Chapter 15

Boscastle case of flash flood modelling and hazards reduction

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15.1 INTRODUCTION

An increase in the frequency and magnitude of flooding is one expected consequence of climate change. The UN Office for Disaster Risk Reduction (UNISDR) and the Belgian-based Centre for Research on the Epidemiology of Disasters (CRED) in their 2015 report 'The Human Cost of Weather Related Disasters' associated 157 000 deaths with flooding since 1995. In the last 20 years, floods accounted for 47% of all other weather disasters with 3062 individual events resulting in 2.3 billion people being affected by floods, an alarming number (UNISDR, 2015).

The event occurrence of different geophysical, meteorological, hydrological and climatological events from 1970 to 2017 were assembled by the International Disaster Database in CRED and are presented in Figure 15.1. A significant increase is seen in extreme events and especially the number of floods (EMDAT, 2017).

In line with the above-mentioned predictions, a considerable increase is also expected in the intensity and frequency of extreme precipitation events. This chapter's focus will be on flash floods which are a destructive natural hazard with one of the highest mortalities. They are short duration floods associated with excessive amounts of rainfall and their different causes include a short duration

Editors: Xiaochang C. Wang and Guangtao Fu
doi: 10.2166/9781789060768_0415

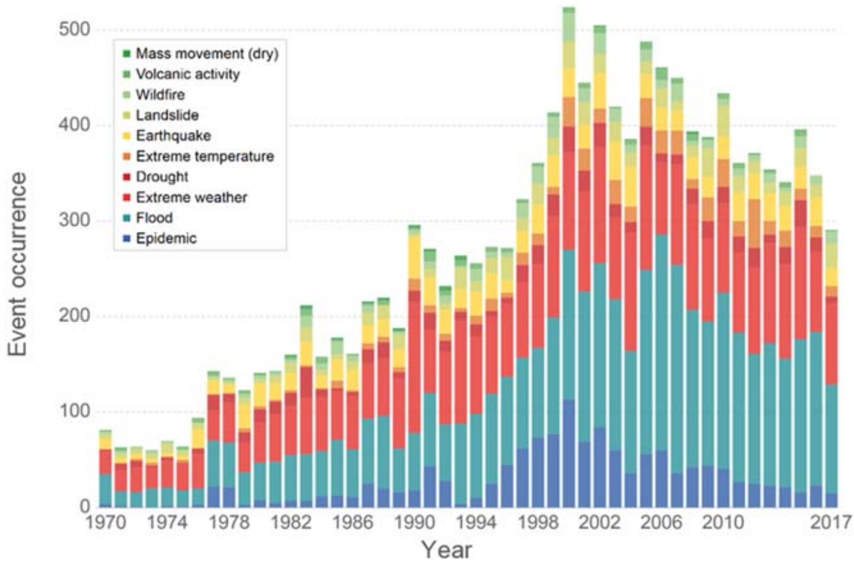

Figure 15.1 Number of disasters from 1970 to 2017 looking at geophysical, meteorological, hydrological and climatological events (EMDAT, 2017).

intense rainfall event, snow melt events, hydraulic structure failures or glacier lake outbursts (Archer & Fowler, 2015; World Meteorological Organisation, 2012).

The current state of climate change and its impact is regularly assessed, and Synthesis Reports are published every few years. All reports target the increase in frequency and intensity of extreme events such as flash floods. The 4th Synthesis Report (AR4) specifically discusses the possibility of an accelerated water cycle. This in turn would lead to an increased storage capacity of water in the atmosphere which would result in higher frequency and intensity storms (IPCC, 2007). The 5th Synthesis Report (AR5) also mentions the probable increase in intensity and frequency of extreme precipitation events (IPCC, 2014) and based on a scoping session in 2017 it is an issue that will also be included in the 6th Synthesis Report (AR6) which will be published in 2022 (IPCC, 2017). This increase in the intensity and frequency of extreme precipitation events will lead to an increase in flash flood events and therefore it is important that the scientific community works to develop new and improved tools to enhance the resilience of urban areas to the threat of extreme flooding through prediction, preparedness strategies and accurate modelling.

In 2018, the European Severe Storms Laboratory (ESSL), taking also into account parts of northern Africa and the Middle East, accounted for 152 fatalities due to flash floods. They plotted all heavy rain events and flash floods events associated with fatalities on the map shown in Figure 15.2. The major highlighted events in Europe were on October 15th in Trebes, France with 13 casualties, on

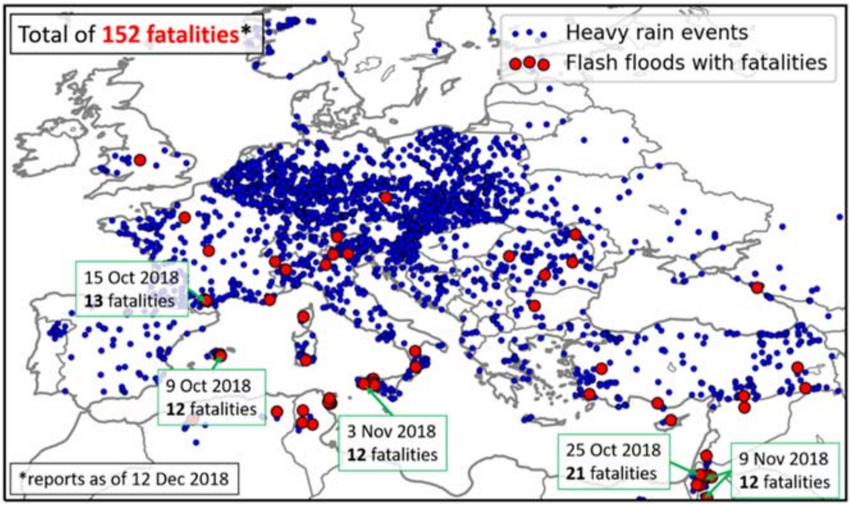

Figure 15.2 Map of deadly flash floods in 2018 produced by the European Severe Storms Laboratory (ESSL, 2018).

October 9th in Mallorca, Spain with 12 casualties and on November 3rd in Sicily, Italy with 12 casualties (ESSL, 2018). Furthermore, there were more flash floods recorded with no casualties in Montenegro, Netherlands, Sweden, Belgium, Poland, Luxembourg, Slovakia, Slovenia, Bulgaria, Macedonia (FYROM), Greece, Ireland, Switzerland, Ukraine and Norway.

It has been recognised that traditional flood management approaches for flooding are not necessarily applicable to flash floods (Kobiyama & Goerl, 2007; World Meteorological Organisation, 2012) and in order to create a more appropriate framework, the differences between these types of events needs to be understood. In this research it is therefore essential to firstly define what a flash flood is, and then to clarify the difference between a large riverine flood and a flash flood. Flash floods have been defined in many different ways but the World Meteorological Organisation (WMO), provides a very descriptive definition of a flash flood as follows (World Meteorological Organisation, 2012):

> ‘A flash flood is a short and sudden local flood with great volume. It has a limited duration which follows within few (usually less than six) hours of heavy or excessive rainfall, rapid snow melt caused by sudden increases in temperature or rain on snow, or after a sudden release of water from a dam or levee failure, or the break-up of an ice jam’.

Discussing the main differences between riverine floods and flash floods was first attempted by Xu *et al.* (2006) who, considering the management of flash floods and sustainable development in the Himalayas, created a table including the main differences between riverine floods and flash floods. Nonetheless, as the table seemed incomplete, it is further improved in this chapter using additional sources (i.e., Archer & Fowler, 2015; Kobiyama & Goerl, 2007; Merz & Bloschl, 2003; Shrestha *et al.* 2008; World Meteorological Organisation, 2012, 2017), as shown in Table 15.1.

Flash floods due to extreme rainfall events are localised hydro-meteorological phenomena and thus the topographical characteristics also play an important role as they have a considerable effect on all hydrological parameters (World Meteorological Organisation, 2007, 2012). The topographical characteristics that affect hydrological properties, and therefore flash floods, include soil moisture,

Table 15.1 Differences between flash floods and riverine floods.

