Chapter 9

Advances in experimental modelling of urban flooding

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9.1 INTRODUCTON: URBAN FLOODING

Flooding impacts more people annually than any other natural hazards, and the 21st century has seen a rise in the number of extreme meteorological events (CRED, 2019; Depietri & McPhearson, 2018). Flooding, including coastal, fluvial and pluvial, costs the global economy US$19.7 billion in 2018, with densely populated urban areas typically exposed to ‘flash flooding’ as a result of intense rainfalls that exceed the anthropogenic and natural drainage capacity of a city (CRED, 2019) (Figure 9.1). Recent years have seen a number of significant floods impacting cities globally; between June and July 2016, flooding is estimated to have impacted over 32 million people in China alone (Tang *et al.*, 2017). While these events, and many others globally, cannot be entirely mitigated, there is an intrinsic vulnerability to flooding associated with living in urban areas which is further exacerbated by increasing urbanisation, and a changing climate (Miller & Hutchins, 2017; Rubinato *et al.*, 2020).

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Figure 9.1 Example of recent (August 2019) pluvial flooding events in urban areas: on the left, flow over streets in Cavarzere, (VE), Italy; on the right, manhole cover removed by the high pressure caused by overflow of the drainage system in Calalzo di Cadore, (BL), Italy. ©LeonardoRubinato and ©MariaGraziaSattin.

With the IPCC (2014) stating that anthropogenic factors have 'unequivocally' altered future climate, the natural global hydrological balance is shifting. Global water scarcity will be exacerbated in the future, particularly in areas that currently face significant droughts, while global flood risk is also likely to increase as a result of a changing water balance (Liu and Jensen, 2018; McMichael *et al.*, 2006; Pozzi *et al.*, 2013; Spinoni *et al.*, 2014; Trenberth, 2011).

The UK is likely to see an increase in extreme rainfall events, with the UK Met Office suggesting an average annual temperature rise for Central England of up to 5.8°C, with winter rainfall increasing up to 33% and summer rainfall decreasing by 57%, by 2070, for a high emission scenario at the 90th Percentile (Met Office, 2018). Further highlighting the likely increase in the risk of flooding as a result of a changing climate, Kundzewicz *et al.* (2014) noted that the one in 20 year return interval rainfall event is likely to become more frequent globally (aside from the Sahara) for all emission scenarios, with the event occurring every four years in South East Asia by the end of the 21st Century.

To coincide with an increasing risk of high intensity rainfall events, the rise in urban population results in aggravated threat of flooding, meaning that historical approaches to flood management are likely to be unsuitable in the future (Reynard *et al.*, 2017). It is anticipated that without adaption, there is likely to be up to US$24 trillion increase in global annual costs due to flooding by the end of the century (Jevrejeva *et al.*, 2018).

Urban flooding is increasingly a risk; statistics demonstrate that 55% of the total global population lives in urban areas, and this figure is expected to increase to 60% by 2030, and the number of global 'megacities' will increase from 33 to 43 during the same time period (UN, 2018). While urban redevelopment can manage some of the growth, the increasing population will drive cities to sprawl into the peri-urban environment (Haaland & van den Bosch, 2015; Miller *et al.*, 2014; Pili *et al.*, 2017). Urbanisation causes a change in the natural hydrological balance by constructing impermeable surfaces, the compaction of soil and the removal of vegetation (Brilly *et al.* 2006; Haaland & van den Bosch, 2015; Lashford *et al.*, 2019; Li *et al.*, 2018; Rubinato *et al.*, 2019). Additionally, the installation of a traditional, pipe-based drainage system, which can efficiently remove water from urban areas to nearby watercourses, increases flood risk by altering the hydrological response to rainfall (Lundy & Wade, 2011; Miller *et al.* 2014).

Since the installation of the hydraulically efficient London Sewerage System in the 1850s, resulting from the need for suitable sanitation post Industrial Revolution, pipe based drainage has been adopted globally (Hughes, 2013; Walsh *et al.*, 2005; Xie *et al.*, 2017). Pre industrial-age approaches to drainage still exist, for example the Cloaca Maxima, Rome, Italy, however they have been largely subsumed by post-industrial drainage, further ensuring water is 'out of sight, out of mind', aiming to rapidly remove water from urban areas (Perales-Momparler *et al.*, 2015). Many cities consequently now rely on ageing drainage systems built in the 19th and 20th Century that are now, with an increasing urban landscape and a changing climate, incapable of managing the current urban pluvial flood risk (Djordjevic *et al.*, 2011; Egger & Maurer, 2015; Guo, 2006). Additionally, the 'clogging' of conventional systems with debris inhibits their potential to effectively remove water, causing a back log through the system and an increased flood risk. The 2007 UK summer floods is a typical example of such scenarios (Fenner, 2000).

