Author response to Anonymous Referee #2 for "Hydrodynamics of long-duration urban floods: experiments and numerical modelling"

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We deeply acknowledge the Referees for their detailed analysis of our manuscript and their valuable inputs. We provide hereafter a point-by-point response to the main comments by Anonymous Referee #2. The corresponding changes will be implemented in the revised version of the manuscript.

1 General comments

> The paper deals with flood propagation in urban areas. Authors performed laboratory experiments in a typical urban district, containing 7 streets along each direction (in total 49 intersections). In total, 16 tests were conducted (i.e. 16 inflow conditions). The authors apply a 2D shallow-water model to simulate the experimental set-up and investigate the role of roughness and turbulence model. They also discuss the up-scaling of the laboratory observations to the field.
>
> The topic of the paper is of interest for NNES readers. The paper is well structured and generally well-written. The laboratory experiments are new and complete the existing ones, although I regret that neither velocity nor flow depth in street intersections were measured, which would provide a nice assessment of the performance of numerical models. Many researchers have provided empirical equations giving the flow partition in street-intersections, but authors cannot use their laboratory measurements to assess some equations (which are actually useful when 1D models are used for simulating urban floods) because the experimental flow partition between is not avaialble in-between all the intersections. The 2D numerical simulations and comparisons with the laboratory observations are sound. I particularly appreciated the discussion section.
>
> **I would recommend acceptation of the paper with minor revisions**. There are still some issues to be addressed by the authors. The most important are: …

In our response to the specific comments below, we details why flow velocity and water depths in the intersections could not be measured so far. Thank you for recommending publication after minor revisions.

2 Specific comments

2.1 Abstract

- Please, complete the abstract by giving the most the most important results of the work.
- Specify that the used numerical model is two-dimensional.

This will be implemented in the revised version of the manuscript.

2.2 Introduction

Water marks are sometimes available but with very high uncertainty. Also, validation of 2D models should be performed on velocity fields, which are not usually available. Authors are invited to comment these two issues (uncertainty and flow velocity fields) in the introduction.

The following sentence will be included in the Introduction section of the revised manuscript:
"Water marks and aerial imagery provide some relevant information but they remain affected by high uncertainties. They are also far from sufficient to reflect the whole complexity of inundation flows in densely urbanized floodplains, the proper description of which requires information on the velocity fields and discharge partitions."

- Authors do not evoke the need of an accurate estimate of the roughness in urban areas (which is, indeed, spatially variable).

The following sentence will be introduced in the Introduction of the revised manuscript:
"*Difficulties remain nonetheless for estimating the roughness parameters which may vary significantly in space, particularly in floodplains.*"

- The laboratory work by Paquier et al. (2009) should be also discussed. Finally, the recent work by Bazin (2013) merits to be discussed.

Paquier, A., Tachrift, H., Riviere, N., El kadi Abderrezzak, K. 2009. Assessing the effects of two non-structural flood mitigation measures using laboratory and real cases. Road map towards a flood resilient urban environment, 26/11/2009 - 27/11/2009, Paris, FRA. Proceedings Final conference of the COST action C22. 8p.
Bazin, P.H. 2013. Flows during floods in urban areas: influence of the detailed topography and the exchanges with the sewer system. Phd dissertation, https://hal.inria.fr/tel-01159518/document

The contribution of Paquier et al. (2009) will be discussed in the Introduction of the revised manuscript and cited in the reference list. Similarly, the study by Bazin (2013) will be cited at different occasions throughout the revised manuscript, particularly in the Introduction. Part of the work of Bazin (2013) was actually already reported in the original manuscript (see reference Mignot et al. 2013). In the revised manuscript, we will also refer to the peer-reviewed paper by Bazin et al. (2014).

- I find the literature review of experimental studies on urban flows too long. It is not necessary to provide the findings of each study. Please, shorten.

It will be shortened in the revised manuscript.

- P.4, L8: "..with respect to the main modelling characteristics". Unclear sentence. Please reformulate

This part of the text will be rephrased as follows:

"The influence of varying the total inflow discharge is analysed in Sect. 3, together with a sensitivity analysis of the computed results considering different roughness parameters, grid spacing and turbulence models."

2.3 Experiments

- It is not clear where water profile was measured? In the central axis?. If yes, this limits the interpretation of the results and drawing of conclusions. Why not measuring near the intersections, where the flow is 3D in character.