	Flash floods	Riverine floods
Causes	High intensity rainstorms or cloudbursts Sudden snow/glacier melt Dam breaks Levee breaches Wet/dry catchment	Prolonged seasonal precipitation Seasonal snow and glacial melt Saturated catchment
Characteristic features	Quick onset Short storm/flood duration Quick water level rise Peak flow in minutes/few hours Quick recession Not related to base flow Rapid response to rainfall, short lag time Limited spatial extent (<30 km^2) Steep slope catchments	Slow onset Long storm/flood duration Slow water level rise Peak flow in hours/days Slow recession High base flow Slow response to rainfall, medium long lag time Regional to large spatial extent All catchments
Associated problems	Large amount of debris High hydraulic force associated with erosion and structural damage	Inundation/flooding
Frequency	All year	Rainy season
Affected areas	River plains, valleys Local extent Small to medium areas	River plains, valleys Local to regional extent Large areas
Forecasting	Forecasting difficult Local information essential Hydro-meteorological problem Coordination for flood response in real-time difficult	Forecasting possible Local information not essential Hydrological problem Coordination for flood response in real-time possible

soil depth, soil permeability, land use, catchment size and the catchment slope (World Meteorological Organisation, 2012). Thus, it has been concluded that topography is an important characteristic in an area's predisposition to flash floods (World Meteorological Organisation, 2012). Thus, small steep upland catchments often have a naturally 'flashy' response to intense rainfall (meaning an almost immediate response to rainfall) resulting in severe damage from small and localised events (Werner & Cranston, 2009).

In the last 20 years, there have been several major flash flood events in the UK, including the 2004 flash flood in Boscastle, Cornwall, where 200 mm of rain fell in 5 h, equivalent to 20% of the annual average rainfall. During this event, 100 people were evacuated, 60 buildings were flooded/damaged and 116 vehicles were carried by the flow (Bettess, 2005; Xia *et al.* 2011a). Second, the 2007 large flood in Hull, Yorkshire, where 135 mm of rain was measured in 24 h, equivalent to 20% of the annual average rainfall, and 8657 houses and 600 streets were flooded/damaged (Coulthard *et al.* 2007; Marsh & Hannaford, 2007). Then, in 2011 the Bournemouth, Dorset, event where 40.6 mm of rain was recorded in 1 h, equivalent to 78% of the monthly average rainfall and 270 houses were flooded and/or damaged (Ambrose, 2011). In 2012, a flash flood in Honister Pass, Cumbria, flooded 100 houses and 71 mm of rain fell in 24 h, equivalent to 40% of the monthly average rainfall (Met Office, 2011b, 2013). Also in 2012, in Aberystwyth, Wales, 125 mm of rain fell in 24 h, equivalent to twice the monthly average rainfall and 150 people had to be evacuated (Climate Data, 2018; Webb, 2013). Finally, in 2018 in Birmingham, West Midlands, 81 mm of rain fell in 1 h, equivalent to 1.3 times the monthly average rainfall, resulting in one casualty (Met Office, 2011a; Muchan *et al.*, 2018).

Flash floods remain a global problem and due to their dynamic nature combined with their limited spatial and temporal scales and short lead times, observation, modelling and forecasting of these events continues to be a challenge (World Meteorological Organisation, 2012). However, even though the accuracy of flood estimation for extreme events and flash floods has been identified to be a common problem, shared databases or common guidelines do not exist, and each individual country is focusing their efforts primarily on national and localised projects. In China, for example, since 2003 (Figure 15.3) the number of flash floods that have resulted in casualties has been decreasing and this can be attributed to China's national flash flood prevention projects, especially the flash flood early-warning systems (Liu *et al.*, 2018).

This restricted and site-specific approach has led to often simplistic and rarely generalised approaches and strategies resulting in further uncertainty in the reliability of flash flood prediction, estimation and mitigation (Kjeldsen *et al.*, 2014). As very limited field data exist from flash floods, a practical approach to generate flash floods, both numerically and experimentally, is through a dam break. This guarantees the main characteristic features of flash flood events including rapid onset and the rate of rise in water level (Archer & Fowler, 2015).

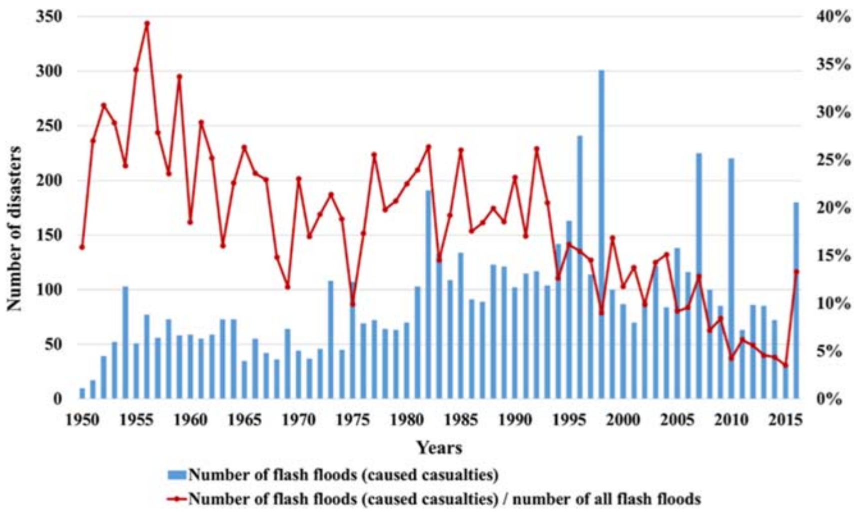

Figure 15.3 Number of flash floods and related casualties in China from 1950 to 2015 (Liu *et al.*, 2018).

15.2 BACKGROUND

15.2.1 Numerical methods used to model extreme events

Hydrodynamic modelling of flood events is usually considered through the use of mathematical models of varying complexity (Xia *et al.*, 2011a). Regardless of a model's complexity, all numerical models make approximations and thus present limitations that can easily lead to inaccurate predictions (Rowiński & Radecki-Pawlik, 2015; Toombes & Chanson, 2011). The main problems presented in regard to hydraulic modelling of floods are (Liang & Borthwick, 2009; Néelz & Pender, 2010; Zech, *et al.*, 2015):

(1) the numerical instabilities present in high-resolution grids,
(2) the computational time,
(3) the modelling of the moving wet-dry interface, specifically the arrival time of the wave front in fluvial floods,
(4) the maximum water depth and, finally
(5) the representation of complex boundaries.

All previously mentioned issues remain challenging limitations and emphasise the need for further advancement in numerical hydrodynamic modelling techniques.

There are several verified 2D hydraulic models commonly used to predict flood inundation extents, but their performance in extreme events such as flash floods, where the flows are fast-transient, remains an active area of research (Huang *et al.*, 2015). Flash flood characteristics, especially their limited spatial and temporal scales, make modelling of these events challenging and complicated.

They are rarely captured in the field and the data associated with such events is very limited. Specific flow features are difficult to model accurately and thus several researchers when modelling flash floods have tried to find a balance between model complexity and computational time, taking into account specific physical mechanisms such as infiltration for example (Huang *et al.*, 2015). They are also localised impact events and therefore local knowledge is important for their modelling (World Meteorological Organisation, 2012).

When predicting the hydrodynamic behaviour of flash floods, a common problem is that the performance of most hydraulic models is not consistent across event magnitudes (Horritt & Bates, 2002). The majority of numerical models are calibrated using a limited number of historical events and thus, assessing a model's ability to predict the flash flood dynamics of the most extreme events (i.e., model validation) is an essential task to ensure the model's credibility (Horritt & Bates, 2002). Considering this in addition to all the previously mentioned challenges (i.e., numerical instabilities in high-resolution grids on complex topographies, computational time, modelling the wet-dry interface dynamics, and the sharp flood wave front), further research through both experimental and numerical modelling is needed.

15.2.2 Flash flood models

There have been a limited number of publications on models specifically designed for flash flood modelling and as support tools for flash flood warning systems. In a laboratory setting the most prominent flash flood experiment is the Testa *et al.* (2007) experiment which was part of the IMPACT project; a project that assessed the risks from extreme flooding. Another large-scale experiment, part of the CADAM Project, was the Chatelet experiment which assessed the effect of a dam break on a triangular bottom sill, in a 38 m long channel (Ferreira *et al.*, 2006). The same experiment was later replicated as part of the IMPACT project on a smaller scale (Soares-Frazão, 2007). Other experiments include Chanson's flash flood surges (Chanson, 2004).