Most urban drainage systems were designed to manage smaller volumes of runoff than faced today, and therefore are vulnerable to failure during high-intensity rainfall events (Butler & Parkinson, 1997; Butler *et al.*, 2018; Mark *et al.*, 2004). The integration of pipe based drainage system at new build sites is still part of typical design culture, with runoff to the sewer system typically flowing underground via gully pots and pipes before reaching the watercourse (Woods-Ballard *et al.*, 2015). This poses an increased flood risk for the outfall as a result of a reduced lag time and increased peak flow at the receiving water course (Qin *et al.*, 2013).

Table 9.1 outlines the design flood frequency for pipe based systems according to the British Standards (British Standards Institution, 2008) and the European Standard EN 752. All drainage systems in a city centre should manage all storms up to and including the one in 30 year storm event, while in comparison, designs are up to the one in 10 year return period for the USA (Guo, 2006). Many cities are consequently at risk of flooding due to insufficient capacity of drainage, which is an even bigger problem in less developed countries due to lower drainage standards in urban areas (Fratini *et al.*, 2012; Guo, 2006; Mark *et al.*, 2004).

Table 9.1 Conventional drainage design storm frequency scenario for different locations (adapted from British Standards Institution 2008 and the European Standard EN 752)

Location	Design Storm Frequency
Rural areas	One in 10 years
Residential areas	One in 20 years
City centres	One in 30 years

In addition to having the primary concern of increased flood risk at the source and the outfall, conventional drainage has also created a water quality issue. Improving runoff quality prior to being released into the watercourse is a neglected aspect of conventional drainage (Hoang & Fenner, 2015). Consequently, runoff transports a variety of urban pollutants without treatment into the watercourse which has an impact on the biodiversity of urban streams (Zhang *et al.*, 2013).

This chapter aims at summarising previous research conducted to improve the accuracy of urban flood modelling, experimentally and numerically, and highlights the need of full-scale and field case studies that could provide hidden insights not achievable via scaled models for a better application and better benefits for multiple urban developments.

9.2 EXPERIMENTAL AND NUMERICAL URBAN FLOOD MODELLING

9.2.1 Input parameters and boundary conditions

Recent advances in technology, and consequently in the performance of physical models, have generated an abundance of data which are crucial to calibrate and validate numerical models (Mignot *et al.*, 2019). The essential data requirements of flood inundation models can be summarised as follows into multiple categories.

Topographic data of the channels and floodplains to act as model bathymetry (Peña & Nardi, 2018) are essential when setting up a numerical model. A high quality Digital Terrain Model (DTM) representing the ground surface with surface objects removed is the basic topographic data requirement. As provided in literature (Ramsbottom & Wicks, 2003), vertical accuracy of about 0.5 m and a spatial resolution of at least 10 m for DTMs are required for rural floodplain modelling, while a vertical accuracy of 5 cm with a spatial resolution of 0.5 m are needed to resolve gaps between buildings (Ozdemir *et al.*, 2013; Smith *et al.*, 2006; Van Ootegem *et al.*, 2016) for numerical modelling over urban floodplains, considering that the knowledge of the micro-topography over large areas may become much more significant.

Time series of bulk flow rates and rainfall are crucial for characterising numerical boundary conditions (Morales-Hernández *et al.*, 2013). Ideally, flow rates should be accurate to 5%, however, this figure may differ consistently and errors may be much higher during flood events. Recent studies have also investigated more complex features such as the rain falling directly into streets (Paquier & Bazin, 2014). Rainfall has been considered for many years as a major uncertainty source, in the accurate prediction of urban flooding events (Niemczynowicz, 1999), but recent progress associated with the use of radar and microwave networks have reduced the uncertainties by facilitating the gathering of sufficient information on temporal and spatial variation of rainfall processes in urban catchments (Fletcher *et al.*, 2013; Schellart *et al.*, 2012).

