Flood Modelling and Hazard Assessment for Extreme Events in Riverine Basins

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Abstract

Throughout the history of mankind, floods have caused destruction and negatively impacted communities. Recently, effects of climate change and the increasing rate of anthropic activities in flood-prone areas are aggravating the dangers posed by floods to people. Hence, it is crucial to have a better understanding of flood hazard aspects, particularly when considering pedestrians. Indeed, one of the main reasons for fatality during flood events is walking through floodwaters. Although authorities strongly advise against wading in floodwaters, people continue this dangerous behaviour. Alternatively, evacuations or the accessing of flooded areas by emergency services might be necessary.

The scope of this research work is to contribute to improving flood hazard assessment and to the design of flood evacuation plans from a pedestrian perspective.

To enhance flood hazard assessment a mechanics-based method has been improved by considering effects of terrain slope and updating values of human body characteristics, as well considering body mass index to identify the critical pedestrian category. Different criteria to assess flood hazard have been considered, including the revised mechanics-based approach reported herein. Results from the application of the different criteria to two different case studies, namely Boscastle and Borth, showed that methods based on a full physical analysis, and which also consider human characteristics, give more insight and reliability in assessing flood hazard, especially when considering pedestrians.

Results in terms of flood hazard assessments can be used to: i) design evacuation plans; ii) identify hotspots in the study area which will help with prioritisation of the adaption measures; iii) improve resilience of sites prone to flooding and plan more resilient future developments. In this regard this research work proposes a novel approach to increasing flood resilience by retrofitting existing infrastructures to enhance evacuation and access routes by reducing flood hazard rate. Results of the application of this novel methodology to the aforementioned case studies highlighted that retrofitting small portions of the existing roads can enhance

people's safety during the evacuation, and hence provide a cost-effective solution to improve the resilience of the existing environment.

Publications

Journal Papers

Musolino G., Ahmadian R., Xia J. **Enhancing Pedestrian Evacuation Routes During Flood Events** - Journal of Hydrology (2021) - Under Review

Musolino G., Ahmadian R., Xia J., Falconer R.A. Comparison of flood hazard assessment criteria for pedestrian with a refined mechanics-based method - Journal of Hydrology (X) (2020)

Musolino G., Ahmadian R., Xia J., Falconer R.A. Mapping the danger to life in flash flood events adopting a mechanics-based methodology and planning evacuation routes - Journal of Flood Risk Management (2020)

Conference Papers

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In Loving Memory of Zio Nino

Giovanni D. Musolino

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1 Introduction

1.1 Overview

River flooding is recognised as being one of the most devastating natural hazards. Flooding occurs frequently and often leads to significant loss of life and economic damages (Bellos et al., 2020; Bracken et al., 2016; Percival and Teeuw, 2019; Salvati et al., 2018; Svetlana et al., 2015). It has been estimated that 31% of all economic loss due to natural hazards worldwide is the direct consequence of flooding (Trigg et al., 2016). In the past twenty years globally, floods have affected 2.3 billion people and caused the third highest amount of economic damage quantified as 662 billion USD (Abebe et al., 2019). In Europe, between 1999 and 2009 the consequences of the most impactful flood events can be quantified in 541 victims and economic loss of 55.2 billion euro (Svetlana et al., 2015). It has been estimated that worldwide between 1980 and 2013 economic losses due to floods exceeded 1 trillion USD and flood related deaths are estimated at around 220,000 (Dottori et al., 2016; Trigg et al., 2016).

Due to the crucial role of water in human life, people tend to build their settlements near to water courses which can offer many advantages but, the drawback is the high danger of flooding. It is worth remembering that floods are a natural part of a river's evolution and "life-cycle", meaning it is clearly impossible to reduce the flood hazard of any river basin to zero (Creutin et al., 2013).

Generally, risk can be defined in different ways by people, and among the scientific community is defined in an unambiguous way as being the product of a hazard and its relative consequences (Kron, 2005). An early definition of risk was as the product of hazard and vulnerability (Birkmann, 2013).

Recently, risk has been defined as a product of three different factors, as reported in Abebe et al., (2019); Costabile et al., (2020); Koks et al., (2015); Mondino et al., (2020); Percival and Teeuw, (2019); Vojinovic et al., (2016). The first factor to consider is the extension and magnitude of the flood which is the hazard expressed as the probability of a hazardous event happening in a specific location.

The second factor to consider is vulnerability, which is a function of the potential damage to elements at risk as a consequence of the manifestation of the hazardous event.

Finally, there is the exposure which is the quantification of the presence of elements at risk in the flooded area, among the other natural and human assets, such as human life, infrastructures, economic and cultural assets, environmental resources, etc. Some authors consider exposure as part of vulnerability using an integrated framework (Turner et al., 2003).

To better understand the complex phenomenon of flooding it is useful to give a classification of the different possible flood events. This is because some flood events may be more typical of some world regions than others and depending on the kind of flood and the place where it happens it is possible to have different flood risk assessment schemes and consequent flood alleviation schemes.

Floods can be classified mainly into four types: river, pluvial, coastal, and flash floods. River or fluvial flooding is the type of flooding which affects the majority of the world's regions, and it happens when rivers overflow due to excessive rainfall over a protracted period of time and consequently water pours out into the floodplain; also, other causes can be fast snowmelt and ice jams (Acosta-Coll et al., 2018; Alfieri et al., 2018).

Pluvial flooding, or surface water flooding, is a phenomenon which occurs typically in urbanised areas when due to very intense rainfall, the sewage and drainage system are insufficient, and the excess of water cannot be absorbed into the soil. In the UK, pluvial flooding is the largest cause of property flooding, accounting for 40% of flood damage (Miller and Hutchins, 2017).

Coastal flooding happens when the sea level exceeds the land's elevation, or natural or human barriers, and the result is water spreading into the land behind it. Other causes can be subsidence, coastal erosion, and earthquakes (Acosta-Coll et al., 2018).

Flash floods are recognised as the most impactful among all the other types of floods and are also responsible for the majority of flood deaths in developed countries (Doocy et al., 2013). Following the definition of the American Meteorological

Society, flash floods can be defined as those floods with a rapid rise and fall, with little or no advance warning, occurring usually as a result of intense rainfall over a relatively small area (Mariani and Lastoria, 2011; Modrick and Georgakakos, 2015). Possible flood events in basins of small to medium size have a particularly rapid hydrological response, with the hydrographs that describe these events showing a short lag time. The typical rapid occurrence and high intensity of such flood events, over a relatively small geographic area, means that this type of flood can be particularly dangerous for the safety of people since the flow peaks are reached within a few hours, leaving a very short warning time or, in some cases, virtually no time at all. It is estimated that 40% of casualties due to flood events in Europe between 1950 and 2005 were caused by flash floods (Marchi et al., 2010).

Several studies have shown that danger due to floods is expected to be of even greater concern in future, due to the combined effects of climate change, population growth, increased urbanisation into flood prone areas, intense natural resource exploitation, inappropriate land use, and inadequate planning (Diakakis et al., 2020; Guerriero et al., 2020; Marchi et al., 2010; Milanesi et al., 2016; Teng et al., 2017; Wang et al., 2018). For example, in Great Britain, the UK Climate Change Risk Assessment considers flooding as the biggest risk posed by climate change (Percival and Teeuw, 2019). Properties located in flood areas raised from 7% in 2013-14 to 11% in 2016-17 increasing exposure and thus increasing risk (Acosta-Coll et al., 2018; Kvočka et al., 2017; Marchi et al., 2010; Ministry of Housing, 2019; Teng et al., 2017; Vojinovic et al., 2016). Urban areas are expected to face the most devastating effects of flooding due to their high vulnerability because of high density of population, infrastructures, economic and cultural assets. It is worth remembering that vulnerability in such urban environments depends not only on infrastructures and planning but also on a combination of physical, economical, sociocultural and institutional conditions (Acosta-Coll et al., 2018).

Projections from climate change analysis make flood-related problems even more concerning in the short and medium term, both for the increasing number and magnitude of flood events and for the increasing vulnerability/exposure (Bertilsson et al., 2019; Dankers and Feyen, 2008; Hammond et al., 2015). The world bank estimates that in 2008 half of the world population lived in urban areas and with an increase to 60% in 2030 and 70% in 2050 (Jha et al., 2012). Forecasts in the UK report that, by 2050, 3.2 million people will be at risk of pluvial flooding in urban areas (Acosta-Coll et al., 2018; Miller and Hutchins, 2017). Thus, it is imperative to continue to develop and improve flood risk assessment.

As shown so far, flood risk is one of the most threatening challenges for all the regions of the world for both developed and developing countries. As aforementioned, it is impossible to reduce the flood risk for any river basin to zero, but it is imperative to try to reduce it as much as possible, adopting specific assessment methods (Martínez-Gomariz et al., 2019) and mitigation solutions adequate for the specific area considered. Thus, a key challenge for flood risk management is to minimise the impact of extreme flood events by reducing vulnerability, despite the short time available for action.

Among flood mitigation defence schemes a classification can be done as suggested by the UN International Strategy for Disaster Reduction (UNISDR) (2009), which distinguishes mitigation schemes as structural and non-structural. Structural mitigation schemes include building physical structures to minimise the hazards deriving from floods, as well using engineering techniques to improve the resilience of communities. Usually, these schemes require large economic investments and a realisation time of medium- to long- term. Non-structural mitigation schemes are a set of tools that can help to reduce risk of life, reduce economic losses, and protect properties. Typical examples of non-structural schemes are: early warning systems, informing and warning residents living in flood-vulnerable areas about flood hazards and evacuation procedures, developing emergency evacuation plans for flood events, disaster recovery plans, spatial planning, and insurance policies (Acosta-Coll et al., 2018; Bodoque et al., 2016; Borowska-Stefańska et al., 2019).

In the past, the general approach was focused mainly on localised flood assessment and protections but, river flood risk for much of the world is not mapped, and if maps exist, they lack in consistency of methodologies or datasets. Some countries like the U.K. and Germany adopted a more consistent and comprehensive understanding of flood hazards collecting different local scale modelling, giving in this way a better insight on a national scale also (Trigg et al., 2016). Recently flood risk management moved towards a more integrated and holistic approach, including natural flood management, non-structural schemes, and focusing on preparedness and resilience, (Arrighi et al., 2019; Dawson et al., 2011; European Union, 2007).

Bearing this in mind, as it will be shown in this research work, in one hand it is important to assess flood hazard with a methodology which considers a full physical analysis of the problem to guarantee consistency and reliability when applying the analysis in different geographical areas.

On the other hand, when considering human beings as an element at risk in the analysis it is important to characterise the analysis for the pedestrian critical class of the study areas, to guarantee safety for all. This is because human body characteristics and thus human stability thresholds, which are used to define people's safety, can be dissimilar when considering different geographical areas due to differences in human body characteristics among different populations (Musolino et al., 2020b).

Essential tools for flood hazard assessment are flood simulation models. Models can simulate past flood events or give forecasts for future flood scenarios in terms of flood extension, water elevation, and flow velocity. It is possible to generate flood maps and/or estimate danger for people and infrastructures using these data alongside different assessment methods.

Thus, flood maps play a key role, as they must be converted into hazard maps according to an established hazard criterion, which in this case is based on the pedestrian stability threshold. Determining flooded area, by the competent authorities, is mandatary according to the regulations of several counties (European Union, 2007; Nones, 2017). Flood maps are used to not only ensure people's safety, but today flood maps are also extensively used on many levels, e.g., to plan development of cities and anthropic activities in general, in the insurance market, for research purposes to study flood mechanisms, historic events, etc.

This briefly shows the importance of flood hazard assessment and its main outcome product: flood maps. Thus, the importance of further developing flood hazard assessment methods is clear. This can be done on different levels as will be shown in this research work; the level of simplification can be reduced in the methods adopted to assess flood hazard including a full physical analysis of the problem, and advances in computer science and hydraulics allow us to use more complex methods which can give more insights and reliable results in short time.

The characteristics of the considered element at risk of the flood can also be introduced in the analysis, e.g. pedestrians, structures, economic activities, etc. In this way the assessment will be specific for the target as flood impacts can be very different depending on the element at risk. In considering human beings in the flood hazard assessment, it will be also important to consider not only human body characteristics, but also psychological factors as they can play a key role in human reactions to flood events.

Also, flood models can be further developed to have faster and more reliable results. Despite huge progress in the computational field, difficulties are still present in producing accurate reconstructions of flood events or reliable predictions of future events. This is due to many factors such as availability/quality of topographic and hydrological data, uncertainty on boundary conditions and roughness, level of simplification of the model, and also the right choice of model to be used. For flood simulation the most used models are 1D, 2D and 1D-2D linked models (Costabile et al., 2020; Vojinovic et al., 2016). The key parameters to represent flood hazards are among others: flow velocity, water depth, flood extent, duration, rate at which water rises, and propagation of water front (De Moel et al., 2009).

A combination of water depth and flow velocity is often used to quantify the effects of the water flow on the considered subject of the study, such as people, vehicles, structures and buildings (Costabile et al., 2020). As illustrated in Chapter 2, the authors presented several combinations of water depth and flow velocity, with results leading to different thresholds of human stability in floodwaters. Results reported in this research work show the importance of choosing the most suitable assessment method when determining flood hazard from a pedestrian perspective. Also underlined is the importance of integrating flood and human characteristics, both physical and phycological in determining stability thresholds.

Walking in floodwaters can be extremely dangerous. People generally underestimate the drag force of the flow, even for shallow water depths, and it is therefore fundamental to give an appropriate quantification of the flood hazard for pedestrians since nowadays people walk on the street at any time for different reasons and in any weather despite the advice of the authorities (Arrighi et al., 2019; Martínez-Gomariz et al., 2016; Musolino et al., 2020b).

Analysis of floods in Italy between 1965-2014 (Salvati et al., 2018) showed that 188 of 493 flood fatalities, i.e. 38.1%, happened in “road/highway” and 137 out of the total, i.e. 37.8%, happened “on foot”. Thus, determination of threshold of stability for pedestrians is a crucial aspect in flood hazard assessment especially in case of flash flood events. These thresholds allow planners to know what the safest paths are and influencing with different techniques the behaviour of pedestrians is possible to sensibly reduce loss of life (Arrighi et al., 2019; Dawson et al., 2011).

Authorities worldwide have assessed the flood hazard for pedestrians using different methods (Cox et al., 2010; Priest et al., 2016). However, it is important to note that there is currently a lack of standardisation between countries in terms of assessing flood hazard from a pedestrian protection perspective (Musolino et al., 2020a). In many countries, flood hazard assessment for pedestrians is not updated to recently available methods and in many cases is not considered at all. Recent advancements in understanding the stability of pedestrians in flood events, together with more readily available data and more accurate modelling resources, means that the flood hazard assessment from a pedestrian protection perspective can be improved and should be considered internationally in a more unified manner, for example, considering methods based on a full physic analysis rather than empirical formula as shown in this research work.

To assess people’s stability in floodwater, two different mechanisms have been explored and reported in the literature and there is general agreement about the two kinds of failure mechanisms, namely, sliding and toppling. Moreover, it is possible to recognise two main approaches to evaluate the stability of people in floodwaters: the first based on an empirical or semi-quantitative criterion, and the second based on formulae derived from a mechanics-based approach and supported by experimentation. More details about flood hazard assessment for pedestrians is provided in the next chapter where a detailed literature review is reported.

An important aspect related to flood mitigation schemes is evacuation of people who are in dangerous situations due to a flood event. As will be shown in detail in the Literature Review chapter, flood evacuation methodologies are today fragmentised and not organically structured (Borowska-Stefańska et al., 2019). Thus, it is vital to design realistic emergency flood plans for the safety of the population, but at the moment there is a lack of detailed information on both evacuations and how much floods can negatively impact on critical infrastructures such as road networks which can be used for evacuations (Coles et al., 2017). Recently, flood hazard maps have been largely used to design flood emergency plans, but, other tools such as those used to assess accessibility of inundated roads and escape routes are rarely used (Coles et al., 2017). In this regard, many researchers pointed out that more attention is needed on the threshold for human stability in floodwater since so far it has not been properly considered especially in the designing of evacuation plans (Arrighi et al., 2017; Kvočka et al., 2016; Martínez-Gomariz et al., 2016; Milanesi et al., 2015).

In design evacuation plans a key aspect is the determination of evacuation routes, as the safety of the people depends on this. Individual evacuation routes are is a very complex process since different drivers have to be taken into account (Percival and Teeuw, 2019), the most important are: human behaviour/psychological factors, flood and flow characteristics, local environment (urban, not urban), evacuation time, hazard assessment for pedestrians, capacity of the road and of the transport system in general (Borowska-Stefańska et al., 2019; Diakakis et al., 2020; Guo et al., 2018; Soon et al., 2018; Zhang et al., 2016; Zheng et al., 2019). It is very challenging to integrate all these factors and especially the human behaviour and psychological response of people when designing evacuation routes.

Bearing this in mind, a key challenge for flood risk management is to minimise the impact of flood events, despite the short time available for action. The main aspects therefore considered in reducing flood risk are: (i) determining the stability threshold of people associated with the water depth and velocity in floods; (ii) implementing flood mitigating defence schemes (both structural and non-structural); (iii) developing emergency evacuation plans for flood events; and (iv) informing and warning residents living in flood-vulnerable areas about flood hazard and evacuation procedures (Bodoque et al., 2016; Borowska-Stefańska et al., 2019).

1.2 Research Aim and Objectives

In the previous section, the magnitude of the impact of floods on mankind, especially when considering pedestrians has been highlighted. There are still significant gaps in improving flood hazard assessment and evacuation planning for pedestrians during flood events. The principal scope of this research work is to improve flood hazard assessment and enhance flood evacuation planning for pedestrians.

Key objectives of this research are:

i) Improving flood hazard assessment by refining a mechanics-based method
ii) Benchmarking existing methods used against the method developed in the previous point to determine which assessment methodology is the most suitable to be used in assessing flood hazard for pedestrians
iii) Improving flood evacuation design/planning

As shown in the following chapters, the achievement of these objectives gives a consistent contribution to the hazard assessment of flood prone areas, especially in the case of extreme flood events. Important outcomes of this work are the realisation of more reliable flood maps and a more physically-based stability threshold for pedestrians during a flood event. This will make a decisive contribution to improvement of flood mitigation schemes, and in designing evacuation plans in case of flood events.

1.3 Outline of the Thesis

The thesis is structured as follows:

CHAPTER 1: Introduction, in this chapter are presented the broad research background, the main scope of this research work, and an outline of the thesis.

CHAPTER 2: Literature Review, in this chapter is presented a detailed review of the literature concerning the research presented in this thesis.

CHAPTER 3: Numerical Modelling, in this chapter are presented a brief overview of the hydraulic numerical modelling methods, the relative mathematical background, and the numerical model used in this research work, namely DIVAST-TVD 2D.

CHAPTER 4: Case Studies, in this chapter is provided a description of the two case studies considered in this research work. Within this chapter it is possible to find a description of the two study areas and the results in terms of flood characteristics obtained by the application of the numerical model DIVAST-TVD 2D.

CHAPTER 5: Flood Hazard Assessment: a pedestrian perspective, in this chapter is presented a comparison between the improved mechanics-based method and the other methods used to assess flood hazard for pedestrians, herein considered. The results obtained in the analysis presented in this research work, offer an insight into the importance of assessing flood hazard with an updated methodology such as the one provided in this research work, to have a better assessment with results which are fine-tuned to the specific location considered. In practical terms, this means to have more reliable results, and consequently more safety for pedestrians.

CHAPTER 6: Vulnerability and Evacuation Plans, in this chapter is presented a novel methodology for determining evacuation routes based on pedestrian characteristics and a new retrofitting scheme for improving evacuation plans and decreasing the flood hazard rate. Moreover, a novel methodology for considering social vulnerability for pedestrians when assessing flood risk.

CHAPTER 7: Conclusion and Future Works, in this chapter are presented the outcomes and the findings of this work and also some suggestions for future works related to this study

2 Literature Review

2.1 Introduction

In this chapter it presented a review of the literature concerning the research discussed in this thesis. Section 2.2 illustrates the most recent flood risk management legislation currently in force in the UK. In Section 2.3 is presented an overview of the flood modelling methods. In Sections 2.4 and 2.5 are presented the review of literature relative to flood hazard assessment and evacuation plans respectively. Section 2.6 reports a summary of the main findings from the review of the literature previously reported.

2.2 Current UK Flood Risk Management Legislation

Traditionally, risk assessment and management was focused principally on pre-disaster management rather than a more integrated approach which includes both pre- and post-disaster management schemes which represent the modern approach to flood risk management (Rauter et al., 2019). In 2007 the European Flood Risk Management Directive was adopted by all member states of the European Union in order to have a common framework to better face flood related risks, especially in a trans-border context. Previously each country developed independent flood risk policies, but the European Commission recognised that different legislation and policy action can undermine both sustainable development and effective flood management, especially in the trans-border areas (European Union, 2007). At the moment there is no available information relative to any change in the UK's flood legislation due to Brexit.

History of flood legislation in the UK can be dated back to 1215 and through the centuries has continued to change influenced by different socio-economic drivers and more recently also including environmental concerns and climate change issues (Klijn et al., 2008). The EU Flood Directive 2007 was interpreted and integrated by British authorities in the Flood Risk Regulations in 2009. These regulations have the main purpose of identifying and taking action in areas affected by significant flood risk. In detail, the Flood Risk Regulations define the flood risk assessment providing a description of what the objectives of the flood risk assessment are and at the same time assigning to the competent agency and/or authority duties in order to achieve the previously stablished aims such as preliminary flood risk assessments, redaction of flood hazard, flood risk maps, and flood risk management plans (HM Government, 2009).

The Water Management Act 2010 was introduced on 8 April 2010 in England and Wales. The act had the main objective of introducing the modern concept of flood risk management and the framework for flood and coastal erosion risk management on both national and local scale. Moreover, the act clearly specifies which bodies are responsible for managing flood risk. The act demands of the competent agencies and authorities a better management of flood risk considering not only the traditional problems relative to flood risk, but also bringing attention to risk deriving from rises in surface water drainage charges and protection of water supplies for the consumer. In particular the Environment Agency is responsible of the management of rivers' basin districts and for developing the National Flood and Coastal Risk Management Strategy. More responsibility is assigned to local authorities which are now responsible for the coordination of flood risk management in their area. A national spatial planning system allows to monitor and control exposure of people and assets to flood hazard, each local authority has to identify flood risks through proper assessment and use this information for future development (Department for Environment Food and Rural Affairs, 2010; Priest et al., 2016). In England, the policy lead for floods and coastal erosion risk management is the Department for Environment, Food and Rural Affairs (DEFRA) which collaborates with other government bodies such as the Treasury, the Cabinet Office (relatively to the emergency response planning), and the Department for Communities and Local Government (relative to land-use and planning policies) when revising or developing new policies. These national policies are delivered by the Risk Assessment Management Authorities (RMAs) which comprise of: (i) the Environment Agency; (ii) the Lead Local Flood Authorities (LLFAs); (iii) District and Borough Councils; (iv) coast protection authorities; (v) water and sewerage companies; (vi) internal drainage boards; and (vii) highway authorities.

As indicated by the Flood and Water Management Act 2010, all of the RMAs have to work together co-operating in a manner with results consistent with the National Flood and Coastal Erosion Risk Management Strategy for England and also consistent with the local flood risk management strategies implemented by the Lead Local Flood Authorities (Department for Environment Food and Rural Affairs, 2010).

