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Experimental analysis on the influence of urban forms on unsteady urban flooding

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ABSTRACT: Unsteady urban flooding, such as dam-break waves, poses catastrophic risks to downstream populations and results in severe damage. To assess and mitigate these risks, it is essential to forecast the influence of urban forms on flooding severity. In this paper, datasets are provided from reduced-scale physical experiments of transient flow through idealized suburban districts. The experiments are conducted in a rectangular horizontal open channel, where flow conditions are achieved by rapidly opening a gate holding a volume of water. To evaluate the impact of urban forms on flow behavior, we investigated two urban parameters; the number and width of streets in the main direction of the flow. The experiments provide complete water hydrographs for thirteen urban forms. Conductive and acoustic gauges are positioned at different locations to track the wavefront and water depth variation. The results illustrate the impact of the two studied urban parameters on flow variables and provide valuable validation data for computational urban planning models.

1 INTRODUCTION

The failure of hydraulic structures can lead to the propagation of flood waves in urban areas, posing catastrophic risks for downstream populations and significant structural damage. In the context of increasing urbanization, the risks associated with flooding are strongly linked to spatial planning policies (Mustafa et al. 2018). Indeed, urban layouts significantly influence flood hazards by altering flow paths (Leandro et al. 2016). Accurately predicting the dominant physical phenomena involved in flood wave propagation through urban areas is crucial for risk assessment and mitigation. However, the rarity of extreme urban flood events results in a scarcity of real-case event data (Aureli et al. 2021). Thus, laboratory experiments on unsteady urban flooding is a valuable tool to provide insight into the features of the flow and collect valuable data for validating numerical models (Aureli et al. 2023; Mignot et al. 2019).

Laboratory tests have extensively reproduced dam break flow, including several scenarios of urban flooding. Initially, numerous experiments focused on the physical characteristics of dam break flow in rectangular channels (Garoosi et al. 2022; Yang et al. 2022; Kocaman et al. 2021; Melis 2018; Lauber and Hager 1998). Additionally, other studies analyzed the impact of dam break waves on isolated obstacles of various shapes (Beteille et al. 2023; Kocaman et al. 2020; Liu et al. 2018; Soares-Frazão and Zech 2007). Then, research was extended to explore the influence of obstacle configurations on unsteady flows (Beteille et al. 2023; Tomiczek et al. 2016; Kim

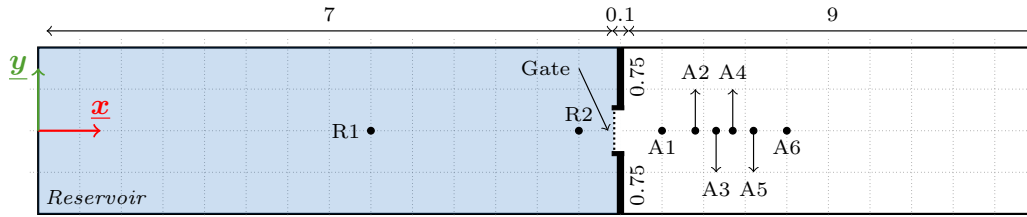


Figure 1. Schematic views of the experimental set-up and plan view of the sensors' location.

et al. 2015; Soares-Frazão and Zech 2008; Testa et al. 2007; Szydłowski and Twaróg 2006). These studies aimed to replicate idealized suburban districts and examine the flow behavior in and around these areas for one isolated tested configuration. Yet, experimental studies focusing on the influence of various urban configurations for steady flow are still relatively scarce (Li et al. 2021; Doumic et al. 2021; Oukacine et al. 2021; Velickovic et al. 2017; Zhou et al. 2016; Huang et al. 2014) and have not been done for dam break flow scenarios.

To improve unsteady urban flooding prediction and understand the influence of urban parameters on flash floods scenarios, this paper presents a comparative experimental study with thirteen different urban forms. Its outline is as follows. Section 2 presents the laboratory experiments performed at EDF Lab Chatou in France. The different configurations studied, and the metrology used are discussed. The experimental results are presented in Section 3 and all urban forms are compared to a reference dam break flow case. The major features of the flow are identified and discussed for all cases through the analysis of water height profiles and time variation.