As very limited field data exist from flash floods, a practical approach to generate flash floods, both numerically and experimentally, is through a dam break as this guarantees the main characteristic features of flash flood events including the rapidity of onset and the rate of rise in water level (Archer & Fowler, 2015). The dam break problem has become a widely researched problem and it has been modelled both experimentally and numerically. Research started as early as 1960 with the US Army Engineers Waterways Experiment Station publishing a report on experimental cases on floods resulting from suddenly breached dams (Corps of Engineers, 1960). The research continued from simple experimental studies such as the initial stages of a dam-break (Stansby *et al.*, 1998) to more complicated problems such as dam-break induced mudflows (Peng and Chen, 2006). Numerically, the dam-break problem has been modelled in 1D, 2D and

3D (Marsooli and Wu, 2014; Zhainakov & Kurbanaliev, 2013) and experimental and numerical results have been compared by several researchers (Aureli *et al.*, 2015; Peng & Chen, 2006).

When fluids interact with structures the complexity of the numerical simulation increases exponentially and requires considerations of the structural dynamics which are not simulated accurately by any numerical scheme. Wave structure interaction is mainly investigated in the design of coastal and offshore structures as they are exposed to extreme situations with breaking waves that can result in very high impact forces on small temporal scales (Chella *et al.*, 2012). Thus, many experimental and numerical studies have been used to examine wave loading, run-up and scattering around such structures (Chen *et al.*, 2014b). Nevertheless, the majority of applications are for offshore applications and in dam break flows there is only very limited research describing the dynamics of these events and studying flood wave structure interaction, such as the work of Trivellato (2004), Kleefsman *et al.* (2005), Bukreev & Zykov (2008), Bukreev (2009), Chen *et al.* (2014a) and Lobovský *et al.* (2014).

15.3 BOSCASTLE, UK

The August 2004 Boscastle flash flood is one of the most known flash flood events in the UK. In 2004 a severe flash flood took place in the Boscastle village in Cornwall where 200 mm of rain was recorded in 5 hours (London's yearly average precipitation is 583.6 mm and Beijing's is 610 mm) and it only took 25 minutes from the moment the river breached its banks to the moment cars and vans were swept by the flow. There were no casualties from the event, but the property damage was extensive, leading to an estimated cost of damage of £15 million. The Boscastle flash flood is a common event in flood risk modelling and has already been modelled by several researchers both numerically and experimentally and both from a hydrological and a meteorological perspective.

15.3.1 Catchment description

To understand the background and the extremity of the 2004 flash flood, the catchment area will first be described in terms of geographical location, geology, catchment description and climate before outlining the 2004 event. Boscastle is a village located in North Cornwall on the southwest coast of the UK and has an annual rainfall total of 961 mm (Met Office, 2010). Figure 15.4 shows the average monthly rainfall in Boscastle where November is typically the wettest month and April the driest. For comparison, Figure 15.5 shows the average rainfall around the UK from 1821 to 2010 for: (a) annual average, (b) November (Boscastle's wettest month) and (c) April (Boscastle's driest month) (Met Office, 2010; World Weather & Climate, 2016). Thus, when considering the presented rainfall profiles for Boscastle (Figures 15.4 and 15.5) it is apparent that the highest monthly average is 100 mm of precipitation in November which is a medium average for the UK.

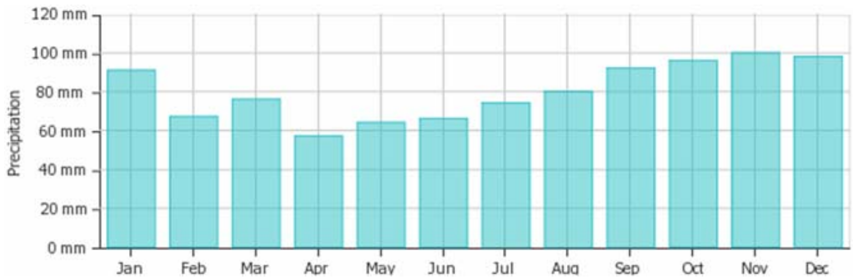

Figure 15.4 Average monthly rainfall in Boscastle (World Weather & Climate, 2016).

Boscastle is positioned in the Valency catchment at the bottom of the valley where two rivers, the Valency River and the Jordan River, meet (Into Cornwall, 2015). The catchment that drains into Boscastle is the Valency catchment which has a round shape (Figure 15.6a), is 8.04 km in length with an area of 20.4 km^2 (Environment Agency, 2016). It is mainly rural and areas of woodland surround the main river (Xia *et al.*, 2011a).

The bedrock geology of the area is a Yeolmbridge formation which contains slate (Figure 15.6b) but there is also sedimentary bedrock and pelagite deposits, due to past domination of sea water (British Geological Survey, 2016). Slate has a hydraulic conductivity of 5×10^{-9} to 5×10^{-6} m/s and a low conductivity value, resulting in relatively slow infiltration through the strata (British Geological Survey, 2006). This, in combination with the small steep rocky catchment, results in increased runoff potential and a steep rising limb in the flood hydrographs. Thus, such a catchment which is characterised by an almost instant response to intense rainfall falls into the category of 'flashy catchments'.

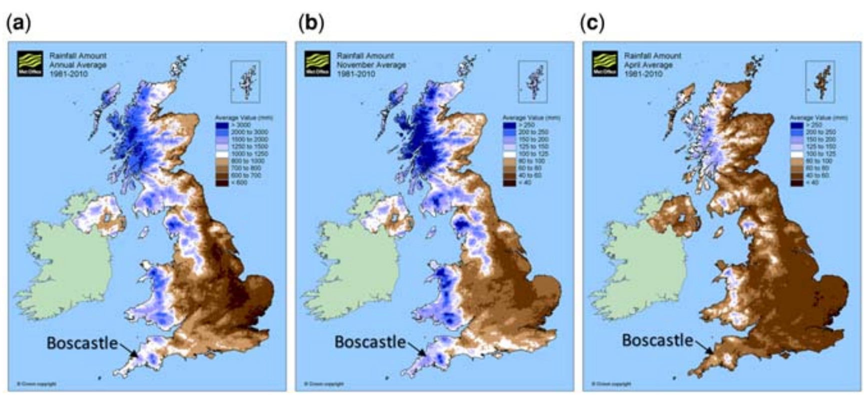

Figure 15.5 Average rainfall 1821–2010: (a) annually; (b) November; and (c) April (Met Office, 2010).

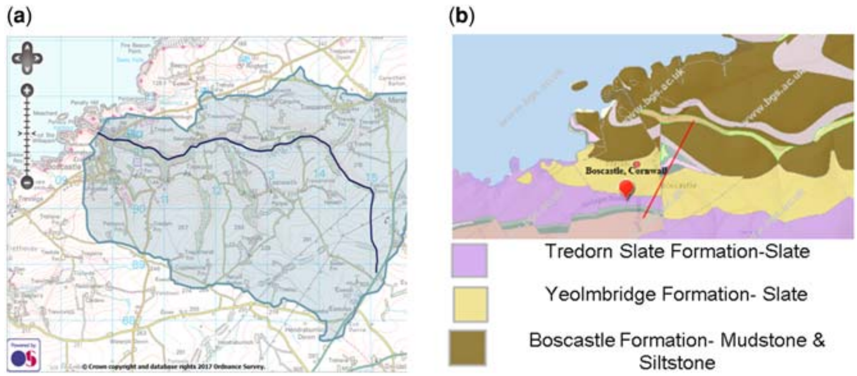

Figure 15.6 (a) Valency catchment (Environment Agency, 2016), (b) Boscastle and surrounding area's geology (British Geological Survey, 2016).

15.3.2 The 2004 flash flood event

Heavy rainfall on the 16th August 2004 caused severe flooding in the Valency catchment and the River Jordan. This resulted in a flash flood in Boscastle which caused severe damage. Even though there were no casualties, at least 100 people had to be evacuated, 60 buildings were flooded, with some of them completely wrecked, and 116 vehicles were carried by the flow (Xia *et al.*, 2011a). From a meteorological point of view, a cyclonic scale in the Atlantic Ocean resulted in a humid and unstable environment over the region of Cornwall. Due to the lack of wind, clouds assimilated and moved north-east resulting in very concentrated rainfall on the Valency catchment with peak rates of precipitation of up to 400 mm/h (Golding *et al.*, 2005). On that day, the soil was already saturated at the onset of the heavy rainfall from previous rainfall. This combined with the overlay of impermeable rock (easily saturated), the steepness of the slopes (1/20) and the static cumulonimbus clouds, resulted in a rapid saturation of the soil and an increase in the surface run-off. Two hundred mm of rainfall accumulated in 5 hours which corresponds to 2.5 times the monthly rainfall average in Boscastle and 21% of the yearly rainfall average. This resulted in an annual probability of occurrence exceedance for the overall storm to be 0.05% (one in 2000 years) (Bettess, 2005).