A brief detail of the roles of the RMAs is here provided (Department for Environment Food and Rural Affairs, 2010):

The Environment Agency has the lead role in overviewing all of the sources of flooding and coastal erosion. It is also responsible for all of the activities concerning flood and coastal erosion risk management on main rivers and the coast, the regulation of reservoir safety, and working in partnership with the Met Office to provide flood forecasts and warnings. It must also consider all opportunities and strategies for maintaining and improving the environment for people and wildlife while carrying out all of its duties.

LLFAs are county councils and unitary authorities. They lead in managing local flood risks. This includes ensuring co-operation between the Risk Management Authorities in their area. Among the duties required by the Flood and Water Management Act 2010 are: (i) to prepare and maintain local strategies for flood risk management, coordinating views and activity with other local bodies and communities through public consultation and scrutiny, and delivery planning; they must consult Risk Management Authorities and the public about their strategy. (ii) Carry out works to manage local flood risks in their area; (iii) keep a register of all the physical features of the assets which have significant effects on flooding; (iii) investigate relevant flood events in their area and publish the outcomes of these investigations; (iv) regulate ordinary watercourses (by powers given by the Land Drainage Act 1991); (v) implement emergency plans and recovery actions after a flood event.

The District and Borough Councils have a key role in planning the local flood risk management as they (i) carry out flood risk alleviation schemes on minor watercourses; (ii) work in partenrship with other RMAs to ensure correct management of flood risk including making decisions concerning the development of their areas.

The coastal protection authorities lead and manage all activities concerning the coastal erosion risk which include shoreline management plans, a holistic long-term framework for managing coastal changes also in relation to flooding problems.

Water and sewerage companies play a major role in managing the flood risk including pollution relative to water supply and sewerage facilities, and also risk deriving from the failure of the relative infrastructures (e.g. pipe networks, purification facilities, reservoirs, etc.)

Internal drainage boards are independent public bodies operating in an area, a so-called drainage district. They are the land drainage authority in such areas and so play a key role in managing flood-related risk and in managing natural habitats. The primary role of the boards is to supervise the land drainage, in other words managing the water levels both in watercourses and the flood defence works on ordinary watercourses.

Finally, highway authorities are responsible for highway and roadside drainage; land owner's adjacent to a highway are responsible (by common law duties) for maintaining the relevant ditches in order to prevent troubles to road users. Moreover, highway authorities collaborate with the other Risk Management Authorities in order to ensure the optimal coordination between the relative activities.

2.3 Flood Modelling

As seen in detail in Chapter 1, flood events are becoming more frequent and challenging due to global environmental change and can lead to enormous life and economic losses (Borga et al., 2014; Khosronejad et al., 2016; Nones, 2017). Projected climate change scenarios lead to an increasing need to assess flood hazard in current and future conditions (Acosta-Coll et al., 2018; Latorre et al., 2010; Pasquier et al., 2018; Winsemius et al., 2013). Today, to assess flood hazard without referring to flood modelling and thus to hydrodynamic models, and more recently AI techniques, is not thinkable.

In the following is provided a description of the different flood modelling tools and their characteristics. It is very important to clarify that there is not a universal model which can be used for all water-related modelling purposes. For example, flood risk assessment in urban environments requires a high level of accuracy of supercritical flow representation; flood forecasts demand assimilation of real-time data and fast run time of the simulations; flood hazard mapping requires maximum flood extent, water depth and flow velocity etc. (Mignot et al., 2019; Teng et al., 2017). Depending on the purpose of the application, modelling requires a contextualisation of the output variables and their time and space scales, and as well as knowing the accuracy level required.

Bearing this in mind, the model's user has to carefully choose the right model considering model complexity, data requirements, and desired outputs (Teng et al., 2017). For example, using a 2D model for modelling structures (such as bridges, flood barrier, sluice gates, etc.) could be very challenging, whereas the use of a 1D model for modelling such structures is more straightforward. Also, using 2D models to simulate flows and elevations in channels and floodplains requires a fine grid to capture all the bathymetric characteristics of the channel. Especially in the case of real-time flood forecasting, the high computational time makes 2D models less practical (Ahmadian et al., 2018).

Considering spatial discretisation of the floodplain, most modelling tools are one-dimensional (1D) or two-dimensional (2D) (Bladé et al., 2012), moreover, it is possible to have 3D models but they are rarely used for river-scale problems due to their huge computational power and input data demands (Crispino et al., 2015; Mignot et al., 2019). The 2D nature of flood hydrodynamics encourages the use of 2D models in order to promote the synergy between distributed observations and predictions, whereas point measurements of stage or discharge are more compatible with 1D models (Chen et al., 2012; Horritt and Bates, 2002; Latorre et al., 2010).

In the followings is reported a brief overview of the main characteristics of 1D, 2D and 1D-2D linked models.

1D models are appropriate to represent most aspects of flood behaviour, but sometimes they are not fully capable of capturing the flood inundation extents due to the limitations inherent in the resolution of 1D models. The main assumption for the 1D models is to consider the flow as one-dimensional along the centreline of the main river channel (Teng et al., 2017). Classic cases of 1D flow are the flow in a pipe or a confined channel, and the flow in an open surface channel. In this case the floodplain flow is assumed to be in one direction parallel to the main channel, and one cross section averaged velocity is used to represent large variation of velocity across the floodplain (Teng et al., 2017). Numerically, 1D models usually solve equations obtained guaranteeing the conservation of both mass and momentum between two consecutive cross sections. Starting from the two-dimensional Saint-Venant equations it is possible to derive one-dimensional simplified equations which as of today have no analytical solutions, so need to be solved recurring to numerical techniques which allow to determine flow characteristics at each cross section for each time step.

1D hydrodynamic models have been used for many different applications as they proved to be numerically efficient and to be able to give reliable results when modelling large and complex systems of channels/rivers and also when modelling hydraulic structures as gates, weirs, sluices, etc. (Lin et al., 2006). On the other side, 1D models present limitations mainly bonded to the initial assumptions; the main limitations are the following: (a) discretisation of the domain as a series of cross sections and not as a surface; (b) lack of capability to simulate the lateral diffusion of a flood wave; (c) dependency to cross section location and orientation (Hunter et al., 2008).

In the 2D models the overland flow is represented as a two-dimensional field. The main assumption of this modelling approach is that water depth, which represents the third dimension, is shallow in comparison to the other two dimensions. Then the two-dimensional Saint-Venant equations are depth averaged thus it is possible to derive the two-dimensional shallow-water equations which represent the mass and momentum conservation (Teng et al., 2017). According to the numerical discretisation technique the model can be classified as finite element, finite difference, or finite volume method.

Considering the discretisation in time the model can be considered implicit or explicit. Implicit models cannot proceed to the next time step until equations for the whole domain are solved, instead explicit models can solve a single unit not solving the whole domain at any time step (Teng et al., 2017). Considering spatial representation, it is possible to use a structured grid (rectangular), unstructured grid (triangular) and also flexible grids where both rectangular and triangular elements are used.

When considering 2D hydrodynamic models, grid resolution and topography are crucial aspects, especially in urban areas. Neelz, S. & Pender, (2013) benchmarking 19 different models, found that large differences in the velocity predictions were obtained for high resolution flood modelling (2m grid) in urban areas where the flood depth is relatively shallow. The findings showed that a finer grid would be more adequate to resolve the underlying topography for this class of flood. However, at the moment is not clear if a grid resolution finer than 2m will improve the quality of the velocity prediction for two main reasons. Firstly, predictions are also influenced by uncertainty in boundary conditions and errors in digital terrain models, at least at the same degree as the grid resolution. Secondly, using a grid resolution finer than 2m will have a big negative impact in terms of computational efficiency (Neelz, S. & Pender, 2013).

Today, the 2D modelling approach is the most used when modelling inundations. This is because this kind of model offers a wide range of information such as water levels, flow velocity, and local velocity variations. All this information can be used by end model users to better understand the flood processes and take the necessary defence measures (Neelz, S. & Pender, 2013).

Recently hybrid models which link 1D and 2D models have been developed and successfully applied to different cases (Aricò et al., 2016; Pasquier et al., 2018; Yu et al., 2018). In coupled models the one-dimension modelling is used to compute the flow velocity and water level in the main channel and the 2D modelling is used to compute the flood velocity and water level in the floodplain when inundated.

A crucial aspect of the coupling technique is how the boundary conditions are considered and settled, due to the fact that the 2D model interacts with the one dimensional through the boundaries (Goutal et al., 2014; Vojinovic and Tutulic, 2009). In terms of computational time, integrating 1D and 2D models reduces computational time and resources. Usually, computational time increases exponentially with the number of the elements used in the modelling to the power of 1.5 or 2. Time differences between approaches can range from a few seconds or a few minutes in 1D to several hours, days or even weeks in a 2D model (Bladé et al., 2012; Echeverribar et al., 2019).

It is possible to group linking strategies in three main families: (i) lateral coupling where the 1D model is used to model the main channel and the 2D model is used for the floodplain when flooded. The flow exchange between the 1D model and the 2D model can be calculated using different methods, for example, water-level linking or discharge linking methods; (ii) super-positional coupling in which higher dimensional models are super positional over a lower dimensional global model; (iii) boundary connected coupling; different dimensional models are connected through boundary conditions i.e. the 2D model provides the values of the water elevation which will be used as a downstream boundary condition for the 1D model. Instead, the 1D model provides information for the inflow boundary condition of the 2D model. Generally, (i) and (ii) are mainly used for river-flood plain systems, and (iii) for river-lake and river-estuary systems (Chen et al., 2012).

With particular focus on urban environments, 1D/2D linked models have been developed. In these models, the 1D model is used to simulate the flow in the urban drainage system and the eventual surcharge flow volume of the ground surface, instead the 2D model is used to simulate in detail flow propagation of the ground's surface (Martínez-Gomariz et al., 2019; Vojinovic and Tutulic, 2009).

There are several 1D/2D modelling packages available today. Some of the most well-known and used are: HEC-RAS that allows 1D steady and unsteady flow modelling, and recently included 2D and 1D/2D coupled modelling tools (Ezzahra Maatar et al., 2015). LISFLOOD-FP is a raster-based inundation model developed to take advantage of high-resolution topographic datasets. TELEMAC-2D is used to simulate free-surface flows in two dimensions of a horizontal space (Merkuryeva et al., 2015). MIKE Flood dynamically links MIKE11 and MIKE21 modes in an single package, and has been widely used for flood risk assessment (Mani et al., 2014). DIVAST-TVD 2D is a research model used to predict flows and water quality indicators. This numerical model combines the MacCormack standard scheme with a symmetric five-point total variation diminishing (TVD) term. This means that a shock capturing algorithm is included in the code for maintaining sharp gradient and thus preventing the emergence of numerical oscillation (Falconer et al., 2001; Kvočka, 2015; Liang et al., 2007b; Lin et al., 2006) The TVD feature has the drawback of requiring more computational time, as pointed out by Wicks et al. (2004) a commercial shock capturing model was more than 50 times slower than a traditional ADI model. Bladé et al. (2012) using as a start point the Iber hydrodynamic model, which offers both 1D and 2D modelling approaches (developed by Flume Research Group at the Technical University of Catalunya) developed a numerical method for coupling 1D and 2D models using a finite volume method to solve the SWE. Both numerical models use a high-resolution Godunov scheme with Roe's Riemann solver and TVD functions. The conservation of both mass and momentum in finite volume schemes are transferred through elements by means of numerical fluxes, and the authors identified that as key for their method to connect 1D and 2D.

Major areas of ongoing research in 2D models and 1D/2D coupled models are the following: faster and more accurate fluid solver; modelling of wetting and drying; processes associated with antecedent soil moisture conditions and surface water ground interaction; simulation of the lateral diffusion on the flood wave (Teng et al., 2017). Moreover, it is necessary for more research in testing the capability of linked models in predicting flow characteristics in cases of rapidly varying flows as is the case of flash floods.

2.4 Flood Hazard Assessment for Pedestrians

As previously presented in the Introduction chapter, flood hazard assessment from a pedestrian perspective is a very important topic in the bigger picture of flood risk management as floods can also pose threats to human health (physical and psychological) (Jonkman and Kelman, 2005). Wading in floodwaters can be extremely dangerous as generally pedestrians underestimate the drag force of the flow, especially in the case of shallow water depths. Misjudging the danger leads to risky behaviours which often have as consequence serious injuries or death. During a flood event, one of the main causes of loss of life is drowning, which can occur whilst inside or outside of a vehicle (Arrighi et al., 2019; Doocy et al., 2013; Enríquez-de-Salamanca, 2020; Jonkman and Kelman, 2005; Shabanikiya et al., 2014). The extensive review by Doocy et al. (2013) shows that there is also a connection between geographical areas, gender, and age with mortality during extreme flood events, hence assessing the hazard taking into account pedestrians characteristics, can help to find the most vulnerable population sub group for the specific area considered. This finding therefore enables early warning systems to be fine-tuned and for preparedness to be planned for flood response action.

Relative to the stability of people in floodwaters, the available literature reports different methodologies to assess the hazard to pedestrians, but there is general agreement about the two main possible failure mechanisms, namely, sliding and toppling. Moreover, two main approaches to evaluate the stability of people in floodwaters have been increasingly used: the first based on an empirical or semi-quantitative criterion, and the second based on formulae derived from a mechanics-based approach and supported by experimentation (Musolino et al., 2020b).

An early study by Foster and Cox (1973) produced test results on the stability of children in floodwaters, covering a range of different values for mass and height. The authors found that the stability of people in floods was determined through a combination of physical, dynamic, and emotional factors. In addition, this study showed that most of the stability failures occurred through sliding. Abt et al. (1989) conducted a series of tests with human subjects and a monolith placed in a flume, with the scope being to determine the threshold of water depth and flow velocity that led to instability; with their study the authors demonstrated the importance of the toppling mechanism. Further studies with both adults and children have been undertaken by several authors (Jonkman and Penning-Rowsell, 2008; Takahashi et al., 1992), all of which considered different clothing features and levels of expertise of the people, as well as different environmental conditions. The results from these experiments provided the basis for the development of an inversely proportional relationship between the mean flow velocity and water depth. Karvonen et al. (2000) carried out further tests with humans through the RESCDAM project, with their findings showing that, depending on the person's weight and height, the critical depth and velocity product ranged from 0.64 m^2/s to 1.29 m^2/s. Russo et al. (2013) used results from 834 experiments, conducted with 23 human subjects, and a real-scale model representing an urban street. They proposed empirical expressions that related the weight and height of a person to the flow conditions, thereby providing relationships for the threshold of stability for a pedestrian in floodwaters. However, the empirical approximation function is purely regressive and hence it is not possible to truly connect the hazard level and physical effects (Milanesi et al., 2015). More recently, Martínez-Gomariz et al. (2016) extended the work of Russo et al. (2013), and conducted tests with human subjects to derive hazard thresholds for pedestrians crossing streets. The thresholds were obtained through considering different combinations of footwear, visibility conditions, different age groups, and the weight of people, with the results showing the importance of considering the size and weight characteristics of the respective human bodies. Moreover, experiments considered various parameters, including longitudinal variable slope, transverse slope, the first step from the sidewalk to the flooded street, and 16 different flow scenarios. The authors integrated their data with the results obtained by Russo in 2009, to obtain more instability points. The stability thresholds obtained with this study were focused especially on shallow depths and fast flow conditions, which are typical of flood conditions in urban environments. An important finding of their work was to point out the importance of the velocity in determining stability thresholds for pedestrians, especially in urban environments. Furthermore, from post-test interviews, it emerged that gaining experience increased the capacity to complete the protocol by test subjects. In addition, all of the subjects agreed that crossing the road, in the transverse direction, was the most difficult action to carry out.

To overcome the limitations of experimental studies involving people (e.g. gaining experience, presence of safety equipment, trained subject), conceptual models with different levels of simplification have been employed to estimate the instability of a human body as a function of flow velocity and water depth.

Love (1989) considered a simplified representation of the human body using an equivalent rectangular solid body and studied the influence of the buoyancy force on the instability of the solid body, especially regarding its likelihood of toppling. Building on this study, Lind et al. (2004) represented the human body as a composition of different cylinders, namely (i) a circular cylindrical body; (ii) a square parallelepiped; and (iii) a composition of cylinders, including two small cylinders to represent the legs and a larger cylinder to represent the torso. These schematisations were used to develop three approximate mechanical models and two empirical models, which were used to derive a limiting function which was calibrated using the results obtained by Abt et al. (1989).

Experimental results from Jonkman and Penning-Rowsell (2008) showed that the sliding mechanism was more dangerous than previous studies had suggested. Another interesting finding of their work was that the sliding mechanism was the dominant mechanism of failure in shallow water depths and high flow velocities, as typically occurs in the case of flash floods in urban environments. Furthermore, their simplified schematics used to evaluate instability, which was generally presented as the product of depth (h) and velocity (v), had a physical connection with the toppling mechanism, but that a better descriptor of the sliding mechanism was the product $h \times v^2$.

Merz et al. (2010) with their research introduced “resistance factors” which depend on the characteristics of flood-prone objects, as one of the parameters also being considered in assessing people’s stability in floodwaters. These resistance factors describe the capability, or incapability, of an object to resist the impact of a flood. Also, mitigation measures, previous experience of flood events, and early warning all influenced the resistance factors.

Xia et al. (2014a) proposed a mechanics-based method which considers a mixed approach using both a theoretical and experimental analysis. The authors conducted experiments on a scaled dummy representing a human body and the proposed methodology considered the failure mechanisms of both toppling and sliding and a non-uniform upstream velocity profile acting on the human body. Moreover, the analysis included the forces acting on a body when immersed in water, such as: buoyancy, friction, drag, normal reaction, and gravitational forces. The resulting formulation parameters were calibrated using flume experiments and datasets available in the literature. Later, this methodology was further extended to include experiments for a range of bed slope conditions (Xia et al., 2014a). The results from their work showed more conservative thresholds than those obtained through working with human subjects. This discrepancy was thought to be due to the fact that people can adjust their standing posture and orientation to best suit the direction of flow (Xia et al., 2014a). One of the advantages of their work was the inclusion of the body shape characteristics in the analysis, through the addition of coefficients describing the typical features of a human body.

More recently Shu et al. (2016) proposed a formula for the toppling instability of people in floodwaters using a similar approach to that of Xia et al. (2014a). The formula was derived from a mechanics-based approach, complemented with flume experiments undertaken for two different sized 3D printed models of a human body considering the effects of different body postures. Furthermore, the authors accounted for grip strength, to take account of the ability of people to resist the forces of floodwaters.

Milanesi et al. (2016) tried to overcome the bias inherent in tests conducted in controlled laboratory conditions (e.g. trained subjects, gained experience during testing, and presence of safety equipment), as well as dealing with the bias of tests conducted on scaled models (e.g. the dummy cannot continuously adjust its posture, the dummy is not affected by psychological factors etc.). Based on the outcome of these tests, the authors proposed a new methodology that extrapolated the flow characteristics from videos available on the web, with the results being verified through observations. The authors suggested studying the stability problem in a statistical framework, rather than in a deterministic manner and, accordingly, proposed a methodology that identified the stability surface and relative thresholds in probabilistic terms.

Arrighi et al. (2017) proposed a "mobility" parameter for people walking in floodwaters, which considers both the flood hydrodynamics and people characteristics. This parameter identifies a unique threshold of instability, depending on the local Froude number. Moreover, the authors discussed the hydrodynamic forces obtained from a 3D numerical model and experimental studies. Their research study highlighted the importance of including the body characteristics in analysing the interaction between a human body and the hydrodynamics in a flood event. In other words, the interaction depends on the portions and shape of the body that are in contact with the floodwater, as well as the flow characteristics.

Chen et al. (2018), expanded the work of Xia et al. (2014a) to include the effects of adjustments to a human body in a flood and they revised some of the key parameters in order to consider American and European body characteristics, as well as those of typical Asian nationals. However, the corresponding formulae were only obtained for toppling and did not include the effects of bed slope.

Recently, Musolino et al. (2020a) proposed a refined mechanics-based methodology based on the work of Xia et al. (2014a) including the effects of the ground slope in the results obtained and linking the flood hazard rating to the human body characteristic. Moreover, the body mass index has been used for a better evaluation of the critical pedestrian class when designing evacuation plans.

Musolino et al. (2020a) further developed the mechanics-based method updating it to not only include the effects of the ground slope but also including new values of human body characteristics for European people. In this study the authors compared the performance of the revised mechanics-based method versus some empirical methodologies adopted by competent authorities worldwide. The main aim of this study was to give more insight into the flood hazard assessment from a pedestrian perspective and giving a contribution to the creating of a more universally- and scientifically-based approach to the assessment of flood hazard for pedestrians.

Various authorities worldwide have often adopted flood hazard assessment methods suggested by some of the studies previously reported, or have developed their own methods, providing a significant step forward in ensuring the safety of pedestrians during floods. However, there is still a lack of homogeneity in assessing flood hazard for pedestrians taking into account not only a flood's main features such as water depth and flow velocity, but also people's characteristics and psychological aspects (Musolino et al., 2020a).

In 1988, The Bureau of Reclamation of the United States Department of the Interior published a report entitled "Downstream Hazard Classification Guidelines" (U.S. Department of the Interior, 1988), with the intent being to provide some guidelines to assess flood hazard due to possible dam break flows. These guidelines provided different graphs to identify and assess the hazard for pedestrians and houses associated with a flood event due to a dam break event and allowed hazard quantification for the following categories: passenger vehicles, adult pedestrian routes, and child pedestrian routes.

In 1996 the General Directorate of the Hydraulics Works and Water Quality of the Spanish Environmental Ministry published its "Technical guidelines for dam classification based on the potential risk of failure" (Ministerio de Medio Ambiente de Espana, 1996). In these guidelines, graphs were provided which correlate the product of water depth and flow velocity with the danger derived from floods due a dam break event and allow hazard quantification.

Ramsbottom et al. (2003 and 2006) developed an empirical method for evaluating flood hazard for the Department for the Environment, Flood and Rural Affairs (DEFRA) and the UK Environmental Agency (EA). The authors tested various empirical formulae using datasets available in the literature and proposed an approach that considers the likelihood of flooding, the probability of exposure to a flood event, and the probability that people exposed to the considered event would be seriously, or even fatally, injured.

The publication of Australian Rainfall and Runoff, by Cox et al. (2010), updated Australia's guidelines on the safety of pedestrians in floodwaters. The authors reviewed their previous work and re-analysed all the available datasets, enabling new guidelines to be produced for the safety of pedestrians in floodwaters and using depth times velocity relationships.

