Experimental modelling of urban flooding: A review

Emmanuel Mignot, Xuefang Li, Benjamin J. Dewals

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Emmanuel Mignot[a*], Xuefang Li[b], Benjamin Dewals[b]

[a] University of Lyon, INSA Lyon, CNRS, LMFA UMR5509, F-69621 Villeurbanne, France

[b] Hydraulics in Environmental and Civil Engineering (HECE), University of Liège (Uliège), Belgium

* Corresponding author: Emmanuel.mignot@insa-lyon.fr

Abstract

We review the 45 available studies of urban flooding based on laboratory experiments. We distinguish between the studies focusing on the flow in *(i)* a single street intersection, *(ii)* surface-sewer exchanges, *(iii)* an array of obstacles and *(iv)* quasi-realistic urban districts. We discuss the main flow processes which are covered in the various studies and detail which flow variables were recorded. This enables identifying flow processes for which comprehensive experimental datasets are available from those which require additional experimental research. We also highlight the typical ranges of scale factors used, which depend mainly on the extent of the studied area (from very local up to the district level). This review aims at helping computational modellers to pinpoint the most suitable dataset for validating their numerical approaches and laboratory modellers to identify gaps in current experimental knowledge of urban flooding.

Keywords: urban flood; experimental models; databases; flow processes; model set-ups.

1. Introduction

Among all natural disasters, floods are the most frequent and they affect the highest number of people globally (UNISDR, 2015). Flood risk is particularly severe in urban areas (Chen et al., 2015). Improving urban flood risk management has become a high priority at virtually all levels of governance (Fang, 2016). The proper design and evaluation of measures to enhance urban flood-resilience should be based on the analysis of a range of scenarios, in which various hydro-meteorological conditions and management options are tested. This requires the accurate modelling of inundation extents, water depths, discharge partition and flow velocity in urbanized flood prone areas, since these parameters are critical inputs for flood impact modelling (Kreibich et al., 2014).

For relatively rural areas, flood modelling and inundation mapping have become common practice (Falconer et al., 2017; Teng et al., 2017). Based on the 1D or 2D shallow-water equations (SWE), the accuracy of these computations depends mainly on the quality of hydrological and topographic input data (Dottori et al., 2013). In contrast, floods in urban areas exhibit more diverse and complex flow processes, as the water follows multiple flow paths such as crossroads, sewers, courtyards, parks, flow around or within buildings and pieces of urban furniture (Paquier et al., 2015; Falconer et al., 2017). Numerical models used for urban flood simulations need to account for these specific features of the urban environment. For about two decades, the quality and complexity of urban flood simulations have steadily increased. Starting from standard 1D or 2D models (Mark et al., 2004; Mignot et al., 2006a), more sophisticated numerical approaches have become gradually available:

- additional processes were included in the models, such as the rain falling directly on the street network (Pons et al., 2005; Paquier and Bazin, 2014), short waves or tsunami long waves invading a city (Park et al., 2013), human evacuation during a flood (Bernardini et al., 2017), among others;
- high resolution digital elevation models (DEM), such as laser altimetry with a resolution as fine as 0.5 m in some urban areas (Van Ootegem et al., 2016), have enabled super precise descriptions of the urban domains (Ozdemir et al., 2013);
- isotropic and anisotropic porosity-based models (e.g., Bruwier et al. (2017)), coupled 1D (in streets) and 2D (in crossroads) models (Ghostine et al., 2015), as well as improved computational techniques such as cloud computing (Glenis et al., 2013) or model implementation on graphical processing unit (Apel et al., 2016; Smith et al., 2015), have been developed to enable efficient coverage of large spatial areas;
- although still in its infancy, modelling the interactions between surface flow and the sewer system has been tested, based on a 1D description of the underground system and 0D, 1D or 2D approaches for surface flow, each with scientific challenges (Leandro et al., 2009; Seyoum et al., 2012; Bazin et al., 2014).