The peak flow rate was calculated and expected to have reached 140 m^3/s and a maximum of 180 m^3/s (Bettess, 2005) with residents describing seeing a '*wall of water*' approaching the harbour (North Cornwall District Council, 2004) later translated to a 2 m high flash flood wave (Xia *et al.*, 2011a). As the catchments were not gauged, in order to derive the full hydrographs shown in Figure 15.7, two methods were used. The first was a statistical approach and the second one was a rainfall-runoff model (Bettess, 2005). Figure 15.7 shows the discharge hydrographs for different locations along the River Valency. Velocities were not

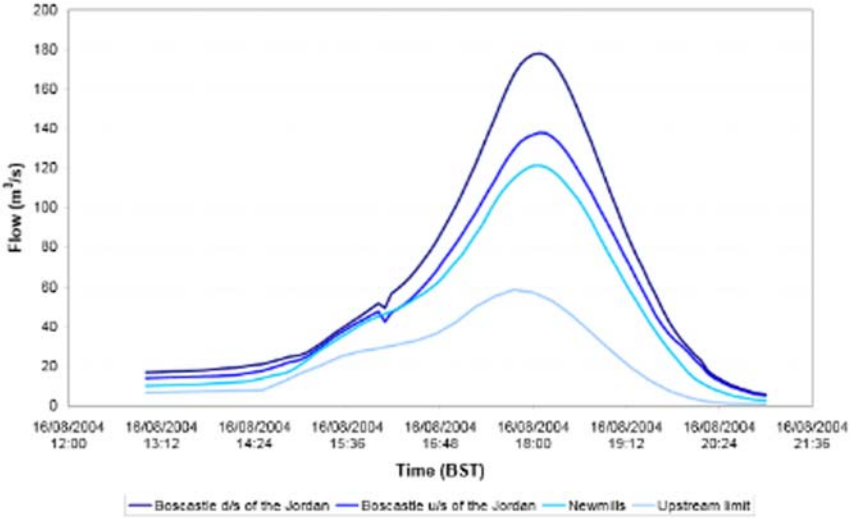

Figure 15.7 Discharge hydrographs for different locations on the River Valency (Bettess, 2005).

measured during the flash flood but they were computed based on the acquired data and measurements (Bettess, 2005). Figure 15.8 shows the maximum velocities modelled for the flood which were at the Valency River, reaching a maximum value of 10 m/s.

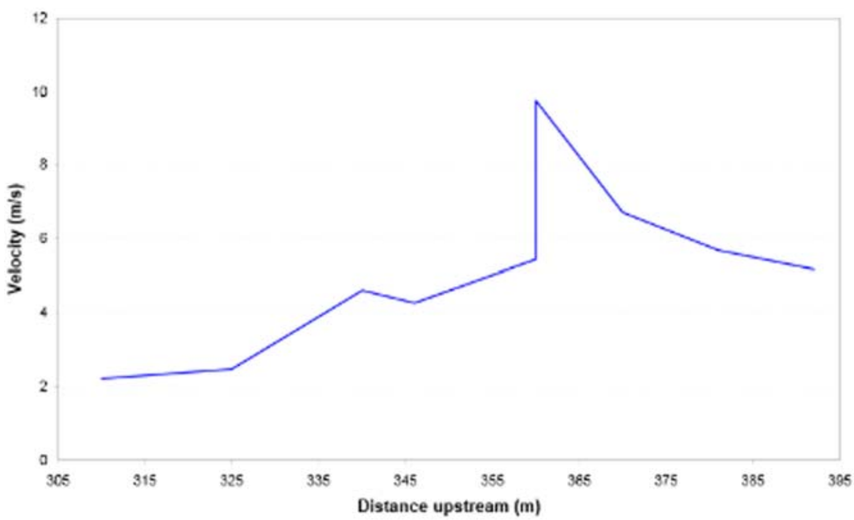

Figure 15.8 Maximum calculated velocities in the Valency River (Bettess, 2005).

Figure 15.9 Boscastle 2004 flash flood: (a) Flooding of the Valency River and blockage of the bridge; (b) Flooding in the town; (c) Flooding of the Valency River (Bettess, 2005).

Some photos from the flood can be seen in Figure 15.9, showing the extent and damage. Despite the 2004 flash flood being a very famous and catastrophic event, it was not the first recorded case of a notably large flood or flash flood in the village. The most important events since 1827 are listed below, supporting the concept that some catchments may be more predisposed to flash floods than others (North Cornwall District Council, 2004):

- 28th October 1827 – No recorded rainfall
- 16th July 1847 – No recorded rainfall
- 6th September 1950 – No recorded rainfall
- 8th June 1957–140 mm in 2.5 h
- 3rd June 1958 – River rose 4.5 m in 20 min
- 6th February 1963 – No recorded rainfall

15.3.3 Mitigation solutions

Following the 2004 event, mitigation solutions were implemented by the Environmental Agency in the village (Figure 15.10) including a £4.2 m project in

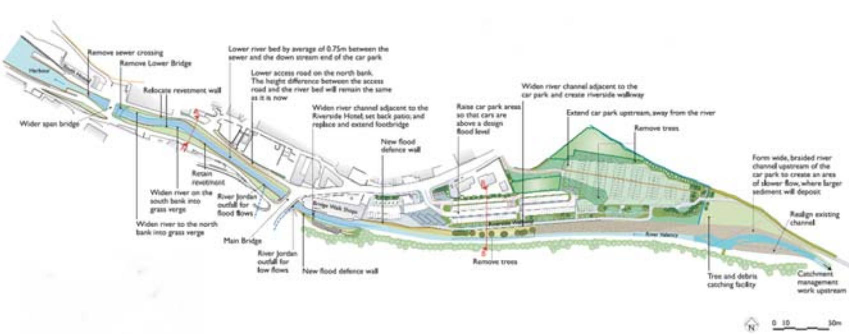

Figure 15.10 Flood defence mitigation Boscastle (Nicholas Pearson Associates, 2012).

October 2006. The most important mitigation solutions were (Halcrow Group Ltd, 2017; Nicholas Pearson Associates, 2012):

(1) erosion control mats which could accommodate 5 m/s flows,
(2) raising the car park level which previously flooded,
(3) installation of SUDS and permeable paving, river dredging, widening and realignment to avoid blockage from fallen trees and slow down its flow,
(4) installation of a flood overflow culvert for the River Jordan,
(5) installation of concrete toe-rail at the foot of the embankment, and
(6) new flood defence walls and new wider span bridge downstream with a one in 100 year flood design life designed to fail in case of a similar event.

The Boscastle event was selected as an inspiration to conduct further laboratory experiments and was simplified and scaled down for experimental purposes. The configuration consisted of an elevated reservoir, followed by a 1/20 slope (slope of Penally Hill, the hill leading to Boscastle harbour), followed by a flat area where different combinations of buildings were positioned, the urban settlement.

15.3.4 Research

Boscastle is a common case in flood risk modelling and the characteristics surrounding the event have been analysed from many different perspectives.

A detailed study by HR Wallingford (2005) described the meteorological, hydrological and hydraulic aspects of the flash flood event. The event was reconstructed numerically and propagation mechanisms, peak flows and peak water levels were presented (Bettess, 2005; HR Wallingford, 2005). Next, Roca and Davison (2010) analysed main flash flood processes using a 2D numerical model and investigated specifically the flow regime changes, the blockage of structures, changes in flow paths and the effect of the geomorphology on flow characteristics. Xia *et al.* (2011a, 2011b, 2014, 2018) conducted extensive research, both experimentally and numerically, looking at submerged vehicles during a flash flood and used the Boscastle flash flood as a case study for their analysis. The Boscastle event has also been modelled extensively hydraulically. Important work was presented by Lhomme *et al.* (2010) who looked at flood extents and forces on buildings using a 2D model, Falconer (2012) who looked at flow interactions of supercritical flow with buildings and Xia *et al.* (2011a) who modelled flash flood risk in urban areas, taking into account not only the flood extent but also the risk to people and properties.

Research has also been conducted on the Boscastle flash flood from a meteorological perspective. The forecasting department of the Met Office analysed the meteorological conditions before the flash flood both from observations and also by using output from a high-resolution land surface model (Golding *et al.*, 2005). Burt (2005) specifically discussed the rainfall observations recorded during the event and compared the Boscastle flash flood to other historical storms in the UK, concluding that even though it is considered as a very extreme event, the historical perspective is important as it showed that there have been many other severe events in the area. Murray *et al.* (2012) modified a flash flood severity assessment, previously created by Collier and Fox (2003), and determined from a hydrometeorological point of view and using a scoring system, the flood susceptibility and severity of a catchment to extreme events. Finally, Warren *et al.* (2014) discussed the similarity of another quasi-convective stationary system in 2010 in the southwest of England which had many similar characteristics to the Boscastle event.