2.5 Vulnerability

As previously reported in Chapter 1, flood risk is defined as the product of three components: hazard, vulnerability, and exposure. Among these three components, vulnerability is the one that has been less investigated due to its intrinsic nature and to date represents one of the less-known factors for a better flood risk assessment (Koks et al., 2015). As suggested by Birkmann (2013) vulnerability highlights the importance of examining conditions and context of communities and elements at risk, for an effective reduction of the risk and for a better climate change adaption. However, in past decades somehow vulnerability has been decreased probably by the shift of focus from structural protection to a more holistic approach which put together classic flood defences with non-structural strategies such as early warning systems, raising awareness among populations, relocation of critical assets, or communities at high risk (Mondino et al., 2020). Even if the term "vulnerability" is used with different meanings in different disciplines, it allows to have a social science perspective on a disaster, in this way not only the technical/engineering point of view will be considered, but also a social dimension will be evaluated. Bearing this in mind, the ability to measure vulnerability is now considered as a key point in reducing risk effectively and in promoting a culture of disaster resilience (Birkmann, 2013)

An early approach for the quantification of vulnerability was predominately focused on a physical dimension, in other words was exclusively a quantification of the physical vulnerability of structures and goods (Armenakis et al., 2017; Jongman et al., 2014; Koks et al., 2014). Alternatively, territorial features can be considered when analysing vulnerability, in this regard land use can be considered to show economic factors and their sensitivity to floods (Jiang et al., 2009) adding in this way an economic dimension to the quantification of the vulnerability.

Birkmann, (2013) suggested that disasters can be better considered as a result of complex relationships between events such as floods, fires, storms, earthquakes, etc., and the vulnerability of a community, the economy, the manmade infrastructures, and the environment which are deeply interconnected with human behaviour.

Koussis et al. (2003) focused their attention on the importance of ecological impacts, while Koks et al. (2015) focused their attention on population density and demographic data. Alternatively, another classic approach to vulnerability assessment was to quantify the risk of life assuming a uniform rate of vulnerability to the population of the study area (Jonkman et al., 2003). This approach did not consider at all the social dimension of the risk and took into account only the damage of structures or goods or human losses as a function of water depth (Koks et al., 2015). Thus it is a key aspect to include a social perspective to the classic approach for vulnerability's assessment and in this regards it is crucial to understand what makes people vulnerable to flooding (Mondino et al., 2020).

Inclusion of social aspects is also reported in the definition of vulnerability given by the United National Development Programme which is "a human condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard" (Birkmann, 2013).

Berndtsson et al. (2019) focused their attention on identifying the key drivers which can increase the impact of both flood hazard and vulnerability in urban areas. The authors found that among the drivers that exacerbate flood hazard there are: climate change, decreasing of permeability, and increasingly unresponsive engineering. Also the authors identified drivers that can negatively affect vulnerability which are: urbanisation and urban sprawl, economic growth, values at increasing risk, and increasing complexity of society. Moreover, the authors found that public awareness and individual willingness to participate in risk reduction measures affect both flood hazard and vulnerability.

Bodoque et al. (2019) with their study, pointed out that risk mitigation must be adequate both in terms of territory and social context as people can have an unrealistic sense of safety when risk management is based only on a technocratic approach. Thus, a social dimension must be considered when assessing vulnerability. Moreover, including social aspects in vulnerability assessment improves preparedness and response as flood mitigation actions and policies will be quickly and efficiently implemented (Bodoque et al., 2019, 2016).

Chanson et al. (2014) and Opper et al. (2010) highlighted the fact that human behaviours are influenced by the flood event and its effect on the local environment, focusing the attention of their studies on effectiveness of the evacuation strategy and level of risk for pedestrians (based on stability thresholds) respectively. Human behaviours can account for different reactions such as rapid escape from a dangerous area, maintaining safe conditions while moving, reaching safe points, and survival rates (Bernardini et al., 2017b). The authors also highlighted the importance of human behaviour in the case of dense urban environment, touristic areas, evacuation procedures, and interaction between people and car/transport systems.

Bodoque et al. (2016) considered human behaviour in different kinds of flood events and focused their research on defining risk-perception aspects. Riad et al. (1999) instead focused their attention more on the psychological aspects considering as a social dimension of vulnerability the social influences and attachment to belongings. Jonkman et al. (2009) in evaluating the vulnerability focused on the factors which lead to loss of life during a flood event with a particular focus on risky behaviours. Ishigaki et al., (2009) focused their attention on the motion speed of pedestrian moving in a flooded environment in relation to specific flow forces.

As pointed out by Bernardini et al. (2017a) at the moment guidelines for competent authorities on emergency planning and risk reduction don't take into account the "human factor" in general and especially when considering vulnerability. In this regard the authors in their work take into account hydrodynamics and human problems concerning flood evacuation. Finally, the authors suggest that an approach which combines hazard, vulnerability, and exposure is fundamental for the definition of policies for risk reduction and also emergency management strategies (i.e. evacuation plans and procedures).

2.6 Evacuation Plans

Evacuation route planning is a key part of emergency management which has as a main objective to reduce loss of life as much as possible during natural or manmade disasters such as flood events, earthquakes, tsunami, hurricanes, fires, nuclear leaks, and also during all events that involve the presence of large numbers of people in the same area, both indoors and outdoors, for example, sport and music events, terrorist attacks, workers in large plant/office buildings, etc (Caunhye et al., 2012; Shekhar et al., 2012; Vermuyten et al., 2016; Zhang et al., 2010).

Emergency management involves a multilayer analysis (territory, hazards, populations) and approaches (modelling approaches). Planning and actions have to be considered both before and after the disaster occurs. Before the disastrous event, policymakers and authorities have to locate hazardous and safe areas, determine modalities of evacuations (e.g. by foot, public transportation, private vehicles). During the evacuations, both need to know the safest path to reach designated safe areas and rescue teams as well as needing to know the safest path to reach and take in safely people who cannot evacuate autonomously (Caunhye et al., 2012; González-Riancho et al., 2013).

All the emergency plans, and in this broad category are also included evacuations plans, have some key objectives in common independently of which type of emergency they are designed. In general, all emergency plans have as main a purpose to reduce firstly fatalities and secondly property damages. More specifically, evacuation plans have three specific objectives, namely (i) maximising the number of people to be evacuated; (ii) minimising the clearance time, which is the time until the last vehicle or evacuee leaves the hazardous area; (iii) minimising the total evacuation time, which is the amount of time which the evacuees are exposed to the hazard until reaching one of the designated safe points (Zhang et al., 2010).

A first, general categorisation of evacuation plans can be done depending on the distance. With this in mind, it is possible to consider small scale evacuations usually done on foot, and long-distance evacuations usually done using vehicles. It is also possible to have hybrid situations where the two typologies are part of a broad evacuation system. Also, evacuations can be classified as autonomous, recommended, and mandatory. Autonomous and recommended evacuations happen when people get warnings. In this case the alert time is relatively longer compared to mandatary evacuations which are generally with short notice and commanded by governments or competent authorities (Li et al., 2014).

Researchers in different fields such as engineers, psychologists, computer scientists, sociologists, and physicists focused their attention on pedestrians and evacuations dynamics. The topic is very complex due to the large number of people involved and the non-linear interactions between them, as well as psychological factors and external factors such as infrastructure, type of catastrophic events, meteorological conditions, etc., which influence human behaviour (Helbing and Johansson, 2012).

In considering pedestrians as the subject of evacuation plans, several approaches can be adopted: macroscopic or microscopic (Mukherjee et al., 2015), discrete or continuous variables (space, time, state), deterministic or stochastic dynamics, rule-based or force-based interactions, and high or low fidelity descriptions (Schadschneider and Seyfried, 2009).

Early studies on pedestrians were based on direct observation, videos, and photographs, and had as a main objective the development of planning guidelines, design elements of pedestrian facilities, and concepts relative to level of service. Several simulation modelling approaches were proposed such as queueing models, transition matrix models, stochastic models, and route choice behaviour. Recent experimental studies also included self-organisation effects in pedestrian crowds, which was not taken in account before (Helbing and Johansson, 2012). More recent studies focused their attention on mathematical models, which want to provide a realistic description of pedestrians' movements and interactions, and on models used to determine optimised evacuation plans (Vermuyten et al., 2016).

Several authors focused on very specific aspects of pedestrian evacuations. Gwynne et al. (1999) reviewed 22 evacuation models and classified them in three main categories depending on the perspective of the model, distinguished as: (i) enclosure representation, where both fine and coarse networks are considered; (ii) population perspectives where individual or global point of view is considered; (iii) behavioural perspectives where the main focus is on representing the decision-making process adopted by the evacuees. More recently, Schadschneider and Seyfried (2009), focused their attention on the calibration of evacuation models and on the use of cellular automata models. Zheng et al. (2009) differently from previous works, classified crowd evacuation models based on seven methodological approaches such as fluid dynamics, cellular automata, social forces models, lattice-gas models, agent-based models, game-theoretic models, and experiment-based methods, which involve experiments with animals such as rats and ants. The authors also pointed out that microscopic approaches (cellular automata, lattice-gas, social force, and agent-based models) can be combined between them to model phenomena relative to pedestrians, but they cannot be combined with macroscopic approaches (fluid dynamics models) to model pedestrian behaviour.

Another distinction relative to evacuation plans can be made depending on the focus of the study. Different thematics can be recognised in the literature. The topics more studied are: the transport system, people's flow, the evacuation process itself, behavioural aspects, crowd aspects and dynamics, how to solve specific problems such as influence of obstacles, bottlenecks, etc.

Bernardini et al. (2017) pointed out the importance of man-floodwater interactions in pedestrian evacuations during a flood event and the fact that the human factor should be more relevant in assessment methods especially in pedestrian evacuations. The authors also proposed a combined microscopic approach, where behavioural rules are organised in an agent-based model coupled with motion criteria based on a social force model.

Zhang et al. (2016) presented an evacuation model based on the results from flood simulation studies, using the DHI MIKE model, and highlighted impassable flooded roads using ArcGIS. Soon et al. (2018) analysed the psychological behaviour of people being evacuated during an unprecedented flood disaster in Malaysia in 2014 by using an empirical analysis. Guo et al. (2018) proposed an integrated model that included modules for predicting the 2D hydrodynamics, hazard degree for pedestrians, evacuation times, and the determination of ideal escape routes, however, this study does not include the effects of ground slope in determining the flood hazard and evacuation route. Clearly the ground slope could affect the optimum evacuation route (González-Riancho et al., 2013). Zheng et al. (2019) proposed a modified flood model, integrating flood spreading processes with the determination of evacuation dynamics in underground metro systems, where the emphasis focused on water depth as the main driver. Four individual water depth thresholds, associated with pedestrian dynamics, were considered and analysed. Borowska-Stefańska et al. (2019) presented a model which included a GIS tool, using different algorithms available from the literature, to determine the optimal evacuation path and giving more credence to the road capacity and transport system during an evacuation.

Musolino et al. (2020a) implemented a flood hazard assessment methodology to determine the less hazardous evacuation routes to be considered when in danger due to a flood event. This approach links flood and human body characteristics and the local environment and also highlighted the danger posed to people due to a loss of stability when a pedestrian interacts with floodwaters.

With the exception of the work of Guo et al. (2018) and Musolino et al. (2020a), the studies reported above do not include any consideration of human stability in floodwaters. This limitation has recently been recognised by several authors as a key aspect in Flood Hazard Assessment (FHA) (Arrighi et al., 2017; Kvočka et al., 2016; Martínez-Gomariz et al., 2016; Milanesi et al., 2015). As seen in this review, several aspects contribute to the complex phenomenon of floodwaters, including physical and psychological parameters.

2.7 Summary

As seen in the previous sections, only in recent years has there been a tentative effort to create a more universal way to approach problems concerning flood risk. Currently, there is a partial agreement in relation to flood hazard assessment for pedestrians. Authors agree on the mechanisms that determine flood instability for pedestrians moving in floodwaters. However, there is a lack of agreement when considering the methods, with the scientific community divided by the traditionally used empirical approach versus a more modern mechanics-based approach.

European Flood Risk Management Directive n.60/2007 made a huge contribution in proposing a common framework to state members, but only in relation to the tools that have to be used in assessing flood risk (i.e. flood maps, hard/soft engineering mitigation solutions, etc.). Especially when considering pedestrians and evacuation, if the problem is contemplated by the competent authority there is a complete lack of homogeneity worldwide. Moreover, the human factors relative to hazard perceptions, preparedness, and people's experience are not considered by the competent authorities in the official frameworks.

Similarly, evacuations in case of flood events are marginally considered by authorities and only recently has there been an increase of interest by both authorities and researchers. Usually factors both physical and psychological relative to pedestrians are not take into account with the result being to have outputs that are still not fully connected with the end user (i.e. pedestrians) of the evacuation process.

3 Numerical Modelling

3.1 Introduction

This Chapter offers a brief overview of the theoretical background related to the fundamental aspects of numerical modelling, especially those associated with flood modelling. The knowledge reported here is fundamental to understand the mathematical and physical foundation of flood modelling and how it is possible to proper switch from the theoretical mathematical formulation of the problem to the "tool" used to determine the flood characteristics, or in other words the numerical model.

Considering the characteristics of a fluid and how they change in space and time cannot be determined in an exact form from a mathematical point of view, then It is fundamental to choose the right approximated solution (depending on the specific problem to be solved) in order to obtain the most reliable results in an efficient way when implementing these approximate solutions in hydrodynamics numerical models (Teng et al., 2017).

3.2 Governing Equations

Governing equations, for describing characteristics of a fluid and their changing in time and space, derive from the fundamental principles of Newtons' Law and Reynold's Transport Theorem (WY Tey et al., 2017).

Fluid motion and all the changes occurring in a time span can be described recurring to the following equation:

a) Equation of state
b) Conservation of energy also known as Bernulli's principle
c) Continuity equation
d) Dynamic equations

Flood propagation over a terrain is a three dimensional time dependent, incompressible, fluid dynamics problem with a free surface (Alcrudo, 2004). Considering incompressible fluids at constant pressure, as is the case for most of the civil and environmental engineering applications, the static and dynamic behaviour of the fluid can be described by solving equations derived from the application of physical laws to fluid motions considering different degrees of simplifications. In particular, we consider the continuity equation, which describes the conservation of mass, and the dynamic equations, which describes the conservation of momentum. The mathematical expression of mass and momentum conservation is given by the well-known Navier-Stokes Equations (Casulli, 2014; Teng et al., 2017).

To overcome turbulence problem, the Navier Stokes equations can be time averaged obtaining the Reynolds Averaged Navier Stokes equations, which describe the mean flow (Alcrudo, 2004).

Classic approach to simplify the mathematical problem is to consider the kinematic boundary condition of the free surface and the assumption of hydrostatic pressure distribution. Under these assumptions it is possible to integrate over the water column the Reynolds-averaged continuity and dynamic equations (Liang et al., 2006) having as result the so called 2D Shallow Water Equations (SWE). SWE are largely used to describe water flow in rivers, overland flow, lake hydrodynamics, surface irrigation, estuarine and coastal circulation (Bradford and Sanders, 2002; Liang et al., 2006) which are object of study of this research work.

It is important to clarify that the SWE do not provide an exact mathematical representation of the flow propagation as many assumptions have been made to be able to solve these equations (Alcrudo, 2002).

Despite the lack of an exact mathematical solution the SWE provide accurate results with a relative low computational cost (Liang et al., 2006). For this reasons such equations have been used in the vast majority of 2D numerical models (Kocaman and Ozmen-Cagatay, 2015; Moreno-Rodenas et al., 2018; Neelz, S. & Pender, 2013; Néelz et al., 2009).

3.3 Numerical Methods

Two-dimensional numerical models use the SWE, by converting the differential equations in a set of algebraic equations. Thus, it is possible to calculate considered variables at a finite set of points in the space-time domain. This process of opportunely replacing differential equations with a set of algebraic equations it is called discretization (Néelz et al., 2009). Different method can be used for discretizing the governing equations in space and time.

In the following are reported most common methods for space discretisation, (Teng et al., 2017):

i. *Finite difference methods*, which have their foundation on Taylor series expansion to approximate the SWE. The partial differential equations are transformed in an algebraic system of equations by using Taylor series. This system expresses the derivative of a variable as the differences between the values of the variable at neighbouring points. The order to which the Taylor series expansions are developed determine the precision of the approximation which is also related to the number of neighbouring points considered (Néelz et al., 2009). The Main advantage of this method is its easy implementation on a structured grid in 2D applications. At the same time this aspect represents as well a potential drawback as from a geometric point of view unstructured grids can be preferable when modelling flood events in complex domains (Alcrudo, 2004; Néelz et al., 2009).

ii. *Finite volume methods,* where the computational domain is sub-divided into so-called finite volumes. Then the conservative forms of the SWE are integrated over each finite volume to obtain equations that give the fluxes through the boundaries of the control volumes. This method results to be conservative for both mass and momentum as a flux values across a given boundary are used for control volumes separated by the boundary (neighbour control volumes) (Néelz et al., 2009). Conservativeness and as conceptual simplicities, and geometric flexibility gave to this method an increasingly popularity in numerical flood simulations, but still there are difficulties associated to the process of wetting and drying over arbitrary topography (Alcrudo, 2004; Bradford and Sanders, 2002). Moreover a finite volume scheme is typically much more computational demanding than a regular finite difference scheme (Neelz, S. & Pender, 2013).

iii. *Finite element method*, in which the domain is sub-divided in a finite number of elements. The original problem is then represented by a set of equations relative to each element. It is possible to determine the unknown variables by approximations using linear combination of piecewise linear functions. The number of these functions is equal to the number of vertices which describe the elements in which the domain has been sub-divided. A global function based on this approximation is substituted in the governing partial differential equations. This equation is then integrated using a weighting function with a minimisation of the residual error to give coefficients for the trial functions which represent an approximate solution (Néelz et al., 2009). Main benefits of this method are: i) a rigorous mathematical basis which allow a posteriori errors analysis and estimation ii) accurate representation of complex geometry, iii) ability to detect all the local effects in the solution process iv) easy representation of the total solution (Alcrudo, 2004). Principal drawback of this method is a large computational time which explains why this method has not been used as much as other approaches in commercial models (Neelz, S. & Pender, 2013).

Considering discretization in time it is possible to have the following major categories (Neelz, S. & Pender, 2013; Teng et al., 2017):

i. *Implicit or backward-looking schemes* where the dependent variables are calculated by considering quantities determined both at the precedent time step (n-1) and the current time step (n). In this kind of scheme all the computational cells are coupled together within the computational procedure. This presents the benefit to allow the transmission of hydraulic effects through all the domain. Another benefit offered by this scheme is the unconditionally stability, despite that to ensure numerical accuracy time steps are often limited (the Courant-Friedrichs-Lewy condition have to be satisfied). Moreover, this kind of scheme presents a high code complexity and large computational cost (Hunter et al., 2007). As an implicit scheme requires that for each new time step the solution cannot proceed through the computations mesh one finite volume (or one node) at a time, and a system of algebraic equations representing the whole domain must be solved simultaneously (Néelz et al., 2009).

ii. *Explicit or forward-looking schemes,* where the dependent variables at the current time step (n) are calculated by using the results obtained in the previous time step (n-1). Explicit schemes are easier to code than implicit ones but, present a higher limitation in terms of Courant-Friedrichs-Lewy condition in order to ensure numerical stability (Néelz et al., 2009). This latter aspects can lead to choose time steps considerably small compared to the physics of the problem examined (Hunter et al., 2007).

iii. *Semi implicit schemes,* which represent a combination of explicit and implicit schemes. In such schemes some of the time derivatives are calculated implicitly and other explicitly. The division between terms to be calculated explicitly and implicitly should be done in the manner that the larger time step for the semi-implicit discretisation is larger than a corresponding explicit method. Nowadays, it is common practice to treat selected linear terms implicitly and the remaining explicitly (Casulli, 2014). The advantage in comparing these schemes with explicit schemes is the ability to use larger time steps, thereby reducing the computational time. Semi-implicit schemes offer reliable solutions as they are unconditionally stable (Neelz, S. & Pender, 2013). As for the implicit schemes, the drawback of using semi-implicit schemes is that they present a high grade of code complexity (Neelz, S. & Pender, 2013).

iv. *Alternating Direction Implicit (ADI) schemes,* where the dependent variables are not determined by solving a full 2D matrix at each time step. Instead, the time step is divided into two half time steps and at each one them a set of one dimensional equations is implicitly calculated (Ahmadian et al., 2018). In particular, the x direction equations' system is solved in the first half time step and the y direction equations' system is then solved in the second half time step. ADI methods offer a good combination between accuracy and computational cost, and they have been largely used in many commercial and research models (Neelz, S. & Pender, 2013). However, they don't offer reliable results when rapidly changing flows are considered, being this a crucial aspect when dealing with flash flood and extreme flood events in general (Kvočka et al., 2015; Liang et al., 2006)

3.4 Shock Capturing methods

The SWE are largely utilised in modelling flood events of different nature. Some flood events such as flash floods, dam breaks, levee breaks, storm surges etc. present a rapid change in flow regimes as for example hydraulic jumps or steep hydraulic gradients (Liang et al., 2007c) which can be considered as numerical discontinuities or shocks, bores or jumps. These give rise to high spatial gradients in depth and velocity which are a challenge in terms of resolution for classical numerical schemes as they present spurious oscillation and generally require addition of artificial viscosity to stabilise the solution (Mingham et al., 2001). Numerical oscillations can be prevented through different approaches including implementation of shock capturing methods (Toro and Garcia-Navarro, 2007). These methods adopt, over the whole domain, a universal solution strategy thus there is no limit on the number and direction of shocks (Liang et al., 2007c).

Several shock capturing schemes are proposed in literature and generally they present as drawback an elevate computational cost. Nevertheless, recent advances in computational power made possible the development and the implementation in research and commercial models of shock capturing schemes (Neelz, S. & Pender, 2013).

Traditional shock capturing methods solve the discontinuity problem by using adjustable parameter or giving the same amount of dissipation to all the grid point. Principal drawback of this approach is that the accuracy of the results is guarantee only when not dealing with strong shock waves (Mingham et al., 2001; Yee et al., 1988).

In contrast with the classic approach, in the modern shock capturing methods the numerical dissipation is distributed non-linearly. Meaning that the level of dissipation varies through all the point of the computational grid which represent the domain and, therefore, adjustable parameters are not more required as the distribution of the dissipation is supported by automatic feedback mechanism (Mingham et al., 2001). In this way, the limitation of the classic approach is overcome and shock capturing algorithm can deal also with strong shock maintaining a high accuracy and robustness (Alcrudo, 2004; Toro and Garcia-

Navarro, 2007) with a little extra cost in terms of computational time (Mingham et al., 2001).

Among shock capturing methods applied in flood modelling the most used are the Lax-Wendroff method, Monotonic Upstream-Centered Schemes for Conservation Laws (MUSCL) the MacCormack method, the Total-Variation Diminishing (TVD) scheme (Néelz et al., 2009).

3.5 DIVAST-TVD

In this research, DIVAST-TVD has been used for modelling flood inundation and extent. DIVAST-TVD is a 2D numerical model based on finite difference introduced by Liang et al. (2006), the model is fully conservative and include shock-capturing algorithm. DIVAST-TVD uses a standard MacCormack scheme in association with a symmetric five points TVD term (Liang et al., 2007b). DIVAST-TVD has been developed to simulate hydrodynamics in river and coastal environments, by solving the SWE. A first-order upwind scheme is implemented to avoid spurious numerical oscillations, and where the solution is smooth a second-order accurate MacCormack scheme is deployed (Liang et al., 2006; Mingham et al., 2001). This numerical scheme is shock capturing, which means that it can capture discontinuities typical of trans- or super-critical river flows (e.g., hydraulic jumps, bore wave etc.). Several techniques are available in the literature to address such non-physical oscillations, with one such technique being the inclusion of a TVD algorithm, that can capture the sharp discontinuities without generating spurious oscillations (Kalita, 2016). The shock capturing feature of DIVAST-TVD makes this model ideal for modelling a short steep catchment, where high Froude number, or trans-critical and supercritical, flows, occur due to the peculiar characteristics of the basin itself (e.g., rapid variations in the channel topography and slope). Traditional 2D models which do not include shock capturing features have as a result inaccurate prediction in the maximum flood levels and the flood inundation extent and velocity field are erroneous. However, the DIVAST-TVD model is highly suitable for simulating flash floods, storm surges, and all flood flow scenarios that involve rapid changes in the hydrodynamic conditions (Liang et al., 2007c). A brief description of the model is given below, with further details in Liang et al. (2007a).