[see also our response to Q. 7 of Anonymous Referee #1]

The water profiles were measured along the centreline of each street. This will be explicitly stated in section 3.1.4 of the revised manuscript. For this reason, comparisons with the numerical simulations were performed by retrieving the computed water depths along the centreline of the streets in the numerical model.

So far, water depths have not been measured beyond the streets centreline because the experimental procedure for conducting water level measurements was particularly slow (optical gauge moving on an automatic traverse system). For each test, water levels were measured at about 600 locations along the centreline of the streets using the automatic traverse system. A single survey of this type (600 points) took almost one whole day. In the future more detailed water level measurements will be performed in the near-field of the street intersections. We will explicitly refer to this as a perspective in the Conclusion of the revised manuscript.

Nonetheless, we used the numerical simulations to investigate to which extent the flow depth varies within a cross-section. As shown by the shaded area ( ) in Figures 1 and 2, significant crosswise variations in the flow depths were obtained only in the near-field of the street intersections, which is consistent with the presence of flow structures such as recirculation zones in these areas.

- Authors are invited to explain why velocity measurements were not performed during the experiment.

The measurement devices installed in the laboratory are moved by means of a traverse system, the automatic control of which requires extensive and accurate data, as well as a complex calibration procedure to avoid any contact with the walls and obstacles. Due to the time allocated to this development, velocity measurements could not be performed up to now. In the revised manuscript, we will highlight the need for velocity measurements in the Introduction and mention it also as a perspective at the end of the Conclusion.

- Please explain how the experiment was scaled according to the Froude similarity.

Assuming a scale factor 1 / 200 for horizontal dimensions, the widths of the narrow and wide streets in the laboratory model correspond respectively to 10 m and 25 m at the prototype scale, which is considered as realistic. Using the same scale factor for vertical dimensions would have led to very small water depths in the laboratory model (e.g., a water depth of 2 m in a real-world floodplain would have been represented by a 1 cm water depth in the laboratory model). Such small water depths would have resulted in significant measurement errors and particularly low Reynolds numbers in the laboratory model. Therefore, a distorted model was considered, assuming a vertical scale factor of 1 / 20. According to the Froude similarity, the scale factor for velocity was defined as the square root of the scale factor for vertical dimensions: $(1/20)^{0.5} \approx 0.22$. Hence, the scale factor for discharge is: $(1/200) \times (1/20) \times (1/20)^{0.5} = 5.6 \times 10^{-5}$. Next, the values of inflow discharge to be supplied to the laboratory model were deduced from typical real-world observations (Mignot et al., 2006) considering moderate and extreme flood conditions, as detailed in Table 1. In the end, the range of investigated inflow discharges was slightly extended to 10 ÷100 m³/h. We believe that details on the scaling of the laboratory model are not a key part of the main message we want to convey in the paper. Therefore, we suggest not inserting this information in the main text; but instead including it as a Supplement of the revised manuscript.

- I think that Colebrook formula was proposed for rough turbulent flow. Setting k = 0 in this formula yields the Von Karman formula. May be replace Colebrook by Von Karman.

We will refer to "von Kármán formula" in the revised manuscript. Nonetheless, we also keep the wording "Colebrook formula" in the text since non-zero values of *k* are considered in sections 3.2.1 and 5.1.

- A description of the hydraulic structures (if any) in the street intersections would be interesting. Authors may discuss the observations according to the existing ones (Mignot, Rivière…).

In the experiments, flow recirculations could be observed downstream of several crossroads. This is consistent with flow descriptions available in literature (e.g., Weber et al., 2001; Neary et al., 1999). These recirculations and the associated *vena contracta* induce significant crosswise variations in the water depths (see also the shaded area in the revised version of Figures 5 and 6). The numerical simulations also highlight the presence of flow recirculations, as shown in Figures 10 and 11 in the original manuscript. Figures 9 and 11 additionally show the presence of control sections in the *vena contracta*, which is consistent with e.g. Figure 5 in Riviere et al. (2014).

In contrast, other hydraulic structures such as hydraulic jumps could hardly be detected in the experiments; but this may result from the absence of velocity measurements. It may also be explained by the overall configuration of the model, in which the downstream intersections generate backwater effects in the upstream region, leading to subcritical flow virtually everywhere.

- Authors are invited to explain why the outflow partition remains virtually independent of the total inflow discharge.

This is an experimental finding which is also confirmed by the 2D numerical simulations. The physical reason has not yet been totally clarified.