Nonetheless, further numerical developments are needed to incorporate more details (urban furniture, street profiles, façade misalignments, parked cars) as well as additional processes generally overlooked so far (water entering the buildings, more realistic interactions river/surface/sewers, transport of cars, pollutants, computing rescue operations …). Since 3D computations (Ghostine et al., 2009; Gems et al., 2016; Rodi, 2017) will not be a viable option for operational flood analysis and mapping in the coming years, many processes will not be captured explicitly by operational flood models. They will have to be reproduced through appropriate analytical-empirical parametrizations. The development and validation of these parametrization requires high quality and reliable reference data.

Field data, such as watermarks and aerial imagery, remain generally scarce, uncertain and insufficient to reflect the whole complexity of inundation flows in urbanized flood-prone areas, particularly under more extreme future conditions (Neal et al., 2009). Additional information on the velocity fields and discharge partitions are necessary to understand the multi-directional flow pathways induced by the built-up network of streets, buildings and underground systems (e.g., drainage network). There is also a lack of observations of pluvial urban floods, mainly due to the short duration and local nature of intense rainfall events. To address this lack of validation data from the field, laboratory models are an appealing alternative, since they provide accurate measurements of flow characteristics under controlled conditions.

Therefore, this paper aims at reviewing the existing datasets of urban flood laboratory experiments. This review may benefit to both numerical modellers willing to test and validate innovative computational approaches, and experimentalists looking for comparison datasets or willing to close knowledge gaps. The paper presents also an inventory of the flow processes for which experimental research was undertaken or still to be handled. Field data are excluded on purpose, as they are generally sparser and more uncertain.

The paper is organized in three parts. The existing experimental datasets dedicated to the analysis of urban flood processes are reviewed in Sect. 2. In Sect. 3, the coverage of the main urban flood process by dedicated laboratory experiments is evaluated; enabling us to point out the flow processes for which no or limited experimental data are currently available. Finally, Sect. 4 links the main findings to the corresponding numerical approaches, highlighting those which lack validation data. Hints for future experimental research are proposed.

2. State of the art of available urban flood datasets

Table 1 lists the available experimental datasets related to urban flooding. Most experiments were performed in the last 15 years, suggesting a growing worldwide interest for urban flood laboratory data, as the corresponding numerical models also improved considerably. The experimental studies focused on four main flow types: *(i)* flow in street intersections, *(ii)* vertical exchanges between the sewer system and the streets, *(iii)* flow within regular grids of emerging rectangular obstacles representing idealized buildings or building blocks and *(iv)* flow within more realistic urban districts. Table 1 is organized in four blocks (I to IV), each of them corresponding to one flow type.

As shown in the first column of Table 1, the experiments considered five different **origins of the water**, i.e. the cause of flooding. First, *upstream runoff* (UR) corresponds to experiments in which the water is supplied from an upstream boundary, mainly via a reservoir with a controlled discharge. It usually refers to flood events for which the overflow or rain takes place upstream of the urban area and water enters the urban domain as surface flow. Second, *river overflow* (RO) corresponds to configurations where the overflow takes place within the urban area and thus the river and the overtopping of the banks are explicitly included in the experiments. In such a case, the upstream boundary condition is a controlled discharge within the river. *Sewer overflow* (SO) is similar to river overflow except that in this case the water invading the surface comes from an exceeded capacity of the sewer within the urban domain; the upstream boundary condition is then a controlled discharge in the sewer inlet. The fourth origin of water is the *rainfall* over the studied domain (RA), which is the case of fully urban watersheds (Pons et al., 2005; Paquier and Bazin, 2014). Then the upstream boundary condition is a complex spatial (and temporal) distribution of water jets from a well-controlled rainfall simulator. Finally, the *tsunami* (TS) type is a long wave imposed off-shore that propagates over the sea domain and invades an urban area when reaching the coast and overtopping the shore protection furniture. Note that these five types of origin of the water can be unique or coupled with each other, as for some UR & SO cases in Table 1 (ID 19, 20, 22, 23).

The diversity of the analysed **flow patterns** (columns 2, 5 and 7 in Table 1) emphasizes the complexity of urban flood processes, involving subcritical and supercritical flow regimes, open-channel and pressurized flow, both at the surface or in the underground system, interacting with obstacles, building blocks *etc*. Among the 45 reported studies, very few address identical flow patterns. The experimental set-ups reproduce either a synthetic urban area (highly simplified streets, 90° intersections and impervious rectangular buildings) or a simplified version of a real city (reproducing the topology of the city but with a highly simplified representation of the facades and street profiles) or finally a more realistic representation of an urban district based on the field DEM (with each individual building being included).