By neglecting Coriolis, wind and viscous forces, the SWEs can be expressed in the following form:

$$\frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{3.1}$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial \left(\frac{\beta q_x^2}{H}\right)}{\partial x} + \frac{\partial \left(\frac{\beta q_x q_y}{H}\right)}{\partial y} = -gH\frac{\partial \eta}{\partial x} - \frac{g q_x \sqrt{q_x^2 + q_y^2}}{H^2 C^2} \tag{3.2}$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial \left(\frac{\beta q_x q_y}{H}\right)}{\partial x} + \frac{\partial \left(\frac{\beta q_y^2}{H}\right)}{\partial y} = -gH\frac{\partial \eta}{\partial y} - \frac{g q_y \sqrt{q_x^2 + q_y^2}}{H^2 C^2} \tag{3.3}$$

where t = time; η = elevation of water surface above still water datum; q_x and q_y = discharges per unit width in the x and y directions respectively; β = momentum correction factor for a non-uniform vertical velocity profile; g = acceleration due to gravity; $H = h + \eta$ = total water column depth (where h is the depth below still water datum); and C = Chezy roughness coefficient.

Usually, the conservative form of the SWEs are deployed. Using this formulation the conservation of mass and momentum is ensured after the discretisation of the equations, in the following form (Liang et al., 2006) :

$$\frac{\partial X}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = S + T \tag{3.4}$$

$$X = \begin{bmatrix} H \\ q_x \\ q_y \end{bmatrix} \tag{3.5}$$

$$F = \begin{bmatrix} q_x \\ \frac{\beta q_x^2}{H} + \frac{gH^2}{2} \\ \frac{\beta q_x q_y}{H} \end{bmatrix} \tag{3.6}$$

$$G = \begin{bmatrix} q_y \\ \frac{\beta q_x q_y}{H} \\ \frac{\beta q_y^2}{H} + \frac{gH^2}{2} \end{bmatrix} \tag{3.7}$$

$$S = \begin{bmatrix} 0 \\ gH\frac{\partial h}{\partial x} - \frac{g q_x \sqrt{q_x^2 + q_y^2}}{H^2 C^2} \\ 0 \end{bmatrix} \tag{3.8}$$

$$T = \begin{bmatrix} 0 \\ 0 \\ gH\frac{\partial h}{\partial y} - \frac{g q_y \sqrt{q_x^2 + q_y^2}}{H^2 C^2} \end{bmatrix} \tag{3.9}$$

Where *X* represents the independent variables H, q_x, q_y; *F* and *G* represent the flux terms and the source terms are being represented by *S* and *T*.

The formulation proposed in equations (3.5) to (3.9) can lead to numerical imbalance associated with the treatment of the bed slope term (Liang et al., 2006). This problem can be amended by transforming the equations (3.5) to (3.9) in such a way the independent variable H is replaced by η (Rogers et al., 2003) and we can express the aforementioned equations as (Liang et al., 2006):

$$X = \begin{bmatrix} \eta \\ q_x \\ q_y \end{bmatrix} \tag{3.10}$$

$$F = \begin{bmatrix} q_x \\ \dfrac{\beta q_x^2}{h+\eta} + \dfrac{g\eta^2}{2} + gh\eta \\ \dfrac{\beta q_x q_y}{h+\eta} \end{bmatrix} \tag{3.11}$$

$$G = \begin{bmatrix} q_y \\ \dfrac{\beta q_x q_y}{h+\eta} \\ \dfrac{\beta q_y^2}{h+\eta} + \dfrac{g\eta^2}{2} + gh\eta \end{bmatrix} \tag{3.12}$$

$$S = \begin{bmatrix} 0 \\ g\eta \dfrac{\partial h}{\partial x} - \dfrac{g q_x \sqrt{q_x^2 + q_y^2}}{(h+\eta)^2 C^2} \\ 0 \end{bmatrix} \tag{3.13}$$

$$T = \begin{bmatrix} 0 \\ 0 \\ g\eta \dfrac{\partial h}{\partial y} - \dfrac{g q_y \sqrt{q_x^2 + q_y^2}}{(h+\eta)^2 C^2} \end{bmatrix} \tag{3.14}$$

Using the operator-splitting technique, the solution to Equation (3.4) is obtained by solving the two one-dimensional equations (3.15) and (3.16) (Liang et al., 2006).

$$\frac{\partial X}{\partial t} + \frac{\partial F}{\partial x} = S \tag{3.15}$$

$$\frac{\partial X}{\partial t} + \frac{\partial G}{\partial y} = T \tag{3.16}$$

which can be explicitly discretised using a regular rectangular grid in this way the equation can be written as (Liang et al., 2006):

$$X_{i,j}^{n+1} = L_x X_{i,j}^{n} \tag{3.17}$$

$$X_{i,j}^{n+1} = L_y X_{i,j}^{n} \tag{3.18}$$

With L_x and L_y being the finite-difference operators and the subscript represent the spatial grid level and the superscript represent temporal time step.

In this way the solution to the equation (3.4) can be approximated by (Liang et al., 2006):

$$X_{i,j}^{n+2} = L_x L_y L_y L_x X_{i,j}^{n} \tag{3.19}$$

In DIVAST TVD the MacCormak scheme is utilised to consecutively solve the two one-dimensional hyperbolic equations at each time step. This scheme belongs to the family of predictor-corrector schemes, where the predictor steps give a rough estimation of the calculation of the unknow variable, and the corrector steps refine the results obtained in the predictor step.

The classic MacCormack scheme is an explicit second-order scheme (Mingham et al., 2001), to remove the undesired non-physical oscillation a TVD term is added to the corrector step (Liang et al., 2006).

The aforementioned TVD term appended to the corrector step of the MacCormack scheme in order to prevent the emergence of non-physical oscillations near the sharp gradient regions and is defined as (Liang et al., 2006):

$$TVD_i^n = \left[G(r_i^+) + G(r_{i+1}^-)\right] \cdot \Delta X_{i+1/2}^{n+1} - \left[G(r_{i-1}^+) + G(r_i^-)\right] \cdot \Delta X_{i-1/2}^{n+1} \tag{3.20}$$

Bearing this in mind, the MacCormack TVD scheme is defined as (Liang et al., 2006):

$$X_j^{n+1} = \frac{\left(X_i^p + X_i^c\right)}{2} + \left[G(r_i^+) + G(r_{i+1}^-)\right] \cdot \Delta X_{i+1/2}^{n+1} - \left[G(r_{i-1}^+) + G(r_i^-)\right] \cdot \Delta X_{i-1/2}^{n+1} \tag{3.21}$$

With:

$$X_{i+1/2}^{n} = X_{i+1}^{n} - X_{i}^{n} \tag{3.22}$$

$$X_{i-1/2}^{n} = X_{i}^{n} - X_{i-1}^{n} \tag{3.23}$$

$$r_{i}^{+} = \frac{\langle \Delta X_{1-1/2}^{n}, \Delta X_{1+1/2}^{n} \rangle}{\langle \Delta X_{1+1/2}^{n}, \Delta X_{1+1/2}^{n} \rangle} \tag{3.24}$$

$$r_{i}^{-} = \frac{\langle \Delta X_{1-1/2}^{n}, \Delta X_{1+1/2}^{n} \rangle}{\langle \Delta X_{1-1/2}^{n}, \Delta X_{1-1/2}^{n} \rangle} \tag{3.25}$$

Where r values are dependent on the gradients around the solution cell and $\langle \quad \rangle$ in equations 3.24 and 3.25 denote the scalar products of the vectors inside the brackets. G is a function dependent on the wave speed direction and the flux limiter function defined as (Liang et al., 2006):

$$G(x) = 0.5 \times C \times [1 - \varphi(x)] \tag{3.26}$$

With:

$$\varphi(x) = max\big(0, min(2x, 1)\big) \tag{3.27}$$

the flux limiter function (Liang et al., 2006);

And the variable C defined as (Liang et al., 2006):

$$C = \begin{cases} C_r \times (1 - C_r), & C_r \leq 0.5 \\ 0.25, & C_r > 0.5 \end{cases} \tag{3.28}$$

With C_r being the local Courant number defined as (Liang et al., 2006) :

$$C_r = \frac{\Delta t \left(\left| \frac{q_x}{H} \right| + \sqrt{gH} \right)}{\Delta x} \tag{3.29}$$

In which q_x is the discharge per unit width in x direction, H the total water column depth, g gravitational acceleration, Δt the time step and Δx the spatial parameter.

Further details on the model verification and relevant case studies can be found in Ahmadian et al.(2018); Hunter et al. (2008); Kvočka et al. (2017); Liang et al. (2007a, 2007b, 2007c); Neelz, S. & Pender, (2013).

3.6 Summary

In this chapter, the theoretical background related to the numerical modelling used in this research has been briefly presented. Various schemes can be adopted for flood modelling with different pros and cons. Bearing this in mind it is important to choose the most appropriate model depending on the scope of the flood analysis and the typology of flood considered in the study (see also Chapter 2 - Literature Review), otherwise the results obtained will not be trustworthy for the considered case study.

For the typology of flood considered in this research study, namely flash floods in steep catchments, it has been decided to use the numerical model DIVAS-TVD 2D. The choice has been done considering that such numerical model is able to solve the SWE also for high Froude number conditions. The additions of the TVD features in DIVAST-TVD 2D makes this model ideal for modelling short, steep catchments and all the cases where trans-critical or supercritical flows occurs (Kalita, 2016; Musolino et al., 2020b).

4 Case Studies

4.1 Introduction

In this chapter, two flash flood events recorded in 2004 and 2012 respectively are considered as case studies. Using the numerical model DIVAST-TVD 2D, flood characteristics, namely water depth, flow velocity and Froud number, were calculated and then used to assess flood hazard in Chapter 5.

Case studies here considered are i) the 2004 Boscastle (UK) flash flood and ii) the 2012 Borth (UK) flash flood. These two case studies have been selected for the availability of existing data both for setting up and validation of the models and for a comparison of the results when applying different assessment methodologies, which helps with verification of the obtained results. Moreover, both the location are famous touristic places in the UK, which is ideal to verify methodologies relative to flood hazard assessment for pedestrians.

Different case studies were selected to test the main assumptions of this research which are: i) determine the most suitable assessment methodology for determining flood hazard for pedestrians in case of extreme flood events as flash floods, ii) mechanics method improvements, iii) improvements in designing flood evacuation plans. Since different flood characteristics, different catchments and level of urbanization are considered, results can confirm general validity of the main assumptions presented in this work. This means that the methods here proposed can be applied to other case studies.

4.2 Description of case studies area

4.2.1 Boscastle

Boscastle is an ancient village located at the end of a narrow and steep catchment in Cornwall – UK (Figure 4.1). Nowadays, it is a touristic place visited by many people especially during summertime. The village is famous among the others for its stunning location and for the local museum which host the world's largest collection of witchcraft artefacts (Rowe, 2004). The village was also used as set for a BBC television show.

On 16th August 2004, an extreme rainfall event occurred over the North coast of Cornwall with up to 200 mm of rain fallen in about 5 hours over a 20 km^2 catchment area (HR Wallingford, 2005; Roca and Davison, 2010). When such amount of rain fell, upon ground that was already saturated due to several previous weeks of heavy rainfall (HR Wallingford, 2005), the water had nowhere to go but down the steep valley and into the harbour, that was already full at high tide. During the flood event streets were inundated by over 2 metres of water (Xia et al., 2011a) and people had to be rescued from cars and rooftops by helicopters (Figure 4.2 and Figure 4.3). This disastrous flash flood severely affected the village and its population, causing extensive damage. The consequences of the flash flood can briefly summarised as follow: 100 people were airlifted to safety, six buildings collapsed due to the strong force of the flood water, over 70 properties were flooded; 79 cars were washed away into the harbour and the two local bridges were blocked, the "Lower Bridge" collapsed and had to be reconstructed after the event (Environment Agency, 2004; Rowe, 2004). Damages also occurred to the sewerage system, and to the water and electricity supplies, causing interruption to these services for some time. Although Boscastle was temporarily inaccessible, it was fortunate that there were no fatalities; damages were estimated in the order of several million pounds without considering psychological consequences suffered by people affected by trauma due to consequences of the flood (Environment Agency, 2004; HR Wallingford, 2005; Rowe, 2004).

Characteristics of both basin and flash flood, made Boscastle an ideal case study for the scope of this research work relative to danger to human life due to flood events (Penning-Rowsell et al., 2013).

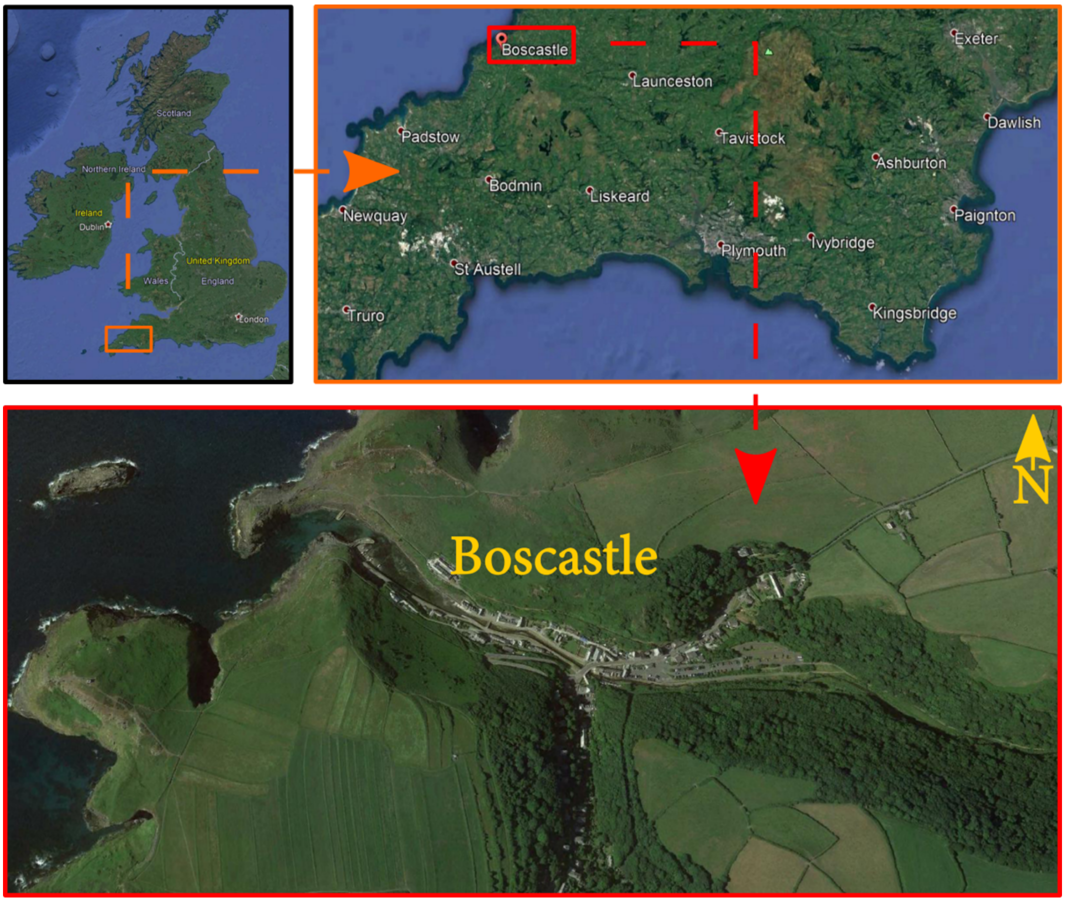


Figure 4.1 – Boscastle (UK), source google maps

Figure 4.2 - Boscastle Consequences of Flood Event

Figure 4.3 – Boscastle a), b), c) people wading in flooding water d) flash flood event (HR Wallingford, 2005; Rowe, 2004)

4.2.2 Borth

Borth is a village located on the coast of West Wales – UK (Figure 4.4). It is part of the Dyfi Biosphere, which is the only UNESCO Biosphere reserve in Wales. The village is situated along the Welsh Coast Path, and it is part of Dyfi National Nature Reserve. There are many touristic attractions and facilities in Borth and surrounding area such as caravan parks, camping site, golf club, zoo, seasonal festival, and Carnival make the area strategic for the local economy. This area is located downstream of river Leri catchment, which is a relatively small steep catchment. Large areas of the floodplain have been developed as camping and caravan sites; thus, these are classified as high exposure areas due to the large number of temporary residents exposed to flood hazard.

On 9th June 2012 heavy rain caused a flash flood. The most severe flooding issues were in Tal-y-bont, Dol-y-bont, Borth and surrounding area. About 60 properties and Caravan parks (238 individual unit were flooded) in those areas were evacuated

(Figure 4.5). This event has been reported as: “the biggest flooding in living memory” (Foulds et al., 2012).

Considering that in West Wales, there is a high demand for touristic area development, an accurate flood hazard assessment and proper flood defence schemes have to be deployed, otherwise negative flood impacts from events as the flash flood occurred in June 2012 will be likely to repeat. Or even more disastrous, like the one that happened in Spain during a flash flood in 2007 where 87 people died in a campsite (Foulds et al., 2012).

The steep catchment were is located the study area and the flash flood happened on the 9th June 2012 are an ideal case study for the scope of this research work even more pondering that flood hazard level for pedestrians is crucial aspect considering the touristic vocation of the place (Musolino et al., 2020a).

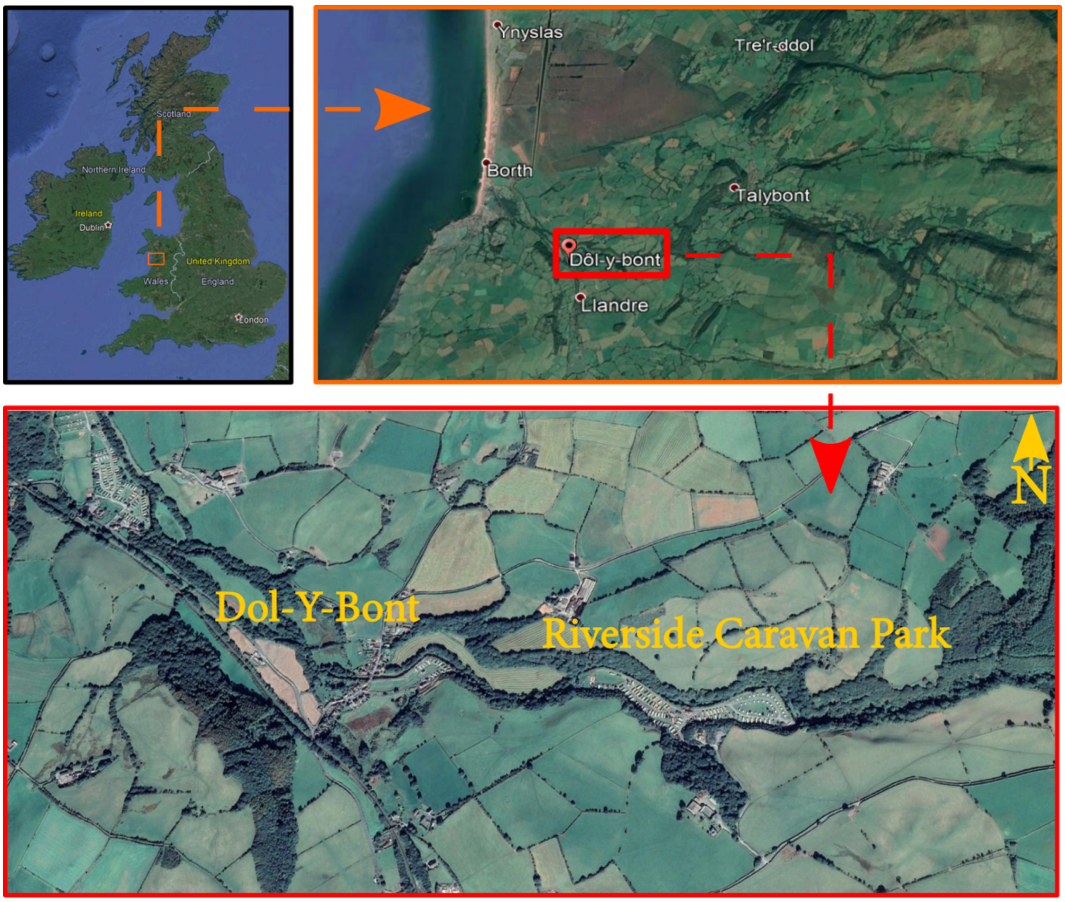


Figure 4.4 - Borth Dol-Y-Bont and Riverside Caravan Park (UK), source google maps

Figure 4.5 – Caravan Park in the Borth surrounding area a), b) Riverside Caravan Park c), d) Aberystwyth Holiday village during the 9th of June 2012 flood event

4.3 Flood Characteristics - Boscastle

The domain analysed for the case study of Boscastle is 235m wide and 665m long, covering a surface of 0.156 km^2 (Figure 4.6), which was divided into square cells, each with an area of 1m^2. Topographic data (Figure 4.7) were collected through LIDAR (Laser Imaging Detection and Ranging), during a survey undertaken by the Environmental Agency.

Figure 4.6 – Boscastle domain, source Google Earth

Post the flood event HR Wallingford (2005) prepared a detailed report after the flood event. This manuscript provided the basis for estimating the roughness characteristics across the domain. A constant Manning's roughness coefficient of value 0.040 was used across the whole domain (Kvočka et al., 2015; Musolino et al., 2020b). Also, the modelling performed by HR Wallingford (2005) to reconstruct the flood event, indicated that the peak discharge, located on the Valency just downstream of the confluence with the Jordan, was of a magnitude of 180 m^3/s (Figure 4.8). The frequency of the flood event, using the FEH statistical and rainfall-runoff methods, was estimated to be of the order of 1 in 400 years (Roca and Davison, 2010). The two bridges present in the computational domain were modelled as fully blocked, setting the computational cells relative to the blockage area as "inactive cells" which are not included into the computational process. This to keep into account what was reported in the post-flood report by HR Wallingford (2005) which indicated that the two bridges where blocked during the early stages of the flood event.

Calibration and validation of the model were undertaken in some detail and were reported previously (Falconer et al. 2012; Kvočka et al. 2017, 2015; Xia et al. 2011b).

Flood inundation levels, velocities, and flow Froude number values are illustrated in Figure 4.9 a, b, c. It can be observed that generally the maximum velocities (Fig. 4.9 b) are greater than 1 m/s and the maximum Froude number (Figure 4.9 c) is generally near to, or greater than 1. As reported by Kvočka et al. (2018), Liang et al. (2007), Mingham et al. (2001), Néelz et al. (2009) and by many more authors, when dealing with trans-critical and/or critical flow regimes which are, and generally when considering flow scenarios which present a quick variation of flow regime, it is necessary to adopt a hydrodynamic model which include a TVD scheme. In this way, shocks (discontinuities) will not affect the reliability of the results.

