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1 Measuring the flow intrusion towards building
2 areas during urban floods: impact of the
3 obstacles located in the streets and on the
4 facade

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10 **1 Abstract**

11 This paper provides, through laboratory experiments, the flow discharge passing
12 from a flooded street to a building area through different types of damaged
13 openings (a door, a window and a gate) along with a sensitivity analysis of
14 this discharge to the presence of obstacles or facade details. Four flow regimes
15 in the street are tested, representing a high or low street slope with a high
16 and low water depth. These flows resemble that over rectangular side weirs,
17 with the major difference that obstacles are usually located near the opening

Notations

b	Channel width (m)
C_d	Side weir discharge coefficient (-)
Fr_1	Froude number at channel centerline facing the upstream end of the opening (-)
h_1	Flow depth at channel centerline facing the upstream end of the opening (m)
h_3	Flow depth at channel centerline facing the downstream end of side weir (m)
h_d	Flow depth at channel centerline, 1m downstream from the center of the opening (m)
h_u	Flow depth at channel centerline 1m upstream from the center of the opening (m)
L	Length of side weir (m)
p	Crest height of side weir (m)
Q_d	Outlet discharge in the main channel (m^3s^{-1})
Q_u	Prescribed upstream discharge in the main channel (m^3s^{-1})
Q_w	Intrusion discharge (m^3s^{-1})
ΔQ_w	Intrusion discharge difference with an obstacle configuration vs without obstacle

in the street or on the facade. 26 configurations of obstacles are then included, one after the other, and their impact on the flow intrusion is measured. For the flow cases without obstacle, the agreement of the semi-analytical equations available in the literature strongly varies from one equation to another. On the other hand, the 220 tested flow cases reveal that the location of the obstacle with regards to the opening strongly modifies the impact of the obstacles, that increasing the Froude number tends to increase the impact of the obstacles and that obstacles have a higher impact on the intrusion discharge through a window than to a door or a gate. Finally we conclude that the largest obstacles (typically parked cars) located in the vicinity of openings should be somehow included in operational numerical models that calculate urban floods for a fair prediction of the intrusion discharge.

2 Keywords

Urban flood; flow intrusion; side weirs; obstacles

3 Introduction

Between 1995 and 2015, floods accounted for 43 % of all weather related disaster events, affecting 2.3 billion and killing 157,000 people (UNISDR and CRED, 2015). Besides, in 2018 four flood events were among the top ten deadliest disaster events (Guha-Sapir, D., 2018). Being prepared and managing flooding events is then of high priority for authorities (Fang, 2016). Besides, the number of inhabitants living within urban areas keeps increasing : from 33.35 % of the world population in 1980 to 55.27 % in 2018 (United Nations Population Division, 2018) and up to a prevision of 70% in 2050 (Gross, 2016). This growing urbanization results in an increase of flooding risk within urbanized areas (Chen et al., 2015). Among the tasks aiming at dealing with such risk events, the zonation of flood risk level throughout the city (Wu et al., 2015) and the planning of citizen evacuation (Baba et al., 2017) are getting more and more attention. These tools are generated by post-processing the urban flood simulation scenarios computed using operational 2D shallow water equation models (Mignot et al., 2006).

The complexity and efficiency of these operational numerical tools has been strongly increasing for the last 15 years, reproducing more and more flow processes, such as (i) the flow exchanges between the flooded streets and the underground sewer network (Chang et al., 2018) or large areas such as malls or metro (Takayama et al., 2007); (ii) the flow interactions with urban furniture (Bazin et al., 2017) or (iii) planing the evacuation of inhabitants (Ishigaki, 2008). However, Mignot et al. (2019) recently listed the remaining flow processes taking place during urban flood events, not reproduced by operational 2D numerical model. For instance, Mignot et al. (2019) state that no pollution dispersion model was developed and tested to reproduce urban flood pollution releases. Similarly, these authors state that the operational numerical models reproduc-

ing urban floods do not simulate the flow entering the building areas (individual houses or building blocks), but rather consider the facades along the streets as impervious. This is odd, given the level of damage and risk of the flow invading the building areas (industrial, commercial and living spaces) where material can be strongly damaged (such as all electronic tools), walls and furniture can rapidly rot and strong risk of drowning exist for inhabitant occupying the buildings.

We believe (1) that operational numerical models that simulate urban floods to assess the spatial distribution of level of risk should reproduce the flow invading building areas and (2) that the validation of these models (analytical or empirical) requires experimental data. Present work then aims at modeling experimentally flow intrusions from a flooded street towards a building for future calibration/validation of models to be developed. A few authors dedicated their research to the flow intrusion within a single building with openings, either experimentally (Liu et al., 2018), or numerically (Gems et al., 2016); or within a group of buildings facing the incoming flow in a highly simplified configuration within a straight channel (Zhou et al., 2016). To the best of our knowledge, the only work dedicated to realistic flow intrusions, in partially urbanized area, was performed by Sturm et al. (2018), with large separated buildings with open doors and windows in a village adjacent to an overtopping torrent. However, the process of flow within a highly urbanized area, where the water flows in a street network and passes from the streets to the building areas, was not studied, neither experimentally or numerically.

During an urban flood, part of the water flowing in the streets enters the buildings through, what we will call here "openings". The most-common ones are doors, windows and gates. Openings are usually initially closed. During frequent floods, flow intrusion thus takes place through leakage on the sides

86 of openings, or through overflows from sewer surcharges, for example through
87 plumbing and sanitary elements. During extreme flood events, the submerged
88 openings can open by themselves, get damaged, or be entirely removed. In
89 these last cases, the flow through the openings is expected to behave similarly
90 as that over side weirs (as long as the level of water does not reach the top of the
91 opening) of quite large thickness, typically that of the wall. One first objective
92 of the present work is then to evaluate if the flow discharge through openings
93 within urban facades can be predicted by available side weir formulas from the
94 literature.

95 One concern, nevertheless is that the flow through openings is expected to
96 be affected by the obstacles located in the street and on the facade, such as
97 trees, mailboxes, parked cars, bus shelters, traffic lights... depending on their
98 sizes and locations with regards to the facade and to the opening. How the
99 obstacles alter the flow discharge passing from the streets to the buildings is of
100 major importance. Indeed, if their impact on the intrusion discharge is high,
101 these obstacles must be included in the topography of the 2D flood simulations
102 or in the semi-analytic weir formulas coupled to the 2D models; oppositely, if
103 their impact is negligible, they can be discarded. Consequently, it is highly
104 important to identify, for each type of opening and flood regime, the magnitude
105 of impact of all obstacles on the intrusion discharges.

106 The present work finally aims at:

- 107 • investigating the processes governing the flow intrusion from a flooded
108 street towards a building area,
- 109 • evaluating the capacities of existing analytical formulas to predict the
110 intrusion discharge through facade openings, for configurations without
111 obstacles
- 112 • quantifying the impact of obstacles typically encountered in a street or on

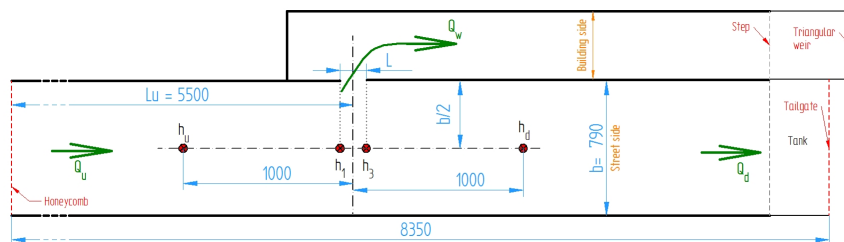


Figure 1: Experimental set-up with all dimensions in mm.

113 a facade on the flow intrusion discharge

- generating a database of flow intrusion towards building areas during urban floods.

This work will then provide for numerical models both a database and a sensitivity analysis dedicated to the intrusion towards buildings during urban floods.

