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Drainage system and detailed urban topography: towards operational 1D-2D modelling for stormwater management

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Abstract

Flash floods are increasingly occurring due to climate change and the dramatic increase of population over areas characterized by aging and undersized drainage systems. Many studies are dealing with the topic of urban pluvial flooding, but few of them thoroughly consider interactions between surface runoff and pipe flow. In addition, to get a better knowledge of the processes leading to flash floods in urban areas, the specificities of urban topography features have to be taken into account while modelling dual drainage, such as streets, sidewalks, road curbs, bridges, *etc*. This paper aims to present a detailed modelling approach at a district scale as a first step, in order to determine impacts of detailed and simplified topography implementation on intense runoff modelling. The second step aims to set up an optimized city scale runoff modelling and management. The coastal Mediterranean city (Nice, France) characterized by steep and low slopes areas suffered from an intense rainfall event in October 2015. This study-case enables to investigate on such problematic as a high-resolution (0.2m) photo-interpreted topographic dataset is available. Investigation based on Geographic Information System (GIS) is followed by 1D and 2D modelling. Results are presented by confronting outcomes given by GIS analysis and hydrodynamic modelling. It is shown that high-resolution data should be used carefully while dealing with urban hydrology and hydraulics. The reflection is driven towards a set of guidelines for modellers interested in helping stormwater operational management.

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Keywords: Stormwater management; dual drainage; urban flood modelling

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1. Introduction

Urban flash floods generated by extreme rainfall events are devastating for populations, assets and city functions. As the urban population is worldwide developing, the risks and their consequences are dramatically increasing. On top of that, sewer systems are very often not proportionally developed to comply with much greater volumes generated by urban expansion. There is therefore a high need for stormwater management, which requires accurate and efficient modelling or methods to quickly give indicative results for population and asset protection.

Urban systems have a double drainage system: surface runoff over streets and underground pipe network which are interacting during rain events. Interactions between overland flow and sewer pipe flow are complex to observe and to model. The interest to take these interactions into account has been studied using different methods **[1]–[4]**. However in an operational framework, in case of a heavy rainfall event, sewer systems can be considered as unavailable. Indeed in practice, because interactions are not well-known and due to grate clogging occurrence, surface runoff can be seen as the most critical contribution to flooding **[5]**.

Another source of complexity for urban flood assessment relies in urban topography and geometry. Urban surface features ranging from macro features (*e.g.* building), to micro features (*e.g.* sidewalks, road curbs, *etc.*), have been included in flood modelling approaches for various urban hydrology and flood assessment purposes **[6]–[9]**. However, the implications of high-resolution data use combined with optimisation procedure for operational 1D-2D urban drainage modelling have not been studied so far.

This paper focuses on the effects of detailed urban geometry on flow paths assessment as it affects in the same time overland runoff and buried pipe flow properties. The aim is to carry out an analysis of the impact of the level of detail of urban above-ground features taken into consideration when assessing catchment drainage. The first question to be raised is indeed how buildings and urban features divert overland flow. As a consequence, the implications for urban flood modelling have to be defined. The second topic raised by this paper is the potential possible simplifications for model building, *i.e.* which level of details is needed to set up a suitable model that is fast and accurate enough to enable operational modelling in order to help sewer operators and risk planners.

To perform this study, a real extreme rain event that occurred on the 3rd October 2015 is applied to a 5 km²-area of a Mediterranean city (Nice, France). The urban surface furniture is split into four levels of details in such a way that produced High-Resolution (HR) Digital Elevation Models (DEMs) are gradually including more details. Then, the method (Section 2) includes two steps of analysis: *(i)* a GIS-based comparison of the datasets giving static observations; *(ii)* a modelling approach which objective is to identify dynamic points of comparison. GIS analysis results are compared and 1D and 2D modelling first results are introduced in Section 3. Perspectives are opened for further study (Section 4) in order to draw guidelines for operational HR urban drainage modelling.