Roughness coefficients for channels and floodplains, which may be spatially distributed (Kirstetter *et al.*, 2016), are another category of essential parameters to use when accurately setting up a numerical model, as well as bottom roughness coefficients in the sewers and floodplain (Bellos *et al.*, 2017). By introducing these parameters, energy losses not represented explicitly in the model equations can be parameterised. Considering that in practice they are usually estimated by calibration, it can be difficult to separate the contribution associated to friction from that attributable to compensation for model structural and input flow errors. It is necessary to calibrate numerical models, adopting two separate roughness coefficients for sewers and floodplains.

Despite the progress in producing essential datasets for calibration and validation of numerical models, there is still a paucity of datasets that are essential to accurately represent detailed features associated with the high complexity of the urban environment (for example multiple flow paths through crossroads, sewers-surface interactions, parks, Sustainable urban Drainage Systems (SuDS)). These features are crucial to assess the hydraulic performance of drainage systems in urban areas and to verify the probability of flooding. The uncertainty associated with the nature of flood events, which are typically characterised with high intensity and a short duration, results in challenges to identify possible locations of flooding in advance. This creates complications when attempting to record the data required for the calibration and validation of numerical models. Furthermore, even if municipalities have the availability of equipment to consistently record flow, water levels and pressure in sewers and streets, it is expensive to optimise the maintenance procedure by checking all these sensors repeatedly over several years, causing eventual gaps or non-reliable datasets.

To cope with this lack of data, physical full and scaled models are important tools to replicate urban flooding conditions as well as field case studies where feasible. Over the last decade, multiple studies have been performed and the next section summarises them based on multiple variables such as flow patterns, hydraulic and geometrical conditions, scale factors tested, and SuDS techniques adopted.

9.2.2 Flow patterns. hydraulic conditions and geometrical setups

As previously mentioned in Section 9.1, by 2030 60% of the world's population will be living in urban areas, increasing to 68% by 2050. Cities across the world continue to develop, targeting different social needs and following various planning criteria established by governments and municipalities, generating different urban scenarios to incorporate flood resilience into urban planning (Bertilsson *et al.*, 2019). As a consequence, flow patterns and their interactions in urban environments are very complex.

To date, experimental studies to estimate these complex flows and/or energy losses in urban drainage systems have been conducted to take into account subcritical (Nania *et al.*, 2011; Riviere *et al.*, 2011; Schindfessel *et al.*, 2015) and supercritical flow regimes (Creëlle *et al.*, 2017; Kemper and Schlenkhoff, 2019; Riviere *et al.*, 2014), open-channel and pressurised flow (Martins *et al.*, 2017; Rubinato *et al.*, 2018a), interactions between the minor and major systems (Beg *et al.*, 2018; Fraga *et al.*, 2017; Gomez & Russo, 2005, 2009; Gomez *et al.*, 2019; JinNoh *et al.*, 2016; Lopes *et al.*, 2014, 2015; Martins *et al.*, 2014, 2018; Rubinato, 2015; Rubinato *et al.*, 2011; Rubinato *et al.*, 2013, 2014, 2017a, b, 2018b; Vasconcelos *et al.*, 2006) and with the presence of obstacles or streets (Arrault *et al.*, 2016; Finaud-Guyot *et al.*, 2018) and building blocks (Güney *et al.*, 2014; Smith *et al.*, 2016). Examples of experimental facilities are shown in Figure 9.2.

Mignot *et al.* (2019) have pointed out that these multiple studies address very few identical flow patterns and these studies, despite providing crucial specific insights to improve the experimental and numerical modelling of urban flood flows, are

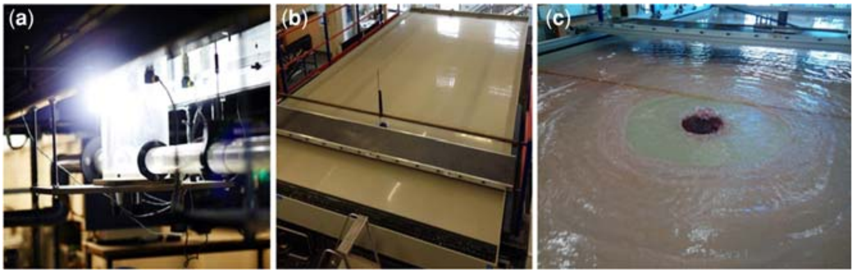

Figure 9.2 Example of experimental urban flood models with sub-surface interaction (Rubinato 2015). (a) View of the scaled drainage system of the sub/surface experimental facility at the University of Sheffield; (b) Birdseye view of the urban floodplain of the sub/surface experimental facility at the University of Sheffield and (c) experimental simulation of sewer overflow. ©MatteoRubinato.

limited to specific hydraulic conditions or have been conducted to optimise a specific case scenario, and hence may be limited to be up-scaled or applied within a variety of urban environments.