The paper is organized as follows. The first section introduces the experimental set-up and measurement devices used in the present research, along with the research methodology, including a list of tested (i) openings, (ii) flow configurations and (iii) obstacles. The second section presents the flow patterns of flow intrusion without any obstacle and evaluates the capacities of existing analytical formulas to predict the intrusion flow discharge for all tested openings and flood regimes. The following section then evaluates the impact of different obstacles on this intrusion discharge. The paper ends up with a discussion regarding the necessity to include obstacles in operational models of flood simulation.

128 4 Experimental setup and methodology

129 4.1 Experimental set-up

130 The experiments are performed at the Laboratory of Fluid Mechanics and
131 Acoustics (LMFA) at the University of Lyon (Insa-Lyon, France). The facil-
132 ity reproduces a highly simplified 1:12 scale model of a street and an adjacent
133 facade within which various openings can be included to reproduce the intrusion
134 flow from the flooded street towards a building area. Neither the layout within
135 the building area nor the possible backward flow from the building area to the
136 street are reproduced here for sake of simplicity.

137 A sketch of the experimental setup is shown in Fig. 1. It consists of a 8.35 m
138 long and 0.79 m wide straight and smooth open-channel of rectangular cross-
139 section and constant slope 1.8/1000, referred to as *street side* on the figure.
140 The topography of the street profile is kept horizontal, the elevation of the
141 sidewalk being neglected. The discharge Q_u entering the channel upstream is
142 measured in the pumping loop using one of the two available electromagnetic
143 flowmeters (Endress-Hauser): the first one is in the range $Q = 5 - 40$ L/s with
144 an uncertainty of 0.2 L/s, while the other is $Q = 0 - 5$ L/s with an uncertainty
145 of 0.05 L/s.

146 The upstream boundary condition consists of a grid buffer and a honeycomb
147 with small mesh (0.5 cm alveolus) in order to stabilize the inflow. Furthermore,
148 a sharp crested tailgate at the outlet of the channel is used to adjust the water
149 depth to the desired value in front of the opening. Water depths along the center
150 of the channel (h_u, h_1, h_3, h_d from up- to downstream on Fig. 1) are measured
151 using a digital point gauge. The left wall of the channel (along $y = 0$ axis) is
152 made of a 1 cm thick PVC plate within which openings can be machined at a
153 distance $L_u = 5.5$ m downstream from the channel entrance. The center of the
154 axis system (x, y, z) is located at the bottom of the center of the opening along

155 the street side of the PVC plate, with x the streamwise axis, y the transverse
156 axis towards the street side and z the direction perpendicular to the bed.

157 As the intrusion discharge Q_w passing through the opening flows towards the
158 outlet of the *building side*, it is measured using a previously calibrated triangular
159 weir. The corresponding upstream flow elevation is measured using an ultrasonic
160 sensor. Note that a step upstream from the triangular weir along with the
161 1.8/1000 slope of the *building side* prevent from any backward effect of the weir
162 affecting the intrusion discharge. Finally, the outlet discharge downstream from
163 the street is obtained by resting the two measured discharges: $Q_d = Q_u - Q_w$

164 For a few configurations, the surface velocity field in street side near the
165 opening is measured by LSPIV (Large-scale particle image velocimetry) with
166 a camera located 1.5 m above the flume, recording images of the free-surface
167 seeded with dry sawdust at a frequency equal to 50 frames per second. Also,
168 2D fields of the water level are measured in the same area using an ultrasonic
169 sensor fixed on an automated mobile car moving along both x and y directions.

170 4.2 List of openings (Op)

171 By looking at photos of highly urbanized areas, it appears that most openings
172 connecting streets to building areas are windows, doors and gates. As these
173 openings are damaged/removed, they leave a large open space available for flow
174 intrusion. To model these configurations, 4 types of openings are considered and
175 sketched in Fig. 2: *Op 1* an open window, *Op 2* is an open/damaged door, *Op 3*
176 a wider window and *Op 4* represents a simplified closed gate with a grid on top.
177 These openings are created in the model by simply drilling the vertical PVC
178 plate at the interface between the street and the building, so that the intrusion
179 water can freely flow through the white areas of each opening in Fig. 2

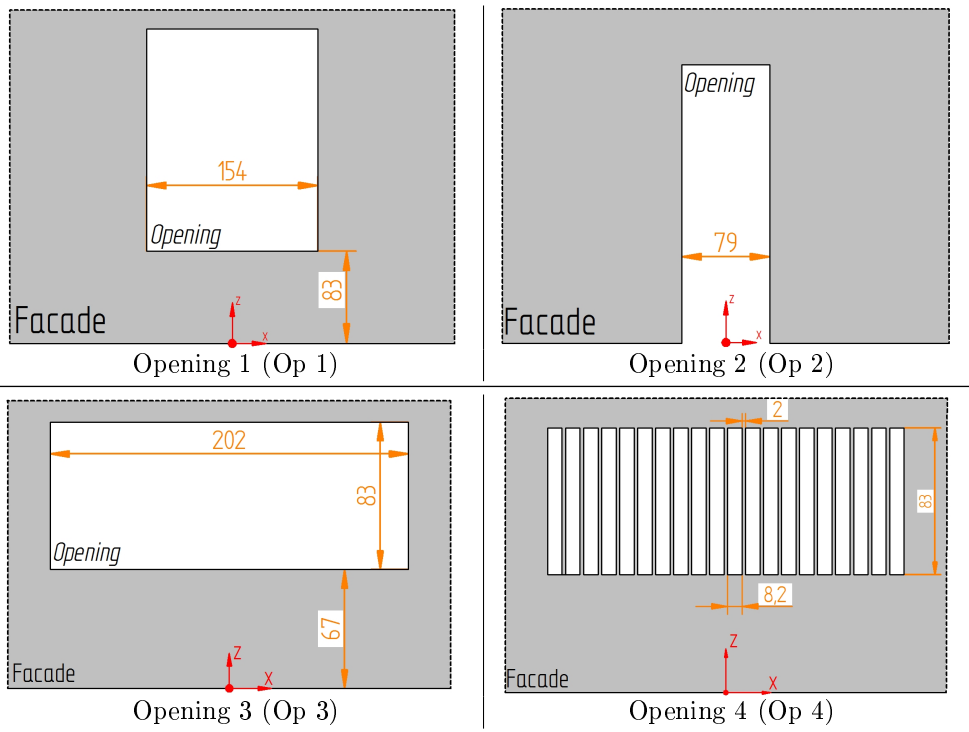


Figure 2: Sketches of the openings with all dimensions in mm.

Flow Id	h_1 (m)	Q_u (L/s)	Fr_1	Re_1
F_1	0.025	2.0	0.2	9,524
F_2	0.108	17.6	0.2	69,980
F_3	0.025	5.4	0.55	25,714
F_4	0.090	36.7	0.55	151,340
F_5	0.108	46	0.52	182,903

Table 1: Tested flow configurations (at laboratory scale)

180 4.3 Tested flow configurations (F)

181 Four different flow configurations are selected to reproduce four flood events:
182 two with a high and two with a low street slope (typically 1/1000 and 1/100);
183 two with a high and two with a low water level (typically 30cm and 1.2m), as
184 given in Table 1, with the Froude number $Fr_1 = Q_u / (bh_1\sqrt{gh_1})$ and Reynolds
185 number $Re_1 = 4Q_u / [(b + 2h_1)\nu]$

186 F_1 and F_2 are flow configurations with a low Froude number (correspond-
187 ing to a low slope urban area) while F_3 , F_4 and F_5 are configurations with a
188 high Froude number (corresponding to a high slope urban area). F_1 and F_3
189 are configurations with a low water depth (2.5 cm at laboratory scale that is
190 $12 \times 2.5 = 30$ cm at real scale) while F_2 , F_4 and F_5 are configurations with a
191 high water depth (about 10 cm at laboratory scale that is $12 \times 10 = 1.2$ m at real
192 scale).