The **location of the set-up** is indicated to help the reader contact the research team responsible for the flume (columns 3 and 4 in Table 1). It also reveals that the experiments were performed in 17 different countries, confirming the global interest for urban flood experimental data.

Columns 6 and 10 in Table 1 provide the **typical dimensions** of the laboratory model. A plausible **scale factor** was derived, by assuming a typical street width equal to 15m and a gully width of 60cm at the prototype scale. Some set-ups aim at analysing in detail local flow features (e.g. flow in a street intersection, single vertical exchange structure, flow around one isolated building …), while others focus on larger scale flow characteristics, such as the flow in a street-network, but with a lower spatial resolution and measurement accuracy. As a consequence, the scale factor of models of street intersections or vertical exchange works typically ranges between 1/10 and 1/50, while those of experiments covering an entire urban district or a grid of obstacles range between 1/30 and 1/200. The experiments of Herbich and Shulits (1964) correspond to the largest model extent for tests involving a grid of obstacles. The largest models of urban districts are those of (Ishigaki et al., 2003; Güney et al., 2014), with a setup length of 20m and 16m, respectively, representing real-world urban areas of 3km and 2.4km in length.

Finally, columns 8 and 9 in Table 1 report the **number of tested configurations** and **type of recorded data**. The measured data strongly depend on the scale of the experiment. For very local flow patterns, such as flows in street intersections and vertical exchange structures (blocks I and II in Table 1), spatially distributed flow characteristics are generally available, including 3D velocity fields and 2D water depth fields, together with more global flow variables such as discharges in the different branches. Moreover, for these local flow pattern experiments, the number of tested configurations remains low (below 10) when spatially distributed data were recorded; whereas it reaches up to 200 configurations when only the discharges were recorded. For the experiments investigating larger scale flow patterns such as obstacle grids and urban districts, spatially distributed data are rare and mostly local velocities and water depths were recorded with pointwise measurement tools, except for surface velocity fields derived in some cases from large scale particle image velocimetry (using a camera located above the experimental setup).

Overall, Table 1 demonstrates the availability of rich laboratory datasets covering a broad spectrum of typical urban flood conditions. In the following, we distinguish between the flow processes comprehensively studied and those calling for more laboratory investigations.

3. Advances of urban flood processes analysis

By listing the existing experimental datasets, Sect. 2 reveals that a wide range of flow processes were reproduced experimentally. Here, we attempt to present an inventory of the main flow processes of engineering relevance in urban flood studies (Table 2), and to relate them to the works listed in Table 1. This enables assessing whether the existing experimental datasets are comprehensive enough for the validation of the representation of each flow process in numerical models. Table 2 suggests that experimental datasets do exist for most urban flow processes of interest; but not for all of them.

Regarding the **origin of water**, most common flood origins were reproduced experimentally. The main deficiency is the intrusion of water waves from a storm surge, with the water from the sea, overtopping the protection dikes and invading coastal cities with very unsteady flows, as described by Maspataud et al. (2013). One main question is the evolution of the unsteadiness as the flow propagates within the urban areas, merges or splits at crossroads and in open spaces: will the typical hydrograph time-scale increase or decrease compared to the surge hydrograph? The validation of numerical simulations certainly requires dedicated experimental data. Moreover, the knowledge on intrusion of water through direct rain on the city domain should be further improved. In particular, as the rain falls on the buildings roofs, part of the water reaches the sewer network (through the gutters) and the rest reaches the surrounding streets or gardens (with possible infiltration) with some surface runoff on the private slots. These processes, computed by Pons et al. (2005) and Paquier and Bazin (2014), still require high quality data to enable deriving empirical parametrizations specific to urban catchments. Future research should also consider the complex coupling between several flood origins.

Numerous datasets of flows in **street networks** (or within arrays of buildings) were published in the recent years. These consider steady or unsteady flows, including steep hydrographs, at single or multiple street intersections. One main deficiency regarding surface flow corresponds to the consideration of obstacles present in the streets (Mignot et al., 2013) and steep urban areas where mostly supercritical flow conditions take place. In such cases, hydraulic jumps occur at the street intersections (Mignot et al., 2008) and in the vicinity of obstacles (Bazin et al., 2017).