2. Materials and methods

The method is synthesised in Fig. 1 and developed in next subsections. To perform this study, a small urban catchment is chosen according to available HR data for the region. Suitable data is composed of evolving information with gradual levels of complexity, starting from a raw Digital Terrain Model (DTM) as basis to DEMs including as many details as possible (S1 to S4 in Fig. 1). Here a photo-interpreted dataset is used (detailed in Section 2.3). Interest of this type of dataset for hydraulic community is that it allows to build a HR DEM encompassing fine features which can be selected for its purpose, depending on the level of complexity of features that the modeller judges relevant to include **[10], [11]**. It should be noted that this judgment is based on expert opinion only and an analysis of the effects of the level of complexity of features included in the DEM depends on the modelling purpose. In this study, four different levels of surface feature information are selected for the study-area (S1-4). Their content has been selected from the available classification of features that has been considered as introducing complexity in surface drainage paths. The classes of selected features (under the vector form) are extruded on the DEM at a 1m-resolution.

Fig. 1 presents the flow chart of the overall approach. As a first step, a GIS analysis is performed on the different defined DEMs S1-4. The results will be compared as describes in Section 2.1. The second step (Section 2.2) consists in a 1D-simulation of the sewer network of the city for the selected event. In parallel, 2D simulations are performed with the objective to confront static observations with dynamic results.