193 4.4 List of obstacles

194 As for openings, the analysis of street photographs permitted to list the most
195 common obstacles encountered in the streets and on the facades. For sake
196 of simplicity, we brought together all obstacles having the same typical size
197 and location with regards to the street and the opening. Note that only big
198 enough and fixed obstacles are considered herein. Mobile obstacles such as
199 waste containers, potted plants can also affect the flow intrusion if they are

Id	Elements	Description
0	n/a	No obstacle
1 : Car(s) or bus shelter(s)		
1a-up	13	Unique car at the upstream end of the opening
1a-cent	10	Unique car facing the opening
1a-dw	14	Unique car at the downstream end of the opening
1a-mid	15	Unique car in the middle of the street
1b-1	8+9+10+11+12	Row of parked cars with one car facing the opening
1b-2	1+2+3+4+5	1b-1 staggered with regards to the opening
1b-2-up	1+2+3+4+5+6	1b-2 with one car added in the middle of the street upstream
1b-2-dw	1+2+3+4+5+7	1b-2 with one car added in the middle of the street downstream
2 : Facade detail(s) (e.g. tree, utility pole, mailbox...) on the sidewalk near the facade		
2a-up	18	Facade detail upstream from the opening
2a-dw	19	Facade detail downstream from the opening
2b	16+17+18+19+20	A row of facade details
2c	18+19	A couple of facade details
3 : Street detail(s) (e.g. tree, utility pole, street light, traffic sign...) on the sidewalk near the traffic lane		
3a-up	23	A street detail upstream from the opening
3a-cent	24	A street detail facing the opening
3a-dw	25	A street detail downstream from the opening
3b	21+22+23+24+25+26	A row of street details
4 : Additional obstacles		
4a	27	A porch
4b	28	A windowsill
4c	29	A stair

Table 2: List of the 19 tested obstacle configurations; see Fig. 3 for the shape, size and location of each individual obstacle element.

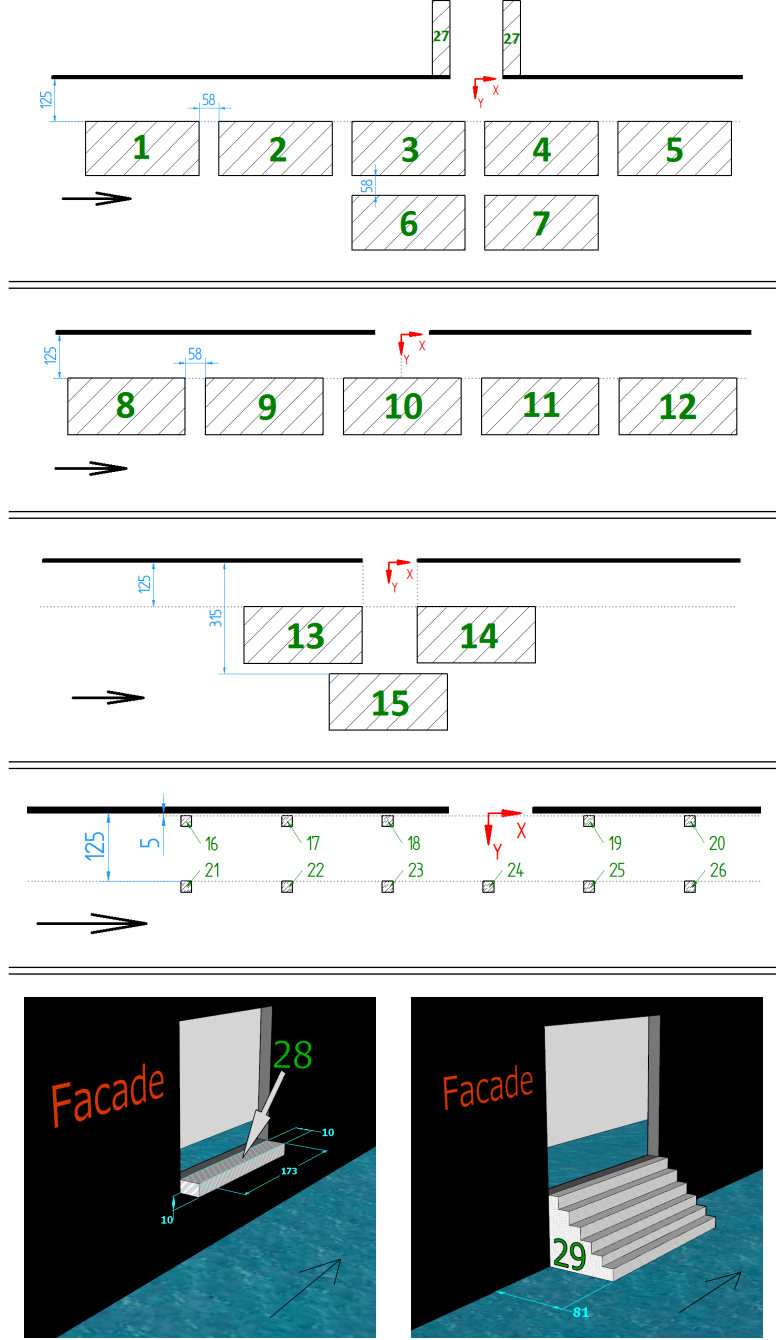


Figure 3: Sketches of all obstacles elements. Their sizes are: for elements 1 to 15 : $Lx = 335$ mm, $Ly = 162$ mm; for elements 16 to 26 : $Lx = Ly = 20$ mm; for elements 27 : $Lx = 52$ mm, $Ly = 220$ mm, with Lx and Ly the dimensions along x and y axes respectively.

200 transported by the flow and partially block the opening, but mobile obstacles are
 201 not considered herein. Moreover, for the highest water levels and flow velocity
 202 magnitudes, some obstacles such as parked cars are expected to be set in motion
 203 (Smith et al., 2019), either blocking the opening or being swept away further
 204 downstream. However, this effect is not considered herein for sake of simplicity.

205 We end-up with four main types of obstacles:

- 206 1. **Cars/bus shelters**, noted "1" as Id in Table 2 : These are parked cars
 207 or bus shelters classically located on or just adjacent to the sidewalk, in
 208 front of building facades.
- 209 2. **Facade details**, noted "2" as Id in Table 2 : These are trees, utility
 210 poles, mailboxes and all other obstacles located on the sidewalk close to
 211 the facade. These obstacles are usually of relatively small horizontal size.
- 212 3. **Street details**, noted "3" as Id in Table 2 : These are trees, utility poles,
 213 street lights, traffic signs and all other obstacles located on the sidewalk
 214 near the traffic lane. These obstacles are assumed to be of same typical
 215 size as facade details.
- 216 4. **Additional obstacles**, noted "4" as Id in Table 2 : These are all obstacles
 217 that do not fit in the three previous types; here we consider a porch inside
 218 the building area, a windowsill attached to the facade and stairs to access
 219 elevated doors.

220 Following this typology, 19 obstacle configurations (plus 7 combinations,
 221 see below) are selected and listed in Table 2. These obstacle configurations
 222 are composed of 1 to 6 obstacle elements (listed as 2^{nd} column of Table 2)
 223 which shapes, dimensions and locations are sketched on Fig. 3). Some obstacle
 224 configurations comprise a single obstacle (a car, a tree, a mailbox, a porch...),
 225 others comprise couples or alignments of individual obstacles (a couple/row

226 of park cars, of trees...) and finally more complex configurations include an
 227 additional fixed car in the middle of the street.

228 As sketched on Fig. 3, all obstacle elements have simplified shapes. Apart
 229 from two obstacles of type 4 (the windowsill and stair), they are all rectangular
 230 prisms, mounted on the bottom of the flume and emerging across the free-
 231 surface. Large obstacles elements (1 to 15 + 27) are made of impervious bricks
 232 (see also Fig.4a) and smaller obstacles (16 to 26) of impervious square bars. The
 233 dimensions of the obstacles (indicated on Fig. 3) are selected to fit at most with
 234 real dimensions (according to the considered 1/12 scale): cars / bus shelters
 235 are 335 mm long and 162 mm wide (about 4 x 2 m at real scale); street and
 236 facade details are 20 mm square base (24 cm at real scale). Fig.4 depicts three
 237 examples of obstacle configurations.