Although the flow in street networks has been deeply studied experimentally, it is not the case of the flow invading **other compartments of the urban fabric**:

- vertical flow interaction between the underground sewer and the street surface was investigated locally, at the level of one exchange structure or a single street, but it remains undocumented at the level of an entire urban district;
- similarly, data on flow exchanges between the streets and the blocks / slots (building blocks, gardens, hospitals, etc…) through openings (gates, doors, windows…) remain scarce, both at the local level (one facade, one building) and at the district level, while such calculations have been performed for already some time (Hingray et al., 2000; Inoue et al., 2000).

Existing experimental works focused not only on the flow dynamics; but so-called "**associated events**" have also been considered due to their importance for operational flood risk management. For instance, much attention has been paid to the stability and safety of human beings and cars within flooded streets. These valuable experiments enable estimating, from the hydrodynamics, the level of risk for citizens and goods in flooded urban areas. Nevertheless, the behaviour of transported cars or other mobile furniture (either floating or within the water column) in a street network, and the possibility of creating dams at crossroads or street contractions (Mignot et al., 2006b) was not yet investigated in laboratory experiments. Also, experiments on people evacuation were conducted at a single institution (DRPI, Kyoto, Japan) and reproducing similar measurements is desirable. Measurements of hydrodynamic forces on buildings or facades, and the transport of sediments in flooded urban areas have received relatively little attention up to now. Finally, neither the access of rescue vehicles through flooded streets, nor the dispersion of pollutants (e.g. from flooded industry or damaged trucks) within a street network have been tested. Improved numerical modelling of these "associated events" would be of substantial added-value for the management of urban flood risk, but this still requires additional experimental data for model development and validation.

4. Conclusion

Based on the analysis of 45 laboratory studies and the identification of the main flow processes of significance in urban flooding, the previous sections have highlighted the need for additional (ambitious) experimental efforts to support the development and validation of more realistic computational models of urban floods. This is particularly the case as next-generation urban flood simulations should not only accurately replicate the water flows but also include the so-called associated events (Sect. 3).

Indeed, as shown in Table 1 and Table 2, validation data are available for assessing most types of numerical models commonly used in engineering and research to simulate urban floods, namely (upper part of Table 3):

- 2D-SWE, or the 2D-SWE coupled with a porosity model, or the coupled 1D (in the streets) and 2D (in the crossroads) SWE, to compute surface flow in the urban area;

- coupled 2D-SWE (in the streets) and 1D-SWE (in the sewer network), along with exchange models, to compute the coupled flows in both the underground and surface layers of the urban area;
- 2D-SWE or Boussinesq-type equations to compute long and/or short waves approaching the shore and invading coastal urban areas;
- 3D Reynolds-averaged Navier-Stokes equations at the level of an isolated building (Gems et al., 2016) or a single street intersection (Ghostine et al., 2009).

In contrast, more advanced numerical models (lower part of Table 3) are required to represent the "associated events" occurring during urban floods, for which dedicated experimental data are virtually unavailable. For instance, empirical or semi-analytical parametrizations are required to estimate the amount of water entering the buildings or blocks, for computing sediment and pollutant transport in urban environments, or entrainment of pieces of urban furniture within a flooded network of streets. Similarly, specific numerical developments are needed for computing the behaviour of rescue vehicles, citizen evacuation, etc. using agent based approaches.

The authors recommend that future experimental research aims at getting more quantitative insights into these associated processes closely intertwined with flow behaviour during urban flooding. High quality experimental observations of these processes will contribute to unlock key bottlenecks in the current modelling practice and, consequently, pave the way for more integrative analyses of the urban water and anthropic systems under (extreme) flooding conditions.