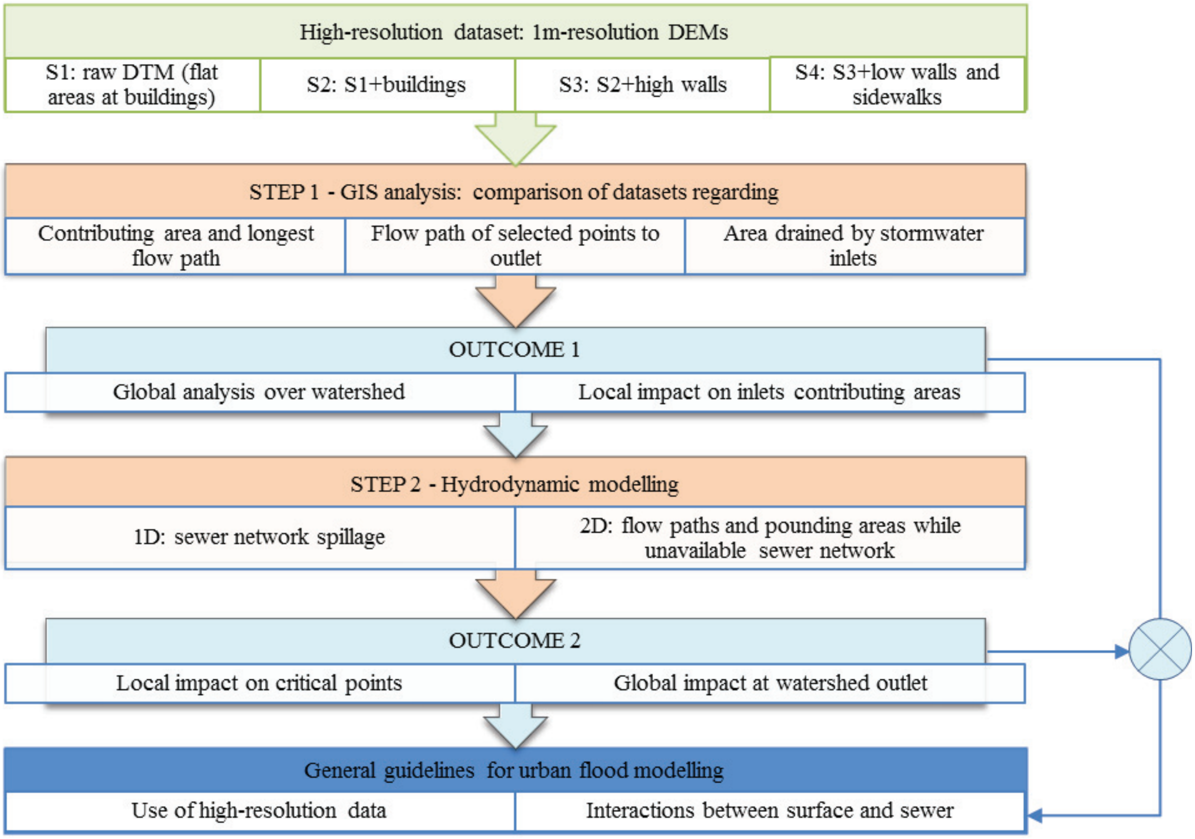

Fig. 1. Overview of the applied methodology.

2.1. GIS analysis

The HR topographic dataset **[12], [10]** available for the study-case is analysed with Arc Hydro Tools within ArcGIS (ESRI) regarding drainage lines and contributing areas. The outlet is chosen according to an existing point of interest regularly flooded, a low point located on a street under a bridge near a train-station representing high traffic load (Fig. 2). The first step of the GIS comparison consists in calculating the areas of contribution and longest flow paths for the previously mentioned dataset. This can be done after filling all sinks, calculating flow direction and flow accumulation, stream definition and segmentation, catchment delineation and drainage line processing. The goal of the second step is to identify potential diversion effects of street furniture and buildings on flow paths in the downstream direction. To do that, a set of 20 random points is defined and their flow path to the outlet of the catchment is computed. The calculation is repeated for each DEM and the length of the flow path is compared between the results obtained for each point. The third aspect of comparison relies on the area drained by each stormwater inlets of the sewer network within the study-area for every DEM. The interest is to detect the changing patterns from the initial DTM to the successive increase of detail level. Furthermore, the total drained area by the set of inlets is calculated and compared for each layer. The interest of this comparison is the observation of the influence of surface features on the connectivity of the surface with the stormwater network, which is a first condition to assess its drainage capacity.

2.2. Modelling approach

1D and 2D models are here run separately; coupling will be presented in future work. The 1D model of the sewer system of the whole city is based on the approximation of the SWEs (Shallow Water Equations) system solution using Mike URBAN (DHI). The model is provided by Nice Municipality and described in **[13]**. The rainfall event of the 3rd of October 2015 has been simulated using a spatially uniform rainfall data recorded every two minutes. The interest to use this model is double: *(i)* the results can be used as a reference and it allows to check the effects of introducing in the model different sizes of contributing areas depending on the GIS analysis; *(ii)* the types of interaction between the sewer system and the surface can be identified by simulating in 1D the rainfall event, which is useful for the upcoming coupling with 2D surface flow model.

The overland flow resulting from the selected intense rainfall event is modelled using the 2D SWEs based code FullSWOF_2D. This code is developed as a free software **[14], [15]** where the 2D SWEs are solved using a well-balanced finite volume scheme based on the hydrostatic reconstruction **[15]**. The finite volume scheme is applied on a structured spatial discretization using regular Cartesian meshing. The hydrostatic reconstruction (which is a well-balanced numerical strategy) allows to ensure that the numerical treatment of the system preserves water depth positivity and does not create numerical oscillation in case of a steady state, where pressures (in the flux) are balanced with the source term (the topography). The aim is to compare the effects of the level of topography detail included in the model on overland flow properties (water level and hydrodynamic) in order to figure out the appropriate level of detail to integrate in the modelling approach. To achieve this goal, the HR (1m) DEMs S1 to S4 were used as computational grids for the simulation. The size of these grids is larger than the sub-catchment area (3.3km²) with 5.9 million of computation points. A variable time step is used for the temporal discretization based on the CFL criterion (fixed to 0.45). Computations were run using the MPI parallel version of the code over 64 CPU and required 24 hours to simulate the 5-hour-event (including the 2-hour-rainfall peak which generated flooding issues). Net rainfall is introduced as spatially homogenous without considering infiltration. However it should be mentioned that the SWEs are not solved over the buildings footprint. The roughness coefficient is set to a spatially uniform value of $0.06 \mathrm{s.m}^{-1/3}$. Access to the sewer system is considered as non-available and the boundary conditions are closed. A second order scheme is used with a HLL solver **[16]**.

