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# **BENEFIT OF COUPLING 1D-2D MODEL OVER AN URBAN AREA TO ASSESS RUNOFF DURING A STORM EVENT**

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## **KEY WORDS**

Stormwater network, urban runoff, floods management, 1D-2D hydraulic model, InfoWorks ICM.

## **Abstract**

Stormwater or rainwater networks are essential infrastructures in urban areas to reduce the runoff during storm events. In recent years, several storm events occurred in France especially in Mediterranean regions leading to severe urban floods, mainly due to the capacity of storm network to cope with runoff generated by extreme rainfall events. Therefore, flood risk analysis is essential to identify vulnerable areas. To do so, numerical modelling tools can be used to assess the performance and potential limitation of storm networks efficiency during heavy rainfall events. One-dimensional (1D) stormwater models are assessment tools commonly used, as they are easy to build, efficient and their computation time is fast. However, 1D model only predicts the overflow from the stormwater system which is transmitted to the surface. The runoff is not considered and therefore the vulnerability of the flood event is not assessed by a simplified approach. To overcome this limitation, tools able to couple the storm network (1D) with the surface runoff (2D) have been developed. Such tools potentially enable a better understanding of the interconnected issues in the domain of storm water management and urban runoff (network overflows, runoff inflows). The objective of the study is to evaluate the benefit of coupling 1D and 2D models to assess the flood management in an urban area. To do so, a 1D stormwater network and a 2D hydraulic runoff network will be built with InfoWorks ICM. The study compares the results obtained with modelling of pluvial and storm flooding in 1D/1D and 1D/2D models to investigate the importance of linking the surface and sub-surface drainage domain in a small area in Nice (France). The results highlight the benefice of coupled 1D/2D model in vulnerable area.

## **1. Introduction**

In recent years, several storm events occurred in France especially in Mediterranean regions: in June 2010 in Draguignan city [1], in June 2012 in the Gard [2], in Cannes city in October 2015 [3, 4]. These events mostly generate severe urban floods mainly due to the lack of capacity of stormwater network to cope with runoff generated by extreme rainfall events. Therefore, identification of vulnerable areas is needed to protect local population and goods, and the assessment of the performance of storm networks during heavy rainfall events is necessary in largely urban area. Modelling tools have become a solution for flood risk analysis. To assess storm network capacity, one-dimensional (1D) numerical modelling tools are commonly used because of the relatively simple model construction, the high efficiency and the short runtime for simulations [5]. However, Chang *et al.* [5] and Mark *et al.* [6] identified the limits of using a 1D model over 2D and remind that the use of a 1D can only predict, in terms of ground surface, the surcharge volume from the drainage system. This volume is then transformed into the flood depth of a sub-catchment using a depth-volume or area-volume function. The runoff surface dynamic is simplified as the approach assumes that there is no flow interaction between sub-catchments. Therefore, to simulate detailed flood propagation on the ground surface, many physically-based 2D numerical modelling tools based on shallow water equations (SWEs) have been developed [7, 8]. Many studies use 1D/2D models in urban area to investigate runoff induced flood inundation model: Seyoum *et al.* [9], Russo *et al.* analysis extremes floods in Barcelona [10] and Salvatore *et al.* review the state of the art on the

scientific knowledge and practice of modelling the urban hydrological system at the catchment scale [11]. Moreover, 1D/2D models are also used to evaluate flood propagation along galleries in a nuclear plant, based on the solution of the SWEs with a finite volume method [12].

As most of the highly urbanized areas in Mediterranean climate region, Nice city is facing flood issues due to intense rainfall events. The 3<sup>rd</sup> of October 2015, in Nice the storm network reached its full capacity during a storm event and storm network overloads occurred and caused floods in the urban area [13]. Furthermore, previous studies have been carried out to investigate flood hazard related to intense rainfall event induced runoff within Nice. Abily *et al.* [14] used high resolution topographic datasets to represent soil features at different levels of details, to evaluate runoff estimations capabilities and uncertainties assessment with 2D numerical modelling tools (FullSWOF [15], Telemac [16] and Mike 21 and 21FM [17]). This work however considered the drainage system as non-operating in its approach to match with conservative needs of the study framework at the time. Later, Salvan *et al.* considered within a study, the drainage system and detailed urban topography and identified the need of coupling 1D-2D modelling for stormwater management [18]. The French Institute for Radiological Protection and Nuclear Safety (IRSN) is in charge of assessing the risk of flooding hazards on nuclear sites, therefore an industrial site should be considered for our study. The study case is thus an industrial site located in Nice: the MIN (Marché d'Intérêt National) platform. Moreover, the stormwater network representation in modelling approaches is investigated to identify its role during storm events to complete previous studies.

Here, the study allows the comparison of the results obtained with two urban flood modelling approaches: 1D/1D and 1D/2D. This study allows to identify the importance of the coupling between the stormwater network and the surface runoff. Through this approach, the objective is to underline, at the spatial extent of an urban district, with a synthetic and an historic rainfall event uses, the added values, limits and complementarity of 1D-1D, 1D-2D modelling in both cases.

This paper reviews the available urban hydraulics modelling tools (part 1), and then presents the models implemented for the study using InfoWorks ICM software: the 1D stormwater network and the 2D surface runoff area, the two rainfall scenarios studied (part 2). Comparisons are made on two criteria: quantification of the volume of water overflowing the stormwater network and the area of water accumulation, with the 1D/1D and 1D/2D models. This is done for the two rainfall scenarios: a 100-year return period rainfall and the 3rd of October 2015 event rainfall (Part 3).

## 2. Material and methods

### 2.1 Hydraulic modelling tools

In recent years, stormwater numerical models describe the main physical processes related to the stormwater flow in urban catchments to study the quantitative and qualitative capacities of storm networks. Such tools play a critical role in urban stormwater drainage management to design, optimize and evaluate flood hazard. Those models are based on coupling rainfall-runoff, sewer and overland flow. To do so, rainfall is transformed into the runoff by the rainfall–runoff module. Runoff is then routed to the flow over the urban surface area (2D) and to the sewer flow module (1D) by the overland flow module [19].