One attempt was to use Eq. (14) in Riviere et al. (2011) to show that, at a single intersection, the ratio between one outflow discharge and one inflow discharge (noted R_q in the cited reference) is almost independent of the inflow discharge (expressed by the non-dimensional parameter R_g in the cited reference). Doing so confirms that indeed R_q varies very little with R_g over the range of values of R_g considered here. However, we believe that this is not truly valid because of the significant differences between the geometric and flow conditions considered in the analysis of Riviere et al. (2011) and those of the present experiments. Indeed, in Riviere et al. (2011),

- all four branches are identical (same width), while here streets of different widths are considered;
- the intersections have right angles, which is not the case here;
- the ratio $R_g = Q_i / [\, b^2 \,(\, g\, b\,)^{0.5}\,]$ (with Q_i the inflow discharge in a given street and b the street width) was varied in the range 0.0226 ÷ <u>0.0651</u>, while in the experiments considered here it varies between 2×10^{-2} and <u>9.3×10^{-1}</u>.

In a second attempt, we undertook additional simulations corresponding to a single "equivalent" 4-branch intersection, with the north-south and west-east streets widths respectively equal to 0.5 m and 0.425 m (see also our response to Q. 6 of Anonymous Referee #1). These widths mimic the cumulative street widths along the north-south and the west-east directions in the experimental model (respectively equal to 0.5 m and 0.425 m). We performed the simulations for the two extreme discharges (20 m^3/h and 100 m^3/h), with equal inflow partition between the west and north faces (ϕ_{west} = 50 %) and assuming a smooth bottom (k = 0 m). Free flow boundary conditions were prescribed at the downstream end of each street, located at a long distance downstream of the crossroad (8 times the street width). We used the finest grid spacing considered in the paper (Δx = 2.5 mm) and we tested the computations with and without activation of the turbulence model.

For both inflow discharges (20 m^3/h and 100 m^3/h), the computed results reveal a partition of the outflow discharge proportional to the street widths (54 % *vs*. 46 %). The same results were obtained with and without activation of the turbulence model. It seems therefore that the geometric effect resulting from the difference in the cumulative street widths along the north-south and west-east directions acts similarly over the whole range of considered inflow discharges (20 m^3/h and 100 m^3/h).

Nonetheless, this geometric effect explains only partly the difference in the experimentally observed outflow discharges (60 % *vs*. 40 %). We attribute the remaining difference to *(i)* the spatial distribution of the wider streets within the scale model, and *(ii)* the inclination of several streets. These two effects are not properly reflected in the single "equivalent" intersection considered here; but they are expected to further amplify the difference in the outflow discharges between the north-south and the west-east directions.

2.4 Numerical simulations

- Specify the time step of the numerical simulation.

The following information will be provided at the end of section 2.2 in the revised manuscript:

"*The time step used in the computations is optimized based on the Courant-Friedrichs-Lewy (CFL) stability condition (e.g., Bates et al., 2010). It takes values of the order of* 10^{-3} *s for simulations of the laboratory model and* 5×10^{-2} *s for the prototype scale.*"

- Discrepancy observed in the curved streets are attributed to the Cartesian grid used, which relies on a "staircase" approximation of the obstacles not aligned with the grid. In practice, urban areas are more complex (presence of different obstacles, street angles…) than the "author" experimental set-up. In what extent, the used Cartesian grid (which induces extra flow resistance) can be recommended in field cases?

The model based on anisotropic porosity parameters (section 5.2) is certainly a viable approach for practical applications. For the experiments considered here, all porosity parameters were *deduced* directly from geometric data and there was no calibration of these porosity parameters: ϕ is simply the void fraction in the cell, while ψ is given by the fraction of each cell interface which is not blocked by obstacles. The same approach may apply for real-world cases, for which a digital terrain model (DTM) is used to describe the topography and vector data are available to locate the position of the buildings. Among others, Schubert and Sanders (2012) applied such a technique to simulate the Baldwin Hills urban dam break scenario (see their "building porosity" approach). Sanders et al. (2008) applied a similar model to the Toce Valley flash flood (see their approach based on "gap-conforming" mesh). This will be mentioned in the conclusion of the revised manuscript.

- Why a particular 2.5 mm grid was tested for the particular total inflow of 20 m^3/h?