2 LABORATORY EXPERIMENTS

2.1 Experimental setup

The experiments are carried out in a rectangular and horizontal channel at EDF Lab Chatou in France. The facility, Figure 1, is 16 m long, 2 m wide, and 0.5 m high with a uniform PVC bottom. A 7 m reservoir is separated from the remaining of the channel by a 0.5 m wide and 0.31 m high rectangular PVC sluice gate. A pneumatic cylinder is used to ensure repeatability of gate opening. The opening time of the gate, obtained from video tracking, is about 1 s. All experiments are realized in dry bed condition with an initial depth upstream of the gate $h_0 = [0.249-0.251]$ m (± 0.5 mm). Leaks at the breach are avoided by pressurizing the cylinder when filling the tank, adding grease along the gate's guides, and using a water Hoover between each test.

2.2 Metrology

The free surface position is measured with two types of wave gauges listed in Table 1. Two conductive wave gauges TDH250, with an accuracy of 0.1 mm, are placed upstream of the gate and six acoustic gauges Mic+35/IU/TC, with an accuracy of 1 mm, are placed downstream of the gate. This choice has been made because of the intrusiveness of the resistive gauge. Note that for the following results, the initial time $t = 0$ s corresponds to the start of the breach opening. As presented in Figure 1, the probes are located in areas of interest such as the obstacles' surroundings. The acquisition frequency of the wave gauges is set to 50 fps and is limited to the lower response time of the acoustic gauges. An investigation of the experimental facility repeatability was performed for the reference dam break case without obstacles, called 0-0 (Beteille et al. 2023). All wave gauges were compared for different numbers of replicates. Since the standard deviation was similar and smaller than 1 mm for all different numbers of tests, the evolution of the free surface is set as the mean of three replicates.

2.3 Performed test and configurations

Thirteen different urban forms are studied in this paper and are summarized in Table 2. The obstacles used are 0.1 m side length cubes representing idealized buildings. The configurations, schematized in Figure 2, correspond to idealized suburban districts. Four independent parameters are used to define the urban forms:

Table 1. List of probe types and locations (m).

	Type	x (m)	y (m)
R1	Resistive	4.00	0.00
R2	Resistive	6.50	0.00
A1	Acoustic	7.50	0.00
A2	Acoustic	7.90	0.00
A3	Acoustic	8.15	0.00
A4	Acoustic	8.35	0.00
A5	Acoustic	8.60	0.00
A6	Acoustic	9.00	0.00

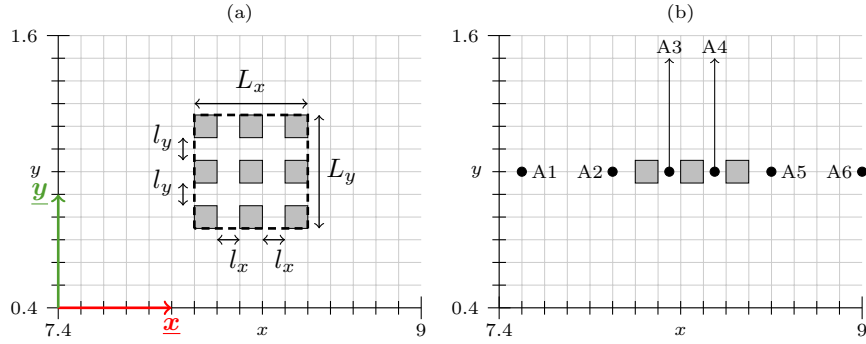


Figure 2. (a) Geometry of the urban form NX2-10 and (b) geometry of the urban form NX0 and sensors' location.

- n_x and n_y : the number of streets along the x and y directions, respectively.
- l_x and l_y : the width of the streets along the x and y directions, respectively.

This study concentrates on examining the influence of two parameters: n_x , representing the number of streets parallel to the main flow direction, and l_y , representing the width of these streets. These parameters were intentionally varied independently to analyze their distinct impacts on the flow. The corresponding parameters of the thirteen urban forms are given in Table 2. All thirteen studied configurations are compared to a dam break flow with no obstacle, called 0-0.

Table 2. Parameters characterizing the urban forms.