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Table 1: Databases available in literature for validation of urban flood numerical models

Water origin [(1)]	Flow pattern	Location of set-up	Reference	Additional remarks	Length of set-up (m)	Steady (S)/ Unsteady (U)	Number of configurations [Availability][(2)]	Types of data	Scale factors[(3)]	ID
I Flow at street intersections										
UR	3-branch subcritical junction	INSA/LMFA (Lyon, France)	Mignot et al. (2012)		5	S	1 [B]	3D velocity field	S_W=0.3m SF~1/50	(1)
		IIHR (Iowa, USA)	Weber et al. (2001)		22	S	6 [A]	3D velocity field	S_W=0.91m SF~1/16	(2)
		Gent University (Gent, Belgium)	Schindfessel et al. (2015)	Rectangular sections with chamfers	33	S	2 [D]	3D velocity field	S_W=0.98m SF~1/15	(3)
		Gent University (Gent, Belgium)	Creëlle et al. (2017)		12	S	6 [D]	Water depth field	S_W=0.4m SF~1/38	(4)
UR	3 branch transcritical and supercritical junction	EPFL (Lausanne, Switzerland)	Hager (1989a & 1989b)		2	S	8 [A] & [C]	2D velocity field	S_W=0.099m SF~1/152	(5)
UR	3-branch subcritical bifurcation	INSA/LMFA (Lyon, France)	Mignot et al. (2013)	Without/with 10 obstacles (urban furniture)	5	S	14 flows x 10 obstacles [D]	* Flow discharge + 2D velocity field (for 1 flow with 10 obstacle configs.)	S_W=0.3m SF~1/50	(6)
		IIHR (Iowa, USA)	Barkdoll et al. (1998)		2.7	S	1 [C]	2D velocity field & water depth field	S_W=0.152m SF~1/100	(7)
UR	3-branch critical & supercritical bifurcation	INSA/LMFA (Lyon, France)	ElKadi et al. (2011)		5	S	~100 [B]	Discharge distribution to the downstream branches + water depth field for 1 flow	S_W=0.3m SF~1/50	(8)
		INSA/LMFA (Lyon, France)	Rivière et al. (2018)		5	S	62 [B]	Discharge distribution and water depth fields	S_W=0.3m SF~1/50	(9)
UR	4-branch subcritical intersection	INSA/LMFA (Lyon, France)	Rivière et al. (2011)		5	S	220 [B]	Discharge distribution to the downstream branches	S_W=0.3m SF~1/50	(10)
		UPC (Barcelona, Spain)	Nanía et al. (2011)		8.5	S	159 [A]	Discharge distribution to the downstream branches	S_W=1.5m SF~1/10	(11)
UR	4-branch transcritical & supercritical flows	INSA/LMFA (Lyon, France)	Rivière et al. (2014)		5	S	113 [B]	Discharge distribution to the downstream branches	S_W=0.3m SF~1/50	(12)
		INSA/LMFA (Lyon, France)	Mignot et al. (2009) & Mignot et al. (2008)		4.5	S	~200 [B] & [B]	Discharge distributions to the downstream branches + 8 water depth fields	S_W=0.3m SF~1/50	(13)
		UPC (Barcelona, Spain)	Nanía et al. (2004) & Nanía et al. (2014)		8.5	S	~200 [B] & [B]	Discharge distribution to the downstream branches	S_W=1.5m SF~1/10	(14)
II Vertical exchanges (street/sewage)										
SO	1 overflow exchange structure (1 way: from	University of Coimbra (Coimbra,	Lopes et al. (2017) & Romagnoli et al.		0.6	S	4 [B] & [B]	3D velocity field	G_W=0.6m SF~1	(15)