2.3. *Study-area*

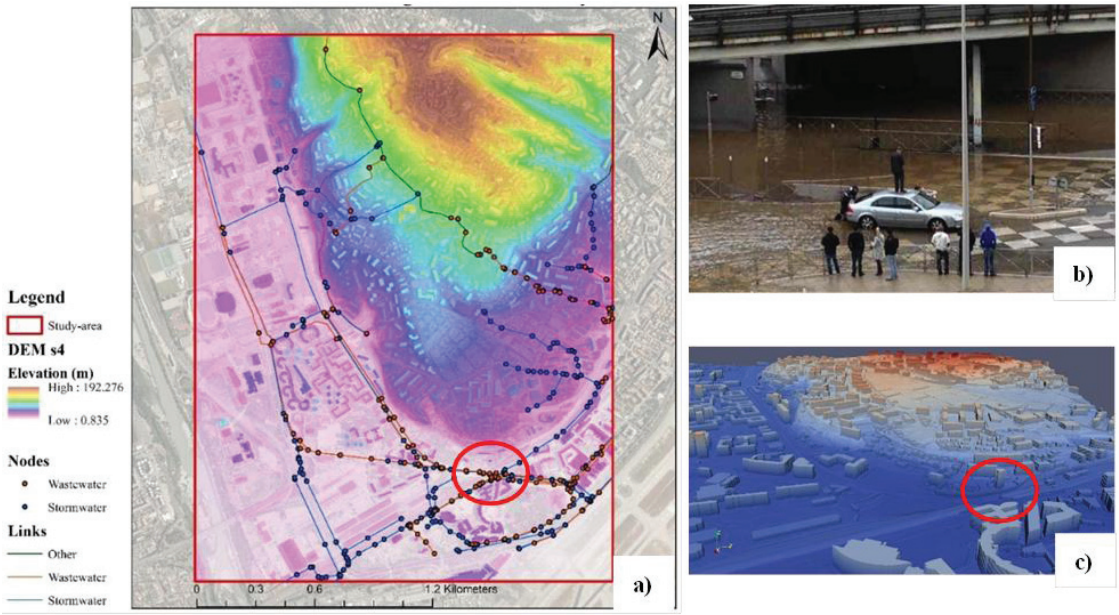

Fig. 2. a) Study-case topography and drainage network; b) Flooded street at the point of interest (under St-Augustin Bridge) (From Nice-Matin); c) 3D visualisation of the S4 DEM over the most downstream part of the catchment (red circle indicating St-Augustin Bridge).

The city of Nice is located in the south-east of France and is characterized by its coastal interface with the Mediterranean Sea and high slopes due to the nearby Alps Mountains. The drainage system of the city is characterized by a 510km-long pipe network. A district is selected according to the purpose of the paper with a problematic under a bridge located in a retention area. An area of 3.2km² is drained to a street under the bridge. This location is regularly flooded during rain events (Fig. 2b,c). The separated drainage network included in the study area contains 253 stormwater inlets (Fig. 2a). The sanitary pipes and manholes are not taken into account.