Configuration*	n_x	l_x (m)	L_x (m)	n_y	l_y (m)	L_y (m)
0-0	-	-	-	-	-	-
NX0	-	0.10	0.50	2	-	-
NX1-05	1	0.10	0.50	2	0.05	0.25
NX1-10	1	0.10	0.50	2	0.10	0.30
NX1-15	1	0.10	0.50	2	0.15	0.35
NX1-20	1	0.10	0.50	2	0.20	0.40
NX2-05	2	0.10	0.50	2	0.05	0.40
NX2-10	2	0.10	0.50	2	0.10	0.50
NX2-15	2	0.10	0.50	2	0.15	0.60
NX2-20	2	0.10	0.50	2	0.20	0.70
NX3-05	3	0.10	0.50	2	0.05	0.55
NX3-10	3	0.10	0.50	2	0.10	0.70
NX3-15	3	0.10	0.50	2	0.15	0.85
NX3-20	3	0.10	0.50	2	0.20	1.00

* Configurations' names = NXn_x-l_x

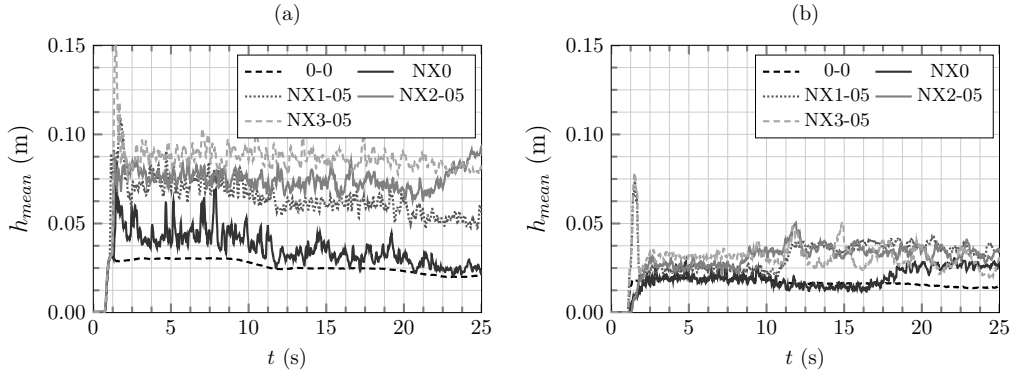


Figure 3. Effect of the street number on water depth variations for cases $l_y = 0.05$ m at positions (a) A2 (upstream) and (b) A5 (downstream).

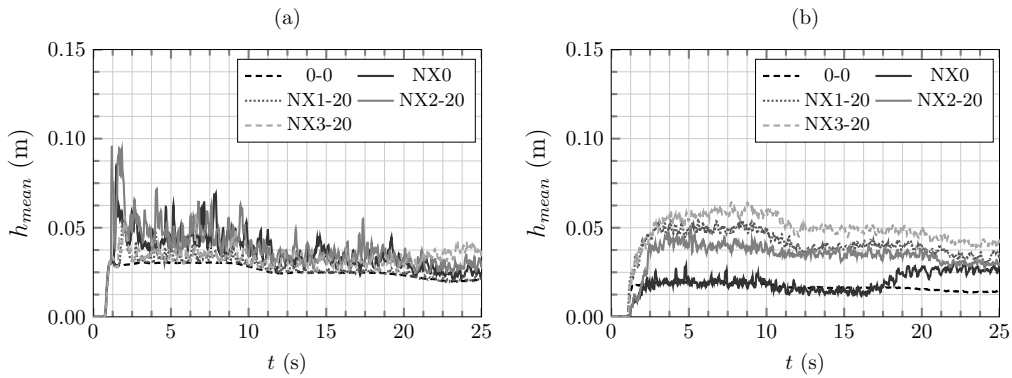


Figure 4. Effect of the street number on water depth variations for cases $l_y = 0.20$ m at positions (a) A2 (upstream) and (b) A5 (downstream).

3 RESULTS: EFFECTS OF URBAN FORMS ON WATER LEVEL VARIATIONS

After the opening of the gate, the water stored in the tank begins to propagate along the channel as a 3D dam-break wave. Upon reaching the side walls of the channel, a reflecting wave is generated, forming a hydraulic jump passing around the studied area. The width of the gate was defined to avoid interference in the measurement zone, ensuring that the two symmetric hydraulic jumps reunite downstream of the obstacle configurations. As the water reaches the obstacles, a surge occurs, leading to water jets and droplets rising vertically. The surge then transforms into a splash-up of varying height and width that can be measured with probe A2. Additionally, downstream of the configurations, a wake zone with lower velocity magnitude is formed.

The results presented in this section focus on comparing water level variation and profiles across the thirteen configurations studied to examine the influence of two urban parameters on flow behavior. The first subsection analyzes the impact of the number of streets, denoted n_x , and the second examines the influence of the street width, denoted l_y .