15.4 FLASH FLOOD EXPERIMENT: BOSCASTLE

As part of a PhD research at the University of Bath, flash floods were generated in a controlled laboratory environment for the validation of numerical hydrodynamic models and the investigation of the effect of land use and intensity on flash flood propagation (Stamataki *et al.*, 2018). A new experimental dataset for flash floods in a controlled environment was developed and the impacts of water levels and loads on downstream urban settlements were investigated. The importance of the experimental study lay within the fact that it is important for flash flood experiments to obtain an impact stage from a flash flood wave in an urban settlement which would not have been possible without a dam break experiment. Thus, this allowed for the effect of land use (vegetated, non-vegetated slope) and the intensity of flash flood characteristics (different initial water depths) to be investigated in a controlled environment.

15.4.1 Description of experiments

The experiments were conducted in a flume located in the Department of Mechanical Engineering in University College London (UCL). The flume is 20 m long and 1.2 m wide, and wave gauges and ultrasonic sensors were installed along its length. An elevated reservoir was built in the upstream part of the experimental apparatus separated by a gate and containing a controlled volume of water allowed to be released instantly upon the opening of the gate. The water was then discharged onto a 6 m long slope with 1/20 gradient followed by a horizontal floodplain area, where buildings were installed, the urban settlement (Figures 15.11 and 15.12).

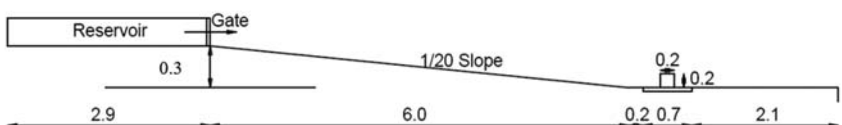

Figure 15.11 Dimensions of experimental set up.

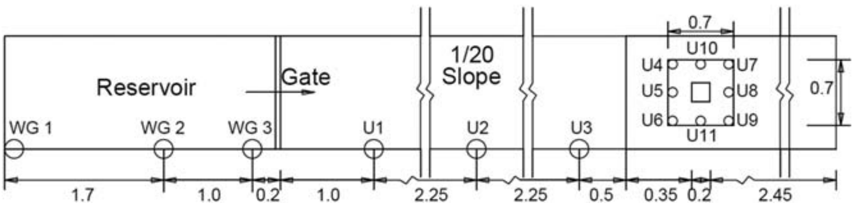

Figure 15.12 Wave gauges (WG1-WG3) and ultrasonic sensor positions (U1-U11) on the experimental setup.

For the scope of this chapter, six main experimental test cases will be discussed in this section:

(1) B1_H100: Single building case with 0.1 m initial water level in the reservoir, no roughness layer on the slope (unvegetated slope).
(2) B1_H200: Single building case with 0.2 m initial water level in the reservoir, no roughness layer on the slope (unvegetated slope).
(3) B1_H100G: Single building case with 0.1 m initial water level in the reservoir, roughness layer on the slope (vegetated slope).
(4) B1_H200G: Single building case with 0.2 m initial water level in the reservoir, roughness layer on the slope (vegetated slope).
(5) B0_H100: No building case with 0.1 m initial water level in the reservoir, no roughness layer on the slope (unvegetated slope).
(6) B0_H200: No building case with 0.2 m initial water level in the reservoir, no roughness layer on the slope (unvegetated slope).

15.4.2 Results

The case B1_H100, which as previously described has an initial water depth in the reservoir of 0.1 m, no roughness layer on the slope and a single building in the urban settlement, will be analytically presented below. Figure 15.13 presents a schematic representation of the case showing the location of selected measurement points.

Once the gate was released, a dam break wave starts propagating downstream along the slope and a negative wave starts moving upstream within the reservoir. The first instruments to record a change were the wave gauges (WG1-WG3) in

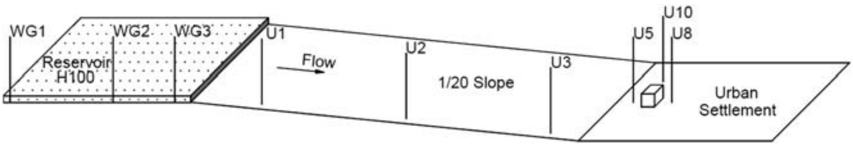

Figure 15.13 Schematic representation of B1_H100 case showing the location of some key instruments.

the reservoir which recorded the change in water depth during the emptying of the reservoir.

Figure 15.14 shows the water depth changes over time, first for the three wave gauges WG1-WG3 (top) and then for the three ultrasonic probes U1-U3 along the slope (bottom). Being the closest to the gate, WG3 is the first instrument to record a sudden change reducing from 0.1 to 0.06 m in 1.2 s and decreases to 0.055 m, where it reaches a plateau. The negative wave reaches WG2 after just under 1 s, which decreases to 0.055 m less suddenly. WG1 has the most delayed response when the negative wave reaches it 2.5 s later and also reaches 0.055 m.

The water depth evolution along the slope is visible from the ultrasonic probes U1-U3 where the arrival of the dam break wave to different positions along the slope is recorded by the probes. The flow on the slope is supercritical and characterised by two components, the propagation of the dam break wave and the presentation of a uniform flow between U2 and U3 from $t = 4$–7 s. The increase in velocity is apparent from the arrival of the dam break wave to the ultrasonic sensors as it travels a distance of 2.25 m from U1 to U2 in 1.6 s (1.4 m/s) and the same distance from U2 to U3 in 1.35 s (1.6 m/s). After $t = 8$ s, it presents the same exponential decay which is evident for all three sensors, with a very small difference in water depth between them. It is important to note the first peak noticeable in U1 at $t = 0.6$ s can be attributed to splashing from the gate opening. The opening is not completely instantaneous and the flow, due to the friction and the gate's sealing,

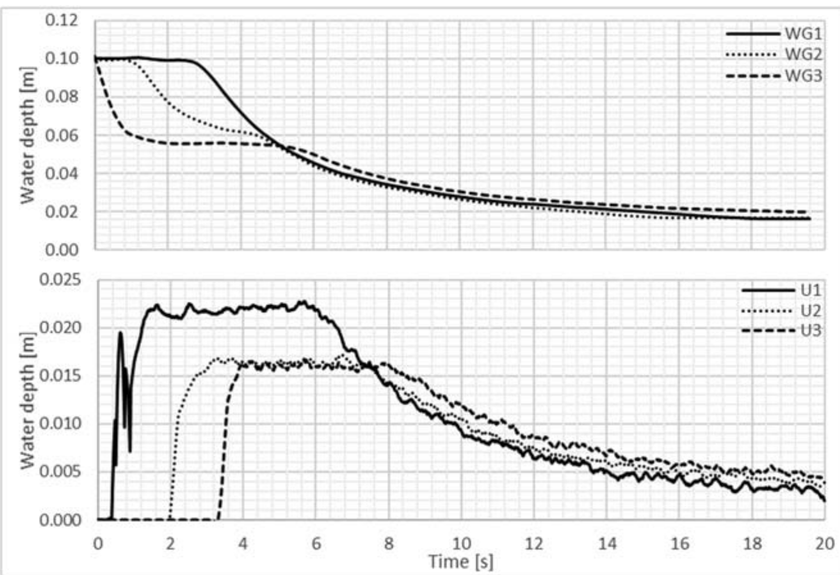

Figure 15.14 Water depth evolution in the reservoir and along the slope for H100.

takes some time to restructure after the gate opening, thus creating the different shapes in water depth evolution at U1 than at U2 and U3 (Figure 15.14, bottom.

Looking further at the other test cases, Figure 15.15 compares the water depth evolution for B0_H100 and B1_H100, thus comparing the changes in water depth in the urban settlement due to the blockage created by the single building.