238 4.5 Measurement uncertainties and scale effects

239 For a given flow configuration, the uncertainties regarding the measured intru-
 240 sion discharge Q_w are related to:

- 241 • uncertainties regarding the exact location of obstacle. To evaluate this
 242 source of uncertainties, three obstacles configurations are added and re-
 243 moved three times for two flow conditions ($F1$ and $F4$) with opening $Op2$.
 244 Typical variations of the intrusion discharge among the three repetitions
 245 equal 0.91% for the flow with low Froude number and 0.93% with the high
 246 Froude number.
- 247 • the measurement method used to estimate the intrusion discharge. Q_w
 248 is measured using a triangular weir for which the water depth upstream
 249 from the weir is measured by an ultrasonic probe and the discharge is
 250 computed using the previously calibrated rating curve. Uncertainties re-
 251 garding the measured water depth is estimated by repeating (at different

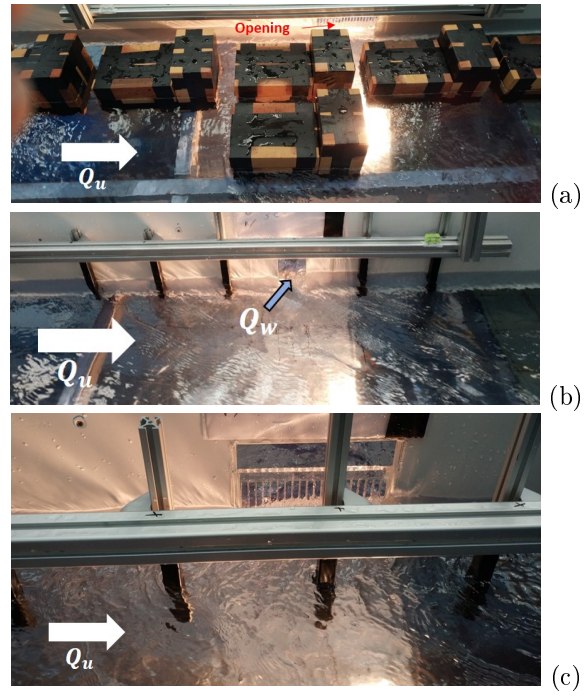


Figure 4: Photographs of three obstacle configurations: (a) = parked cars (obstacle 1b-2-up), (b) = facade details (obstacle 2b) and (c) = street details (obstacle 3b). Note that the horizontal bar on (b) and (c) permits to maintain the obstacle steady and remains above the free-surface.

times) several same flow/opening/obstacle configurations. The variability between the measured water depths remains smaller than 1.8% for the low Froude number cases and 2.0% for the high Froude number cases. Moreover, uncertainties reported when establishing the calibration curve of the triangular weir is about 1.5% for the measured discharge.

In the end, the measured intrusion discharge uncertainty does not exceed 3%. Note that by sake of clarity, results graphs in the sequel do not contain errorbars related to this level of uncertainty.

Moreover, scale effects are expected to distort the extrapolation of the measurements obtained on the present small-scale model (1:12) to the real (prototype) scale. Indeed, while the length ratios and Froude number are at scale with real events, the Reynolds numbers considered herein (Table 1) are much lower than those of real scale. Using a Froude similarity, the prototype Reynolds number is expected to be $12^{3/2}$ times higher than the model Reynolds number. Similarly, the Weber number We , accounting for the influence of surface tension, will vary. Above the windows crest, We is estimated smaller than about 100 in the experiments, indicating that some capillary effects can affect present results. They will be absent at the prototype scale. Indeed, assuming roughly that the inlet discharge is correctly estimated by a De Marchi formula (Eq.1) with a constant discharge coefficient, the prototype Weber number will be 12^2 times higher than in experiments. Care should thus be taken when extrapolating the present results to real scale flood events.

4.6 Methodology

Note that all openings are studied for the flows without obstacle, while only three openings ($Op1$, $Op2$ and $Op4$) are used with obstacles. Moreover, for the elevated openings ($Op1$, $Op3$ and $Op4$) the low water level for flows $F1$

and $F3$ does not reach the opening and these configurations are discarded. To summarize, we measure the flow intrusion for 10 combinations of flow/openings without obstacles and 8 combinations of flow/openings with the 26 obstacle configurations (except for obstacles $4b$ only used with the window ($Op1$) and $4c$ only used with the door ($Op2$)).

For each combination of flow and opening configuration, the following strategy is employed:

1. The boundary conditions are adjusted according to Table 1: the upstream discharge Q_u and the weir crest height to reach the desired water depth. This flow is labeled "0", i.e. without obstacle, in the sequel. The intrusion discharge is recorded.
2. Each obstacle configuration is installed in the channel one after the other and the intrusion discharge is recorded once the steady state is reached. It is verified that h_1 hardly varies when changing the obstacles.

5 Flow configurations without obstacles

Present results section depicts the intrusion flow from the flooded street to the building area in absence of any obstacle in the street or on the facade.

5.1 Flow description

Fig. 5(a) depicts the surface velocity field in the street near the opening, for flow $F2$ with opening $Op2$ and Fig. 6(a) depicts the 2D field of water elevation field for flow $F4$ with opening $Op2$. In such condition, the flow pattern is very similar to canonical flow configuration at a rectangular side weir. As expected, when approaching the opening section, the surface velocity increases and rotates towards the opening, while the velocity downstream the opening strongly

decreases. Due to the intrusion discharge leaving the street side, the discharge in the street decreases towards downstream so that the mean velocity in the sections downstream the opening is smaller than that upstream. Moreover, the water depth field shows a local depression with low water levels near the upstream corner of the opening and a local maximum of water level near the downstream corner. This behavior is in agreement with previously measured water level profiles along rectangular side weirs, as that from Bagheri et al. (2013).

5.2 Discharge equation

The prediction of intrusion discharge through a rectangular side weir adjacent to a straight and smooth rectangular channel, has been performed by many authors (listed in Table 3) since the 1970's. Emiroglu et al. (2011) listed more than 1500 measured intrusion discharges available in the literature. Most authors proposed semi-empirical formulas permitting to predict the intrusion discharge using the classical De Marchi (1934) equation:

$$C_d = \frac{(3/2)Q_w}{\sqrt{2g}(h_1 - p)^{3/2}L} \quad (1)$$

where p is the crest height, L the length of the lateral weir, and h_1 the water depth at the upstream section of the opening along the center of the channel. The authors then proposed semi-empirical formulas for the discharge coefficient (C_d) based on the non-dimensional parameters that arise from the dimensional analysis: Fr_1 , p/h_1 and L/b , with b the channel width. Table 3 lists 12 among the best known available formulas for coefficient C_d (made more and more complex along time) along with the ranges of parameters used for fitting their formulas. For sake of comparison, the three last lines of Table 3