3.1 Street number impact (n_x)

In this subsection, the impact of the number of streets on water depth variation is analyzed for configurations with narrow streets (width $l_y = 0.05$ m, in Figure 3) and wide streets (width $l_y = 0.20$ m, in Figure 4). This analysis is performed upstream (probe A2) and downstream (probe A5) of the urban area. Additionally, the water depth profile for cases with $l_y = 0.10$ m (Figure 5) is analyzed at various time steps to investigate the evolution of water depth within the urban forms.

Figures 3 and 4 compare the water depth variations for two street widths, narrow and wide, across various numbers of streets. For narrow streets, results illustrate the impact of the number of streets on the water depth upstream of the urban forms (Figure 3a). For instance, case NX0,

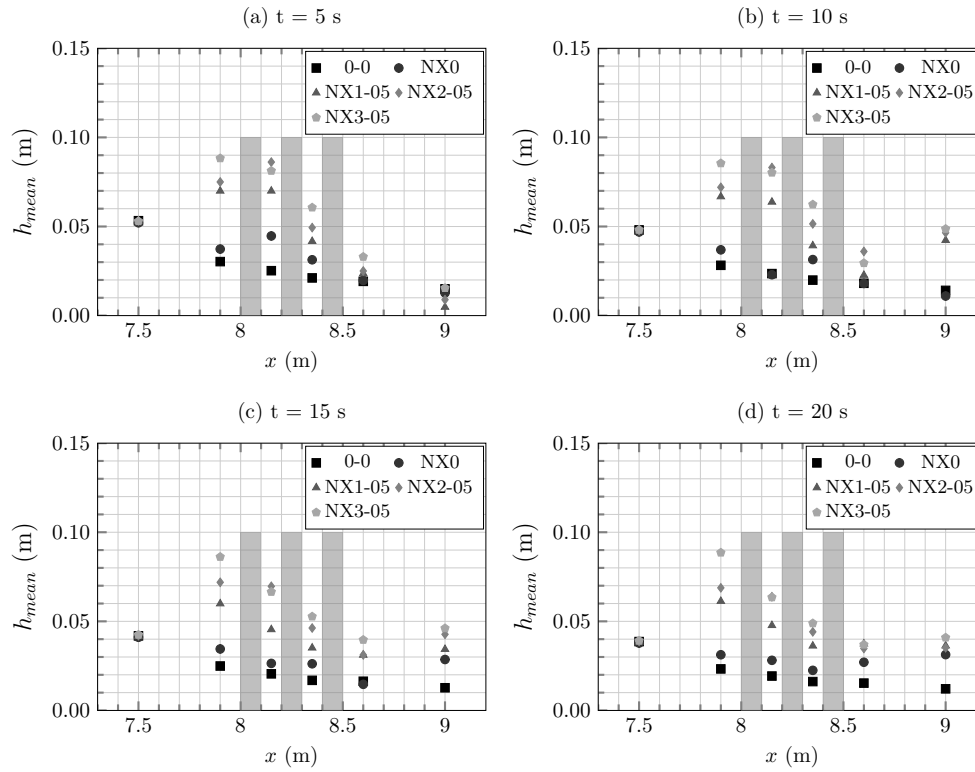


Figure 5. Cases $l_y = 0.05$ m. Water depth profile along $y = 0$ m at times (a) $t = 5$ s, (b) $t = 10$ s, (c) $t = 15$ s, and (d) $t = 20$ s.

shows a water depth variation closer to case 0-0 compared to the other test cases. In contrast, for the remaining cases, the greater the number of streets, the higher the water height becomes. Additionally, during the impact process between the dam break wave and the urban forms, the surge reaches its maximum for cases with higher street number. Downstream of the urban forms (Figure 3b), the effect of street number can also be observed. The water depth evolution for case NX0 is similar with case 0-0 from the start of the experiment until $t = 17$ s, after which the water level starts to rise. Same phenomenon can be observed for case NX1-05 but water depth rises earlier. Moreover, oscillations of the free surface can be observed for cases NX2-05 and NX3-05 at $t = 10$ s. Finally, the impact between the dam break wave and the urban forms is visible for those two cases due to high water jets passing over the obstacles at $t = 1$ s.

For wider streets, as shown in Figure 4, results reveal that the impact of the street number on the flow is less pronounced upstream of the urban form. For street width $l_y = 0.20$ m, the water depth in the splash-up area is closer to the 0-0 water depth for all tested configurations, indicating a low impact of street number for large streets on water depth variations upstream of the urban form. Downstream, as illustrated in Figure 4b, the wake zone is less pronounced and the water depth is increased by the street number. Results suggest that wider streets led to more subtle obstacles impact on the flow upstream of the urban forms. Yet, the number of street continues to influence the downstream water depth.