Furthermore, experimental models have been developed to date to provide datasets to represent local energy (head) losses (friction and local losses) (Butler & Davies, 2011; Butler *et al.*, 2018) at junctions and urban drainage features for improving the performance of existing numerical models and better predicting future scenarios.

Multiple parameters have been found to affect head losses during the last two decades, including the channel water depths between the upstream branches and the downstream channel (Hsu & Lee, 1998); upstream and downstream subcritical or supercritical hydraulic conditions (Gargano & Hager, 2002; Hager & Gisonni, 2005; Zhao *et al.*, 2008); the joining angle between any lateral pipes and the main pipe (Pfister & Gisonni, 2014); and the ratio between pipe diameter and manhole diameter (Ramamurthy & Zhu, 1997). Bearing in mind that these outputs were mainly obtained replicating physical scale models of singular structures (e.g. single manholes), the impacts of these parameters are likely to be different when considering an entire drainage system including several structures, with a hypothetical 'domino' effect towards the downstream section of the area under investigation.

Additionally, previous research has provided an insight into consequences of floodwater flowing on streets in urban areas (Beg *et al.*, 2020). Based on the amount of water and the geometrical conditions of the roads (e.g. slope), vehicles parked on the sides of streets can be swept away, causing various hazards to people and properties (Xia *et al.*, 2014).

Stability criteria for vehicles in floodwaters were determined by Gordon and Stone (1973), Keller and Mitsch (1993), Shu *et al.* (2011) and Xia *et al.* (2011), and experimental data were used to validate the derived formulae based on the principles of similarity and scale ratios. Limitations due to scaling effects have also made it not possible to apply the results to corresponding prototype vehicles in the study conducted by Teo *et al.* (2012).

Runoff on streets is also a hazard for pedestrians attempting to cross the roads under a variety of water depths and velocities (Martinez-Gomariz *et al.*, 2016). Experimental studies for human body stability in laboratory setups by using real human bodies started with Foster and Cox (1973), and have been expanded by Abt *et al.* (1989) who adopted different ground surfaces and Jonkman and Penning-Rowsell (2008) who tested high velocities and psychological factors. In the UK, Defra and the Environment Agency provided a method to quantify the hazards for pedestrians based on velocity, depth and presence of debris within the flows (Defra, 2006). Russo (2009) focused on the impact of pedestrians of different ages and weights, with diverse visibility conditions and the use of hands, wearing dissimilar footwear.

9.2.3 Sustainable drainage systems

Section 9.1 identified the challenges regarding traditional drainage methods and flood risk reduction, consequently the UK has moved to produce non-statutory guidance for SuDS, advocating their role at new build sites, to minimise an increase in flood risk post-development (Defra, 2015). This was developed as a result of the 2007 UK floods, which cost the UK economy approximately £3 billion, and paved the way for the UK Flood and Water Management Act (HM Government, 2010), which, as part of Schedule 3 of the act, further identifies SuDS as being a critical approach to sustainable flood management for the future (Pitt, 2008).

Due to the need to make cities more sustainable, a number of experimental studies have also been completed to examine the impact that SuDS can have at reducing runoff and ultimately flooding, in an urban setting (Fach & Dierkes, 2011; Nnadi *et al.*, 2012; Sanudo-Fontaneda *et al.*, 2018; van Woert *et al.*, 2005). It is understood that by integrating 'green infrastructure' into urban design, or by simply reducing the total coverage of impermeable surfaces, it is possible to reduce localised, pluvial flooding (see Figure 9.3) (Eckart *et al.*, 2017).

At the laboratory scale, experimental control tests of SuDS have been undertaken over the last 20 years (Sanudo-Fontaneda *et al.*, 2018; van Woert *et al.*, 2005). Models to determine the effectiveness of both extensive and intensive green roofs have demonstrated their ability to reduce runoff received from traditional tiled roofs (Bouzouidja *et al.*, 2018; Lee *et al.*, 2013; van Woert *et al.,* 2005). Stovin *et al.* (2015a) monitored a number of rainfall scenarios over a four year period to analyse the water retention capabilities of a green roof, taking into account the effects of the vegetation type, density and structure of the green roof. Subsequently, it was possible to determine roughness coefficients in a numerical model to determine energy losses (Stovin *et al.*, 2015b) (see Section 9.2.1).