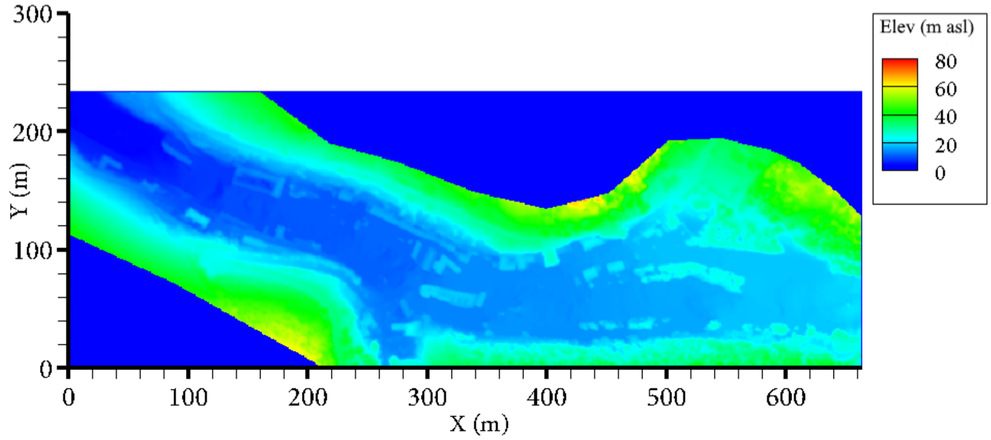
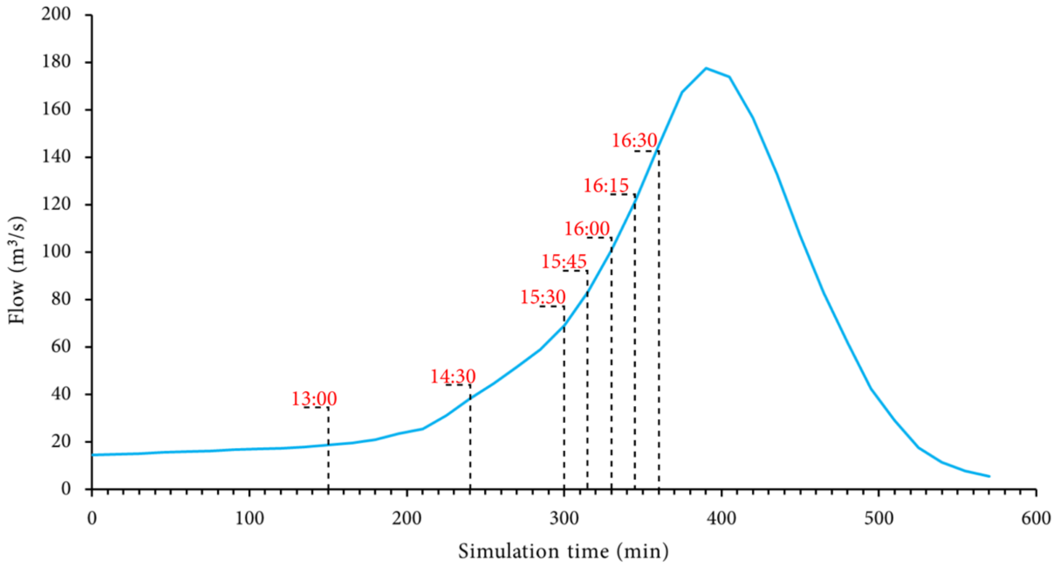


Figure 4.7 – Boscastle topographic data



13:00 River rose by 6 feet with lot of debris

14:30 Valency begins to spills over right bank

15:30 Cars floating in the car park

15:45 Valency begins to spills over North bank between the two bridges

16:00 Witnesses see 3m wall of floodwater; B3263 is impassable

16:15 Main road bridge blocked by debris causing water levels upstream to rise rapidly

16:30 People start to evacuate buildings

Figure 4.8 - Hydrograph and Timeline of the events: HR Wallingford (2005) & E.A. (UK) (2004)

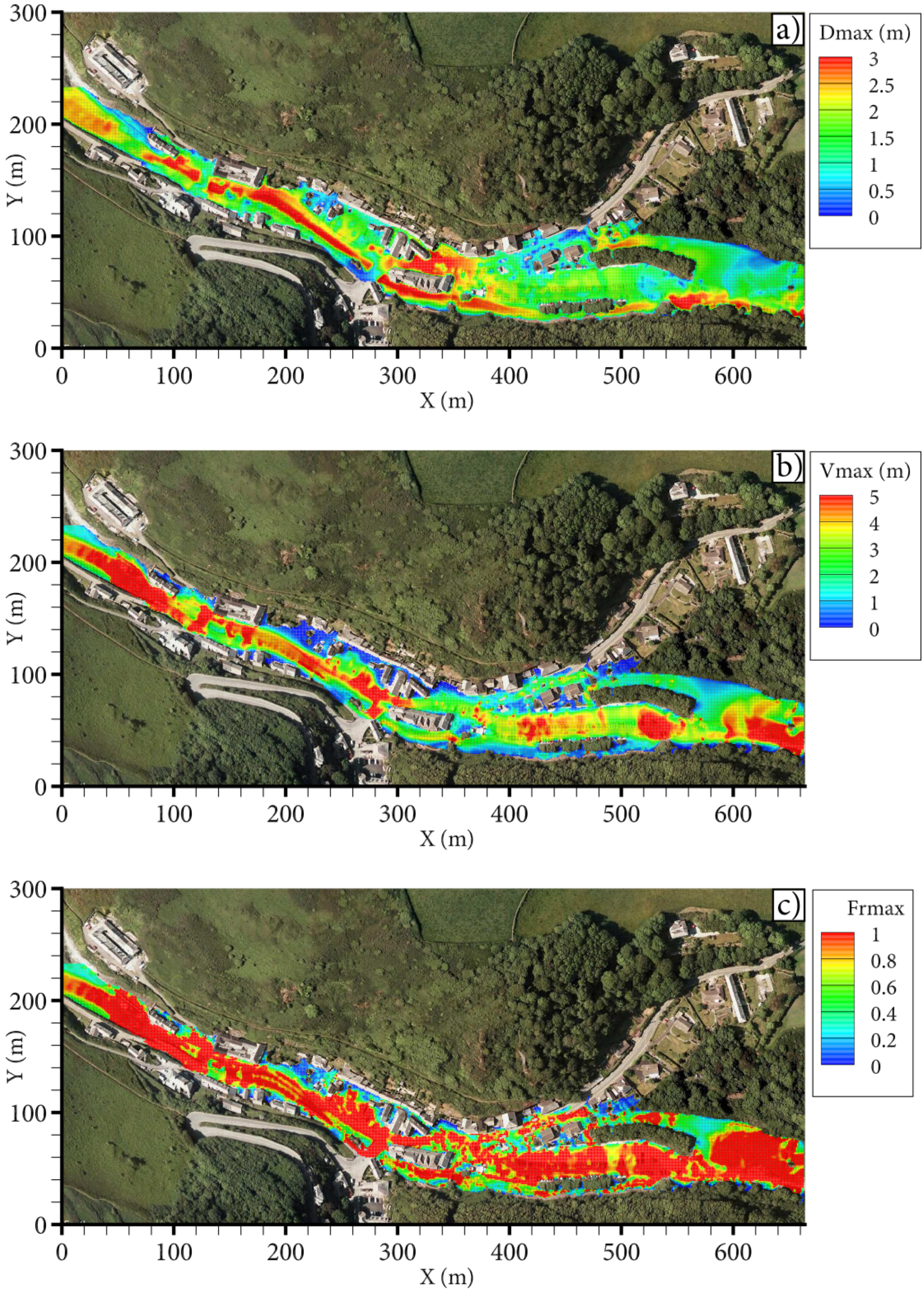


Figure 4.9 - Flow characteristics a) max water depth, b) max flow velocity, c) max Froude number - Boscastle case study

4.4 Flood Characteristics - Borth

Relatively to Borth, the domain insists on an area of 63 km^2 (9 km long and 7 km wide) (Figure 4.10) including the areas of Borth, Tal-y-bont and Dol-y-bont. Topographic data necessary as input data to set up the hydrodynamic model, have been extracted from a 2m LIDAR (Laser Imaging Detection and Ranging). The flow entering trough the mains rivers, (i.e., River Leri and River Cuelen), was used as upstream boundary condition. The simulated flood event was a 1:100-year flood event, with a discharge peak of 64.5 m^3/s for River Leri and 19.1 m^3/s for the River Cuelen. Water levels in the Dify estuary were set as downstream boundary condition (Musolino et al., 2020a). Roughness parameters were assigned on the basis of Kvočka et al. (2018), to the floodplain it were assigned the value of 0.05, the value of 0.04 was assigned for both river channel and drainage channel on the Cors. Calibration and validation of the model was undertaken and has been reported previously by Kvočka et al.(2018)

Flood inundation levels, velocities and flow Froude number values are illustrated in Figure 4.11 a, b, c, and it can be observed that generally the maximum velocities (Fig. 4.11 b) are greater than 1 m/s and the maximum Froude number (Figure 4.11 c) is generally near to 1.

Dealing with flow conditions as the one illustrated in Figure 4.11 a, b, c, and in general with flow scenarios related to flash floods, being this the case, can represent a challenge for many numerical models (Néelz et al., 2009)(see also Chapters 2 and 3) as this flow conditions present sudden change in the flow regime which lead to discontinuities in the model solutions (Kvočka et al., 2018), in such case it is necessary to include in the numerical model schemes as the TVD scheme included in DIVAST-TVD 2D, which are able to overcome the limitations of models that are not including such schemes (Liang et al., 2007c; Mingham et al., 2001).

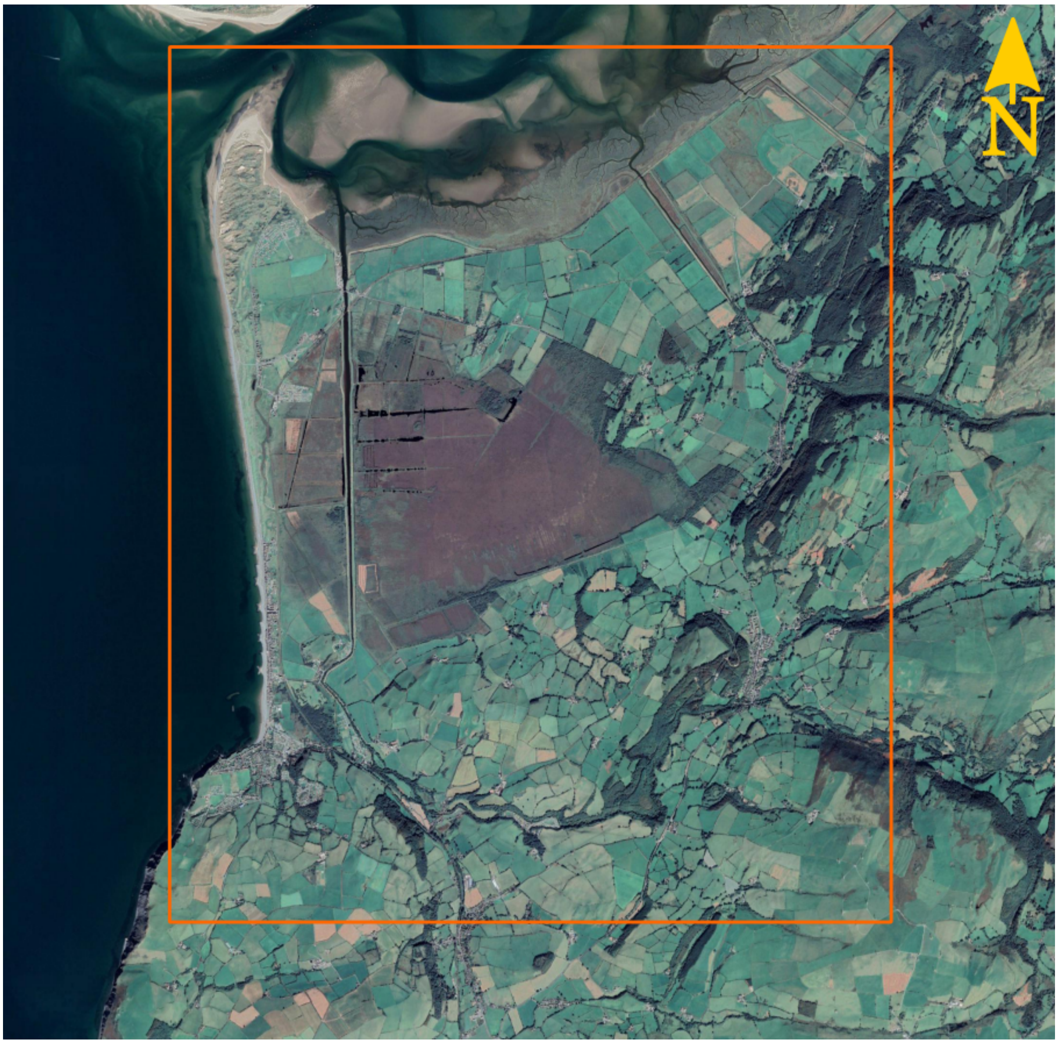
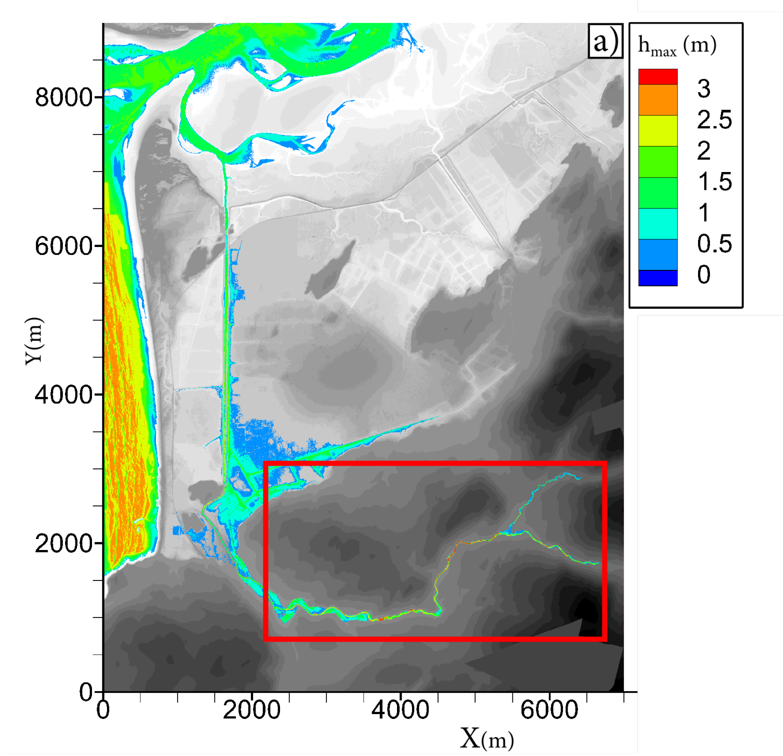
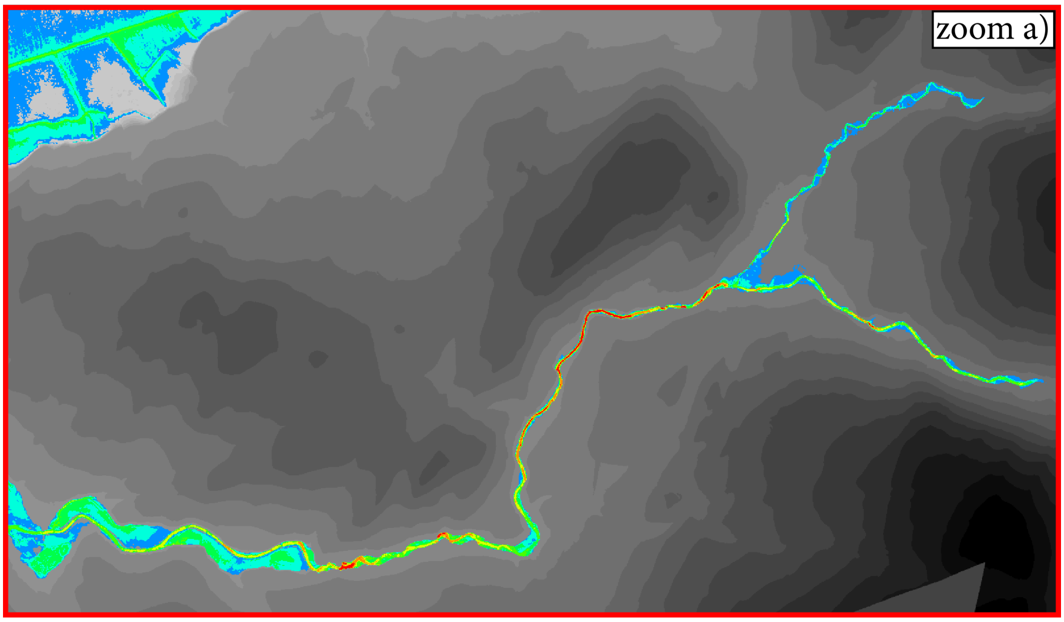
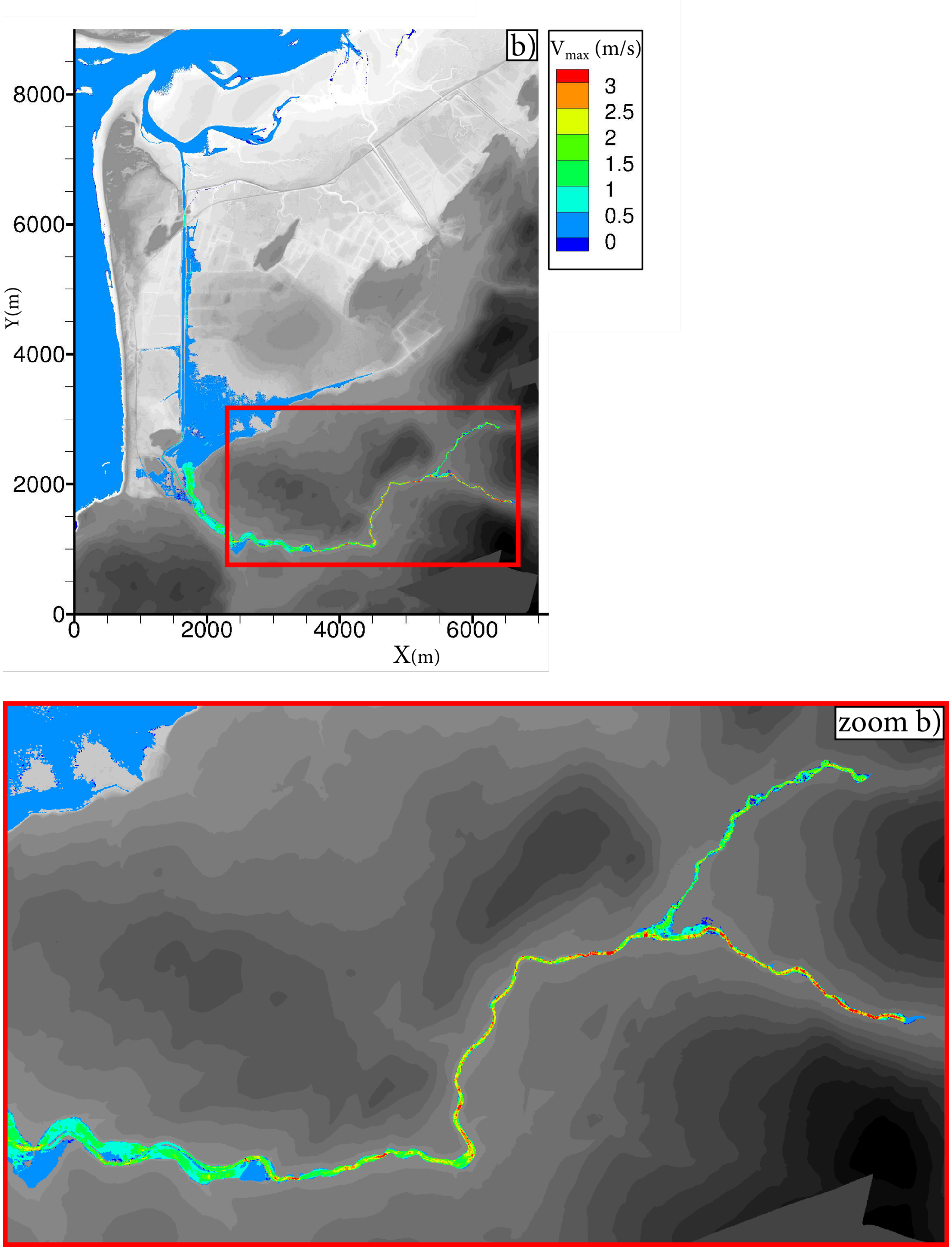


Figure 4.10 - Borth domain, source google earth


a)
h_{max} (m)
3
2.5
2
1.5
1
0.5
0
8000
6000
4000
2000
0
Y(m)
0
2000
4000
6000
X(m)


zoom a)


b)
V max (m/s)
3
2.5
2
1.5
1
0.5
0
8000
6000
4000
2000
0
Y(m)
0
2000
4000
6000
X(m)
zoom b)

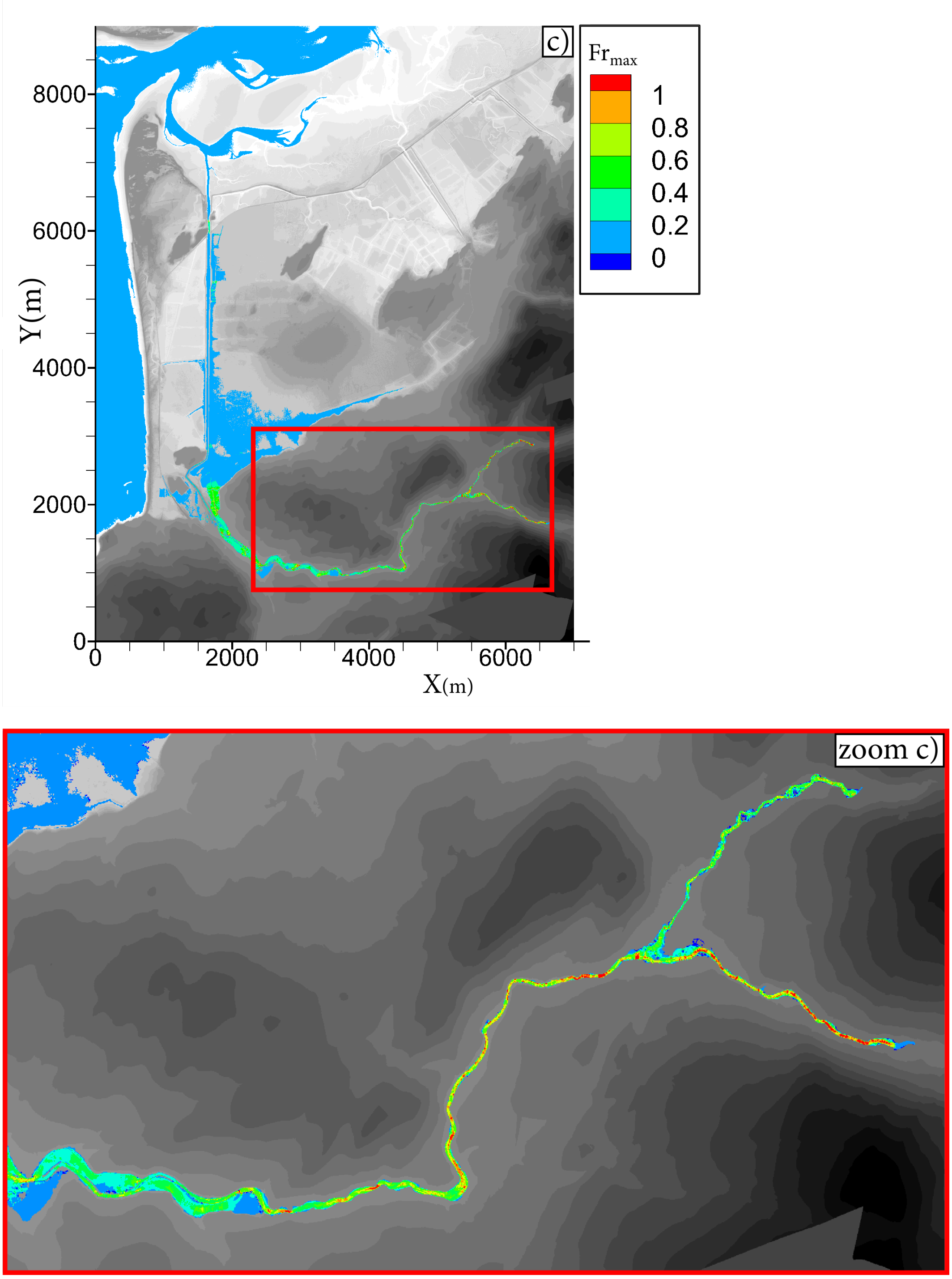


Figure 4.11 - Flow characteristics a) max water depth, b) max flow velocity, c) max Froude number - Borth case study

4.5 Summary

In this Chapter a description of the case studies and of the flood events considered is reported in conjunction with the main parameters used for the flood modelling. Results of the simulations for flood events in both Boscastle and Borth are also presented. These results will be used in the next chapters as input data for the flood hazard assessment considered and for evacuation plans design.