Figure 5 illustrates the water depth profile along $y = 0$ m at various time steps for configurations with different street numbers and a street width $l_y = 0.10$ m. Each point corresponds to an acoustic probe, ranging from A1 on the left to A6 on the right. Each gray rectangle represents a row of obstacles. Several trends can be identified. First, the measurements for the NX0 case are close to the no-obstacle case (0-0) across all studied time steps. Moreover, the flow tends towards a steady state from $t = 10$ s to the end of the acquisition. However, probe A6, located downstream of the obstacles, still presents some variation over time. Lastly, the water depth measured by all probes appears to increase with the number of streets for a given street width, with A2 recording the maximum water depth for all cases. Overall, results highlight the influence of street number on water depth for both narrow and wide streets. While this effect on water depth is more pronounced

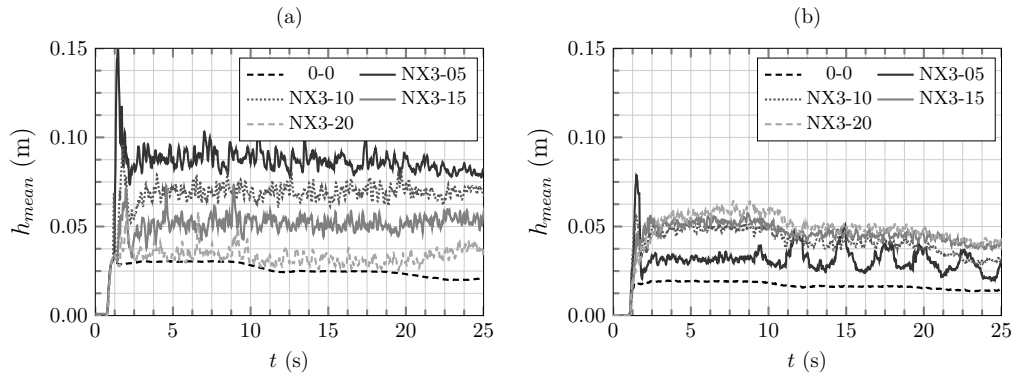


Figure 6. Effect of street width on water depth variations for cases $n_x = 3$ at positions (a) A2 (upstream) and (b) A5 (downstream).

upstream than downstream of the urban form for narrow streets, the opposite trend is observed for wider streets.

3.2 Street width impact (l_x)

In this subsection, the influence of street width on water depth variation for unsteady urban flooding is analyzed for configurations with three streets in the flow direction ($n_x = 3$). This analysis is performed upstream (Figure 6a, probe A2) and downstream (Figure 6b, probe A5) of the urban area. Also, the water depth profile for cases $n_x = 3$ (Figure 7) is analyzed at different time step to highlight the evolution of the water depth inside of the urban forms.

Upstream of the urban area (Figure 6a), results illustrate a clear correlation between street width and water depth. Narrower streets, particularly those with a width of 0.05 m, present a higher water depth, approaching approximately 0.08 m after the impact. This suggests that smaller streets create a blockage effect leading to higher water depth upstream of the urban configuration. Conversely, as the street width expands to larger width (0.1 m, 0.15 m, and 0.2 m), the water depth progressively approaches the reference scenario (0-0). Such trend indicates that wider streets mitigate the blockage effect. Downstream of the urban area (Figure 6b), the impact of street width on water depth becomes less distinct. The water depth evolution for street widths of 0.10 m, 0.15 m, and 0.20 m shows similarities, suggesting that the downstream flow is less sensitive to variations in street width. Moreover, as discussed in the previous subsection, narrow streets (for cases with $l_y = 0.05$ m) induce oscillations in the free surface downstream of the urban area. These oscillations appears at $t = 10$ s and are visible until the end of the acquisition.

Figure 7 illustrates the water depth profile along $y = 0$ m at various time steps for configurations with three streets ($n_x = 3$) and various street width. Each point corresponds to an acoustic probe, extending from A1 on the left to A6 on the right. Each gray rectangle represents a row of obstacles. Several tendencies can be observed. First, as illustrated on Figure 3 and 4, the splash-up zone height upstream of the urban form is directly proportional to street width; narrower streets correlate with higher water depth. Moreover, the water depth tends toward a steady state from $t = 10$ s to the end of the acquisition, as observed in the previous subsection. Additionally, for wide streets ($l_y = [0.10, 0.15, 0.20]$ m), the water depth inside the urban configuration is higher than in the splash-up zone. Conversely, in narrower streets, the water depth peaks upstream of the obstacles and decreases gradually downstream. Finally, wider streets induce higher water height in the wake zone (probe A5), while narrower streets induce higher water depth downstream the wake zone (probe A6).