A high resolution photo-interpreted dataset covering the whole extent of the city has been gathered by the municipality in 2011 **[12], [10]**. A low altitude flight, a pixel resolution of 0.1m at the ground level, a high level of overlapping among aerial pictures (80%), and the use of an important number of markers for geo-referencing (about 200), lead to a high level of accuracy over the urban area of the city. The average accuracy of the dataset is 0.2m in both vertical and horizontal dimensions. Errors in photo-interpretation are estimated to be around 5% after verifications with terrestrial topographic measurements performed by DIGNCA over 10% of the domain covered by the photogrammetric campaign. The selected rain event occurred on the 3rd of October 2015 and is characterized by a severe violence in the region with considerable material damages and 17 human losses in cities located nearby Nice. Over the study-area, precipitations have been less important but still of the order of 100-year-return period with a peak intensity of 78mm/h and an accumulated volume of 74mm within one hour.

3. Results and discussion

3.1. GIS-based results and interpretations

- Contributing area and longest flow path

The comparison of the four DEMs gives useful information regarding surface drainage. According to drainage lines calculations, the contributing area varies. Fig. 3 shows watershed delineation and longest flow path for each case from S1 to S4. The numerical values are presented in Table 1.

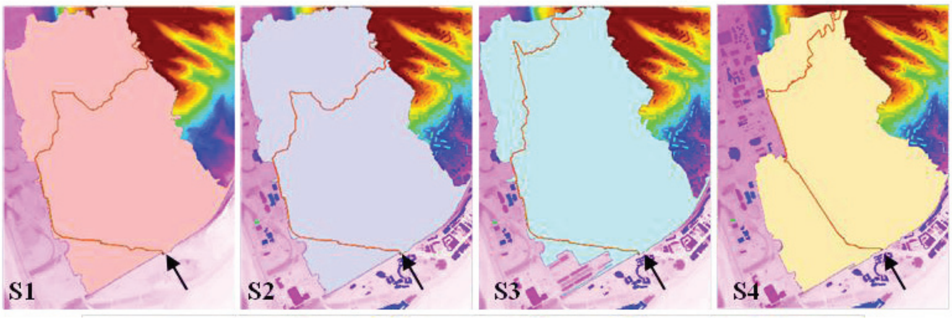

Fig. 3. Direct contributing areas and longest flow paths to outlet under St-Augustin Bridge (pointed out by the arrow).

Table 1. Results of calculations of contributing areas and longest flow paths.

DEM	Direct contributing area (km²)	Longest flow path (km)
S1	3.24	4.44
S2	3.28	4.51
S3	3.12	4.54
S4	2.73	4.14

Differences can be observed in the delineation of the contributing area. A major difference occurs for S3 DEM in the South-West part of the study area and for S4 in the North-West part. These results show that, taking for reference S1 (DTM without construction), the presence of buildings (S2) provokes a very slight increase of drained area (by 1%). However, when considering high walls (S3) the drained area is decreased by almost 5%. This means that some walls are diverting drainage lines outside the original catchment boundary. This effect can be observed at a higher magnitude when considering S4, the DEM containing the higher level of details. S4 is characterised by a significantly smaller contributing area, almost 13% less than the contributing area of S3. The evolution of the longest flow path has to be noticed as well. This path is very similar between S1 and S2, while its North part varies. The most noticeable qualitative change can be seen for the south part of the area between S1 to S3 which are similar, and S4, which shows a very different flow path, following another street compared to other layers. Regarding length, S4 shows the most significant difference as well with a longest flow path almost 7% shorter compared to S1. These results demonstrate that the choice of the level of detail will directly influence overland flow modelling. Indeed, as S4 presents a smaller drained area, lower water depths are expected at the outlet of the watershed.

- Flow path of selected points to outlet

Fig. 4 presents the comparison of the computed values of flow length for a set of 20 random points to the outlet (St-Augustin Bridge) for each case from S1 to S4.