In order to choose the most suitable commercial software for the study, a comparison of different softwares available in the market was conducted on their fields of use, the type of model used, the complexity of use, the type of simulation and finally the input and output data [20]. The softwares studied are MIKE URBAN [21], PCSWMM [22], HydroCAD [23], InfoWorks ICM [24], CivilStorm [25] and Hydra [26] (Table 1).

Software	Water networks modelling capability	Model	Input data	Output data
<b>Mike Urban</b>	Stormwater, wastewater, watershed and water distribution systems	Hydrology hydraulic	/ Rainfall data and network, topography	Hydrograph, water level
<b>PC SWMM</b>	Stormwater, wastewater, watershed and water distribution systems	Hydrology hydraulic	/ Rainfall data and network	Hydrograph, water level
<b>HydroCAD</b>	Water network for civil engineer	Hydrology	Autocad network data, sub catchments	Hydrograph
<b>InfoWorks ICM</b>	River and water networks (risk management, water management, rainfall, sediments transport)	Hydrology hydraulic	/ Rainfall data, Network, sub catchment, land use	2D hydrograph, maps, water level

<b>CivilStorm</b>	Stormwater (management, quality)	network water	Hydrology hydraulic	/	Rainfall data and network, topography	2D and 3D maps, hydrograph
<b>Hydra</b>	Water management, prevention and water quality	resource flood and protection,	Hydrology hydraulic	/	Rainfall data and network	1D/2D simulation, hydrograph, water level

**Table 1. Hydraulic numerical modelling tools descriptions**

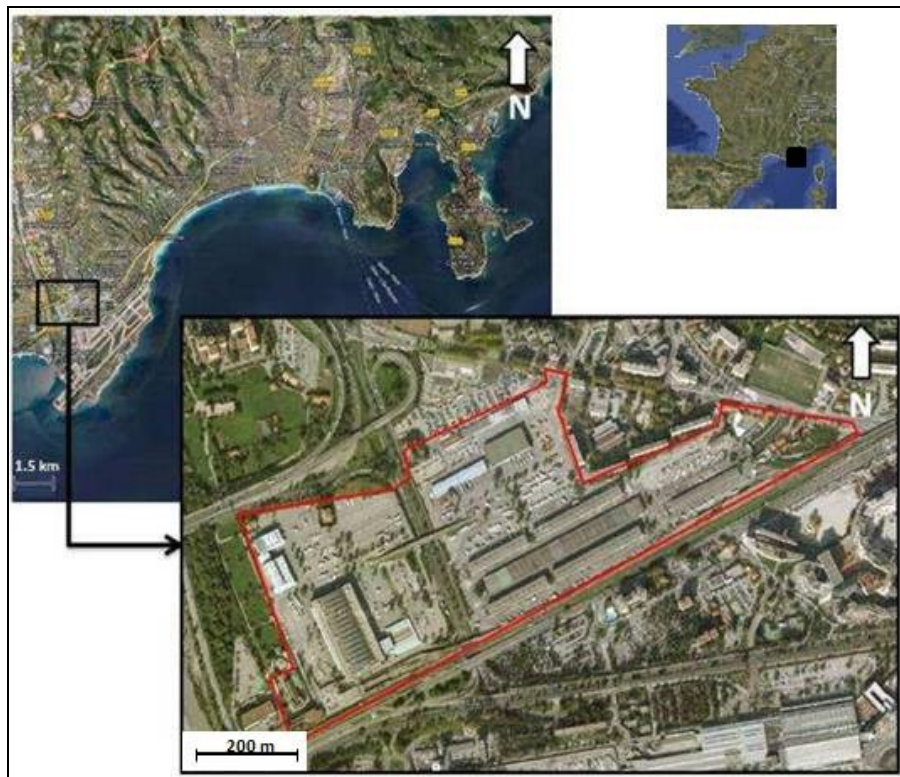
InfoWorks ICM is the selected tool for our study as the software includes all the relevant processes and phenomena that play a role in the physical runoff system, from the rainfall at the inlet to the outfall at the outlet. In InfoWorks ICM, the included processes are the runoff calculation and flow convergence for the hydrological model, the one-dimensional hydrodynamic simulation for the underground pipe networks, and the two-dimensional hydrodynamic simulation for surface inundation.

InfoWorks ICM hydrological model adopts a distributed method to simulate the rainfall-runoff process by dividing the study area into detailed sub catchment areas which may have various runoff surfaces of different flow characteristics. The runoff calculation and flow convergence process of the hydrological model can employ various models. The hydrodynamic simulation for the underground pipe networks is implemented by solving the Saint-Venant equations [27]. The flow in the underground pipes has two states, that is, surface flow and pressurized flow, and the Preissmann slot [28] is used to handle both kinds of flow and their transition. The two-dimensional hydrodynamic simulation of the surface inundation is implemented by solving the shallow water equations (SWE).

## 2.2 Case Study

The selected case study is the MIN (Marché d'Intérêt National) platform which is located in Nice (France) (Figure 1). The surface area of the MIN platform is 60.4 ha. The stormwater network data is available and provided by the Nice Côte d'Azur metropolis. Topographic and photogrammetric data collection campaigns, respectively in 2005 and 2010-2011, are also available.