Water origin [1]	Flow pattern	Location of set-up	Reference	Additional remarks	Length of set-up (m)	Steady (S)/ Unsteady (U)	Number of configurations [Availability][2]	Types of data	Scale factors[3]	ID
	sewer to surface)	Portugal)	(2013)							
UR	1 inlet exchange structure (1 way: from surface to sewer)	UPC (Barcelona, Spain)	Russo, Gómez, and Tellez (2013)		5.5	S	280 [B]	Exchanged discharge to sewer	SF=1	(16)
UR	1 inlet exchange structure (1 way: from surface to sewer)	Faculty of Civil Engineering (Belgrade, Serbia)	Despotovic et al. (2005)	(without and with clogging effects)	5	S	~100 [C]	Exchanged discharge to sewer + flow spreading on the street	SF~1	(17)
UR	1 inlet exchange structure (1 way: from surface to sewer)	DPRI (Kyoto, Japan)	Lee et al. (2012)		6	S	12 [B]	Exchanged discharge + water depths	SF=1/10	(18)
UR & SO	1 exchange structure (2 ways between surface and sewer)	University of Sheffield (UK)	Rubinato et al. (2017) & Martins et al. (2017)		8	S + U	46 [A] & [A]	Exchanged discharges (steady + time evolution) + water depths	SF=1/6	(19)
UR & SO	1 exchange structure (2 ways between surface and sewer)	U. of Coimbra (Portugal)	Beg et al. (2017)		9.5	S	19 [B]	Exchanged discharges + velocity fields + pressure heads	G_W=0.6 SF~1	(20)
UR	1 street with several inlets	U. of Coimbra (Portugal)	Leandro et al. (2010)		36	S	36 [B]	Exchanged discharge	S_W=0.5m SF~1/30	(21)
UR & SO	1 street with several exchange structures (2 ways)	DPRI (Kyoto, Japan)	Bazin et al. (2014)		10	S + U	2 steady 2 unsteady [C]	Water depth and pressure head along the street (+ total exchanged discharge for Bazin2014)	S_w=0.8m SF~1/20	(22)
UR & SO	1 street with several exchange structures (2 ways)	DPRI (Kyoto, Japan)	JinNoh et al. (2016)		10	S + U	6 steady 2 unsteady [B]	Water depth and pressure head along the street (+ total exchanged discharge for Bazin2014)	SF=1/20	(22)
UR & SO	1 half-street + 3 exchange structures (2 ways: collect and overflow)	University of A Coruna (A Coruna, Spain)	Fraga et al. (2017)		6	S + U	5 [B]	Water depth in street and in pipes + discharge in pipes	SF=1	(23)
III Flow through a regular grid of emerging obstacles										
UR	Non-uniform flow in a patch of obstacles	UCL (Louvain la Neuve, Belgium)	Soares-Frazão and Zech (2008)	aligned obstacle grid (aligned with flow axis and rotated)	15	U (dam break)	2 [B]	Water depth Surface velocity fields	S_w=0.1m SF~1/150	(24)
UR	Non-uniform flow in a patch of obstacles	UCL (Louvain la Neuve, Belgium)	Velickovic et al. (2017)	aligned obstacle grid (aligned with flow axis and rotated)	15	S	20 [B]	Water depth profiles	S_w=0.1m SF~1/150	(25)
UR	Non-uniform flow in a patch of obstacles	UCL (Louvain la Neuve, Belgium)	Lhomme et al. (2007)	Staggered obstacle grid (aligned with flow axis)	15	S	1 [D]	Water depths Surface velocity fields	S_w=0.1m SF~1/150	(26)
UR	Non-uniform flow in a patch of obstacles	CESI (Milan, Italy)	Testa et al. (2007)	aligned & staggered obstacles	5	U (dam break)	12 [A]	Water depths	SF=1/100	(27)
UR	Non-uniform flow in a patch of obstacles	National Taiwan University (Taiwan)	Huang et al. (2014)	aligned obstacles (aligned with flow axis)	8	S	7 [D]	Water depth profiles	Various S_w	(28)
UR	Non-uniform flow in a patch of obstacles	KICT (South Korea)	Kim et al. (2015)	Aligned obstacles	30	U (dam break)	2 [D]	Water depths	S_W=0.1m SF~1/150	(29)