The floods herein considered are flash floods, moreover the study areas is located over steep catchments, reasons why it is important to use a numerical model able to deal with shocks (as DIVAST-TVD 2D), otherwise results can be not reliable (Kvočka et al., 2018; Liang et al., 2007c; Néelz et al., 2009). The case studies described in this Chapter represent a variety of flood characteristics (i.e., peak flow, return period, flood extension, flow velocity, etc.) and as well level of urbanisation and terrain conditions. This aspect it is very important because it will guarantee a general validity in terms of results when using such results in applications as flood hazard assessment for pedestrians and evacuation plan designing presented in Chapter 5 and 6.

5 Flood Hazard Assessment: a pedestrian perspective

5.1 Introduction

This chapter is dedicated to the analysis of the methods used for assessing the hazard posed by floods to pedestrians. Two main approaches have been considered for assessment of flood hazard: (i) a revised mechanics-based approach and (ii) experimental approaches, with particular focus on the criteria for the stability of pedestrians in floods used by regulatory authorities in the USA (method A), Australia (method B), the UK (method C) and Spain (method D), as well as the empirical method (method E) proposed by Martínez-Gomariz et al. (2016).

These methodologies are illustrated in Sections 5.2.1 to 5.2.6 respectively. In Section 5.3 are presented the results from the application of the methodologies, with these results being analysed and discussed in Section 5.4. Then, in Section 5.5 are reported the main findings of this chapter.

The scope of these applications is to show the benefits of flood hazard assessment for pedestrians when using an improved mechanics-based method, especially in case of extreme flood events as flash flood. With this being one of the key objectives of this research work.

5.2 Methods

5.2.1 Revised Mechanics Based Method

This Mechanics Based Method (MBM) was initially proposed by Xia et al. (2014a, 2014b), who developed a stability criterion for a human body immersed in flood water, for various ground slopes, by merging a theoretical analysis and experimental results. The method considers both toppling and sliding as failure mechanics and includes the effects of the forces acting on a human body when moving in floodwaters (Figure 5.1), namely, buoyancy force, frictional force, drag force, normal reaction force and gravitational force. The authors also included effects of a non-uniform upstream velocity profile acting on the human body, which moved on a horizontal or sloping ground in flood waters, the impact of the net buoyancy force on a human body for the case of rapidly varying water depths is also included.

Experimental data collected during flume experiments, and the datasets available in the literature, were used to calibrate the parameters included in the formulae.

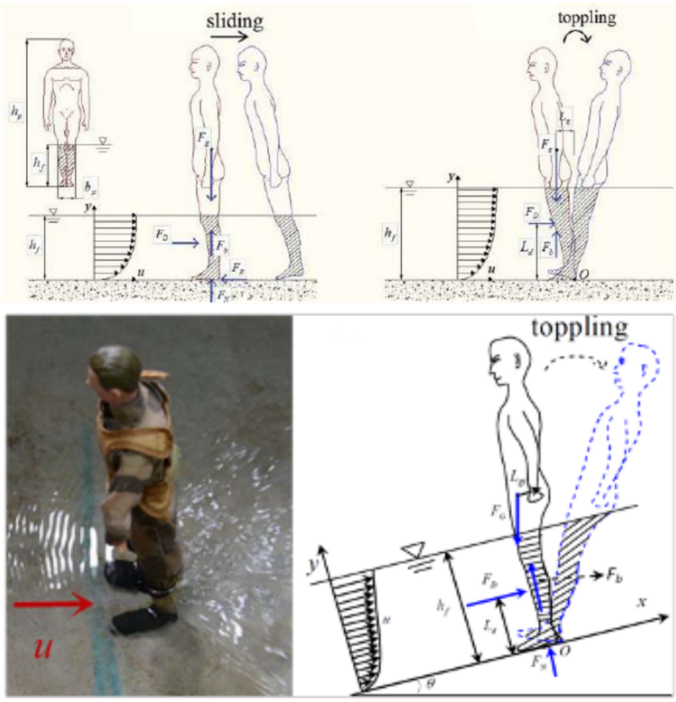


Figure 5.1 – scheme of forces applied to a human body in floodwaters (Xia et al., 2014b)

Firstly, to determine pedestrians' instability in floodwaters, it is necessary to calculate their incipient velocity. For pedestrians such velocity is defined similarly to the incipient velocity of sediment particles in sediment transport formulation, and it can be described as the velocity at which a person loses stability in floodwaters, through the mechanisms of sliding or toppling, before starting to move with the flow.

The sliding failure mechanism is given as (Xia et al., 2014a):

$$U_c = \alpha \left(\frac{h_f}{h_p}\right)^{\beta} \sqrt{\frac{m_P}{\rho_f h_p hf} - \left(a_1 \frac{h_f}{h_p} + b_1\right)\left(\frac{a_2 m_P + b_2}{h_p^2}\right)} \tag{5.1}$$

For a sloping terrain, the toppling failure mechanism is given as (Xia et al., 2014a):

$$U_c = \alpha \left(\frac{h_f}{h_p}\right)^{\beta} \sqrt{\frac{m_P}{h_f^2 \rho_f}(\cos\theta + \gamma \sin\theta) - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_P}\right)(a_2 m_P + b_2)} \tag{5.2}$$

where U_c = incipient velocity, h_f = water depth (m), h_p = height of pedestrian (m), m_p = weight of pedestrian (kg), ρ_f = density of water (kg/m^3), α and β = empirical coefficients, and a_1, a_2, b_1, b_2 = coefficients defining the characteristic features of a human body as shown in Table 5.1, θ = angle of the sloping ground, and γ = correction constant.

Values for the coefficients a_1, b_1, a_2, b_2 can be evaluated from the typical features of a human body, such as: height, mass, and volume, as well as the mass of the body segment parameters (such as legs, arms, torso, etc.). Since both case studies are in the UK, the values used for the characteristics of a pedestrian are based on the typical dimensions of an average British person (except for α and β, since these are not available at the moment), and as given in Table 5.1.

The parameters α and β depend on several factors, such as the shape of the human body, pedestrian's ability to adjust his/her position to maintain stability in floodwaters (i.e., to resist sliding or toppling in flood waters), and the drag and friction coefficients between the pedestrian and the ground surface. Typical values for α and β are different when considering toppling or sliding and allow the calibration of the method using both tests with real pedestrians and dummies (Musolino et al., 2020b).

Table 5.1 - Revised MBM parameters used

Parameter	Value	Reference
a_1	0.735	(Q. Chen et al., 2018)
b_1	0.265	(Q. Chen et al., 2018)
a_2	1.015×10^{-3} m^3/kg	(Q. Chen et al., 2018)
b_2	-4.927×10^{-3}m^3	(Q. Chen et al., 2018)
α	1.705 (toppling)	(Xia et al., 2014a)
β	0.197 (toppling)	(Xia et al., 2014a)
α	7.975 (sliding)	(Xia et al., 2014b)
β	0.018 (sliding)	(Xia et al., 2014b)
ρ_f	1000 kg/m^3	(Xia et al., 2014b)
γ	10.0	(Xia et al., 2014b)
h_p	1.75m	(ONS - Office for National Statistics (UK), 2010)
m_p	83.7 kg	(ONS - Office for National Statistics (UK), 2010)

Once incipient velocity is determined for both sliding and toppling failure mechanism, it is possible to determine the Flood Hazard Rating (FHR) as follows:

$$FHR = MIN\left(1, \frac{U}{U_c}\right) \tag{5.3}$$

where U = flow velocity and U_c = incipient velocity, which is the minimum velocity of either $U_{toppling}$ or $U_{sliding}$.

Regarding the values of the incipient velocity, two values are fixed in this method. The first fixed value is for a water depth of zero. In this case the value of the incipient velocity is fixed as 25 m/s, otherwise the resulting calculations would lead to an error due to the division by zero. The second fixed value is of incipient velocity equal to 0.5 m/s. This value was assumed when that part of Equation 5.1 and 5.2 under the root square sign was less than zero. This second fixed value represents a critical state for the flood hazard assessment as it is the minimum value of the incipient velocity and is the one that gives the highest flood hazard rate. In its original formulation the MBM assessed the flood hazard for pedestrian using the principle of bivalence. In other words, there is a single threshold value defining the state of hazard or not for pedestrians. For a better classification of the stability of a human body in floodwaters and thus, a more meaningful assessment, two more thresholds have been added including 0.3 and 0.6 this subdivision corresponds to the classification of the method actually used in the UK e.g. method C in this research work (Kvočka et al., 2016; Musolino et al., 2020b). A classification and description of the thresholds is reported in Table 5.2.

Table 5.2 – Classification and description of MBM's thresholds

FHR	Description	
FHR <0.30	Low	Caution
0.30 ≤ FHR <0.60	Moderate	Dangerous for some
0.6 ≤ FHR <1.0	Significant	Dangerous for most
FHR =1.0	Extreme	Dangerous for all

The main aspect that differentiates the revised MBM and empirically derived flood hazard methods is the way the forces induced by the flood condition are considered. Formulae derived by using empirical methods, the overturning force applied to a body is proportional to the water depth times velocity (i.e. $H_f \cdot v$)(Arrighi et al., 2017; Musolino et al., 2020b). In contrast, for the mechanics-based method the overturning force is proportional to the water depth times the square of the velocity (i.e., $H_f \cdot v^2$). Consequence of this different formulation is that higher velocities and thereby momentum, have more relevance in this method, particularly for high velocity flood flows (Musolino et al., 2020b). This aspect allows the method to be particularly suitable for conditions where sudden changes occur in the flood regime, such as extreme flood events, flash floods, etc, which are generally characterised by deeper floodwaters, higher flow velocities and sudden variations in the flow regime. It is necessary to include the full physical analysis, as for the mechanics based approach in order to obtain a reliable assessment of the flood hazard for pedestrians (Arrighi et al., 2017; Kvočka et al., 2016; Milanesi et al., 2015; Musolino et al., 2020b).

Slope is an important factor which can significantly affect the flood hazard assessment for pedestrians (González-Riancho et al., 2013; Musolino et al., 2020a). One of the refinements of this research has been the inclusion in the calculations, of the term related to the slope in Equation 5.2. Initially, this term was proposed by (Xia et al., 2014a) but, in practical application has generally been omitted for simplicity. The term relative to the slope in Equation 5.2 is represented through the additional term, given by $(cos\,\theta + \gamma\, sin\,\theta)$, in which θ represents the slope angle of the ground. In this research the incipient velocity equations, (Equation 5.1 and 5.2), have been included in the DIVAST-TVD presented in Chapter 3. The slope of each computational cell was calculated by first evaluating the ground slope between the centre of the cell and the centre of the four neighbouring cells, as shown in Figure 5.2. The highest slope calculated was then selected as the critical slope to be used for the value of θ in Equation 5.2. In this way, the most adverse situation is considered to ensure safety.

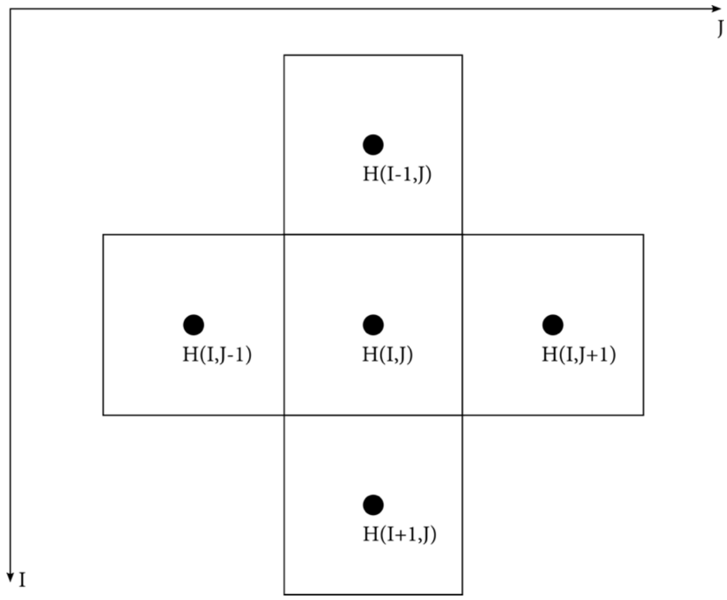


Figure 5.2 - Computational cells configuration considered for the determination of ground slope angle

In considering the complex shape of a human body and its interaction with the hydrodynamics of a flood flow, such connection depends not only on the flow conditions, but also on the portions and shape of the body that are in contact with flood waters (Arrighi et al., 2017). Hence, a relevant aspect of the revised MBM is that it is possible to obtain accurate physics based stability thresholds for a population that live in different geographic areas or countries (e.g. Europe, America, Asia, etc.), as well as considering the population's sub categories (e.g. male, female, children, elderly etc.) (Kvočka et al., 2016; Milanesi et al., 2015; Musolino et al., 2020b; Xia et al., 2014b, 2014a).

5.2.2 Method A

In the 1988 the U.S. Department of the Interior published the technical report: "Downstream Hazard Classification Guidelines" which includes guidelines for assessing the flood hazard derived from floodwaters released at the structure or water released by complete or partial failure of a dam and/or associated structures (e.g., a dike). The guidelines specify that "only direct effects of a dam-break flood on persons, property or outstanding natural resources at officially designated parks, recreation areas, or preserves downstream form the dam are considered (U.S. Department of the Interior, 1988).

These guidelines provide several graphs for assessing the flood hazard for different categories as house built on foundations, mobile homes, passengers of vehicles, adults and children (pedestrians) with "adult" being defined by the guidelines as a person over 1.5 m in height and 54 kg in weight. These graphs has been derived by authors of the guidelines (U.S. Department of the Interior, 1988) using previous works of Abt et al.(1989); Black, (1975); Love, (1989). In Figure 5.3, it is reported the graphs proposed for pedestrian routes for children (Figure 5.3 a) and adults (Figure 5.3 b). The graphs reported in Figure 5.3 are "depth-velocity flood danger level relationship" (U.S. Department of the Interior, 1988) in other word the hazard level is assigned based on the product of depth and velocity (DV) relationships. Using the graph in Figure 5.3 a) or Figure 5.3 b) is a decision that the guidelines leave to the analysts, who have to make the choice on the basis of their knowledge and understanding of the population. However, the guidelines suggest that in case of mixed population (i.e., adults and children) it is recommended to use the children's graph, adults' graphs should be used in cases where children are not expected as worksites or adults-only residential area. Infants are not considered separately as it is assumed to be safely attended by adults (U.S. Department of the Interior, 1988).

As suggested by the guidelines, all the pedestrian staying inside the inundated area are considered as "lives in jeopardy" (U.S. Department of the Interior, 1988) and subject to a combination of flood depth and velocity plotting above the low danger zone reported in Figure 5.3 a) and 5.3 b). Only when a strong justification is presented by the analyst, no lives in jeopardy can be attributed to pedestrian subject to a combination of water depth and velocity plotting within the judgment zone. Instead, for a combination of water depth and velocity plotting within the high danger area all pedestrians can be considered as "lives in jeopardy", except in cases where a strong justification can be presented by the analysts.

According with the guidelines, if flood depth and velocity cannot be determined with reasonable accuracy, then all person inside the inundated area should be considered as in danger of life, and the hazard assigned accordingly.

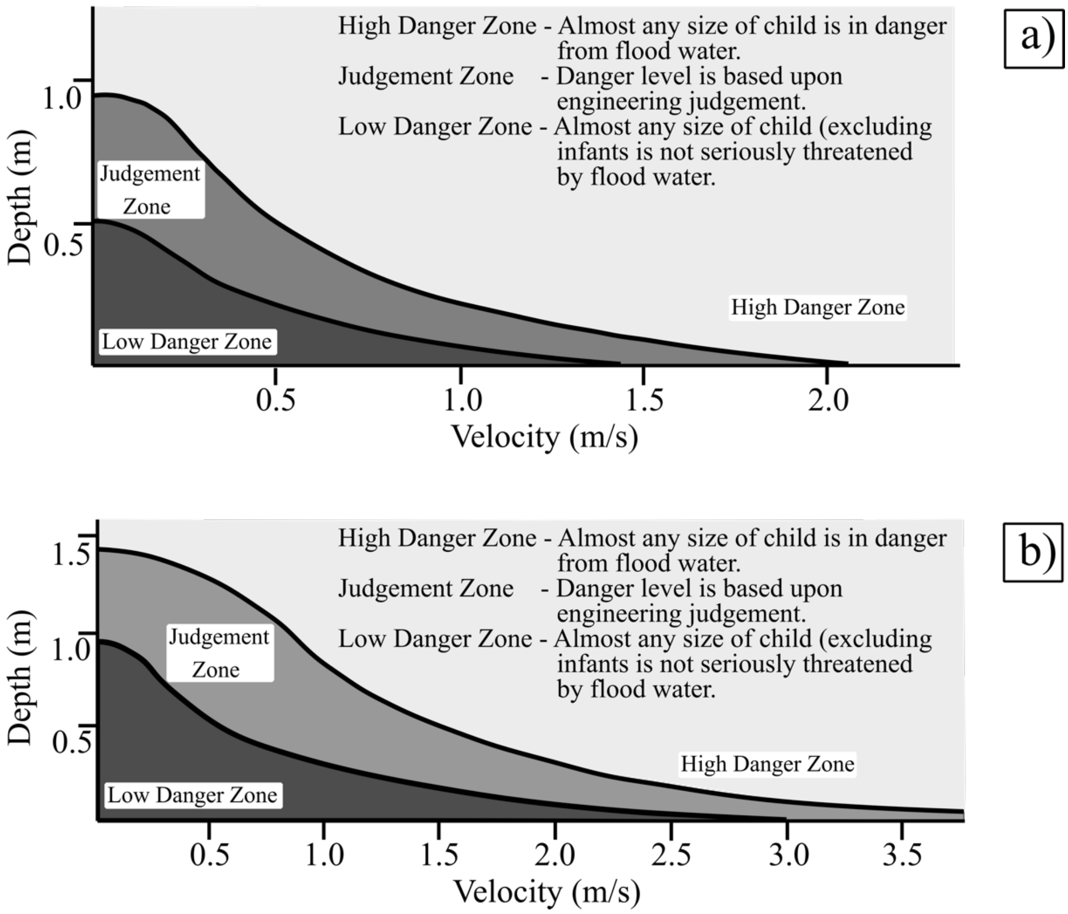


Figure 5.3 - DV relationship and related FHR for (a) children and (b) adults (U.S. Department of the Interior, 1988)

5.2.3 Method B

In 2010 the publication of Australian Rainfall and Runoff Revision Project 10 by Cox et al. (2010), updated Australian's guidelines relative to safety of pedestrians involved with flood waters. The authors in updating previous guidelines used both experimental data coming from tests conducted on human and empirical expressions available at the time. At the same time, all the available datasets were re-analysed, Cox et al. (2010) observed significant scatter in experimental datasets and this is even more noticeable when all data sets were combined (Figure 5.4); the authors also highlighted the importance of the "training" factor, or in other words, previous experience in walking in floodwaters, a person who already had such experience is more able to resist higher flow rates as they learned how to position their body to increase their stability.

Cox et al. (2010) also underlined the importance to give separate thresholds according to people characteristics as a general flood hazard threshold is not representing the wide range of characteristics of population.

The new guidelines for pedestrians' safety proposed by Cox et al. (2010), establishing different levels of hazard based on DV relationships reported in Figure 5.4.

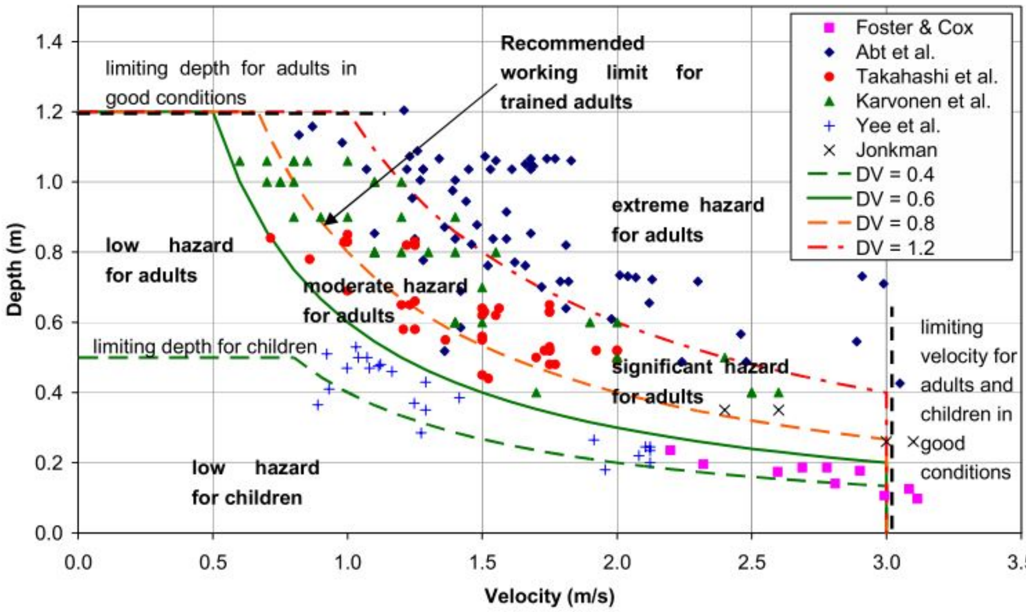


Figure 5.4 – DV relationship, related flood hazard level for children and adults and experimental point analysed (Cox et al., 2010)

The authors proposed four different thresholds based on different D and V products. There was also a limiting D and V considered for both children and adults. The limiting velocity was 3.0 m/s for both children and adults, while limiting depths were 0.5 m and 1.2 m for children and adults, respectively. These values represent the depth and velocity thresholds for extreme danger.