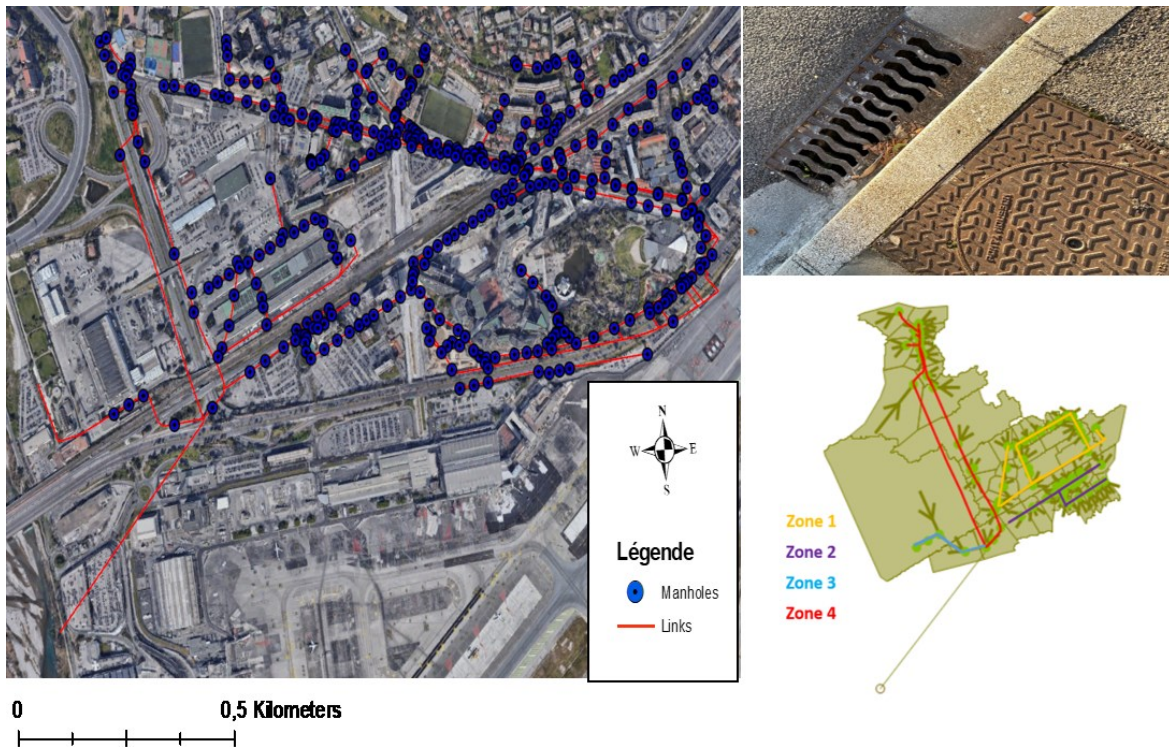
As mentioned beforehand, previous studies have assessed the flood hazard in the MIN. These studies have identified the influence of the features represented in the 2D models (buildings, sidewalks, roundabouts, road gutters) to assess flood hazards and the related uncertainties [14, 18]. Eventually, whereas our zone of specific interest (red rectangular in Figure 1) is a platform delimited by urban structures (roads, elevated train ways, *etc.*) where direct surface runoff area of contribution is thus bounded, the storm water network covers of the MIN is connected to a larger area.



**Figure 1: MIN site – Nice in France (from [29]).**

### 2.3 1D Stormwater network

The available data describing the stormwater network (manholes and links) are presented in Figure 2. 81 nodes and links were kept and introduced in our 1D model. The outlet of the network is located in the Var River, 537m away from the nearest node. For the descriptions of the gullies and manholes, the ground level of the node was systematically omitted as well as the description of the chamber. The storm network modelled is 4 km long. 19% of the links have a diameter of 2000 mm, 1% of 700 mm and for 80% the size is unknown. Therefore, the missing parameters such as pipes diameters were deducted according to information available for the downstream and upstream links.



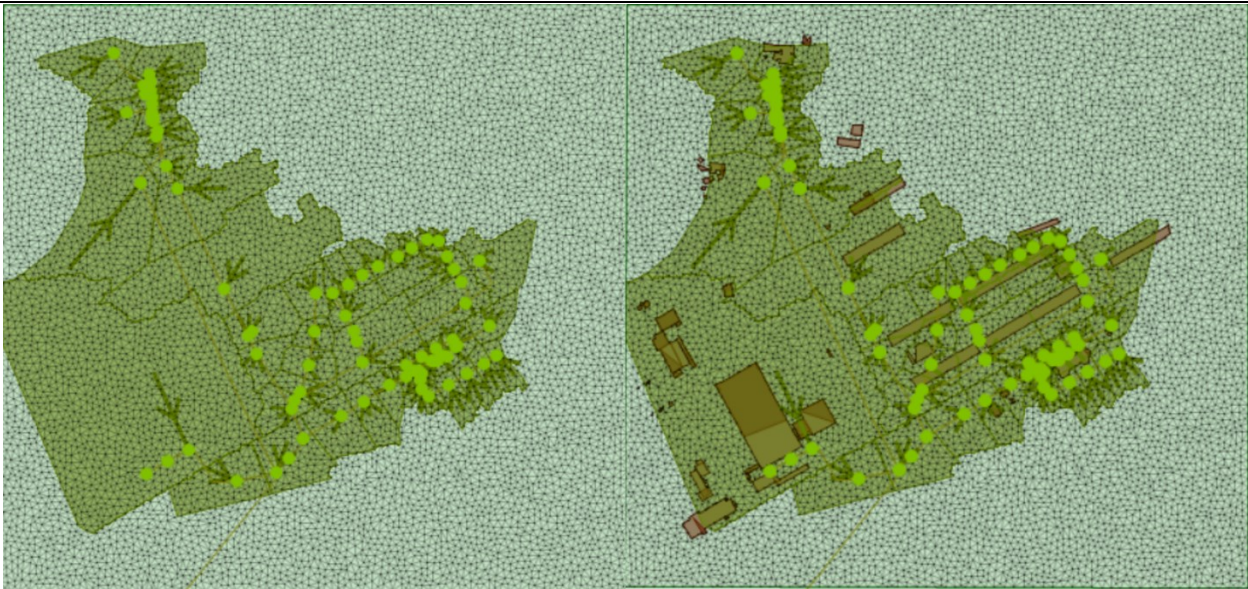
**Figure 2.** Available manholes and links present on the MIN (left), manhole picture (top right), model 1D build in InfoWorks ICM (bottom right).