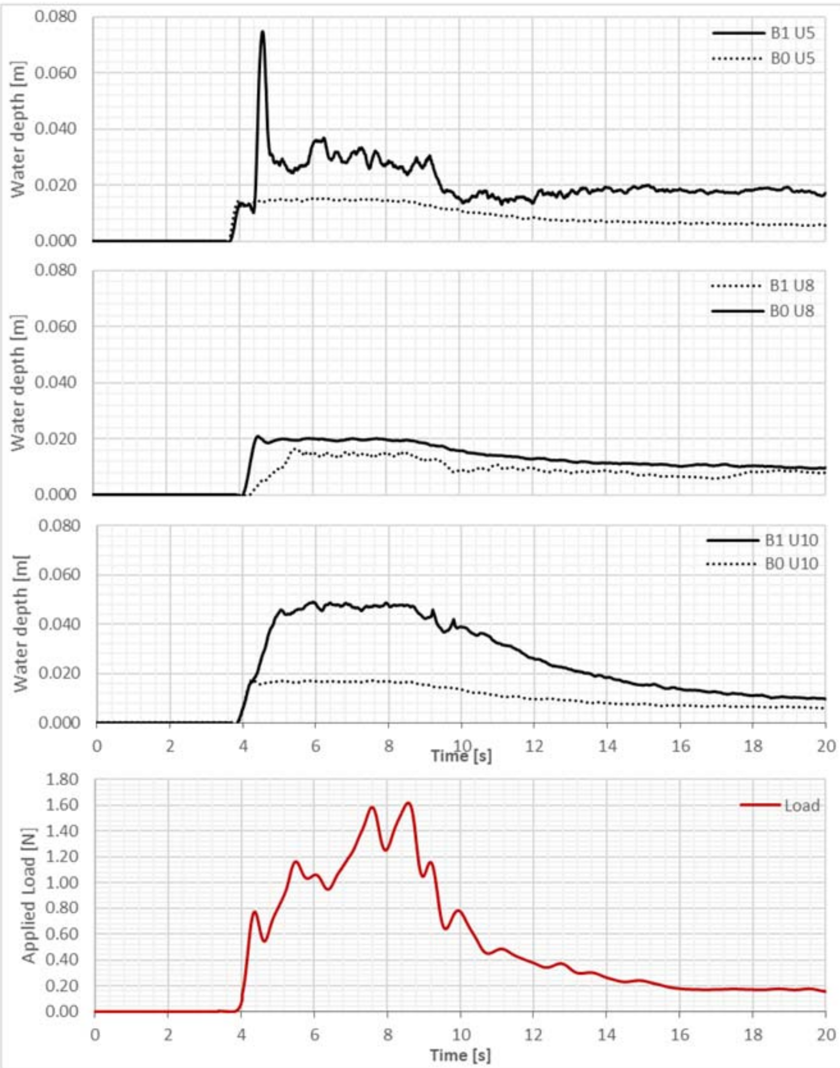

Figure 15.15 Water depth evolution around the building (U5, U8, U10) for B0_H100 and B1_H100 and load acting on the structure for B1_H100.

The top graph shows U5, the second corresponds to U8, followed by U10 and finally the load acting on the building is presented. The highest water level depth is in front of the building as would be expected due to the blockage and the creation of the hydraulic jump while U8 is less affected by the blockage, resulting in similar water depths to those observed for the B0_H100 case. U10 shows an increase that is, attributed to the reflection from the blockage thus increasing the water depth in the B1_H100 case.

Figure 15.16 shows the comparison of each ultrasonic sensor with and without roughness for H100 and H200 respectively. What is evident from the comparisons between the cases with and without the roughness layer on the slope is the decrease in velocity. In both cases, the water reaches the first sensor simultaneously (U1) regardless of the roughness layer. However, as the water propagates down the slope the velocity decrease is more visible. When comparing the time it takes the dam break wave to reach U3, it is 1.37 and 1.2 times slower with the roughness layer than without for H100 and H200, respectively, showing that the change in roughness has a more important effect with lower water depths and lower velocities.

Once the water reached the flat part of the urban settlement, it slowed down regardless of the level of blockage. The water depth results in this part of the experiment were affected by three factors: the initial water depth in the reservoir, 0.1 m for H100 and 0.2 m for H200; the roughness layer in the cases H100G and H200G, and finally the level of the blockage B0 for no building, B1 for a single building. In all cases the reflection wave created from the buildings' blockage resulted in the formation of a hydraulic jump, a stationary surge wave through which the depth of the flow increases and occurs in a situation where the flow upstream is supercritical and downstream subcritical (Chaudhry, 2008).

The impact on the downstream urban settlement is based on the theory of an object in supercritical flow and can be described in four distinctive stages: (i) Impact, (ii) Development of the hydraulic jump, (iii) Steady high Fr flow (around an obstacle) and (iv) Decaying quasi-steady flow with decreasing high Fr number. Both graphs in Figure 15.17 has been synchronised for the moment of impact and show the load over time for the H100 and H100G and for the H200 and H200G cases, respectively. The roughness layer decreases the peak load for H200 but creates a higher peak load in the H100 case which is attributed to the slower flow and increased water depth around the building.

15.4.3 Discussion

Once the flow reached the urban settlement in the experiment, the reflection and blockage from the building made the flow subcritical, thus creating a hydraulic jump in front of the building. The different configurations affected the flow in a

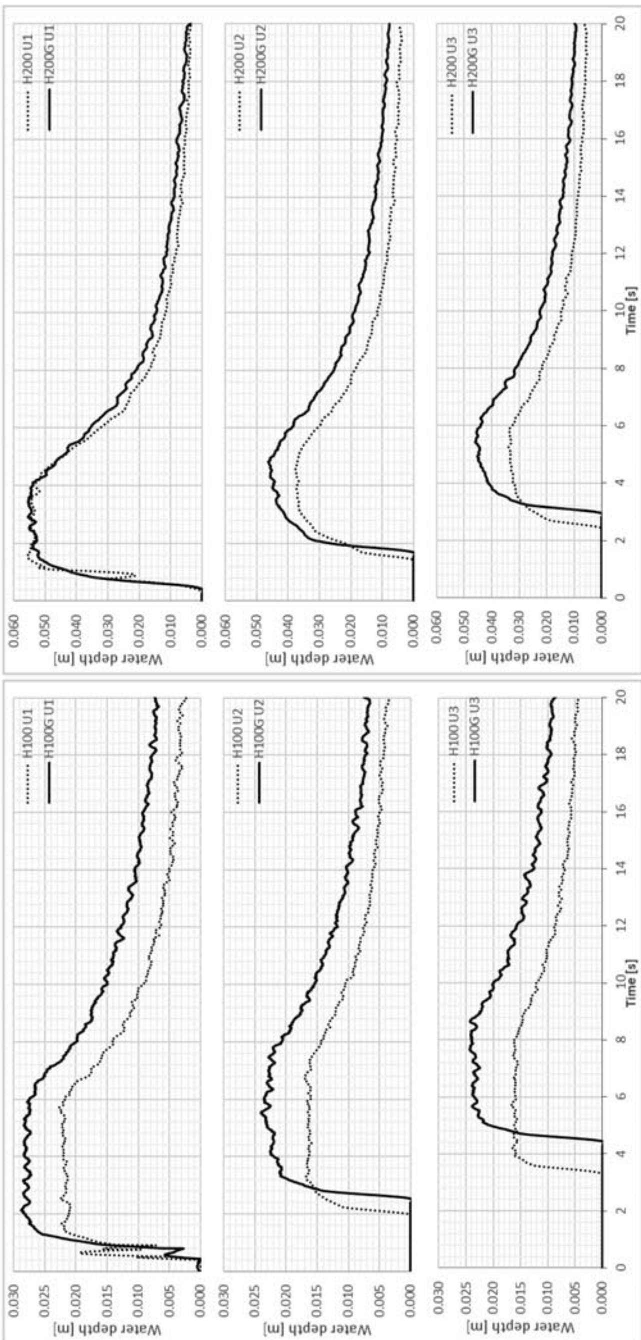

Figure 15.16 Comparison of water depths at U1, U2 and U3 for (left) H100 and H100G (with roughness) and (right) H200 and H200G (with roughness).