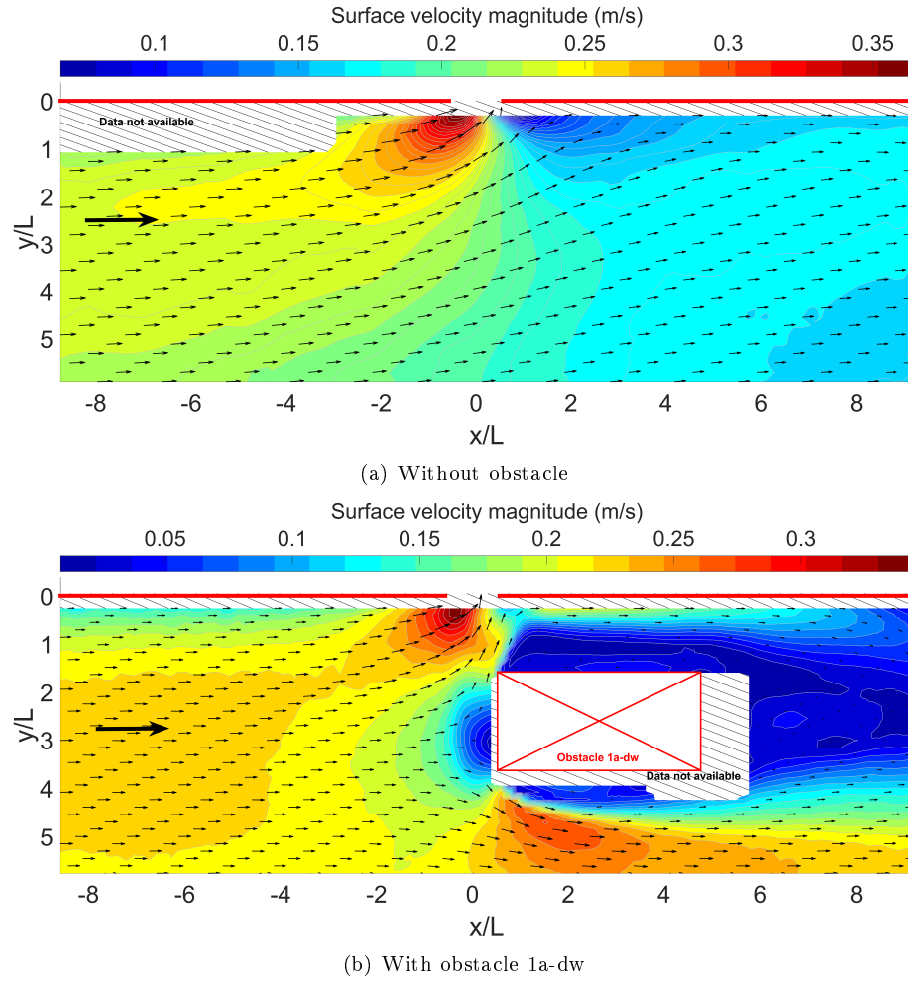
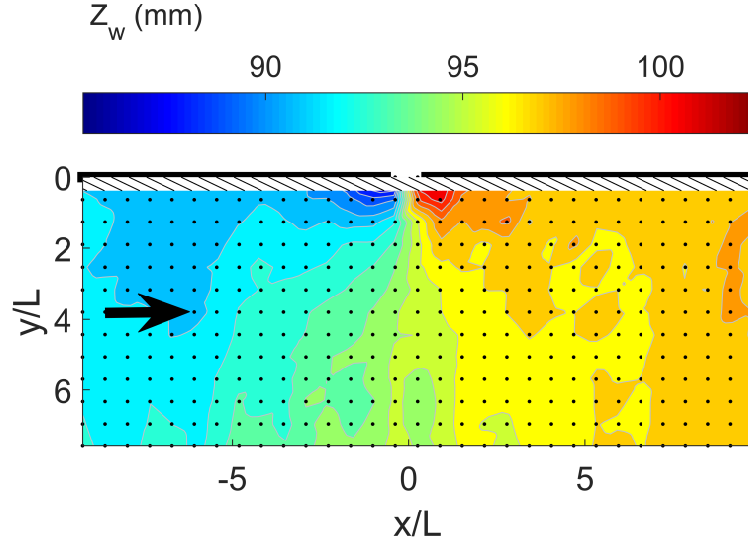
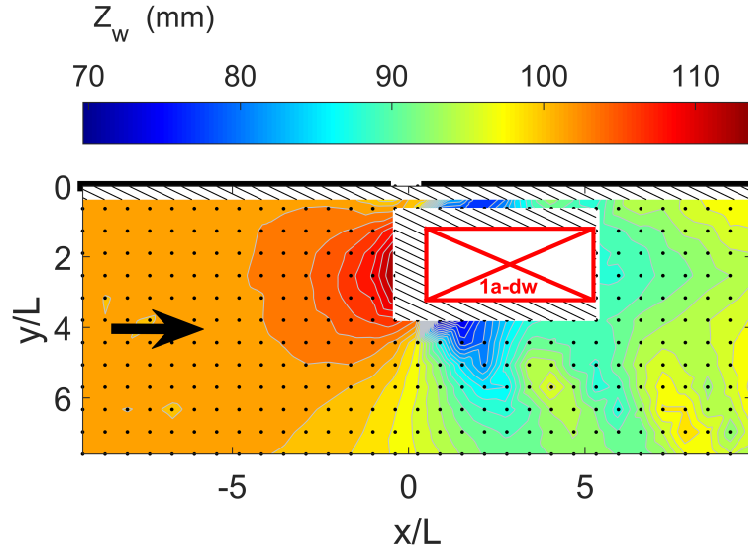


Figure 5: Surface velocity fields for flow configuration $F2$ and opening $Op2$ (the door) without (a) and with (b) obstacle 1a-dw.



(a) Without obstacle



(b) With obstacle 1a-dw

Figure 6: Elevation of the free-surface with regards to the channel bed at the center of the opening ($x/L = 0$; $y/L = 0$) for flow configuration *F4* and opening *Op2* without (a) and with (b) obstacle 1a-dw. Black dots correspond to the measurement grid points.

325 comprise the range of parameters of our experimental campaigns (see Table. 1).

Source	Discharge coefficient C_d	Fr_1	p/h_1	L/b
Nandesamoorthy and Thomson (1972)	$C_d = 0.432 \left(\frac{2+Fr_1^2}{1+2Fr_1^2} \right)^{0.5}$	0.02-4.3	0-0.96	0.2-1.0
Subramanya and Awasthy (1972)	$C_d = 0.611 \left(1 - \frac{3Fr_1^2}{2+Fr_1^2} \right)^{0.5}$	0.02-4.3	0-0.96	0.2-1.0
Yu-Tech (1972)	$C_d = 0.622 - 0.222Fr_1$	0.02-4.3	0-0.96	0.2-1.0
Ranga Raju et al. (1979)	$C_d = 0.81 - 0.6Fr_1$	n/a	n/a	0.2-1.25
Hager (1987)	$C_d = 0.485 \left(\frac{2+Fr_1^2}{2+3Fr_1^2} \right)^{0.5}$	0.3-2	n/a	3.33
Singh et al. (1994)	$C_d = 0.33 - 0.18Fr_1 + 0.49 \frac{p}{h_1}$	0.22-0.45	0.45-0.85	0.4-0.8
Swamee et al. (1994a)	$C_d = 0.447 \left[\left(\frac{44.7p}{49p+h_1} \right)^{6.67} + \left(\frac{h_1-p}{h_1} \right)^{6.67} \right]^{-0.15}$	0.10-0.93	0-1.25	0.4-1
Swamee et al. (1994b)	$C_d = 1.06 \left[\left(\frac{14.14p}{8.15p+h_1} \right)^{10} + \left(\frac{h_1}{h_1+p} \right)^{15} \right]^{-0.1}$	0-0.6	0-1	n/a
Jalili and Borghei (1996)	$C_d = 0.71 - 0.41Fr_1 - 0.22 \frac{p}{h_1}$	0.1-2	0.05-0.87	0.67-2.5
Borghei et al. (1999)	$C_d = 0.7 - 0.48Fr_1 - 0.3 \frac{p}{h_1} + 0.06 \frac{L}{b}$	0.1-0.9	0.02-0.87	0.67-2.33
Emiroglu et al. (2011)	$C_d = \left[0.836 + \left(-0.035 + 0.39 \left(\frac{p}{h_1} \right)^{12.69} + 0.158 \left(\frac{L}{b} \right)^{0.59} + 0.049 \left(\frac{L}{h_1} \right)^{0.42} + 0.244Fr_1^{2.125} \right)^{3.018-5.36} \right]$	0.08-0.92	0.34-0.91	0.30-3.00
Bagheri et al. (2013)	$C_d = -1.423Fr_1^{0.138} + 0.744 \left(\frac{h_1-p}{L} \right)^{-0.083} + 0.723 \left(\frac{h_1-p}{p} \right)^{0.088} + 0.182 \left(\frac{L}{b} \right)^{-0.241}$	0.08-0.91	0.22-0.9	0.5-1.5
Present study (Op1)	-	0.2-0.52	0.77	0.19
Present study (Op2)	-	0.2-0.55	0	0.1
Present study (Op3)	-	0.20-0.52	0.62	0.26

Table 3: Existing equations for the side weir discharge coefficient (C_d) and corresponding tested parameters (plus present range of parameters; note that Op 4 is not indicated here due to its specific geometry)

326 In order to test the validity of the formulas from Table 3, Fig. 7 plots ΔQ_w ,
 327 the error in predicted intrusion discharge compared to present measurements.
 328 The general agreement is quite poor, as could be expected given the low agree-
 329 ment between these formulas already mentioned by Emiroglu et al. (2011). Nev-
 330 ertheless, Swamee et al. (1994b) formula appears to perform well (averaged er-
 331 ror of 6%) for predicting the intrusion discharge through open windows (Op1
 332 and Op3) while formulas from Nandesamoorthy and Thomson (1972), Yu-Tech
 333 (1972) and Jalili and Borghei (1996) appear to perform well (averaged error of
 334 10%) for the intrusion discharge through the door (Op2).