Finally, 60 sub catchments were created using available topography and with the Thiessen polygon method with a maximum of 3 manholes per catchment area. Within the sub catchment, the surface type has been considered as impervious and therefore the runoff coefficient is 1. The surface of the MIN modelled is 40.6 ha. The largest catchment, located on the south West of the MIN, has a size of 12.1 ha, 52 sub catchments are smaller than 1 ha, 4 sub catchments between 1 and 2 ha, 1 is equal to 3 and 1 to 4 ha. It can be noticed that the sub catchments size are unequal due to the topography and the density of manhole present in the MIN area.

### 2.2 2D surface model

A DTM (Digital Terrain Model) available for Nice Métropole (2019) with a resolution of 5 m was used to generate the mesh. For this first study, only buildings have been added in the 2D runoff model. A uniform Manning's roughness coefficient value of 0.0125 has been applied to all the 2D cells. This value is commonly used for a concrete area [30]. Figure 3 introduces the 2D scenario designed for this first study.



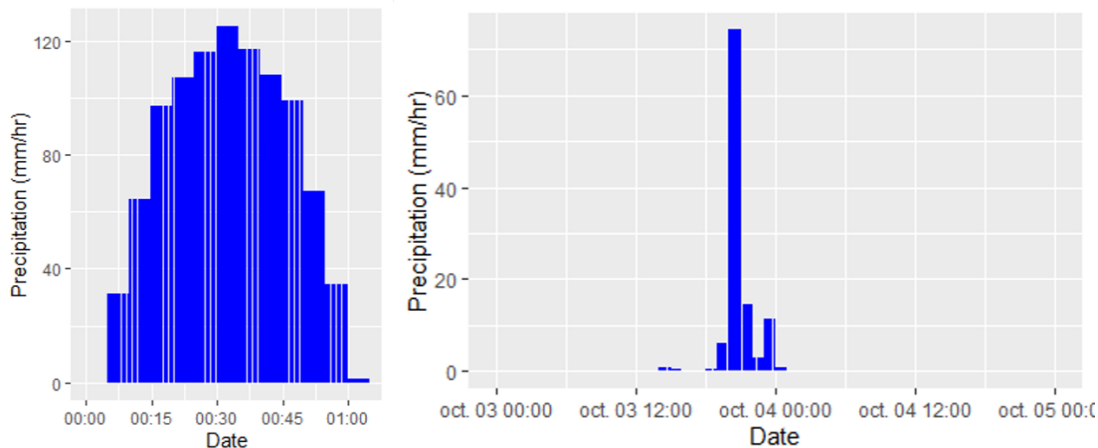


**Figure 3. Mesh grids generated without building (left) and with buildings included in mesh (right), where green lines represent the sub catchments and green dots the 81 manholes of the study area**

The model has not been calibrated as the stormwater network is not monitored and data from previous extreme rainfall events were not available.

### 2.3 Rainfall events

Two rainfall events have been selected for this present study: *i*) one hour synthetic 100 years return period event hyetograph (estimated by Météo France from the Nice airport gaging station located 1km from the study area) [31], *ii*) recorded rainfall storm event of the 3<sup>rd</sup> October 2015 by Météo France (Figure 4). These two events represent 80.7 mm in 1 hour for the 100 years return period event and 112 mm in 5 hours for 3<sup>rd</sup> of October 2015.



**Figure 4. Hyetographs for the 100 years return period (left) and the 3rd October 2015 event (right).**

### 2.4 Simulations

The simulations run during the study are presented within the **Table 2**. The computational time of the simulations is relatively short (few minutes).

	Simulations		
Rainfall events	1D-1D	1D-2D without building	1D-2D buildings
100-year rainfall	S1D_1	S2D_1	S2DB_1
3rd October 2015	S1D_2	S2D_2	S2DB_2

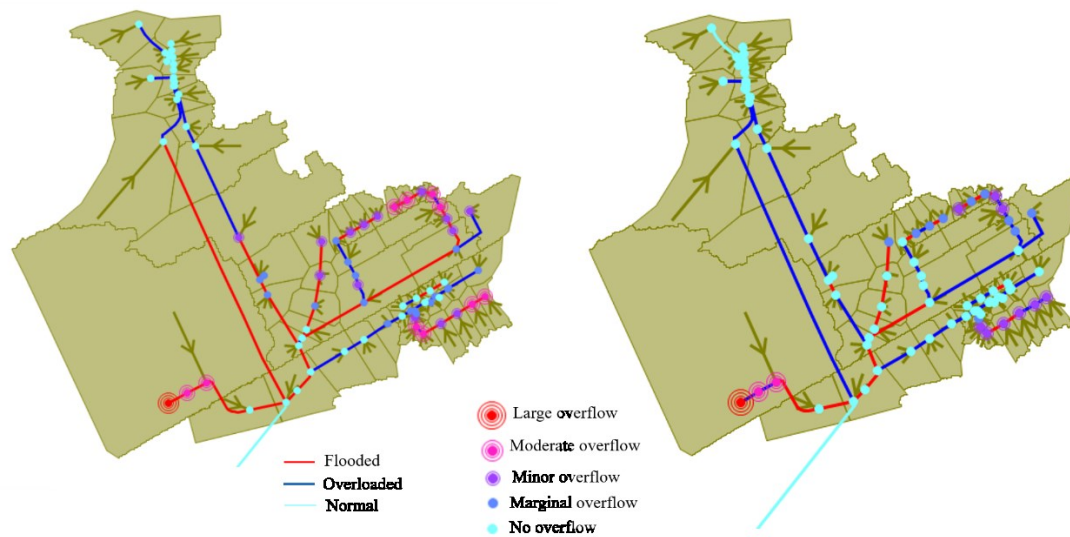
**Table 2. Simulations performed.**

### 3. Results and discussion

#### 3.1 Analysis of the stormwater network overflows

To start with, a comparison of the flooded areas by the 1D stormwater drainage network during the two storm events selected has been carried out. Figure 5 is a synopsis of the worst-case conditions encountered by the system over the entire modelling run (overflow, overtopping) for each node and pipe in the 1D model for both events. These worst states are not necessarily simultaneous. The network discharges the greatest volume of water to the surface for the 100-year rainfall event. Three pipe branches in the system are loaded (zones 1, 2, and 3 in Figure 5) and excess water is released to the surface.