When the grid spacing is reduced to 2.5 mm, the computational cost is magnified by a factor ~ 8 compared to a grid spacing of 5 mm and is about 64 higher than with a grid spacing of 1 cm. This is the reason why the simulations with a grid spacing of 2.5 mm were not repeated for all inflow discharges.

- Does the grid impact the computation of the hydraulic structures in street intersections?

To some extent, it does. This was already acknowledged in the original manuscript. Indeed, in section 3.2.2, we wrote: "*Changing the grid size leads also to local changes in the flow pattern. As an example, Figure 9 shows the details of the flow field near the downstream end of street 4 in the case of test Q100-W050 computed with cell sizes of 1 cm and 5 mm … lead in some cases to the development of flow structures (such as cross waves), which as a matter of fact are mesh-dependent (Figure 9a and b). Their impact remains however very limited …*".

- Porosity model: is it an isotropic porosity model?

The porosity model is based on anisotropic porosity parameters, as shown in Figure 15 of the original manuscript. This will also be explicitly stated in section 5.2 of the revised manuscript.

- The used porosity model includes two porosities (storage and conveyance), which is in my opinion sound. However, so such detailed model cannot be easily applied to field cases, because the spatial distribution of porosities is needed. In what way can a model of this type contribute to flood risk studies based on the scale and accuracy at which flow attributes (depth, velocity) are predicted? How the model would be constructed to account for spatial distributions of porosity which might be required for practical applications?

[SAME RESPONSE AS FOUR COMMENTS ABOVE]

The model based on anisotropic porosity parameters (section 5.2) is certainly a viable approach for practical applications. For the experiments considered here, all porosity parameters were *deduced* directly from geometric data and there was no calibration of these porosity parameters: ϕ is simply the void fraction in the cell, while ψ is given by the fraction of each cell interface which is not blocked by obstacles. The same approach may apply for real-world cases, for which a digital terrain model (DTM) is used to describe the topography and vector data are available to locate the position of the buildings. Among others, Schubert and Sanders (2012) applied such a technique to simulate the Baldwin Hills urban dam break scenario (see their “building porosity” approach). Sanders et al. (2008) applied a similar model to the Toce Valley flash flood (see their approach based on “gap-conforming” mesh). This will be mentioned in the conclusion of the revised manuscript.

2.5 Conclusions

- Too long. Please shorten and keep only the most important findings.
- Use only one tense to summarize: either present or past.

This will be corrected in the revised version of the manuscript.

References

The cited references which are already listed in the original manuscript are not repeated here.

Bazin, P.-H., Nakagawa, H., Kawaike, K., Paquier, A., Mignot, E. (2014). Modeling flow exchanges between a street and an underground drainage pipe during urban floods. *Journal of Hydraulic Engineering*, **140**(10), 04014051.

Neary, V., Sotiropoulos, F., and Odgaard, A. (1999). Three-Dimensional Numerical Model of Lateral-Intake Inflows. *J. Hydraul. Eng.*, **125**(2), 126-140.

Tables

Table 1: Scaling of the experimental model according to the Froude similarity for moderate and extreme flood conditions as reported by Mignot et al. (2006).

	Moderate flood conditions	Extreme flood conditions
Typical real-world water depth	0.3 m	
Typical real-world flow velocity	1 m/s	
Discharge in real-world narrow streets (10 m in width)	3 m³/s	20 m³/s
Discharge in real-world wide streets (25 m in width)	7.5 m³/s	50 m³/s
Inflow discharge in the narrow streets of the laboratory model	0.6 m³/h	4 m³/h
Inflow discharge in the wide streets of the laboratory model	1.5 m³/h	10 m³/h
Total inflow into the laboratory model	11.2 m³/h	74.5 m³/h