Water origin (1)	Flow pattern	Location of set-up	Reference	Additional remarks	Length of set-up (m)	Steady (S)/ Unsteady (U)	Number of configurations [Availability](2)	Types of data	Scale factors(3)	ID
		Tsinghua Université (Beijing, China)	Zhou and W. Yu (2016)	Aligned obstacles: pervious & impervious	10	S	30 [D]	Water depths + 2D velocity fields	S_w=0.05m SF~1/300	(30)
UR	Uniform flow in a large grid of obstacles	INSA/LMFA (Lyon, France)	Guillen-Ludena et al. (2017)	Aligned obstacles on rough bed with forces on buildings	8	S	50 [B]	Normal water depth + Forces on buildings (50 exp) & 2D velocity field (1 exp)	Various S_w	(31)
		Pennsylvania State U. (USA)	Herbich and Shulits (1964)	Staggered obstacles	16	S	80 [C]	Normal water depth (uniform flow)	Various S_w	(32)
RO	River overflow around obstacles	Polytechnico di Milano (Italy)	Beretta et al. (2018)		2.23	S	1 [B]	Local velocities and water depths	SF=1/25	(33)
RA	Rain over a group of buildings	University of Coimbra (Portugal)	Isidoro et al. (2013)	Rain with/without wind effect and static/dynamic storm effects. 4 tested building distributions	2	U	30 [B]	Outflow hydrographs	Various S_w	(34)
			Cea et al. (2010)	Rain over buildings with roofs	2.5	U	72 [B]	Outflow hydrographs	Various S_w	(35)
TS	Long wave over an obstacle grid at the shore	DPRI (Kyoto, Japan)	Tomiczek et al. (2016)	Aligned obstacles	45	U	63 (2 repetitions) [B]	Water depth + pressure on obstacles	SF=1/20	(36)
		Leibniz University (Hanover, Germany)	Goseberg (2013)	Aligned and staggered obstacles	18		24 (290 with repetitions) [A]	Maximum run-up extension, water depths, velocities	Various S_w	(37)
				IV Urban district						
UR	Flow in a street network	DPRI (Kyoto, Japan)	Ishigaki et al. (2003)	With & without connections (48) to underground	20	U	2 [C]	Water depths, surface velocities & outflow discharges	SF=1/100	(38)
		IMFS (Strasbourg, France)	Arrault et al. (2016) and Finaud-Guyot et al. (2018)	Synthetic district	5	S	16 [B]	Water depth profiles & Outflow discharges	SF=1/200	(39)
RO	Flow around buildings	Univ. of South Carolina (Columbia, USA)	LaRocque et al. (2013)	River overtopping towards urbanized area	12	S	2 [A]	Surface velocity field + water depth field	SF=1/50	(40)
UR		UNSW (Sydney, Australia)	Smith et al. (2016)	Mostly supercritical flows	12.5	S	1 [A]	Surface velocity field + water depth field	SF=1/30	(41)
UR		Dokuz Eylül University (Izmir,	Güney et al. (2014)	Dam break on a group of buildings	16	U	1 (5 repetitions) [D]	Water depths (10 locations) and velocities (4 locations)	SF=1/150	(42)

Water origin (1)	Flow pattern	Location of set-up	Reference	Additional remarks	Length of set-up (m)	Steady (S)/ Unsteady (U)	Number of configurations [Availability](2)	Types of data	Scale factors(3)	ID
		Turquey)								
RO		University of Innsbruck (Austria)	Sturm et al. (2018)	Supercritical & flow within buildings	9	U (Fixed discharge in the river upstream)	140 [D]	Forces on buildings, water depths, flow velocities	SF=1/30	(43)
TS	Long wave over a realistic planning at the shore	PARI (Yokosuda, Japan)	Yasuda (2004)	with openings towards underground	34	U	4 [C]	Water depths + flood extension	SF=1/50	(44)
		Oregon State University (Corvallis, USA)	Park et al. (2013)		40		1 (99 repetitions) [B]	Water depths and velocities	SF=1/50	(45)

(1) UR=Upstream runoff, RO = River overflow, SO = Sewer overflow, TS=Tsunami, RA = Rain over the domain
(2) A = Available on the Internet or in the article, B = Available upon demand, C = Likely not available, D = No information about availability
(3) S_w= street width in model, G_W = gully width in model, SF= horizontal scale factor reported by authors or computed using typical field values S_w=15m and G_W=0.6m in prototype

Note: In terms of discharge distribution in 3-branch subcritical and transcritical bifurcation flow configurations without obstacle (very simple cases), the recent works by Rivière et al. (2011, 2014) propose a review of available discharge distribution data. The reader can refer to these papers for a list of available data and corresponding references.