Figure 9.3 Example of a SuDS system, comprising of rock-lined swales and vegetated detention ponds, in Leicester, England. ©CraigLashford.

Similar experimental laboratory tests have been conducted on permeable paving (Nnadi *et al.*, 2012; Sanudo-Fontaneda *et al.*, 2014). By altering the topographic variables, runoff surface length and surface slope of a laboratory scale permeable pavement design, it is possible to maximise runoff reduction (Sanudo-Fontaneda *et al.*, 2014). To further optimise a design, Nnadi *et al.* (2014) analysed the possible influence of membrane layers, such as more traditional geotextile or OASIS®, not only on total outflow, but also water quality. However, experimental models are still required to better understand the scale of reduction, and to maximise the benefits that can be achieved by integrating SuDS into the urban landscape.

9.2.4 Scale factors: the need for full-scale and field models

Urban areas are complex, and most experimental setups previously described either reproduce a simplified urban city or a synthetic urban area (simple streets, 45 and 90° junctions, rectangular buildings) by adopting scale factors based on specific similitudes, hence these are called physical scale models.

Despite providing important insights and better understanding of urban flooding scenarios, physical scale models include assumptions and 'artefacts' that typically do not completely resemble real-world prototype observations. This is due to governing non-dimensional parameters (i.e. force ratios) which are not completely identical between the model and its prototype (Heller, 2011). Consequently, the application of these features may include a slight alteration of the flow regime (laminar, turbulent and transition phase), or of the relative importance of frictional resistance, generating datasets that could be dissimilar from those linked with real environments (Heller, 2011).

Considering, for example, the ageing conditions of existing sewer systems in the UK and worldwide networks, an extended number of variables (e.g. ground water level, traffic, number of house connections, materials, age, and diameters) are affecting the identification of techniques and solutions for the rehabilitation of existing infrastructure. Experimental models tend to view systems separately, focusing on a specific problem without taking into account the interaction and possible synergies between subsystems (Tscheikner-Gratl *et al.*, 2015). For example, companies building or repairing sewers on-site are required to follow steps regarding excavation, backfill and compaction. Existing studies (Del Borghi *et al.*, 2008; Uche *et al.*, 2013) focused on the use of concrete and aggregates for pipes bending, but did not include the paving of the roads using bitumen, a product typically included, hence materials and their properties may differ from scale models to real sites. Furthermore, CCTV (closed-circuit television) inspection may be expensive, and the quality of the analysis conducted on existing sewer systems may be dependent on the quality of the pictures taken as well as the skills and the experience of the technician analysing them (Wirahadikusumah *et al.*, 1998).

Figure 9.4 Upstream and downstream view of the full experimental facility constructed at ICAIR, plus a detailed view of a full-scale manhole. ©The University of Sheffield and ©SimonTait.

To address this gap, full-scale facilities have been developed, or are under development, such as the Integrated Civil and Infrastructure Research Centre (ICAIR) at the University of Sheffield (Figure 9.4) and the full sub-surface model at the IKT – Institute for Underground Infrastructure in Germany (Figure 9.5).

Their common aim focuses on producing results that could identify inaccurate assumptions or specifications, and supporting numerical models for the simulation of precipitation and runoff events in urban areas. By obtaining this outcome, numerical models could be better calibrated and validated, and could