Figures

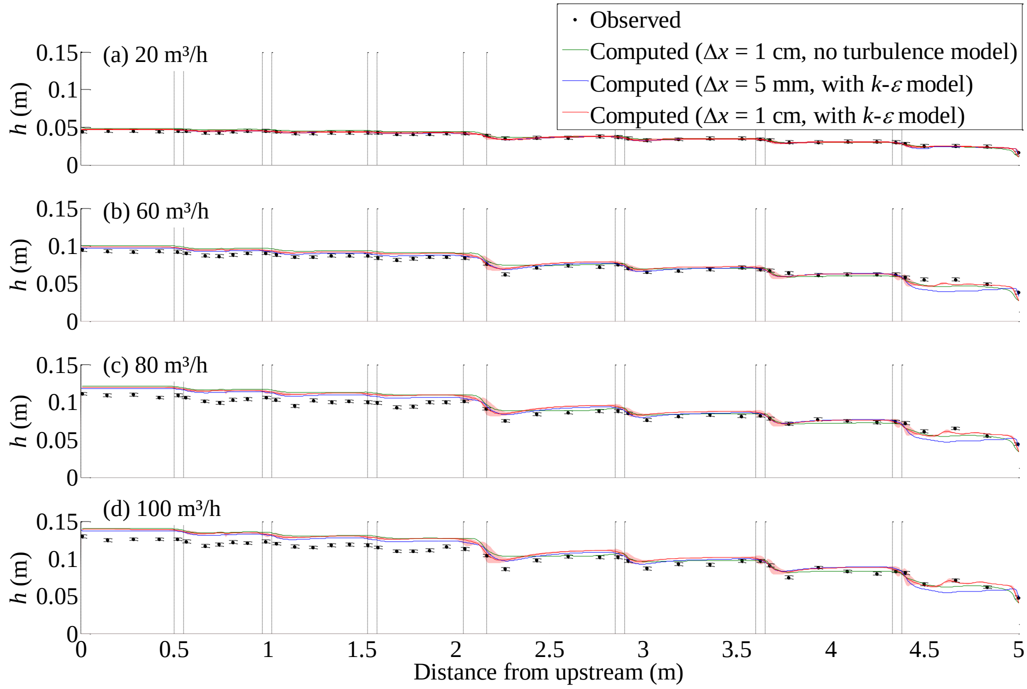

Figure 1 (revised version of Figure 5 in the original manuscript): Observed and computed water depths h for inflow discharges varying between 20 m³/h and 100 m³/h in street C. The shaded area (■) represents the range of variation along the crosswise direction of the computed water depths (Δx = 1 cm, with k-ε model).

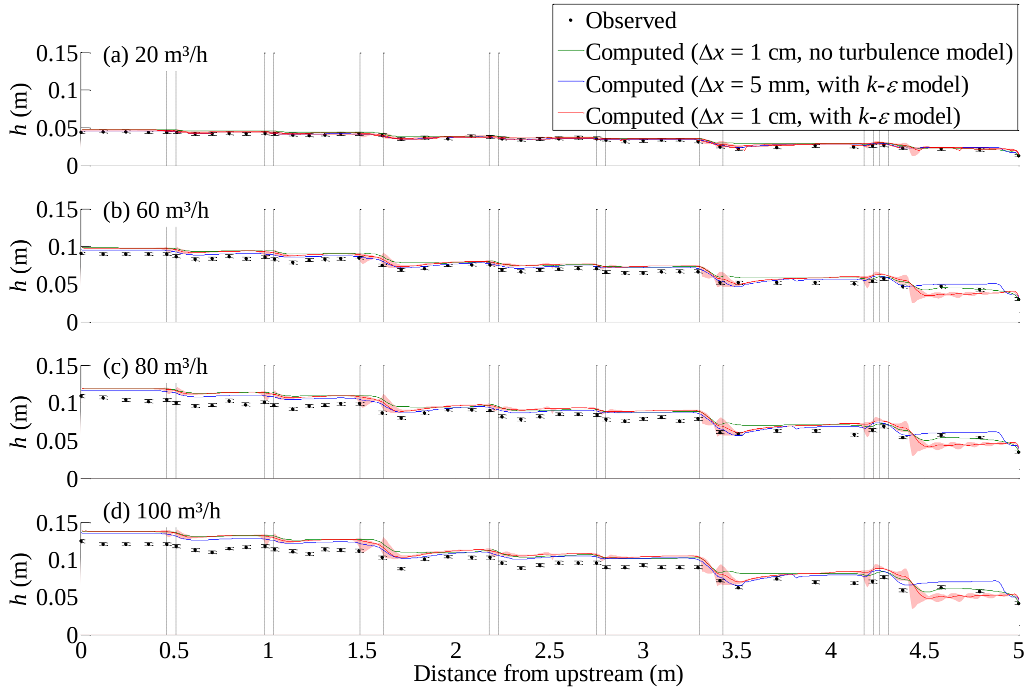

Figure 2 (revised version of Figure 6 in the original manuscript): Observed and computed water depths h for inflow discharges varying between 20 m³/h and 100 m³/h in street 4. The shaded area (■) represents the range of variation along the crosswise direction of the computed water depths (Δx = 1 cm, with k-ε model).