37 manholes overflow for the 100-year return period event compared to 19 for the 3<sup>rd</sup> of October 2015 event. The total volume of water released to the surface for the 100-year event is 11,350 m<sup>3</sup> against 9,894 m<sup>3</sup>. Most of the total volume flooded is generated by a manhole located in the largest sub catchment (Zone 3 mentioned in Section 2.1) for both rainfall events. The October 2015 event generates a slightly larger amount of water released (9,565 against 9,475 m<sup>3</sup>) in Zone 3. For the rest of the domain, the model estimates a volume of less than 250 m<sup>3</sup>.



**Figure 5.** States of the sewer pipes and manholes for the 100 years event return period (left) and the historical rainfall event of 3rd of October 2015 (right).

Table 3 compares the total quantified volumes for each storm system branch, model, and rainfall event. As previously observed, the analysis highlights a limited risk of stormwater flooding in Zone 4, with modelling estimating no stormwater overflow for the October 2015 rainfall event and a low overflow volume for the 100-year rainfall event. Moreover, there is no building located in this area. For zones 1 and 2, larger volumes overflowing are observed with the 1D/2D models than with the 1D/1D model. The difference between the 1D/2D scenarios with and without buildings is marginal. This result is not confirmed for zone 3 where the flooded volume is much larger when buildings are introduced in the mesh for both events. As observed previously, the quantified volumes for zone 3 are larger for the October 2015 event. These initial results highlight a difference regarding the flood volume overflowing from the stormwater system for the different modelling scenarios.

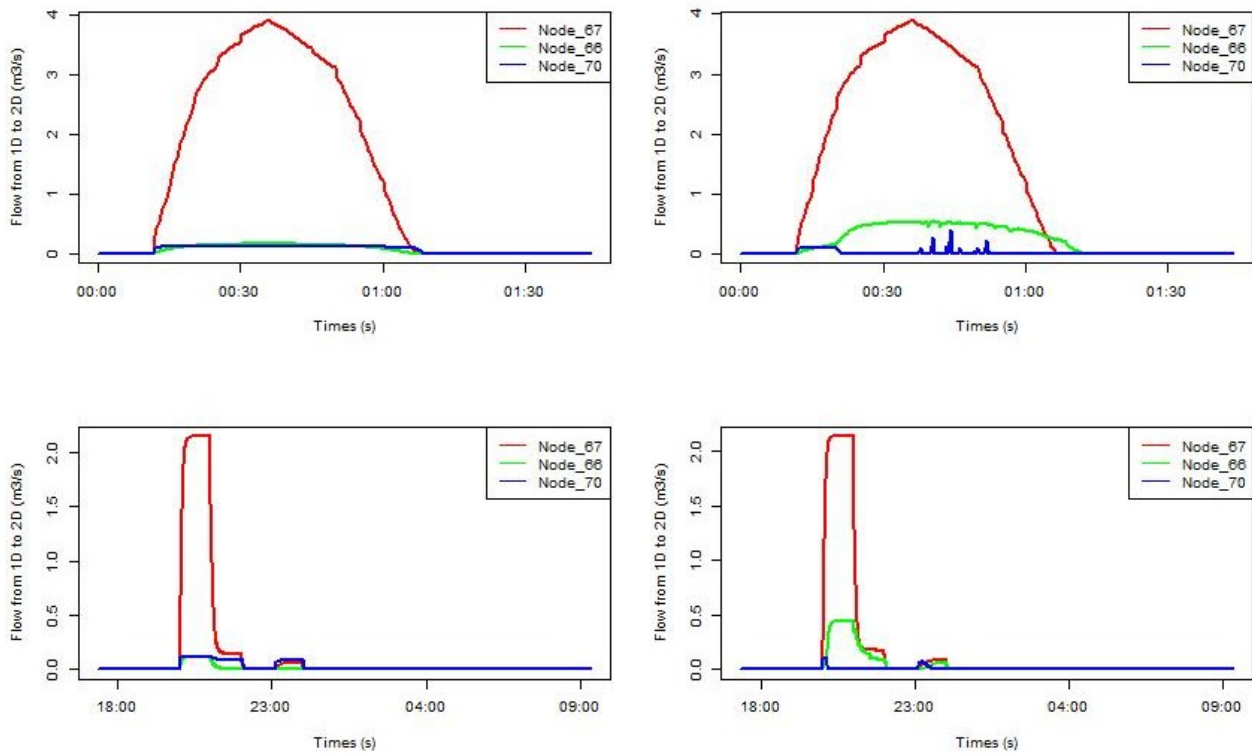
	Rainfall events					
	100-year rainfall			3rd October 2015		
	1D-1D	1D-2D	1D-2D buildings	1D-1D	1D-2D	1D-2D buildings
Zone 1	1,056	1,764	1,767	86	359	361
Zone 2	554	1,057	1,058	243	514	515
Zone 3	9,475	9,183	9,749	9,565	9,816	10,652
Zone 4	266	966	969	0	0	0
Total Volume (m <sup>3</sup> )	11,351	12,970	13,543	9,894	10,689	11,527

**Table 3.** Summary of stormwater network flooding volume overflowing in m3 for the two events for the 4 zones.

Then, the dynamic of the overflows from the stormwater network to the 2D surface runoff is presented in Figure 6 for the 1D/2D models. The impact of buildings on the overflow from the 1D stormwater system to the 2D surface runoff

area is highlighted in Figure 6. Indeed, for the simulations where buildings are present, overflows are identified for each manholes located in zone 3 (named Node\_66, Node\_67 and Node\_70 in InfoWorks ICM).

