefore, the runoff that is retained on the surface in the FD model due to overland singularities cannot reach this flooded area, resulting in a lower flooded area and flood depth comparing with the SD.

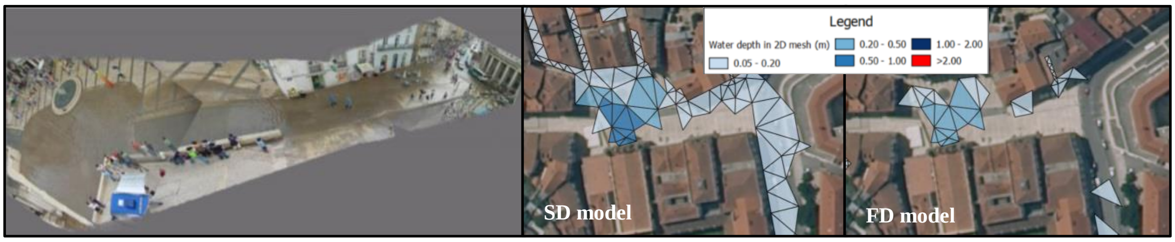

Figure 6. Flood recorded on 9 June 2006 in "Zona Central" catchment, Coimbra, Portugal; flood levels obtained with the SD and FD models.

DISCUSSION

The presented results of the SD and FD models implemented for the "Zona Central" catchment leads to several discussion points, namely the connections between the rainfall-runoff and flow modules of urban drainage models, their hydrological characterisation and calibration.

Connections between the modules of urban drainage models. The most evident difference between SD and FD models is the definition of the rainfall-runoff models and its connection with the overland and sewer flow modules. SD models are based on delineated sub-catchments that discharge directly to the sewer network. In FD models the runoff is routed on the overland surface and discharged to the sewer system through inlet nodes. In the present case study, surface overland singularities generally retained water volumes in the FD, where private sewer connections should drain these areas. This is not a problem in the SD model, since the water is directly assigned to a sewer node. This suggests that FD models require higher detail in the sewer network data to include also private networks. However, as this option can make the sewer flow module very complex, other possibility can be to define the FD model only on open areas (without buildings - e.g. roads, green areas) combined with sub-catchments on the other areas covered by the catchment.

Hydrological characterisation. FD models can be very detailed depending on the resolution of the overland mesh elements and on the data available.
Infoworks ICM v4.5 makes use of polygons to characterise the overland zones, such as the infiltration parameters. Since the overland surface is defined by continuous spatial data, a different approach could be adopted based on raster layers commonly used in Geographical Information System (GIS). This possibility would enable the use of several GIS functions to characterize the overland surface, such as obtained by remote sensing, and improve the details in the model definition.
In the presented case study, infiltration zones were defined with OSM data and buildings polygons, but future work should include a more detailed definition of zones. The use of raster data to characterise these hydrological parameters should bring more details to the model and physical based models would be adopted to simulate infiltration processes.

Model calibration. Calibrating an urban drainage model is usually a very complex task since it involves various parameters in all the four modules of urban drainage models. In the present case study the most sensible parameters were related with the definition of gullies inlet capacity to the sewer network and the hydrological characterization of rainfall-runoff models.
The inlet capacity of the gullies is dependent on the type of inlet structures and their local conditions. It should be defined with experimental data and could be represented in urban drainage models with virtual nodes connected directly with the overland flow model and the sub-catchments and connected with the sewer flow model with orifices and flap valves. In the present case study, real tests were taken at 8 May Square to verify the inlet capacity of the local inlet structures and define inlet equations (Pina, 2010). Nerveless, in a catchment scale, various inlet structures types can be found and their local conditions (how they are built and if they are cleaned) can influence significantly their inlet capacity. Therefore, the definition of the inlet capacity for an urban catchment can introduce a large source of uncertainty in urban drainage models.
The hydrological characterisation involves several parameters to define stormwater losses. These parameters are usually calibrated with results in the sewer network, where measurements can be taken (like in the present case the water depths in sewers). Therefore, this calibration is dependent on the assumed capacity for the inlet structures. Since this inlet capacity can introduce large source of uncertainty in this models, the hydrological calibration can also be compromised.

In the case study presented the main problem was to separate the calibration of the inlet structures capacity with the calibration of hydrological parameters. There is a need of larger datasets of monitoring data, which should include flooding events, to accurately calibrate urban drainage models.

CONCLUSIONS

This paper presented a comparison between two types of 1D2D dual drainage models: SD and FD. Model building concepts are presented for these two models and results of a case study are presented leading to the discussion points: connections between the modules of urban drainage models, hydrological characterization and calibration of the inlet structures and hydrological parameters.

These discussion points would indicate the an answer to the question posed in this paper: SD or FD rainfall-runoff models for urban pluvial flood modelling? There is no direct answer to this question. FD models seems more realistic and physically based, avoiding the hydrological models simplifications applied for sub-catchments in some SD models. This means that FD should be more detailed since the models concepts are more realistic. However, the necessary resolution and accuracy of the available data, either to define modules connections, hydrological characterization or even to do a proper calibration, seems to be higher for FD.

As a general conclusion, there are unanswered questions related with the FD models that are outlined in this paper and needs further research.

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