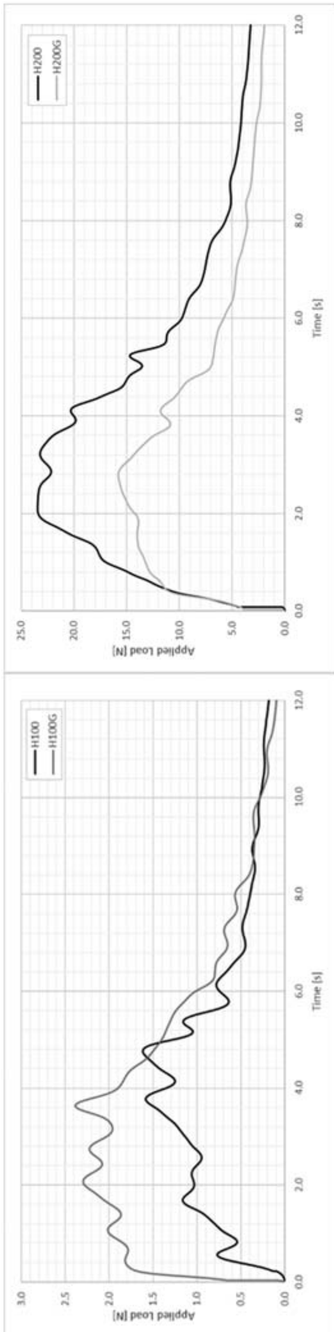

Figure 15.17 Applied load over time for (left) H100 and H100G and (right) H200 and H200G.

three-dimensional way creating different cross-waves and flow patterns depending on the blockage investigated. As expected, the vegetated slope increased the friction, thus slowing down the flow and reducing its Froude number considerably. This translated to a decrease in applied load on the buildings in the higher water depth cases. In terms of applied load on the urban settlements, the level of blockage had no effect on the higher water depth cases while it aggravated the applied load in the lower water depths. This was attributed to the hydraulic jump created in the lower water depths resulting in the buildings being submerged for longer.

15.5 NUMERICAL MODELLING OF FLASH FLOODS

The Boscastle inspired laboratory experiment was also used as a validation case to investigate flash floods numerically and to develop a methodology and an optimal parametrisation for the hydraulic modelling of these types of events. Two- and three-dimensional OpenFOAM models were used to further investigate the interaction of the flood wave with the urban settlement of the experiment.

15.5.1 OpenFOAM software

OpenFOAM is a C++ toolbox used for the solving of computational fluid dynamic problems (Damián, 2012), developed in the 1980s and finally released as an open-source software in 2004 (Damián, 2012). The multiphase solver *interFoam* (part of OpenFOAM's CFD solver library) which models the interface between the water and the air was used here to provide further understanding of the physical processes of flash floods. *InterFoam* solves the Navier–Stokes equations and records the position of the water/air interface, using the VoF method (Volume of Fluid).

15.5.2 Slope

The dam break itself and the accelerated supercritical flow on the slope were 2D in nature, and thus a two-dimensional OpenFOAM model was used to represent the flow propagation. A parametric analysis was undertaken to best represent the flash flood event. First, following a sensitivity analysis for different mesh sizes, a mesh of 0.00025 m was selected and tested for different Courant numbers. Following that, a Courant number of 0.2 was selected as the most converged solution as it seemed to best capture the highest water depth. This agrees with Berberović *et al.* (2009) who states that for these types of open channel simulations, the Courant number criteria should be always set to less than 0.2. Then, different turbulence parameters were tested and $k = 0.2$ and $\epsilon = 0.2$ were selected, resulting in an eddy viscosity of $\mu_t = 18\ m/s^2$. Finally, the results presented in Figure 15.18 are a combined turbulent and laminar model where a

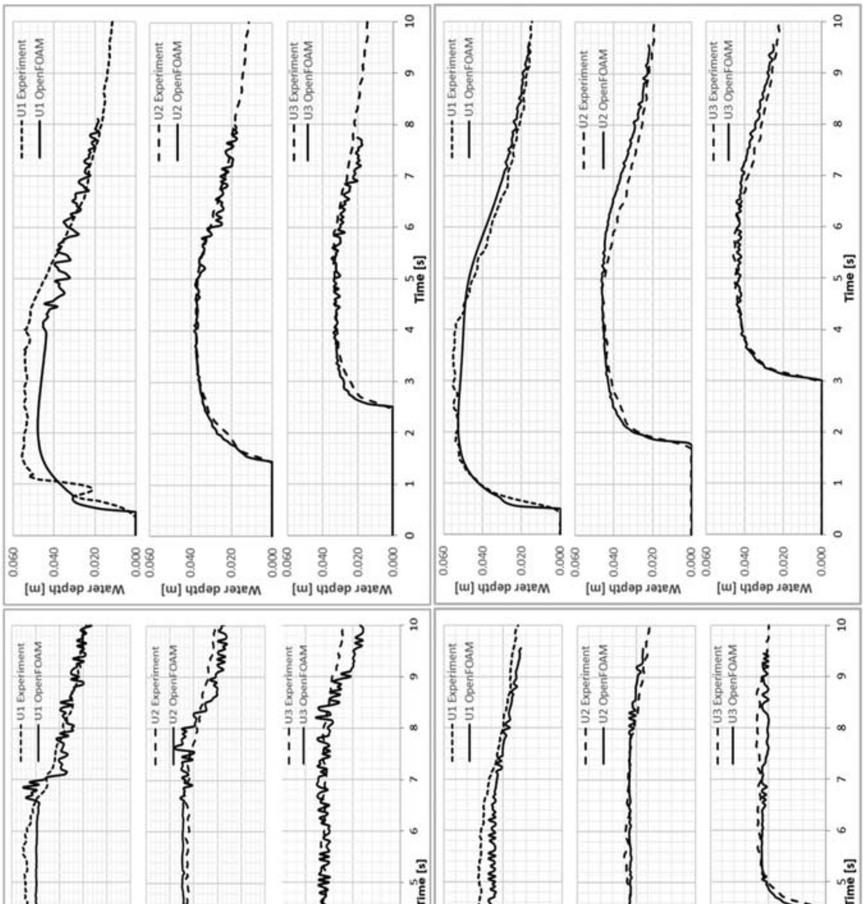

Figure 15.18 Comparison of experimental (dashed line) and numerical water depth (solid line) evolution along the slope for H100, H200, H100G and H200G at locations U1, U2 and U3.

turbulent model has been used to represent the initial stages of the water depth propagation and a laminar model to represent the stabilisation and decrease in the water depth elevation.

Figure 15.18 shows the comparison between experimental and simulated water depth results over time for the three ultrasonic probes, U1-U3, along the slope for H100, H200, H100G and H200G. A very good agreement is achieved between the model simulations and the experimental data at locations U2 and U3 and disparities found in location U1 are attributed to splashing from the gate opening and is an acceptable error for the numerical model.

In the 2D numerical simulations, using the combination of turbulent and laminar flow the model outputs were found to provide a very good fit to the experimental results in all four cases. In terms of the numerical simulation, the application of a 2D OpenFOAM model has highlighted the sensitivity of the flow to the model's parametrisation, the two-dimensionality of the flow in this part of the experiment has also shown that OpenFOAM is capable of simulating the supercritical flow on the slope very accurately.

15.5.3 Urban settlement

While the dam break itself and the accelerated supercritical flow on the slope described in the previous section were 2D in nature, and could be accurately approximated in a two-dimensional plane, modelling the interactions between the urban settlement and the dam break wave requires three dimensions.

Experimental photos of B1_H100 and B1_H200 are compared in Figures 15.19 and 15.20, with the relevant modelled snapshots in the 3D OpenFOAM simulations. In the OpenFOAM modelled images (A_3, A_4, B_3, B_4, C_3, C_4) arrows show the velocity direction and the different colours represent the range of the velocity magnitude from blue to red, representing a range of 0.00021 to 2.1 m/s.

The 3D OpenFOAM model proved an appropriate tool for modelling dam break events and wave structure interactions and accurately captured the hydraulic features of the flow in the urban settlement that were not modelled with the 2D model. The model is capable of reproducing the different flow characteristics, hydraulic jumps and wake zones and match substantially the arrival time of reflected waves. However, the parametrisation of such events is complex due to the range of specifications and variable factors that include mesh accuracy, refinement and alignment, the choice of the order of accuracy of the numerical model and the selection of the eddy viscosity and roughness coefficients. Simulation run speed in 2D and coarse meshes remain practical for consultants, engineers and designers but the additional detail provided in a 3D model leads to a deeper understanding of the fluid dynamics of the events, confirming that the use of 3D models can have positive effects on flood risk management decision making.