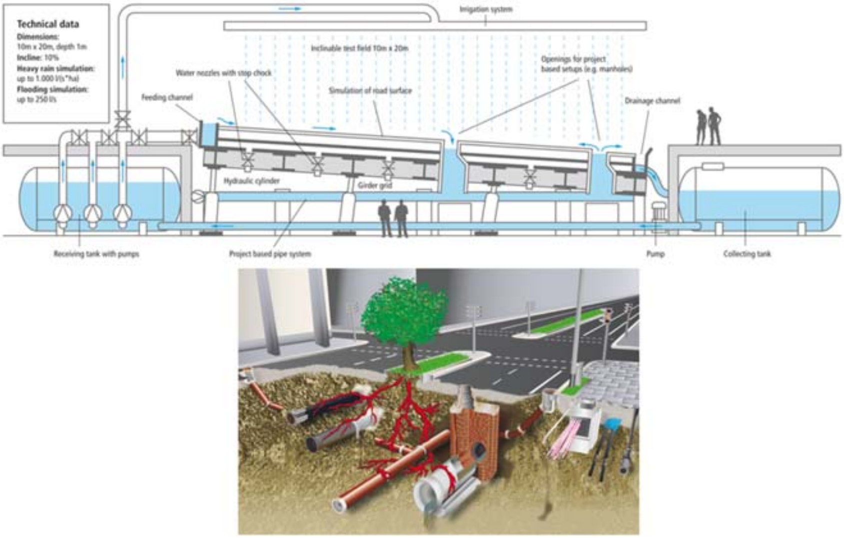

Figure 9.5 Scheme of the full-scale experimental facility designed and under development at IKT-Institute for Underground Infrastructure. ©IKT-Institute for Underground Infrastructure (Goerke, 2019).

increase their ability to assess the hydraulic performance of existing and new drainage systems, making a stronger impact in municipalities and reducing the potential damages associated with urban flooding. By increasing accuracy, full-scale experimental facilities (Figures 9.4 and 9.5) can take into consideration typical hydraulic conditions (backwater effects, overflow situations, rain-runoff interaction) on the road surface in connection with underneath sewer systems, that if replicated within a scale model, may not be precisely replicated with all associated features included. Furthermore, multiple existing materials and geometries adopted in different countries can be tested for efficiency without the issue of having to scale properties that could be fundamental in the replication of the phenomenon to investigate.

Outside of the laboratory, there has been a recent shift to better understand sustainable design through the use of 'living labs', i.e. experimental field study space constructed into the built environment (Hutley *et al.*, 2011; Lima & Ribeiro, 2016). While there has been an acknowledgement through much of the 21st Century of the role that SuDS can play at limiting urban runoff, their integration with both new and existing urban drainage schemes has been limited, particularly in England (Melville-Shreeve *et al.*, 2018). It is imperative therefore that SuDS design is optimised through experimental field modelling, as well as that at the laboratory scale, to ensure standards are retained, and the most effective design is integrated (Tedoldi *et al.*, 2016). There are now a number of best practice installation, which have also been used for experimental field studies (Fach & Dierkes, 2011; Garcia-Serrana *et al.*, 2017). By integrating a two-phased calibration and validation approach, it is possible to model field data with an acceptable level of accuracy, accounting for epistemic and aleatory uncertainty (Beven, 2016; Lamera *et al.*, 2014; Mei *et al.*, 2018; Versini *et al.*, 2015).

Using experimental data previously described is crucial to validate numerical models and hence develop confidence on the predictions for future events of similar magnitude. To date, only a few experimental datasets have been available for numerical model validation (bulk flow measurements taken at a small number of points in the model domain, often including the catchment outlet, water levels obtained by CCTW cameras). However, the 2D nature of modern distributed models requires spatially distributed observational data (e.g. water depth or flow velocity) at a scale adequate to model predictions for successful validation. Full-scale facilities already constructed and those under development can expand the possibility to secure these records over the course of a simulated flood event. Successfully validated experimental field scale studies allow for a better understanding of external parameters, which often cannot be replicated in a laboratory setting, for example the ability to understand the influence of maintenance of sites, the availability of a long term, ideally continuous, dataset and the ability to utilise dynamic catchment-scale rainfall and ultimately, flow.

Sites such as the 12.5 km^2 Pontbren catchment in Powys, Wales, which was maintained between 2004 and 2009, provide an experimental field site to better understand the influence of different land management methods (Marshall *et al.*, 2009; Marshall *et al.*, 2014; Wheater & Evans, 2009). The Pontbren project aimed to provide a long-term, continuous record of how different farming techniques and catchment management approaches altered the hydrology of the area, by monitoring soil structure change, infiltration rates, peak flow and rainfall (Bulygina *et al.*, 2013; McIntyre & Marshall, 2010). A further example of catchment-scale experimental research is by Heal *et al.* (2006), at the Dunfermeline Eastern Expanse, a 5 km^2 site consisting of three ponds (the largest being 15,495 m^3) and an 18,633 m^2 wetland area. The research enabled a better understanding of how each pond and the wetland system managed stormwater quantity and quality over a four-year period, informing future maintenance to ensure standards for water quality improvements, and quantity reduction are retained.