Overall, results reflect the influence of street width on water depth for configurations with three streets. Notably, the maximum water depth position can be located in the surge zone for narrow streets or in the urban form for wide streets.

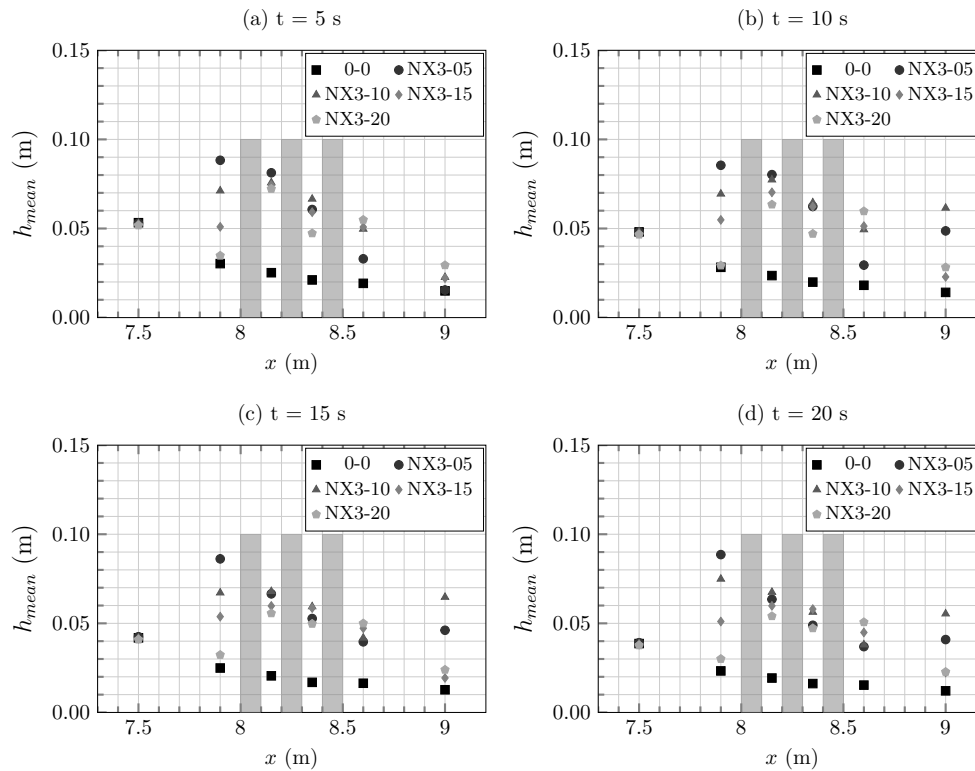


Figure 7. Cases $n_x = 3$. Evolution of the water depth profile ($y = 0$ m) at times (a) $t = 5$ s, (b) $t = 10$ s, (c) $t = 15$ s, and (d) $t = 20$ s. Grey rectangles represent cubes position.

4 CONCLUSIONS

This study presents a novel experimental investigation of unsteady dam break flow propagation across a large range of urban configurations. Thirteen distinct urban forms were studied, using two key urban parameters: n_x – the number of streets parallel to the main flow direction, and l_y – the width of these streets. The effects of these urban parameters on flood scenarios were explored, using water depth measurements both within and around the urban forms. Moreover, the outcome from the laboratory experiments constitutes a valuable new dataset for validating numerical models.

Results indicate a significant influence of the obstacle configurations on the flow. Three main observations are made: First, the street number significantly influences water depth variation, with differences observed for both narrow and wide streets. For narrow streets, the impact on water depth is more pronounced upstream; the inverse was observed for wider streets. Secondly, the emergence of oscillations in the wake zone for configurations with narrow streets is highlighted. Finally, the width of the street directly influences the position of the maximum water depth.

Future work aims to extend this experimental protocol to include the analysis of the free surface velocity field using Large-Scale Particle Image Velocimetry (LSPIV) both within and around the urban area. Such data shall be useful for numerical validation purposes, phenomenological models calibration and to better understand and quantify obstacles impact on unsteady dam break flow.

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