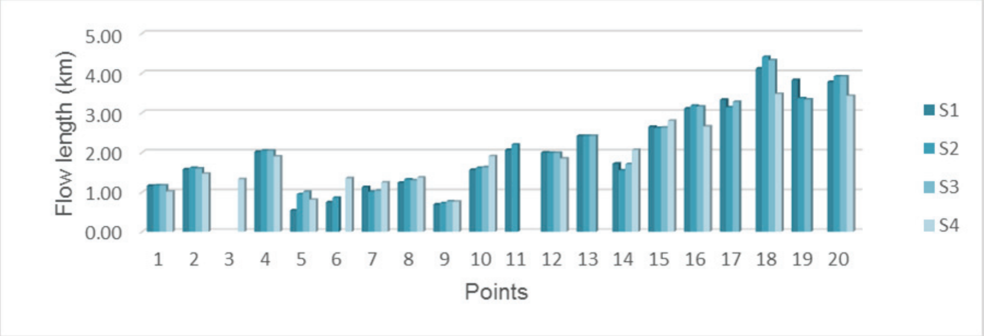

Fig. 4. Comparison of flow length to the outlet for 20 points between S1 to S4 (0 value means no connection to catchment).

In average, the minimum value is increased by 21% within a range going from 0 up to 87%. These gaps may influence overland flow significantly. Flood kinetics is thus depending on street furniture included in the DEM. According to the graph, there is no general trend regarding which layer gives a longer flow path. S4 shows the minimum value for six points and the maximum for seven other points out of 20. Six points have their minimum value with S1 layer. For further comparison, a higher number of points should be selected.

- Area drained by stormwater inlets

The drainage area of each of the 253 stormwater inlets is computed individually and summed to obtain a total drained area for each DEM S1-4. Several comparisons are presented in Table 2.

Table 2. Comparison of the total drained area to stormwater inlets.

DEM	Total drained area (km²)	Difference to S1 (%)	Difference to S2 (%)	Difference to S3 (%)
S1	3.94	+ 0.0	/	/
S2	4.49	+ 14.0	+ 0.0	/
S3	4.48	+ 13.9	- 0.12	+ 0.0
S4	4.22	+ 7.22	- 5.96	-5.84

The differences to S1 situation show that the drained area is highly increased with buildings by 14%. The difference between S2 and S3 is not significant (-0.12%). However, the fourth and fifth columns show that the consideration of all urban features (S4) reduces the drained area by almost 6% compared to the presence of buildings (S2) and the presence of buildings and high walls (S3). This means that using S4 catchment delineation, lower volumes would be drained to the sewer system in the 1D-modelling step.

3.2. Discussions and perspectives on hydrodynamic modelling

The existing validated 1D-model of the sewer network of the whole city created with Mike URBAN software (DHI) is run for the 3rd of October rainfall event. Six nodes where the sewer system is contributing to the surface flow are detected in the study area. They are located in the downstream part of the catchment, in a rather steep subarea which is contributing to the point of interest for both surface and underground flow. Future work regarding 1D-sewer system modelling aims to perform a sensitivity analysis using S1-S4 new detailed sub-catchments delineation to define manhole contributing areas. Purpose will be to study impacts of these sub-catchment delineation variations on the sewer drainage modelling. Moreover, considering future coupling with 2D models, the interactions between sewer and surface model drainage (*e.g.* nodes identified as contributing to surface flow) might be different and require further thorough analysis.

Second step for future improvement will use results of the 2D surface runoff modelling. 2D-results presented in Fig. 5 are in a realistic order of magnitude according to the observations under the bridge. Four models using S1 to S4 were run. Fig. 5a illustrates results of the 3rd of October flood event modelled using HR DEM (S3). As expected, it shows that the magnitude and kinetic of the water depth evolution is impacted by the HR level of topography (Fig. 5b). Moreover an illustration of the impact of the detail of the topography on overland runoff flow path confirms that a street can be flooded or not (Fig. 5c red dotted line and black arrow) depending on included street features on the surface model. A deeper analysis on the required optimal level of detail will be performed focusing on water levels over manholes location when using 2D surface modelling to better understand and quantify effects of the HR topography on 1D-2D coupling between drainage models. Moreover, these tests with FullSWOF_2D code are a first step in the process of analysing HR topography details impact. Indeed, for the objective of operational tool for stormwater management, to optimize computation time, other codes (*e.g.* DHI's Mike 21) will be tested and compared. Other approaches such as simplified approaches (*e.g.* diffusive wave approach with Mike SHE (DHI)) will be tested and compared as well.