However, there are issues to be faced when using active urban drainage systems as test models that can be associated with the likelihood of equipment being damaged or stolen, depending on the site chosen (Gomani *et al.*, 2010; Rivett *et al.*, 2008; Ruhl *et al.*, 2001). There is a need for continuous data to understand long-term trends of SuDS systems, as runoff is inherently dynamic, but also for example, to understand how natural seasonal vegetation growth cycles influence runoff, however this is not always possible due to extraneous circumstances, such as data-drop-out, battery-life span and equipment failure (Roinas *et al.*, 2014). It is therefore common for urban modelling to utilise less expensive monitoring equipment, which can be of a reduced resolution, to negate the cost-impact of tampering of equipment (Chetpattananondh *et al.* 2014; Rivett *et al.*, 2008).

9.3 CONCLUSIONS

Climate change, urbanisation and ageing conditions make future urban flood events very difficult to predict. However, despite this huge challenge that engineers, urban planners and policymakers will have to deal with, it is crucial to be able to develop a better understanding of this uncertain phenomenon, to facilitate decision-making and the identification of tools and strategies to adopt, and to achieve the desirable goal of reducing urban flooding and its negative impacts.

This chapter has grouped research studies conducted to date to enhance the quality of experimental and numerical urban flood modelling for a better prediction of future flood events. It is clear that there is a great emphasis in the literature on improving the accuracy of models, and continuous progress is being made on understanding areas for improvement to reduce impacts on existing and new infrastructure. This development is directly associated with the availability of data, which is limited or may not exist for specific hydraulic conditions. The understanding of precise links between each variable involved during flooding conditions still requires more assessments and more research is needed and should be prioritised to assess and reduce flood impacts. To achieve more consistent and less incomplete flood impact assessments, the collection of more data would be highly valuable to build upon.

Continuous development of technology aids the improvement of new tools and measurement techniques (Nichols *et al*., 2020; Rojas Arques *et al*., 2018) to design and inspect more accurate scaled and full-scale models. Multiple aspects need to be advanced in the future, and stakeholders should all combine resources and strengths to:

- Provide a better understanding of urban flooding and its causes, studying features not fully investigated to date such as manhole covers removal due to high pressure in overflowing manholes; sediment transport in pipes and in streets and the interaction of the two systems during flooding scenarios; micro plastics settled in the road-deposited dust and urban surface soil. Data obtained should be made open access so that numerical modellers across the world can calibrate and validate their models. There is a need for practically orientated technological solutions to provide protection for the environment and property and to maintain the functionality of the entire infrastructure. Concepts for both public and private wastewater systems which result in the most damage-free removal of the precipitation water and minimise the risk of flooding events (e.g. temporary retention of large volumes of water, delayed passing-on of precipitation and combined wastewater, throttling of influxes and outflows) are, in particular, thus gaining in importance.
- Make cities more liveable, combining both ‘soft’ and ‘hard’ engineering solutions to achieve sustainability of urban systems. Sustainable Drainage Systems and reuse and recycling technologies are in continuous progress and efforts should be made to facilitate the transition to these new systems.
- Identify procedures for better monitoring, repairing and rehabilitating existing infrastructure. Methods are required to reduce groundwater infiltration into sewers, to reduce the risk of sewer blockages to improve their serviceability. Rehabilitation techniques such as cured-in place pipes are continuously increasing their confidence, however to be able to generate benefits in many countries around the world, they need to guarantee not only the structural repair of the old pipe, but also ecological compatibility with different materials, under varying chemicals and environmental conditions from one country to another. New materials, such as glass-fibre-reinforced plastics GRP, needle-felt, plastic coatings and reactive resins, for example, are coming into use everywhere for the rehabilitation of existing systems. The behaviour of these materials raises new questions, particularly with respect to such aspects as durability,

> high-cycle fatigue performance, ecological efficiency and sustainability – and also in respect of anticipated new requirements. Changing environmental conditions (e.g. longer dry periods, increasingly frequent heavy rainfall events), and also greater volumes of road traffic (e.g. increases in heavy-goods traffic) definitively influence material performance.

Nowadays, new technologies continue to be introduced at a rapid rate, therefore new accurate and sophisticated equipment as well as faster computers can be used to enhance the quality of physical modelling and its outcomes. To further improve existing ideas, communities should be promoting awareness and improving environmental education. The public should be invited to respond to plans and proposals designed by authorities and private companies, providing invaluable local experience to refine planned physical models because community engagement is an essential component of sustainable flood risk management. Public participation can thus directly inform decisions and support the execution of actions rather than only raise awareness.

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