The presence of buildings influences the storm network floods as we can see in Figure 6, the flow from 1D to 2D is coming from more manholes. This explains the difference in overflow volumes between the 1D/2D models depending on the consideration of buildings (Table 3). In addition, the presence of buildings in the mesh also influences the surface flow dynamics as well as the accumulated water depths.



**Figure 6. Flow from 1D to 2D for nodes presents in zone 3 for the 1D/2D without building model (left) 1D/2D with building model (right) and for 100 years return period event (top) and 3rd October 2015 event (bottom).**

Finally, the accumulated water heights as well as the extent of flooded areas are examined here. For the 1D/2D model with buildings, a synopsis of the accumulated water depths over the entire model area is shown in Figure 7. For both rainfall scenarios considered, it can be observed that a large amount of water is accumulated around the large buildings in zone 3. A synopsis of the maximum simulated heights for each of the rainfall scenarios is presented in Figure 8 when buildings are present in the mesh. For the 100-year scenario, a maximum water height of 1.20 m is reached along the buildings. For the October 2015 scenario, a maximum height of 1.15 m is calculated at the same location. An analysis of the DTM showed that the surroundings of the buildings has a bowl-shape without manhole, which is favorable to water accumulation. Indeed, an accumulation of water is observed for each of the scenarios in this area in



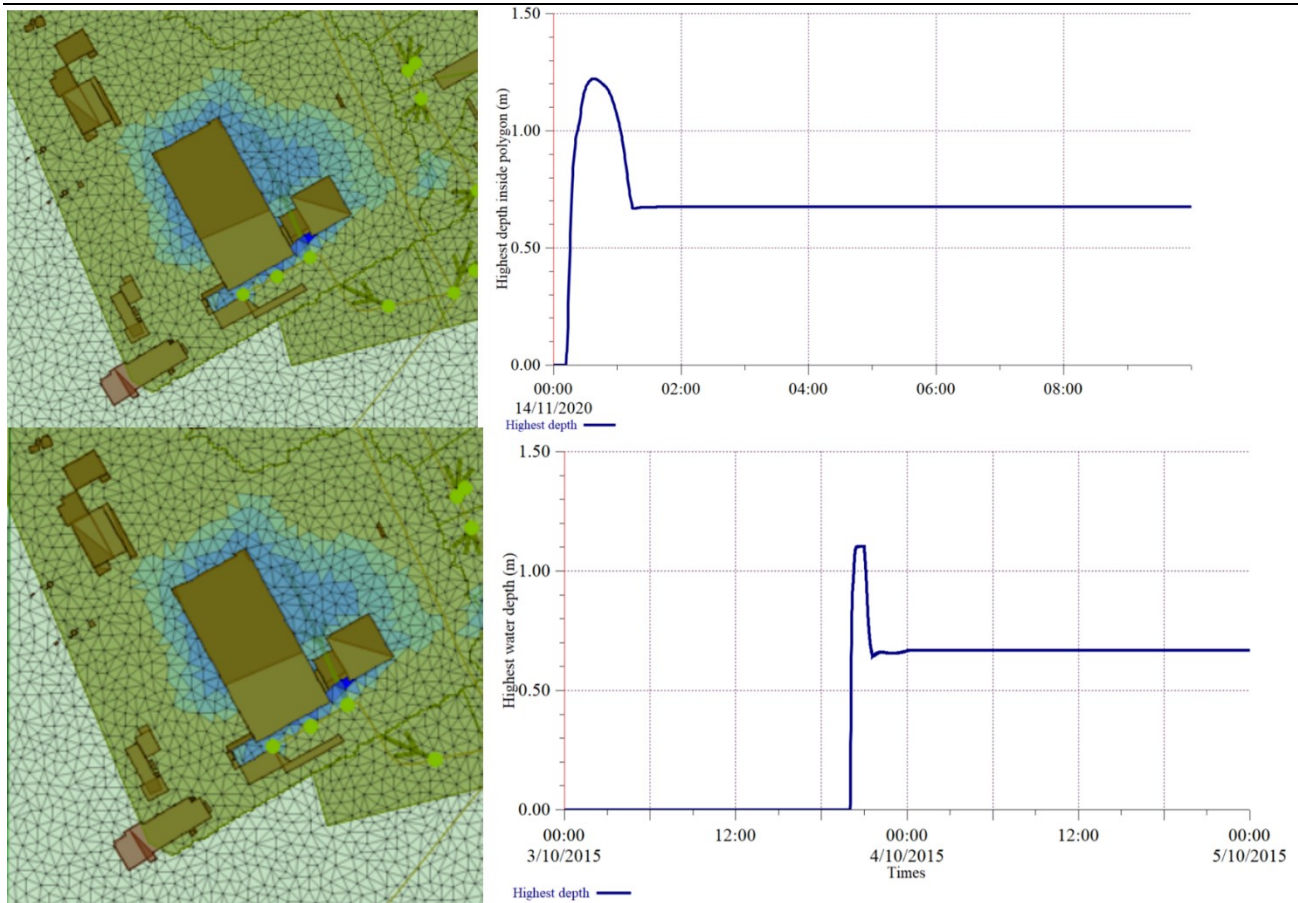
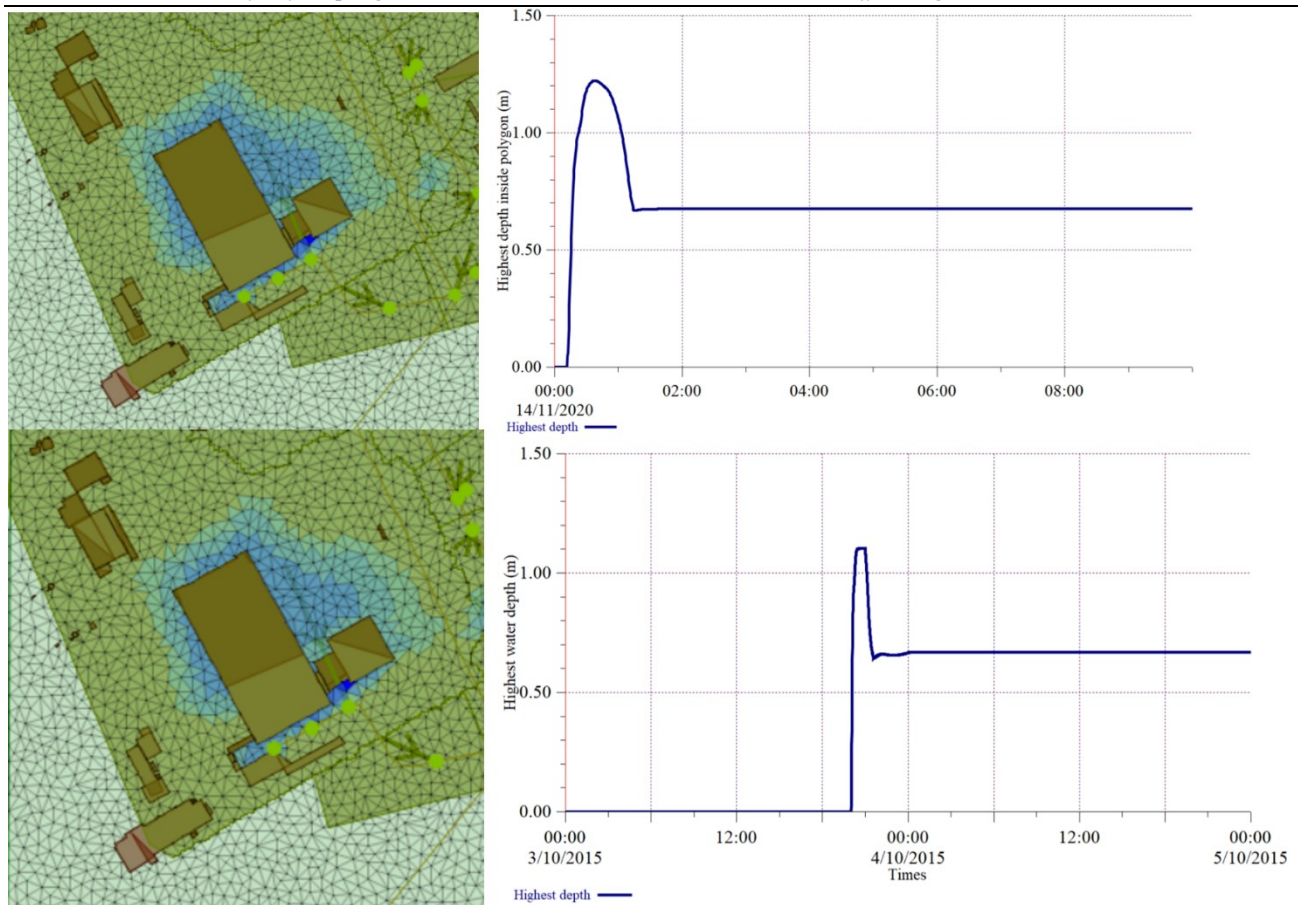