Table 2: Urban flood processes and corresponding data availability for validation

Main processes	Sub-processes	Id. from Table 1	S,C *
Origin of the water	Rain on urban domain	34, 35	S
	River overtopping towards urban area	33, 40, 43	C
	Dam break upstream from city	24, 27, 29, 42	C
	Tsunami (long) wave invading the city	36, 37, 44, 45	C
	Wave submersion / storm surges	**Not available**	-
	Sewage overflow	15, 19-23	C
Flow in streets	Open-channel flows around a group of buildings:		
	• *Steady sate*	25, 26, 28, 30-33, 40, 41	C
	• *Transient flow (bank overtopping, flood wave, dike submersion wave…)*	24, 27, 29, 34-37, 42-45	C
	• *Subcritical flow regime*	25, 26, 28, 30-33	C
	• *Supercritical flow regime*	41, 43	S
	• *Wave front*	24, 27, 29, 36, 37, 42, 44, 45	C
	Open-channel flows in one street intersection	1-14	C
	Open-channel flows in a street network:		
	• *Steady*	39	S
	• *Transient flow*	38	S
	• *Subcritical flow regime*	38, 39	S
	• *Supercritical flow regime*	**Not available**	-
	Flow interaction with fixed furniture	6	S
Flow in other compart-ments of the urban fabric	Sewer-street exchanges:		
	• *1 exchange structure*	15-20	C
	• *1 street & 1 pipe with exchange structures*	21-23	S
	• *Street & pipe network with exchange structures*	**Not available**	-
	Flow within and through buildings / building blocks	30, 43 + Liu et al. (2018)	S
	Flow through open-areas: gardens / semi-urbanized private parcel / above walls / through vegetated or semi-pervious fences…	**Not available**	-
	Flow in underground spaces	38 + Takayama et al. (2007)	S
Associated events	Cars transport :		
	• *Stability of a single car*	Ref (1)	C
	• *A group of cars in one street intersection creating dams*	**Not available**	-
	• *Single car or a group of cars transported in a street network*	**Not available**	-
	Risk and evacuation of people :		
	• *Human stability*	Ref (2)	C
	• *Human evacuation (through doors, corridor, staircase, from cars)*	Ref (3)	S
	Forces on buildings	31, 43	S
	Sediment transport	43	S
	Rescue access and processes (via army, ambulance, fire-men, etc…)	**Not available**	-
	Pollution dispersion	**Not available**	-

* S=scare, C=comprehensive

(1) see recent extensive review by Martínez-Gomariz et al. (2018) and recent work by Martínez-Gomariz et al. (2017).

(2) see Abt et al. (1989), Russo, Gómez, and Macchione (2013), Xia et al. (2014), Martínez-Gomariz et al. (2016) and the review by Kvocka et al. (2016); older papers also exist.

[3] see Ishigaki et al. (2008) and Baba et al. (2017)

Table 3: Typology of numerical models applied to compute urban flood events

Type of model	Typical processes	Level of development[4]	Available exp. data (Yes, No)
3D RANS[1] or LES[2]	1 street intersection Flow around 1 building	C	Y
2D SWE[3]	Street surface (local to large scale)	C	Y
2D SWE + porosity models	Urban district	C / R	Y
1D-2D SWE (1D=streets / 2D=crossroads)	Urban district	R	Y
1D-2D SWE (1D=sewer / 2D=streets)	Coupled flow in streets and sewers	R	Y
2D SWE or Boussinesq-type equations	Overland Tsunami	C	Y
Hydrodynamics + morphodynamic model	Building foundation scour, sediment deposits around buildings…	U	N
Hydrodynamics + empirical /analytical exchange formulae	Flow exchange between streets and built-up or open areas through openings (gates, doors, windows…)	U	N
Hydrodynamics + advection-diffusion model	Pollutant transport	U	N
Hydrodynamics + Lagrangian model	Transport of urban furniture and debris (cars, trees, etc…)	U	N
Hydrodynamics + agent based model	Citizen evacuation, rescue access	R[5]	N

(1) Reynolds-averaged Navier-Stokes equations;
(2) Large-Eddy simulations;
(3) Shallow-water equations (see Rodi (2017) for details of the models and applications);
(4) C = common practice, R = research models, U = unavailable in the context of urban flood modelling;
(5) Mostly for tsunami cases, see for instance Wang et al. (2016).