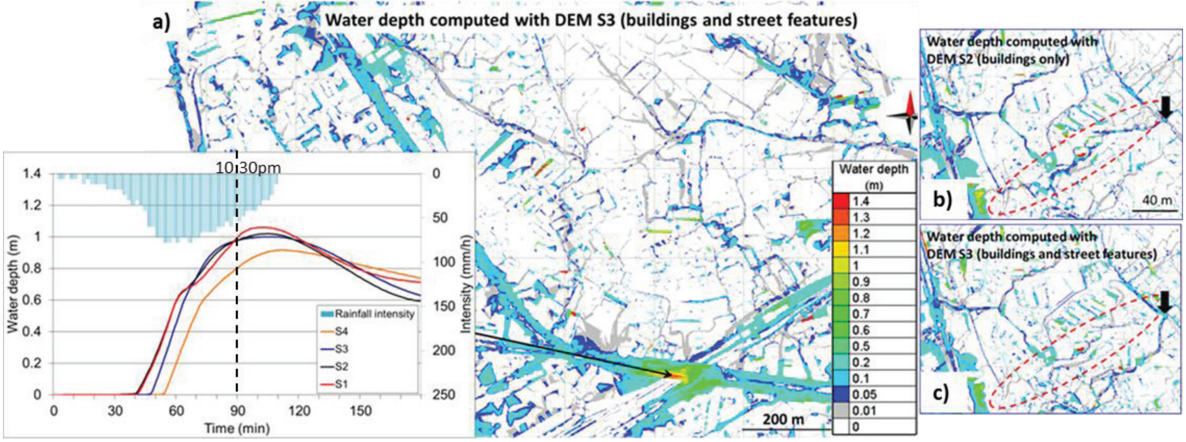

Fig. 5. a) Overview of the simulated water depth of the flood event at 10:30 pm using DEM S3 at the southern part of the catchment; b) Water depth evolution at St-Augustin Bridge with S1-4; c) Simulated water depth of the flood event at 10:30 pm comparing DEMs S2 and S3 at a northern part of the catchment.

4. Conclusion and prospects

This study has presented preliminary results given by a method set in order to improve operational modelling of urban systems regarding flood kinetics throughout detailed urban topography. Results showed that a thorough analysis is required to select the best conceptualisation of the topography representation in models. Indeed, the selection of the level of topography details to include impacts the results to a great extent. This statement is confirmed to be valid for both buried drainage system (by impacting collecting areas definition) and surface drainage modelling. The higher level of details is not necessarily the best choice to model urban flood in a realistic way. Moreover, in this modelling approaches (GIS and Hydrodynamic modelling) surface features are included in the topography and therefore hundred percent impermeable which is not a fully satisfying statement. Furthermore, effects not encompassed here such as clogging effects, surface features which temporally evolve quickly over urban area or which can be destroyed by flood event, *etc.* are sources of uncertainty affecting drainage path. However, it is promising to achieve an analysis of the optimal feeding that this emerging type of dataset can provide to operational 1D-2D modelling for stormwater management. Finally, it is interesting to mention that this study not only confirms the important impact of the level of details of topography on both surface and sewer drainage systems, but presents a methodology to qualify and quantify these effects. The presented study-case and methodology opens the door to tackle this problematic. The reach of this study allows to continue working on improving assessment of an effective operational 1D-2D coupling. Next directions for future work will be: *(i)* adaptation of 1D-model according to GIS findings (regarding manholes and drained areas connectivity); *(ii)* 2D-modelling analysis and optimization (sensitivity to DEM properties); *(iii)* 1D-2D coupling for several study-areas in Nice (optimized strategy for bigger-scale catchment).

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