335 **6 Impact of obstacles on the flow intrusion**

336 As discussed above, flow intrusion from a flooded street to an adjacent building
 337 area is made more complicated than a classical rectangular side weir due to
 338 the presence of obstacles in the street and on the facade. The aim of present
 339 section is then to identify the effect of such obstacles on the flow pattern near
 340 the opening and on the intrusion flow discharge.

341 **6.1 Flow description**

342 Fig. 5(b) depicts the impact of a single car parked just downstream an open
 343 door on the surface velocity field near the door (*Op2*) for flow *F2*. As expected
 344 low velocity regions are measured upstream, downstream and on the side of the
 345 obstacle. Indeed, flow detachment on the side and downstream from the car
 346 is enhanced by the sharp corners of the obstacle. The flow approaching the
 347 obstacle rotates towards both sides: towards the open door on the left side and
 348 towards the center of the street on the right side of the obstacle. This behavior is
 349 very similar to that measured by Mignot et al. (2013) around standing obstacles
 350 in the middle of flooded crossroads. Moreover, Fig. 6(a) and (b) compares the

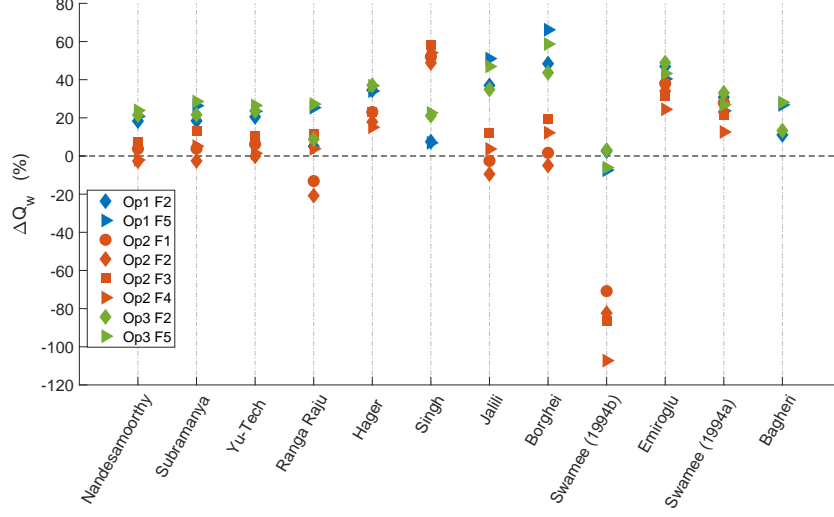


Figure 7: Relative difference between Q_w calculated with the semi-empirical law from Table 3 and measured Q_w (without obstacle).

free surface elevation with and without this parked car for a flow with a higher Froude number. As expected, the water level is increased in front of the car and decreased on its sides. Globally, the whole flow pattern in the vicinity of the obstacle appears to be strongly affected by the obstacle, so that the corresponding intrusion flow discharge is also expected to be much affected.

6.2 Impact of obstacles on the intrusion discharge

The aim of present section is to quantify the impact of obstacles on the intrusion discharge toward the building area. The relative difference between intrusion discharge with an obstacle O_i and without any obstacle, for the same opening and flow configuration reads: $\Delta Q_w = \frac{Q_{w,i} - Q_{w,0}}{Q_{w,0}}$, where subscript 0 refers to the configuration without obstacle. Fig. 8 plots the impact of the 26 obstacle configurations on the 8 tested flow configurations (openings / flow conditions) and reveals that the obstacles impact the intrusion discharge up to ± 100 %.

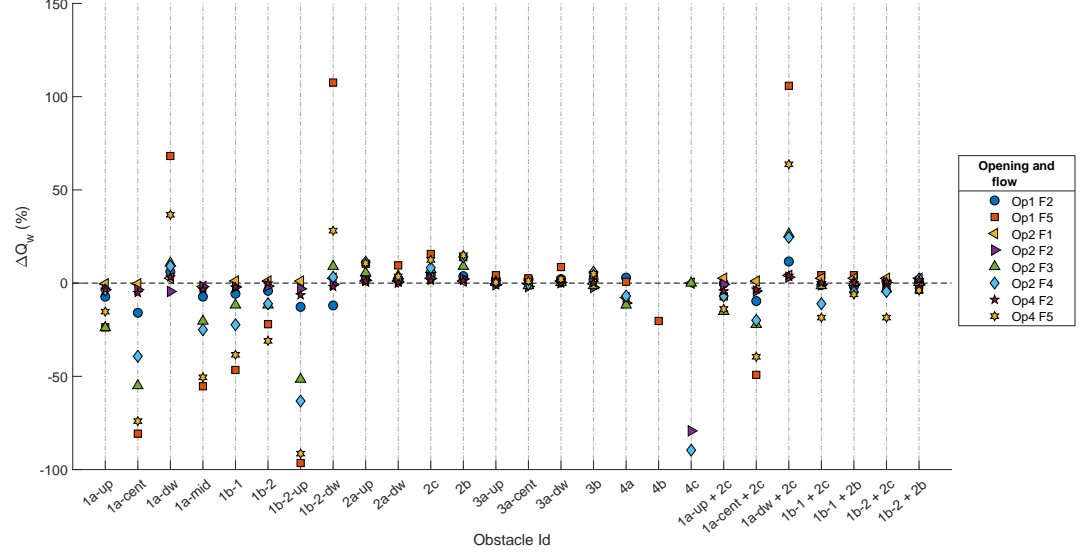


Figure 8: Overview of the impact of the obstacles on the intrusion discharge.

Moreover, some obstacles increase ($\Delta Q_w > 0$) while others decrease ($\Delta Q_w < 0$) the intrusion discharge. As expected, the large obstacles (cars / bus shelters, assumed to remain fixed for sake of simplicity) have a more significant impact than the smaller obstacles (facade and street details). On the other hand, for a given obstacle configuration (a given abscissa on the figure), the sign of ΔQ_w mostly stays the same for the 8 flow configurations, except for some given obstacles (e.g. $1a - dw$ or $1b - 2 - dw$).

A deeper analysis on these impacts is proposed in the next section with the influence of (i) the position of the obstacle with regards to the opening, (ii) the Froude number and (iii) the non-dimensional water depth of the approaching flow in the street and (iv) finally the type of opening.

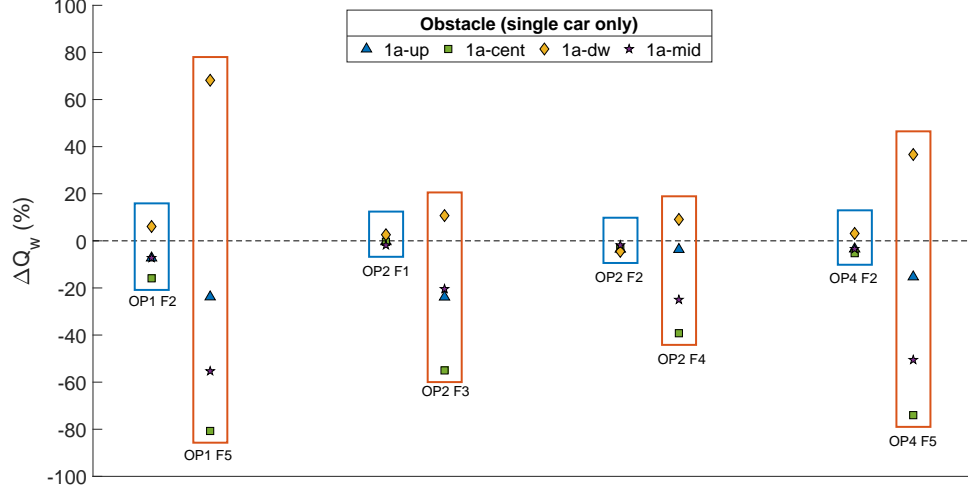


Figure 9: Impact of the position of a single car (1a-up, 1a-cent, 1a-dw and 1a-mid) on Q_w . Orange rectangles highlight the flow configurations with a high Froude number while blue rectangles highlight the flows with a low Froude number.