Figure 8. The right-hand side of figure 8 illustrates the dynamics of the water level in this area. Again we see that the accumulation effect after a peak. Without taking evaporation and infiltration into account, the water would remain accumulated here for several hours.



Figure 7. Maximum water depths modelled with 1D/2D model for the 100 years return period event



**Figure 8. Highest depths of water within the flooded area for 100 year return period event (top) and 3rd October 2015 event (bottom).**

Through this first study, we obviously notice that a 1D/1D model does not allow a direct quantification of the water heights accumulated on the surface around the vulnerable areas (a post processing should be done). Moreover, the overflow volumes for this model are lower than those calculated by the 1D/2D models. For the 1D/2D model, the way to model the buildings does not seem to have much impact, this should be quantified in a future study. Through the two rainfall scenarios, we observed a difference in the overall dynamics of the study area as reported in [32]. It seems at least necessary to study the vulnerability of a site with different shapes of hyetograms for the same return period.

## 4. Conclusions

The study compares the results obtained with two urban flood modeling approaches: 1D/1D and 1D/2D of an industrial site called the MIN in Nice with the software InfoWorks ICM. A simple approach was implemented to compare: the total volume of water overflowed from the stormwater system, the dynamics of overflows from the stormwater system to the 2D surface runoff model, as well as the maximum water elevation in the areas for two rainfall events, a 100-year synthetic return period and the October 3, 2015 events.

This study identifies the importance of the coupling between the stormwater system and surface runoff. Indeed, the 1D/2D models, in addition to allowing a quantification of the water heights reached at any point of the vulnerable zones, allows a more realistic representation of the overflows of the stormwater network and to understand the dynamics of the water heights reached in the vulnerable zones.

Furthermore, the importance of using accurate topographic data as a prerequisite for generating accurate flood volume estimates over surfaces is frequently emphasized [6, 14]. So far, in our study, the 2D mesh is rather simple (large mesh, buildings). Thus, the coupled 2D model needs to be refined using updated topographic data and taking into account subsurface features that may influence runoff.