DV relationship and the respective hazard level for different categories are reported in Table 5.3 (Cox et al., 2010). With HM representing the product between height (H) and mass (M).

Table - 5.3 AR&R DV relationship and respective flood hazard level for different categories

DV (m^2s^{-1})	Infants, small children and frail/elderly persons (HM≤25 m•kg)	Children (HM= 25 to 50 mkg)	Adults (HM>50 mkg)
0	Safe	Safe	Safe
0-0.4	Extreme Hazard	Low Hazard	Low Hazard
0.4-0.6	Extreme Hazard	Significant Hazard	Low Hazard
0.6-0.8	Extreme Hazard	Extreme Hazard	Moderate Hazard
0.8-1.2	Extreme Hazard	Extreme Hazard	Significant Hazard
>1.2	Extreme Hazard	Extreme Hazard	Extreme Hazard

As reported in Table 5.3 infants, very young children and frail/elderly persons are always considered unsafe in any flow condition, so it is very important to locate children centres, kindergartens, aged care and retirement villages in order to avoid safety problems for this population's fraction.

Classification of flood hazard level is reported in Table 5.4 (Cox et al., 2010).

Table 5.4 - AR&R FHR classification

FHR	Description
Low Hazard	Stability uncompromised for person within laboratory testing program at the indicated flows
Moderate Hazard (Dangerous to some)	Working limit for trained safety workers or experienced and well-equipped person
Significant Hazard (Dangerous to most)	Upper limit of stability observed during most investigations
Extreme Hazard (Dangerous to all)	No one result stable

5.2.4 Method C

In 2003 and 2006 the British Department for Environment, Food & Rural Affairs (DEFRA) and Environment Agency (EA) published technical reports which have as aim "the development of a methodology for assessing and mapping the risk to death or serious harm to people caused by flooding"(Ramsbottom et al., 2006, 2003) The authors focused their attention on the impact of the flood on people which happens during or up to a week after the flood event. Impacts of the flood on people are considered as follows: i) death (usually as consequence of drowning), ii) physical injuries both caused by the immediate and direct consequence of deep and/or fast flows, iii) death/physical injuries occurring aftermath the flood events but still connected to the flood event.

Ramsbottom et al. (2006, 2003) proposed a flood risk assessment approach that considers the likelihood of a flood, the probability of exposure to that flood event and the probability that people exposed to the considered event will be seriously, or even fatally, injured. The authors identified as main factors of death/injuries to people during a flood event the flow depth and velocity and the level of exposure of the people to the flood. Generally, the exposure is related to the suddenness of the flood, morphological characteristics of the flood plain, where people are when the flood hits (e.g., cars, streets, house) etc. Moreover, risk to people is also determined by social factors as vulnerability and behaviour (Ramsbottom et al., 2003). The authors tested several empirical formulae using laboratory and field experiments available in the literature, resulting in the following proposed empirical formula (Ramsbottom et al., 2006):

$$FHR = d(v + 0.5) + DF \tag{5.4}$$

where FHR = flood hazard rating value, d = water depth (m), v = velocity of the flow (m/s) and DF = debris factor that assumes values of 0 or 0.5 or depending on the probability that debris will lead to a significantly greater hazard. Ramsbottom et al. (2006) proposed the flood hazard classifications reported in Table 5.5.

Table 5.5 – Method C FHR

FHR	Description	
<0.75	Low	Caution
0.75 – 1.25	Moderate	Dangerous for some
1.25 – 2.5	Significant	Dangerous for most
>2.5	Extreme	Dangerous for all

5.2.5 Method D

In 1996, Spanish Ministerio de Medio Ambiente de Espana published guidelines for assessing hazard for pedestrins exposed to floodwaters, in particular for the hazard deriving by the failure of dams. The failure of a dam can deliver great level of damages downstream of the structure including urban environment (Russo et al., 2014). Similar to the guidelines provided by the US, "Technical Guidelines for dam classification based on the potential risk of failure" (Ministerio de Medio Ambiente de Espana, 1996), two graphs were developed to assess the flood hazard for the case of a dam failure in Spain based on the DV relationships (Figure 5.5). The graphs in Figure 5.5 show the DV relationships and the associated flood hazard levels for (a) urban areas, and (b) rural (or non-urban) areas. The graphs are based on the product of the depth and velocity, if the product of water depth and velocity is in the "Afección Leve" area there is a low danger that means that almost any adult or child is not seriously threatened by floodwaters. For combinations of water depth and flow velocity which gives to results inside the "Area Indefinida", the hazard level is left to the engineer judgment. If the result of the products of water depth and flow velocity is whitin the "Afección Grave" area, there is a high level of hazard and almost all adult/children are seriously threatened by floodwaters.

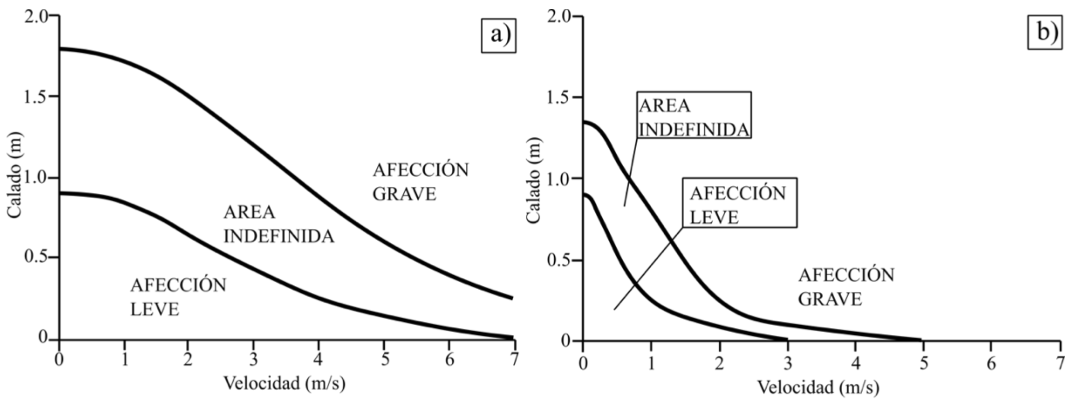


Figure 5.5 – DV relationship and related flood hazard level for: (a) urban and (b) unurbanized areas *(Ministerio de Medio Ambiente de Espana, 1996)*

A description and classification of the hazard level based on this method is reported in Table 5.6.

Table 5.6 – Method D FHR classification (Ministerio de Medio Ambiente de Espana, 1996)

FHR	Description
Low danger zone	Almost any size of adult/child is not seriously threatened by flood waters
Undefined zone	Danger level is based upon engineering judgment
Severe danger zone	Almost any size of adult/child is threatened by flood water

As firstly noticed by Russo et al. (2014) there is high grade of similitude between the graphs of the pedestrian route for adults using Method A (Figure 5.3 a) and the graph for the unurbanized area of Method D (Figure 5.5 b) and as well there is a high grade of similitude between the Spanish not urban graph and the graph relative to house built on foundations of the Method A.

From an analysis of the method proposed by the Spanish government is possible to notice that there is a lack of distinction between children and adults, which is very important for many authors as seen in Chapter 2 and demonstrated in this research work in the following Chapters. Moreover, as also noticed by Russo et al. (2014) a distinction between urban and not-urban area does not seems adequate as the pedestrian stability thresholds, defined by criteria bases on the product of depth and velocity, are unique and not defined by the area where they are wading.

5.2.6 Method E

Martínez-Gomariz et al. (2016) proposed an empirical equation for pedestrians based on results obtained from experiments with human subjects, of different ages and gender. This method was proposed to be used in urban drainage master plans. Tested conditions were those frequent when pluvial floods in urban areas occur, i.e., high velocities and low water depth. The authors have merged these new data, with previous data published by Russo in 2009, to obtain more instability conditions. This new merged dataset has been used to define the lower limit function expressed by Equation 5.5 (Martínez-Gomariz et al., 2016). Thus, depending on the value of DV relationship (Equation 5.5) it is possible to determine the stability of a pedestrian as shown in Figure 5.6.

$$(DV) = 0.22\ m^2 s^{-1} \tag{5.5}$$

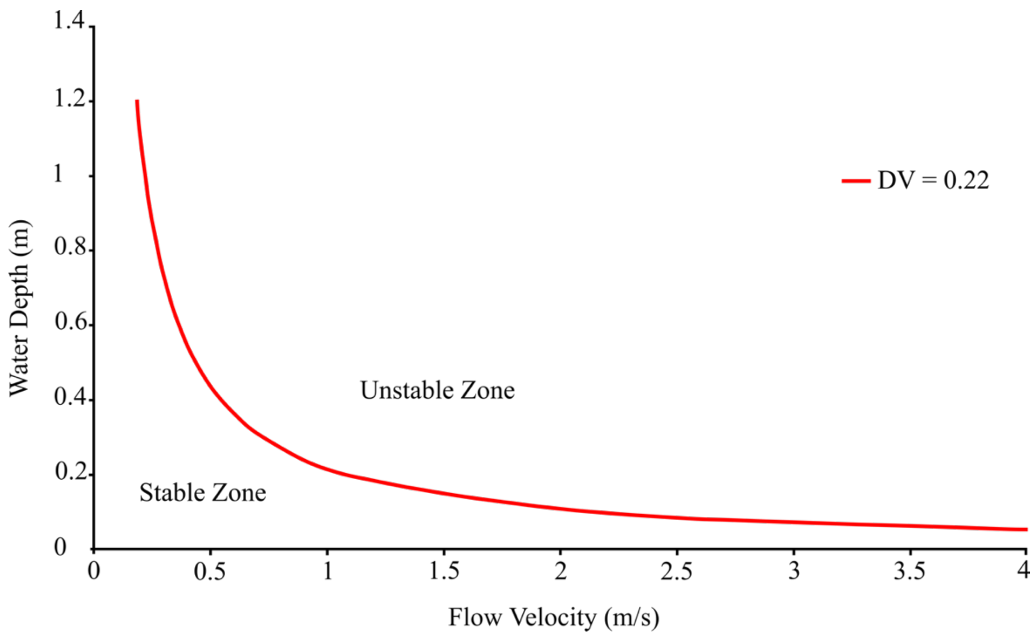


Figure 5.6 – Stability threshold for pedestrian in floodwaters for Method E (Martínez-Gomariz et al., 2016)

Classification of the hazard level is reported in Table 5.7.

Table 5.7 – Method E FHR classification

FHR	Description
Low	Subjects can complete the protocol without inconvenience
Medium	Subjects had great difficulty to complete the protocol
High	Subjects lost stability completely

The experimental set up utilised to obtain the new datasets, consisted in a physical model of sufficient dimension to avoid scale effects and to allow tests with human subjects. The model design aimed to represent a typical, realistic scenario of an urban street crossing, with dimension of 1.6 m in width and 5 m in length. The longitudinal slope can vary between 0 and 10% and a fixed slope equal to 2%, it is considered for the transverse slope. A sidewalk street interface to keep also into account the first step from the sidewalk to the street it was also considered. In this the shock received by the tested subject caused to the sudden introduction of force upon entering the flooded street from a dry place, it is also considered. Martínez-Gomariz et al.(2016) utilised 16 flood scenarios considering combinations of slope and discharges. Regarding to the human subjects, all the pedestrians wore the same type of clothing but for each discharge model slope combination the testing protocol made them to wear different kind of shoes, had the hand free or not free, as well good or bad visibility conditions were considered during the tests. Human subjects considered both male (5 subjects) and female (16 subjects) and different ages as well up to 55 years old person and 5 children (under 15 years of age). Weight of the subjects ranged between 37 and 71 kg and heights ranged between 1.32 and 1.73 m (Martínez-Gomariz et al., 2016).

The test protocol consisted of moving through the flows in three different directions, transverse, diagonal and longitudinal with respects to the main flow direction. Moreover, the subject must enter into the flooded street from the dry sidewalk and then keep walk along the three directions considered. At the end of each session each subject was interviewed, and personal feelings recorded. To ensure a certain level of randomness not all the subjects carried the same task and/or number of sessions (Martínez-Gomariz et al., 2016). An important aspect of the protocol was the fact that gaining experience in walking in flooded road was minimised, and this is very important because as previously mentioned (See Chapter 2), this would increase the ability of the subject and thus the threshold will be underestimated.

5.3 Results

In this section results of flood hazard assessment are presented. More detailed comparisons between the revised MBM and the empirical methods adopted by American authority (Method A), Australian authority (Method B), by British authority (Method C), by Spanish authority (Method D) are shown in Sections 5.3.1 to 5.3.4. Section 5.3.5 shows a comparison between the revised MBM and a fully experimental method by Spanish researchers (Martínez-Gomariz et al., 2016) (Method E) which can be considered the state of the art of experimental procedures.

For the comparison process different time steps have been selected to check whether differences in results are dependent by the evolution of the flood events (i.e., changing in time of flood characteristics) or not. In Figure 5.7 is reported the hydrograph for Boscastle case study with notation of simulation's time steps. In Figure 5.8 are reported the DV relationships for the methods described in the previous Sections.

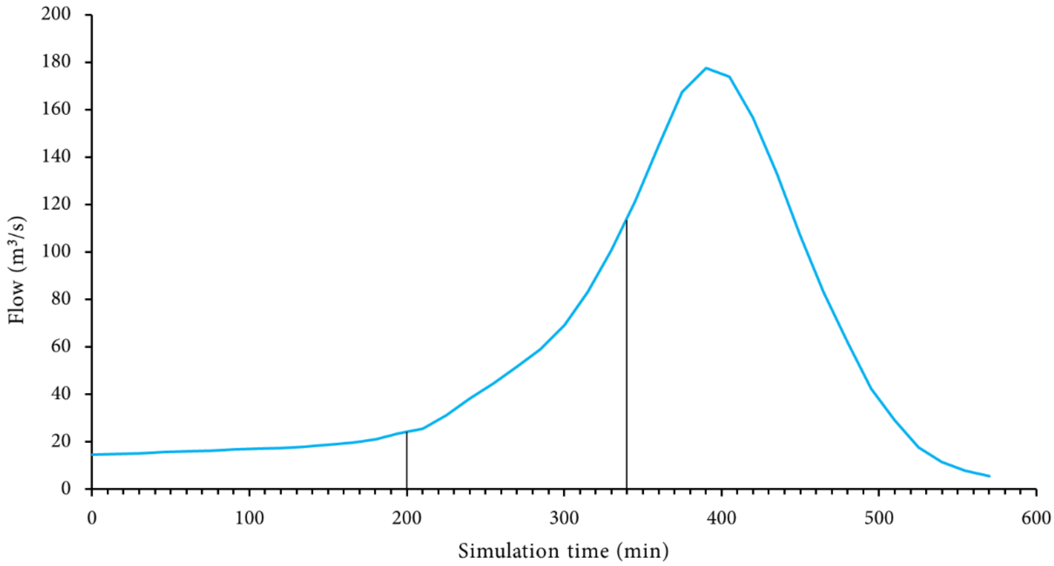


Figure 5.7 – hydrograph of Boscastle flood events with notation of simulation's time steps used to plot the results.

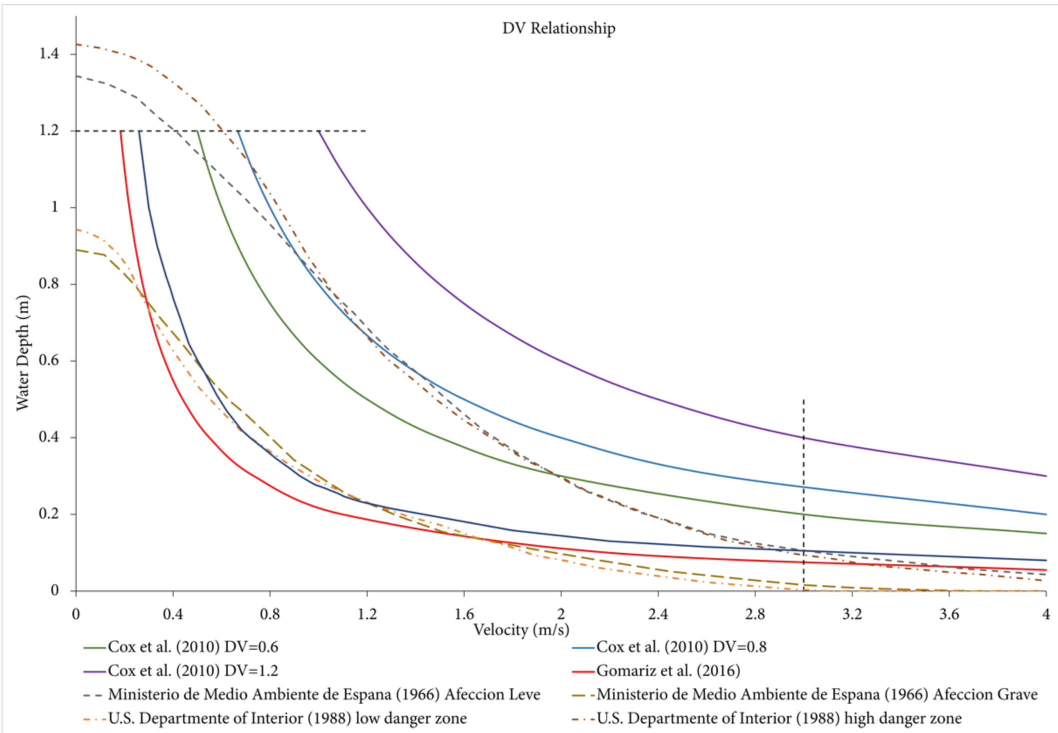


Figure 5.8 DV relationships(adults) for the methods herein considered. Black dash lines are limiting depth and velocity respectively.

5.3.1 Revised MBM vs Method A

In this section, the results related to the application of the revised MBM, and the empirical methods adopted by American authority are reported.

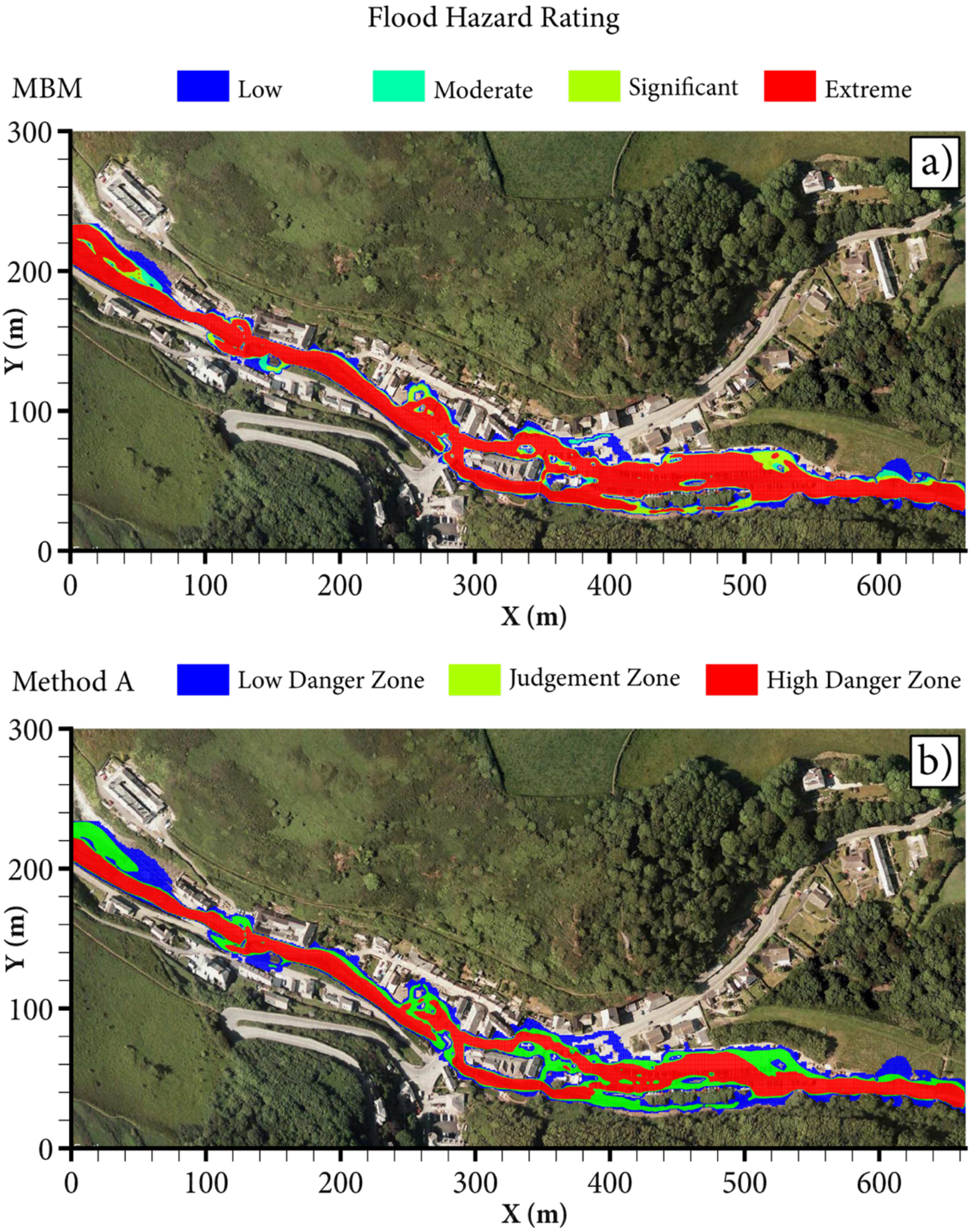


Figure 5.9 - Boscastle case study - FHR comparison between revised MBM and Method A – simulation time 200 min