6.2.1 Influence of the position of the obstacle (single cars)

Fig. 9 plots ΔQ_w for the four single car configurations (with the car located upstream (*up*), in front of (*cent*), downstream (*dw*) from the opening or in the middle of the street (*mid*)). The figure shows that the location of the obstacle strongly affects the intrusion discharge with a positive ΔQ_w when the car is located downstream from the opening and a negative value for the other locations. As expected, the intrusion is particularly reduced when the car is located just in front of (i.e. blocking) the opening. Moreover, the variability of the influence of a single parked car location is very high (up to +/- 80%), i.e. of same order as the intrusion discharge itself.

385 6.2.2 Influence of the Froude number

386 In Fig. 9, ΔQ_w is split as a function of the Froude number: blue boxes refer
387 to flow configurations with a low Froude number while red boxes refer to flow
388 configurations with a high Froude number. The tendency is similar for the 4
389 opening / water depth configurations: the modification of intrusion discharge is
390 much larger with the higher Froude number.

391 To get a more quantified effet of the Froude number, Fig. 10 plots, for the
392 four same opening/water depth configurations, the absolute value of ratio ΔQ_w
393 between the high and low Froude numbers for the 26 obstacle configurations with
394 :

$$\Delta Q_w \text{ ratio} = \frac{\Delta Q_w, \text{High Froude number}}{\Delta Q_w, \text{Low Froude number}} \quad (2)$$

395 In agreement with Fig. 9, the modification of intrusion discharges usually in-
396 creases as the Froude number increases, and this increase can reach up to 100%.
397 However, for some configurations the increasing Froude number decreases the
398 impact of the obstacle. But, more interestingly, for these obstacles configu-
399 rations, the increasing Froude number either increase or decrease the obstacle
400 impact on ΔQ_w depending of the flow and the opening properties. For in-
401 stance, in the case of the street detail centered in front the door (*3a-cent* with
402 *Op2*) ΔQ_w ratio is below 1 for flow cases with a high water depth (*F2* & *F4*)
403 but above 1 with a low water depth (*F1* & *F3*).

404 6.2.3 Influence of the water depth

405 This section aims at establishing how the impact of obstacles is affected by the
406 water depth. This analysis can only be performed for the door (*Op2*), as for
407 the elevated openings, the low water depth does not lead to any flow intrusion.

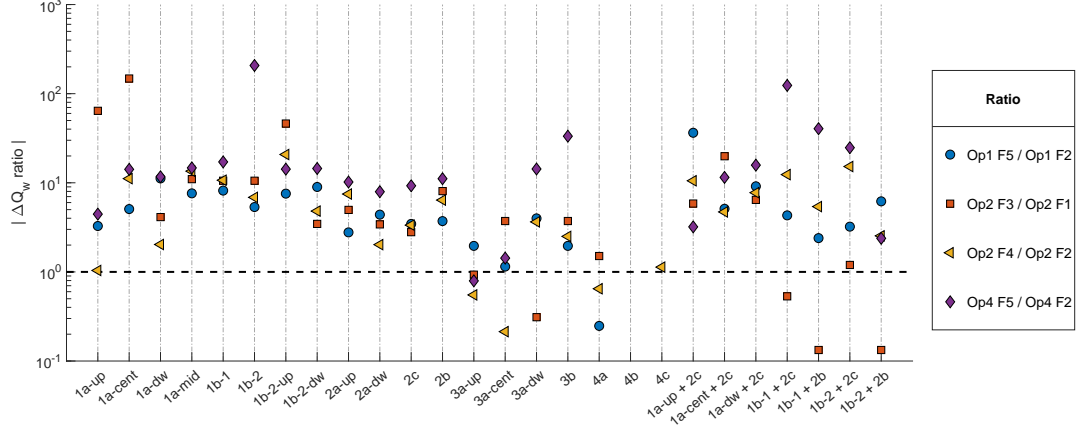


Figure 10: Impact of the Froude number on the modification of intrusion discharge due to an obstacle configuration.

408 Fig. 11 compares the intrusion discharges with low and high water depths for
 409 two configurations (with low and high Froude number) using $\Delta Q_w ratio$:

$$\Delta Q_w ratio = \frac{\Delta Q_w, High\ water\ depth}{\Delta Q_w, Low\ water\ depth} \quad (3)$$

410 The impact of obstacles appears to be strongly affected by the water depth,
 411 some ratios reaching up to 10 (or 1/10). However, no main tendency arises from
 412 this analysis.

413 6.2.4 Influence of the type of opening

414 Finally, the absolute value of obstacle impact on the intrusion discharge $|\Delta Q_w|$ is
 415 plotted on Fig. 12 for the three openings (for the flow configuration with a high
 416 Froude number and a high water depth). For most obstacle configurations, the
 417 impact of the obstacle on the intrusion discharge is maximum for the window
 418 (Op 1), then for the door (Op 2) and finally the gate (Op 4). This result

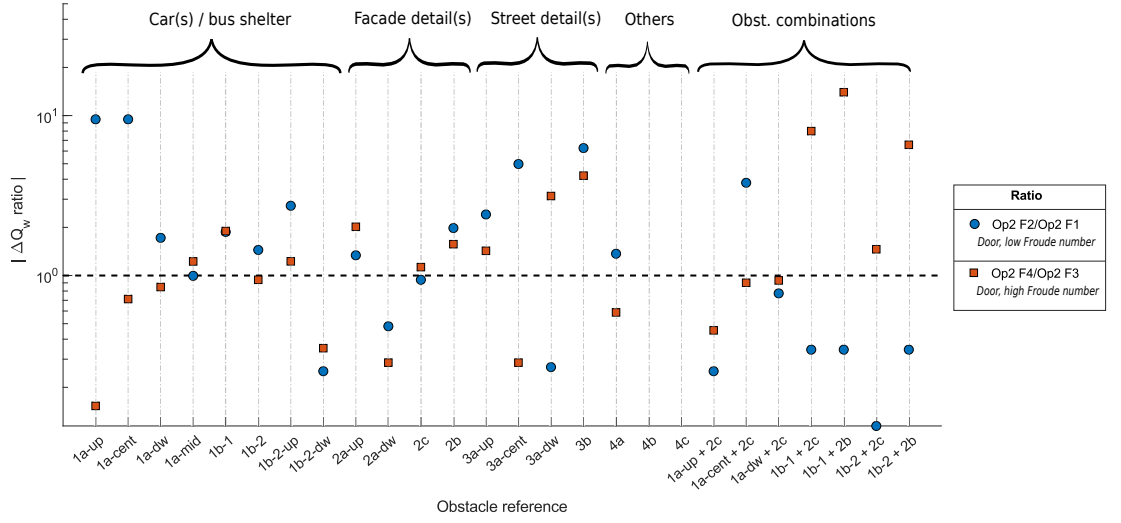


Figure 11: Impact of the water depth on the modification of the intrusion discharge due to the obstacles.