In perspective, as the knowledge of the network used to build the 1D model was limited (diameters are missing). To go further, it would be valuable to quantify the uncertainties related to the parameters of the stormwater network input data deduced during its construction. In conclusion, an overall sensitivity analysis associated with the stormwater model

could be performed to evaluate the influence of the model parameters: stormwater network description, topography, soil characteristics and rainfall events.

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## REFERENCES

- [1] Javelle, P. and al. (2014). Evaluating flash-flood warnings at ungauged locations using post-event surveys: a case study with the AIGA warning system. *Hydrological sciences journal*, **59**(7), p. 1390-1402.
- [2] Delrieu, G. and al. (2005). The catastrophic flash-flood event of 8–9 September 2002 in the Gard Region, France: a first case study for the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory. *Journal of hydrometeorology*, **6**(1), p. 34-52.
- [3] Carrega, P. (2016). Les inondations azuréennes du 3 octobre 2015: un lourd bilan lié à un risque composite. 2268-3798.
- [4] Kirstetter, G. and al. (2021). B-flood 1.0: an open-source Saint-Venant model for flash flood simulation using adaptive refinement. *Geoscientific Model Development Discussions*, p. 1-24.
- [5] Chang, T.-J., Wang, C.-H. and Chen, A.S. (2015). A novel approach to model dynamic flow interactions between storm sewer system and overland surface for different land covers in urban areas. *Journal of Hydrology*, **524**, p. 662-679.
- [6] Mark, O. and al. (2004). Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology*, **299**(3-4), p. 284-299.
- [7] Pender, G. and Néelz, S. (2010). Benchmarking of 2D hydraulic modelling packages. *SC080035/R2 Environmental Agency, Bristol*, p. 169.
- [8] Teng, J. and al. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, **90**, p. 201-216.
- [9] Seyoum, S.D. and al. (2012). Coupled 1D and noninertia 2D flood inundation model for simulation of urban flooding. *Journal of hydraulic engineering*, **138**(1), p. 23-34.
- [10] Russo, B. and al. (2015). Analysis of extreme flooding events through a calibrated 1D/2D coupled model: the case of Barcelona (Spain). *Journal of Hydroinformatics*, **17**(3), p. 473-491.
- [11] Salvatore, E., Bronders, J. and Batelaan, O. (2015). Hydrological modelling of urbanized catchments: A review and future directions. *Journal of Hydrology*, **529**, p. 62-81.
- [12] Bladé, E. and al. (2019). Modelling flood propagation in the service galleries of a nuclear power plant. *Nuclear Engineering and Design*, **352**, p. 110180.
- [13] Salvan, L. (2017). Connaissances et modélisations pour la gestion du pluvial en zone urbaine: application à la ville de Nice. Phd thesis, Côte d'Azur.
- [14] Abily, M. and al. (2016). Spatial Global Sensitivity Analysis of High Resolution classified topographic data use in 2D urban flood modelling. *Environmental Modelling & Software*, **77**, p. 183-195.
- [15] Delestre, O. and al. (2017). FullSWOF: Full Shallow-Water equations for Overland Flow. *Journal of Open Source Software*, **2**(20), p. 448.
- [16] Hervouet, J.-M. (1999). TELEMAC, a hydroinformatic system. *La houille blanche*, (3-4), p. 21-28.



- [17] DHI, M. Flow Model Hydrodynamic Module: Scientific Documentation. 2012.
- [18] Salvan, L. and al. (2016). Drainage system and detailed urban topography: towards operational 1D-2D modelling for stormwater management. *Procedia Engineering*, **154**, p. 890-897.
- [19] Pina, R.D. and al. (2016). Semi-vs. fully-distributed urban stormwater models: model set up and comparison with two real case studies. *Water*, **8**(2), p. 58.
- [20] Lind, J., 2015 - "Stormwater modelling tools: a comparison and evaluation".
- [21] Web site DHI - "MIKE URBAN : Integrated urban water modelling". Available from <https://www.mikepoweredbydhi.com/products/mike-urban>.
- [22] Web site CHI - "PCSWMM : Advanced modelling software for stormwater". Available from <https://www.pcswmm.com/>.
- [23] Web site HydroCAD - "HydroCAD : Stormwater Modeling". Available from <https://hydrocad.net/info.htm>.
- [24] Web site GEOMOD - "InfoWorks ICM : un outil de modélisation hydraulique complet". Available from <https://www.geomod.fr/fr/gestion-de-l-eau/infoworks-icm/>.
- [25] Web site BENTLEY - "Open Flows CivilStorm : All-in-one stormwater management". Available from <https://www.bentley.com/en/products/product-line/hydraulics-and-hydrology-software/civilstorm>.
- [26] Web site Hydra - "Hydra : le premier outil complet de modélisation rivières et assainissement intégré dans un SIG open source". Available from <http://hydra-software.net/>.
- [27] de Saint-Venant, A.J.-C. (1871). Théorie du mouvement non-permanent des eaux, avec application aux crues des rivières et à l'introduction des marées dans leur lit Comptes Rendus de l'Académie des Sciences.
- [28] Chunge, J. (1964). Numerical integration of Barre de Saint-Venant's flow equations by means of an implicit scheme of finite differences. *La houille blanche*, **1**, p. 33-39.
- [29] Abily, M. (2015). Modélisation hydraulique à surface libre haute-résolution: utilisation de données topographiques haute-résolution pour la caractérisation du risque inondation en milieux urbains et industriels. Phd thesis, Nice.
- [30] Chow, V.T. (1959). Open-channel hydraulics. *McGraw-Hill civil engineering series*.
- [31] Fiche statistiques sur la période 1966-2011 France, M., 2012 - "Durées de retour de fortes précipitations".
- [32] Mignot, E., Paquier, A. and Haider, S. (2006). Modeling floods in a dense urban area using 2D shallow water equations. *Journal of Hydrology*, **327**(1-2), p. 186-199.