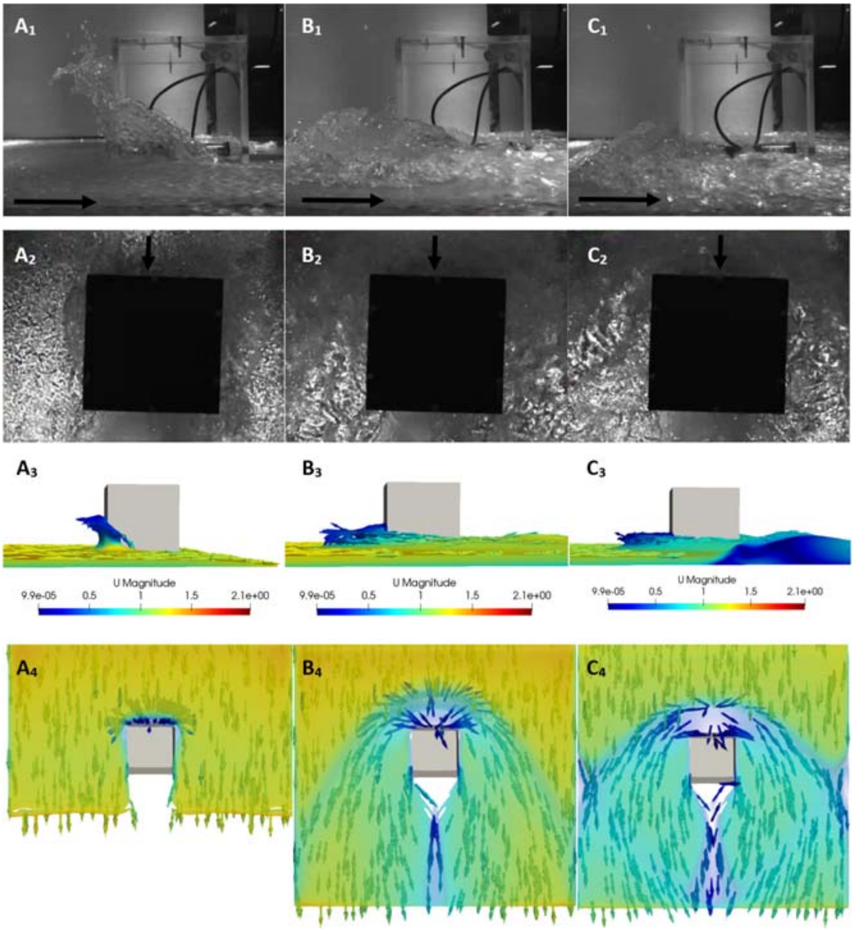

Figure 15.19 Comparison of photos and numerical snapshots of water impact on building for B1_H100 case at times $t = 4.18$ s (A_1, A_2, A_3, A_4), $t = 5.16$ s (B_1, B_2, B_3, B_4) and $t = 10$ s (C_1, C_2, C_3, C_4) from side (first and third row) and top view (second and fourth row).

15.6 FLASH FLOOD MODELLING FOR FLOOD RISK ANALYSIS

An increase in the frequency and magnitude of flooding is one of the severe expected consequences of climate change. Flash floods are of a challenging nature and as they are expected to be exacerbated by climate change understanding flash flood dynamics and the effect different drivers have on the influence of flood propagation is essential. It is therefore crucial to know how to accurately predict flood propagation and inundation extents in order to contribute

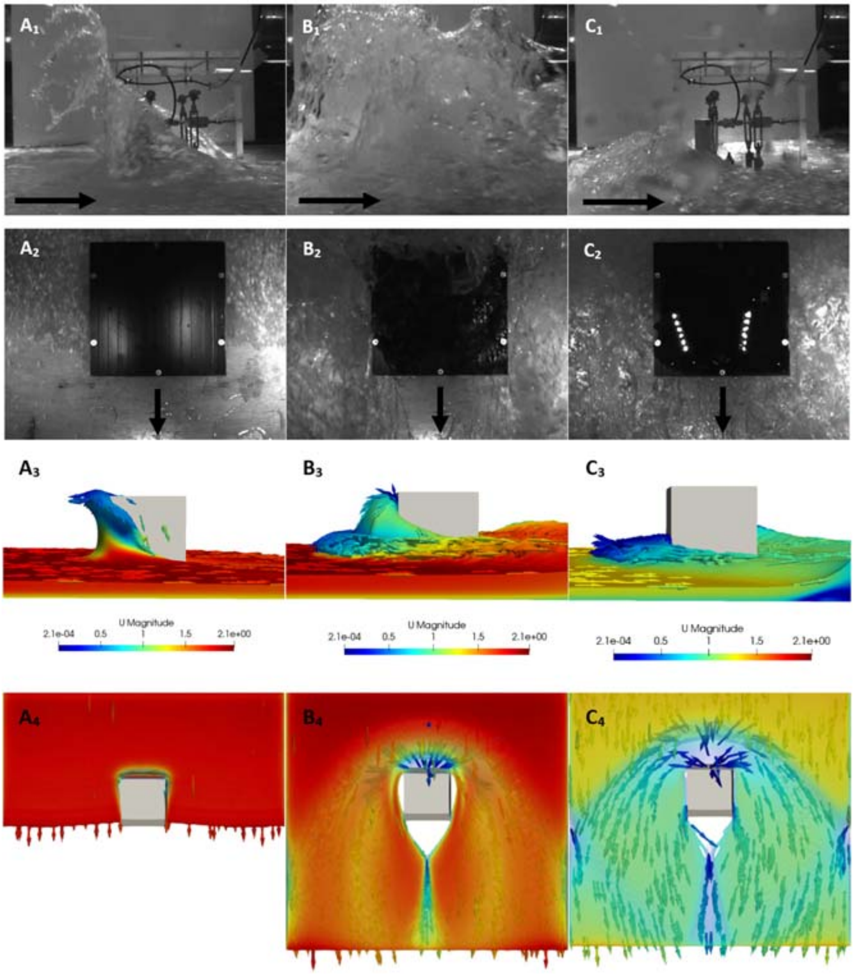

Figure 15.20 Comparison of photos and numerical snapshots of water impact on building for B1_H100 case at times $t = 2.96$ s (A_1, A_2, A_3, A_4), $t = 3.45$ s (B_1, B_2, B_3, B_4) and $t = 10$ s (C_1, C_2, C_3, C_4) from side (first and third row) and top view (second and fourth row).

to the development of better adaptation and preparedness strategies in flash flood prone areas.

15.6.1 Mitigations

Flash floods can be unpredictable but a factor that worsens them is land use due to human activities, projects and river interventions which strengthens the deterioration of the eco-geological systems (Arlikatti *et al.*, 2018). In terms of mitigation strategies, research has shown that in flood prone areas, the lack of preparation planning for recovery and mitigation strategies inevitably results in higher susceptibility and a deficient approach (Arlikatti *et al.*, 2018). Mitigation strategies that can be considered in flash flood management can be separated into two categories: (i) structural mitigations and (ii) non-structural mitigations. These include but are not limited to: erosion control mats, sustainable drainage systems SuDS, permeable paving, river dredging and realignment, overflow culverts, defence walls, rebuilding of bridges and flood protection structures, books, leaflets and documentaries.

Some further mitigation initiatives, in addition to the mitigations already in place, mainly applicable to the UK are presented below:

- Flash flood prone catchment areas should be identified, especially for catchments with historical flash floods (e.g., Boscastle). The local administration should invest in numerical modelling of the area in case of a flash flood to obtain more detailed information on inundation extents, water depths and applied loads on the buildings, thus reducing the risk to life and property.
- Policies and building guidelines in flash flood prone areas should then be re-assessed. Legal frameworks should therefore be put in place for future construction in these areas and a list of structural mitigations should be considered for the reinforcement of existing structures in the urban settlements.
- Blockage level: Depending on the blockage level of an urban settlement the residents should invest collectively on reinforcement, for example, of the front houses that would be the first exposed to a flash flood wave.
- Fences: Further work needs to be done in the investigation of different types of fences (ideal heights, widths and distance from the building) in order to have an effective breakwater for the first impact wave while ensuring that such a fence would not create additional water submersion for the buildings.
- Wall reinforcement: Reinforcement of existing walls should be considered for the buildings that would be strongly impacted by the flood waves.
- Low-vegetated slopes and higher roughness roads should be incorporated in catchment management plans as it has been shown that they can lead to a considerable reduction in the applied loads on the buildings.
- Outreach programs with educational material (e.g., videos) are necessary to emphasise the dangers and raise awareness for flash floods in flash flood prone areas. Residents need to be aware of potential solutions that can even be applied on a resident level and visual aids are a strong persuasion tool.

With the threat of an increase in the intensity, frequency and magnitude of extreme events, today more than ever we should continue to find the most suitable ways to manage flash flood prone catchments so that extreme events do not overwhelm and overthrow existing mitigation strategies.

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