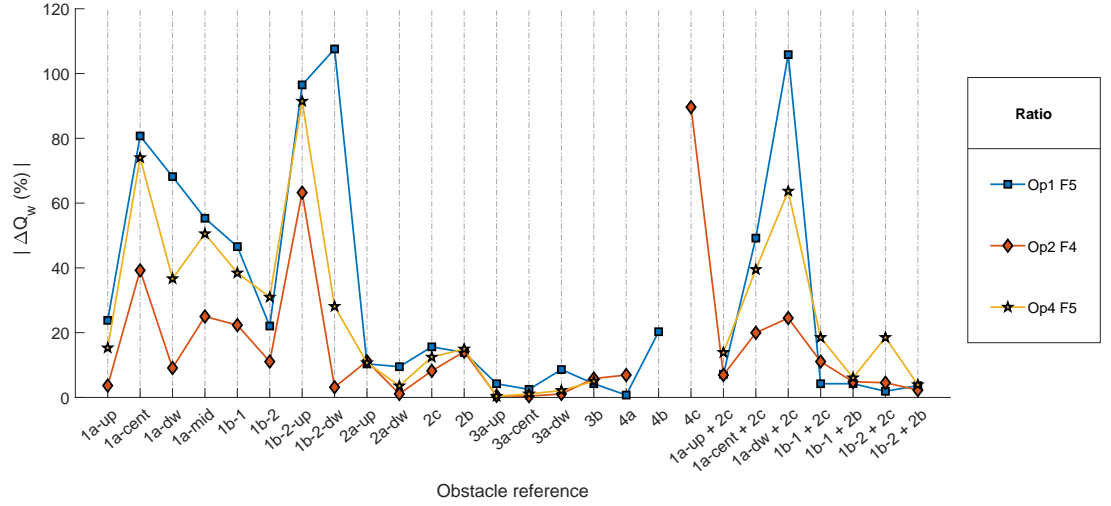


Figure 12: Impact of the type of opening on the intrusion discharge.

419 is logical as a given water depth fluctuation induced by the presence of an
 420 obstacle promotes a higher relative variation above an elevated side weir (i.e.
 421 the window) than above a mounted opening (i.e. the door). This is consistent
 422 with differences that are higher when the obstacle is located downstream (i.e.
 423 for configurations 1a-dw, 1b-2-dw and 1a-dw+2c).

424 **6.3 Impact of the obstacle shape simplification**

425 As exposed above, all obstacles have a highly simplified shape, they are rect-
 426 angular prism, mounted on the bed and emerging across the free-surface. To
 427 estimate the effect of simplifying the shape of the obstacles, a realistic car of
 428 scale 1:12 is inserted (fixed on the bed), either looking upstream ("Car-up") or
 429 downstream ("Car-dw"), at the same location as obstacle configuration 1a-mid
 430 (that is obstacle element 15 in Fig. 3). The impact of the realistic car on the
 431 intrusion discharge is compared to that of the simplified shape obstacle with the
 432 door as opening (*Op2*) for two flows with high water depths.

433 While all three obstacles hardly impact the intrusion discharge for the low
 434 Froude number, with the high Froude number the intrusion discharge highly
 435 differs between the realistic and simplified shapes and in a lesser extent with
 436 the car orientation. These differences are attributed to the water passing be-
 437 low the car, which is not the case for the simplified obstacle shapes that mimic
 438 with higher fidelity the bus shelters. These results do not affect the conclusions
 439 of present sensitivity analysis that exhibits a variability of several tens of per-
 440 cent of the intrusion discharge in presence/absence of obstacles. However, they
 441 show that a quantitative estimate of the intrusion discharge for a particular
 442 opening/obstacle case would require realistic ad-hoc models of furniture/face
 443 details.



(a) Realistic car



(b) Car-dw



(c) Car-up

Figure 13: Photographs of the realistic parked car, looking upstream and downstream

Obstacle	Q_w (L/s)		ΔQ_w (%)	
	F_2	F_5	F_2	F_5
0	4.19	3.49	-	-
1a-mid	4.11	3.29	-1.91	-5.73
Car-dw	4.03	2.91	-3.82	-16.62
Car-up	4.09	2.96	-2.39	-15.19

Table 4: Comparison of the intrusion discharge (Q_w) and the effect of obstacle (ΔQ_w) using realistic parked cars looking downstream (Car-dw) and upstream (Car-up) and the simplified shape obstacle 1a-mid.

7 Discussion and conclusions

This work aimed at investigating the flow processes involved as a flow passes from a flooded street to an adjacent building area via an opening in the facade and measuring the corresponding discharge. Three openings and four flow regimes were tested. Moreover, 26 obstacle configuration, representative of typical obstacles encountered in streets were included for three of the openings to assess the impact of these obstacles on the intrusion discharge.

It was observed that the flow pattern through an opening is quite similar to that over a lateral rectangular side weir, commonly described in the litera-

453 ture. The semi-analytical laws available in the literature to predict the intru-
 454 sion discharges were then tested for the flow configurations without obstacles.
 455 It appears that, while some equations fairly agree with present measurements
 456 for the flows through doors (Nandesamoorthy and Thomson (1972), Yu-Tech
 457 (1972) and Jalili and Borghei (1996) with a typical difference of 10%) and oth-
 458 ers through windows (Swamee et al. (1994b) with a typical difference of 6%),
 459 other equations strongly over- or under-estimate the intrusion discharge (by up
 460 to 100%).

461 When adding obstacles, the flow pattern and intrusion discharge are affected.
 462 The impact of the obstacles strongly depends on the following parameters: the
 463 location of the obstacle(s) with regards to the opening, the Froude number and
 464 water depth of the approaching flow in the street and the characteristics of the
 465 opening. Globally:

- 466 • Urban furniture (without parked cars) affect the intrusion discharge (in-
 467 creasing or decreasing it) by about 12% (for doors) to 15% (for windows)
 468 when the Froude number is high (≈ 0.5) and about 3% (for doors) to 5%
 469 (for windows) when the Froude number is lower (≈ 0.2).
- 470 • Obstacles miming parked cars or bus shelters (with or without urban fur-
 471 niture) affect the intrusion discharge by about 50% (for doors) to 80% (for
 472 windows) when the Froude number is high and about 5% (for doors) to
 473 15% (for windows) when the Froude number is lower.

474 This work then permitted to evaluate the level of variability of the intrusion
 475 discharge towards a building with regards to the hydraulic and geometric pa-
 476 rameters of the flooded street and of the opening and to the type of obstacle
 477 that can be encountered during urban floods. It provides an estimate of the
 478 errors made by numerical computations according to the degree of details of the
 479 street/facade geometry.

480 Finally this database, gathering 220 measured intrusion discharges, is now
481 available for the inclusion and calibration of analytical/empirical equations in
482 operational models adapted to simulate urban floods. Including openings in
483 these models would however require to identify their locations along with their
484 characteristics (width, crest elevation...) along the facades. This information is
485 sometimes available in GIS data bases of the cities, or would have to be located
486 using photographs such as in "Google Street View". Regarding the impact of
487 obstacles on the flow discharge, a simple, first step would be to identify the
488 facades in front of which cars parking is permitted, and to consider the effect of
489 parked cars only for these openings.

490 Nevertheless, the approach presented herein was much simplified and thus
491 present several major limitations. First, a single opening was considered while
492 several neighboring openings on a facade may be damaged simultaneously. In
493 this case, the intrusion flow pattern towards one opening is expected to be af-
494 fected by the intrusions through the openings located upstream. Second, open-
495 ings considered herein are expected to be removed by the flow, leaving a large
496 rectangular open space for the flow intrusion. In the reality, the openings are
497 expected to be only partially damaged and more complex shapes of open spaces
498 are expected to be encountered. Third, in the present work, no backward effect
499 of the flow within the building area is considered: the intrusion flow through
500 the opening remains similar to that over an unsubmerged side weir. In a real
501 situation, the storage capacity of a building and the outflows from the building
502 to a neighboring street through another opening are limited, so that stored vol-
503 ume of water is expected to affect the intrusion discharge (in the same way as
504 for a partially submerged side weir). Fourth, some obstacles not-attached to the
505 ground such as trash containers, potted plants, cars (Smith et al., 2019)... can
506 be mobile under high flow levels and, if partially blocking the openings could

507 also affect the intrusion discharges. Fifth, in some wide streets, the width of
508 the sidewalk can be large enough so that the effect of the parked cars on the
509 flow intrusion dramatically reduces. Next step for the understanding of flow
510 exchanges between streets and building areas during urban floods will then be
511 to consider experimental set-ups that represent small urban districts where the
512 building areas are connected to several surrounding streets with various open-
513 ings, as proposed by Mejia Morales et al. (in press).

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