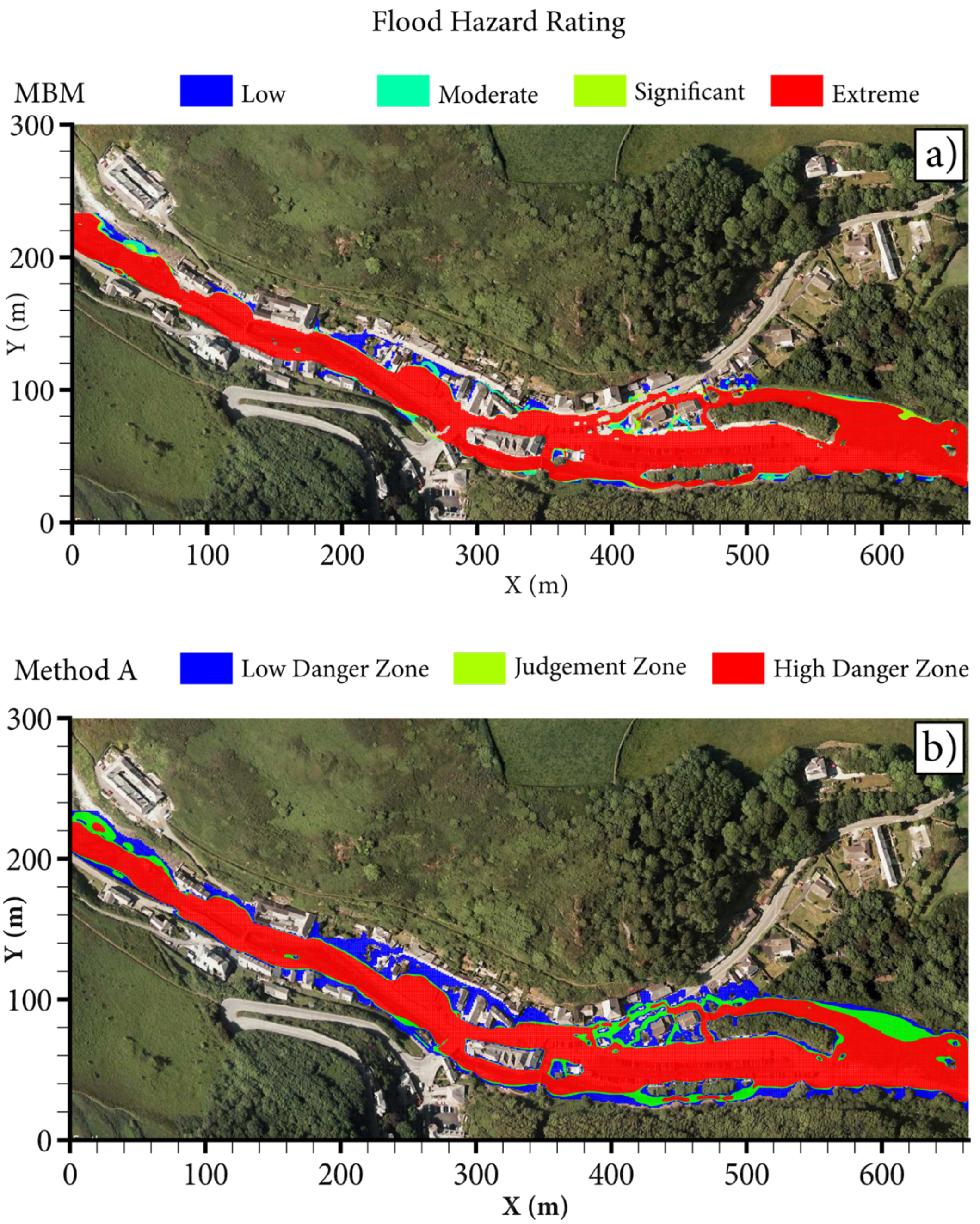


Figure 5.10 – Boscastle case study - FHR comparison between revised MBM and Method A - simulation time 340 min

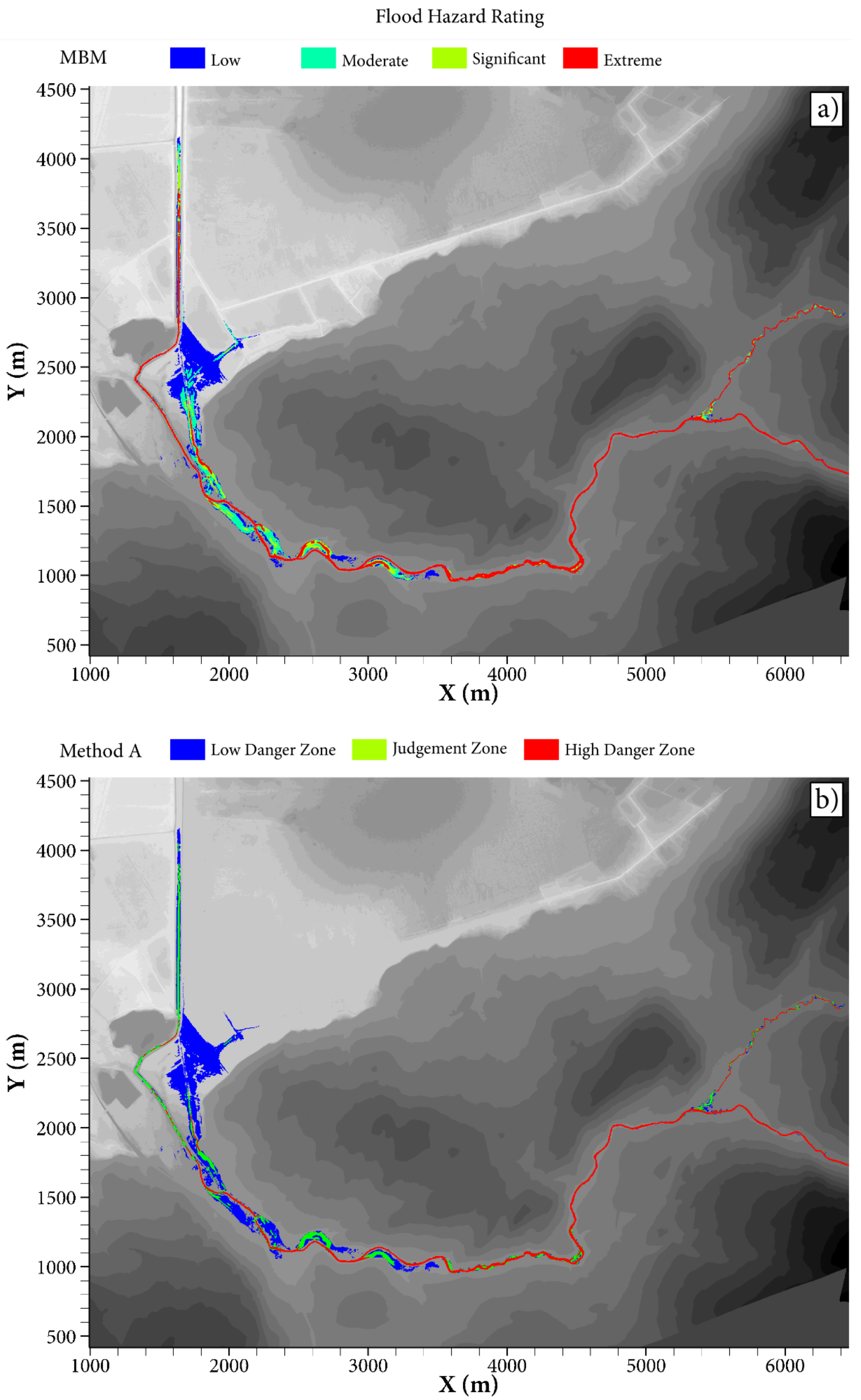


Figure 5.11 - Borth case study - FHR comparison between revised MBM and Method A – simulation time 420 min

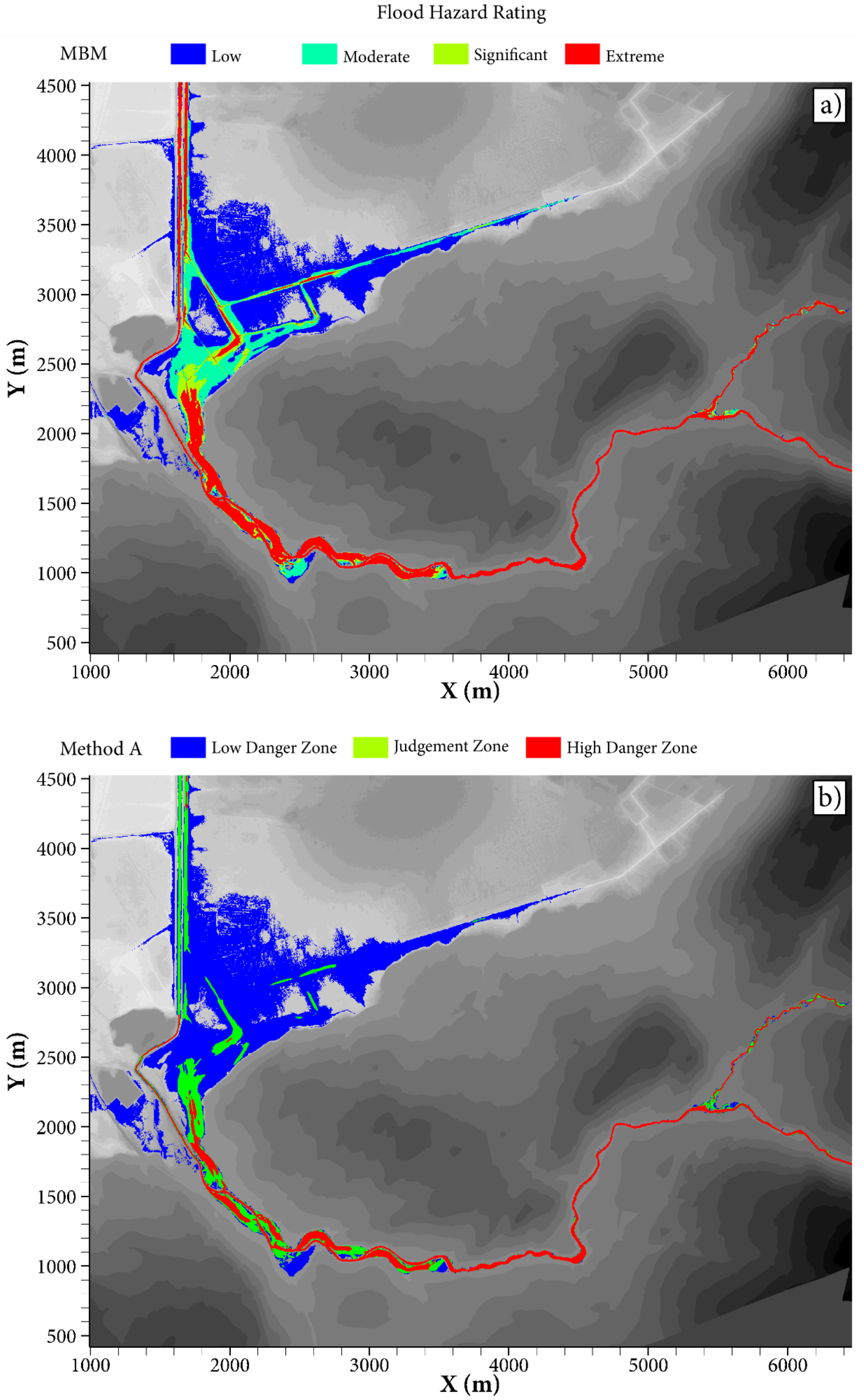


Figure 5.12 - Borth case study - FHR comparison between revised MBM and Method A – simulation time 720 min

From the comparisons it can be seen that when using the revised MBM, rather than Method A, there is a greater extension of the areas with an extreme FHR. In considering the Boscastle site, Method A assessed 29.54% less area characterised by extreme FHR at simulation time 200 min (Figure 5.9) and 3.51% less at simulation time 340 min (Figure 5.10). Similarly, for the Borth site, Method A assessed 28.96% and 48.71% less extreme FHR areas at simulation time 420 min (Figure 5.11 a) and simulation time 720 min (Figure 5.12 b) respectively.

5.3.2 Revised MBM vs Method B

In this section, a comparison between the mechanics-based method and the empirical methods adopted by the competent authority of Australia is conducted.

The results of the revised MBM and Method B for the sites at Boscastle are compared and illustrated in Figures 5.13 and 5.14. It can be seen from the results that when using Method B there are less regions characterised with an extreme FHR, in particular there is 55.60% and 15.27% less area for simulation times 200 min (Figure 5.13) and 340 min (Figure 5.14) respectively. For Borth there are the 28.95% at simulation time 420 min (Figure 5.15) and 48.71% at simulation time 720 min (Figure 5.16) less areas of extreme FHR when using Method B instead of the revised MBM.

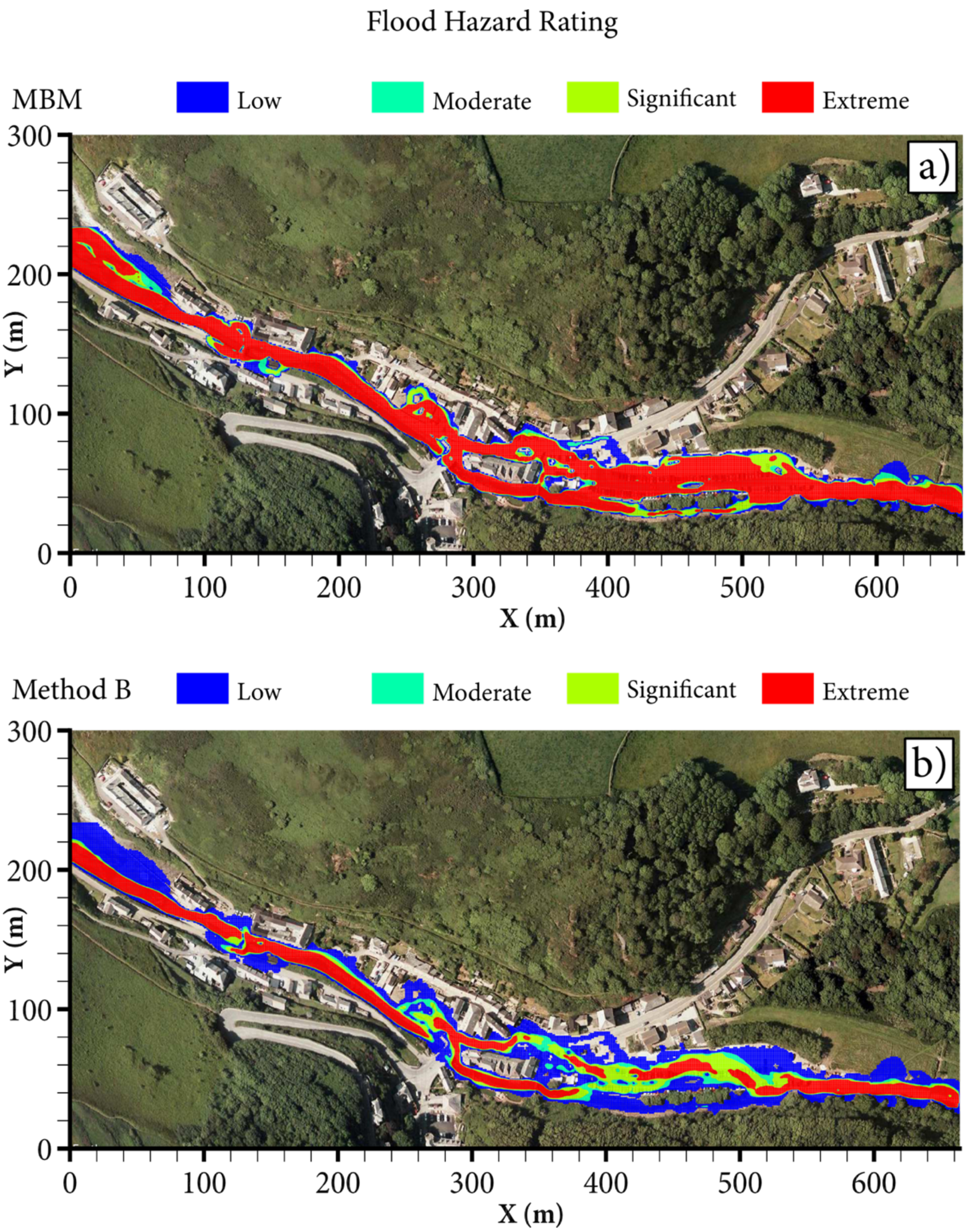


Figure 5.13 – Boscastle case study - FHR compared between revised MBM and Method B - simulation time 200 min

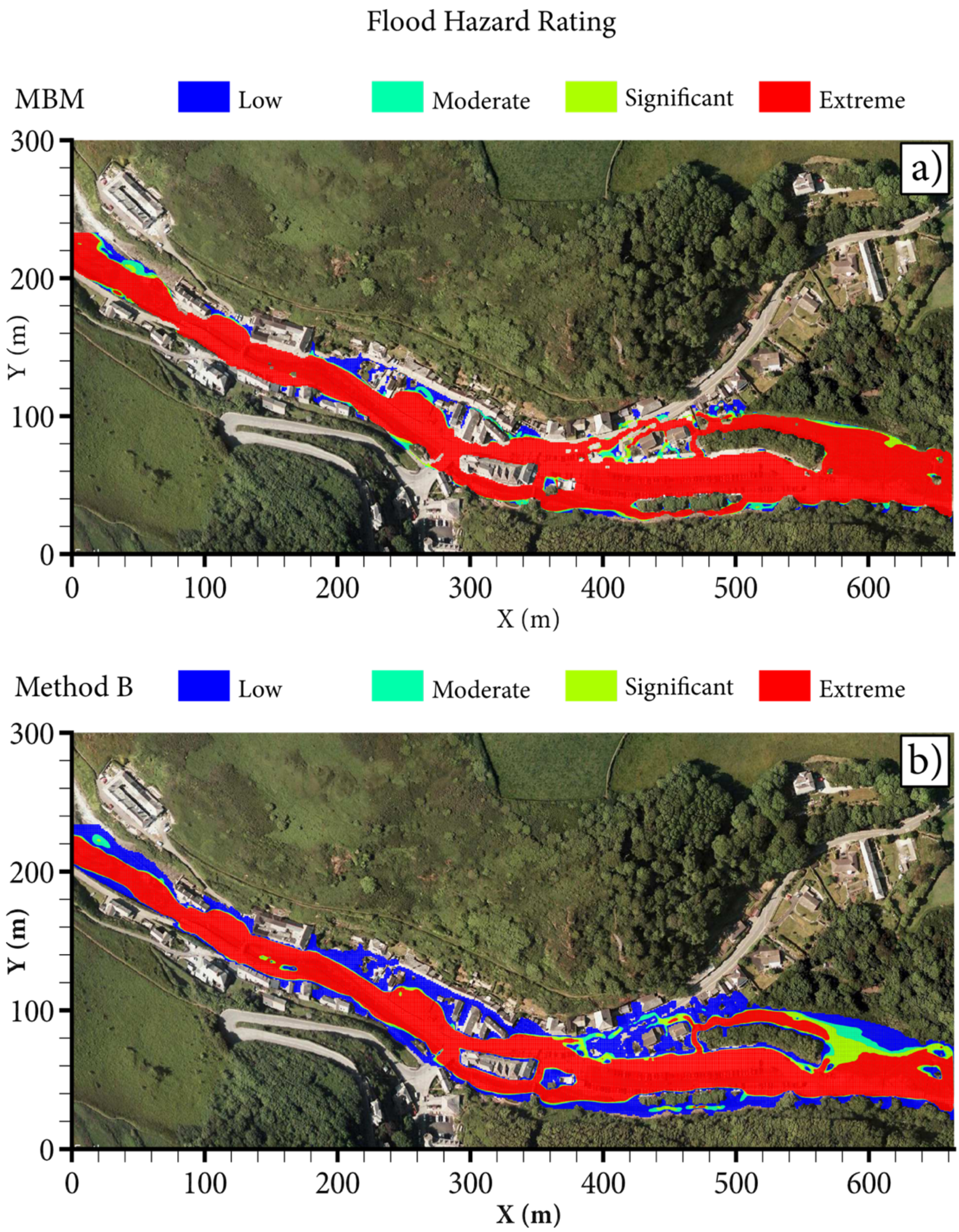


Figure 5.14 – Boscastle case study - FHR compared between revised MBM and Method B - simulation time 340 min

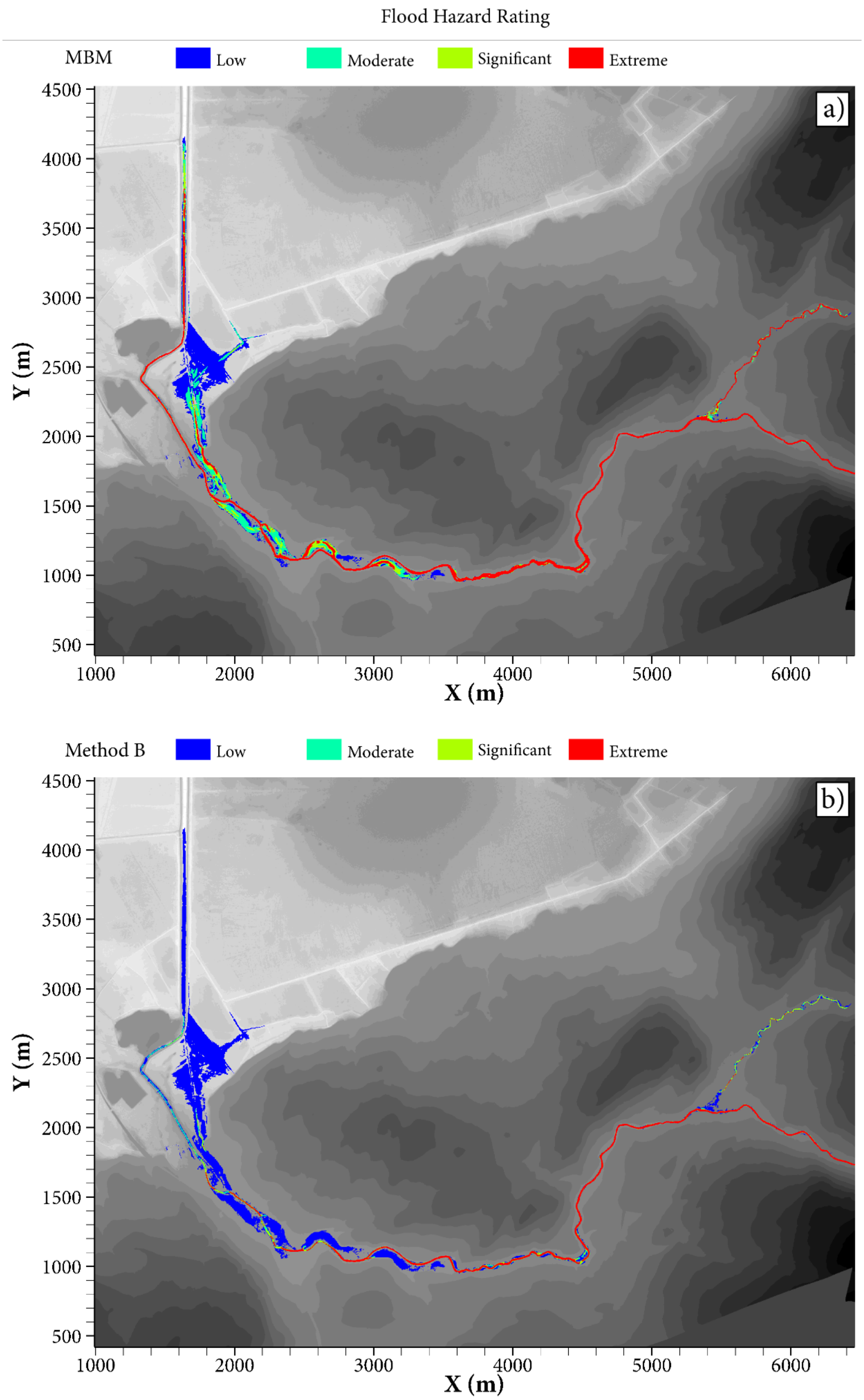


Figure 5.15 - Borth case study - FHR comparison between revised MBM and Method B – simulation time 420 min

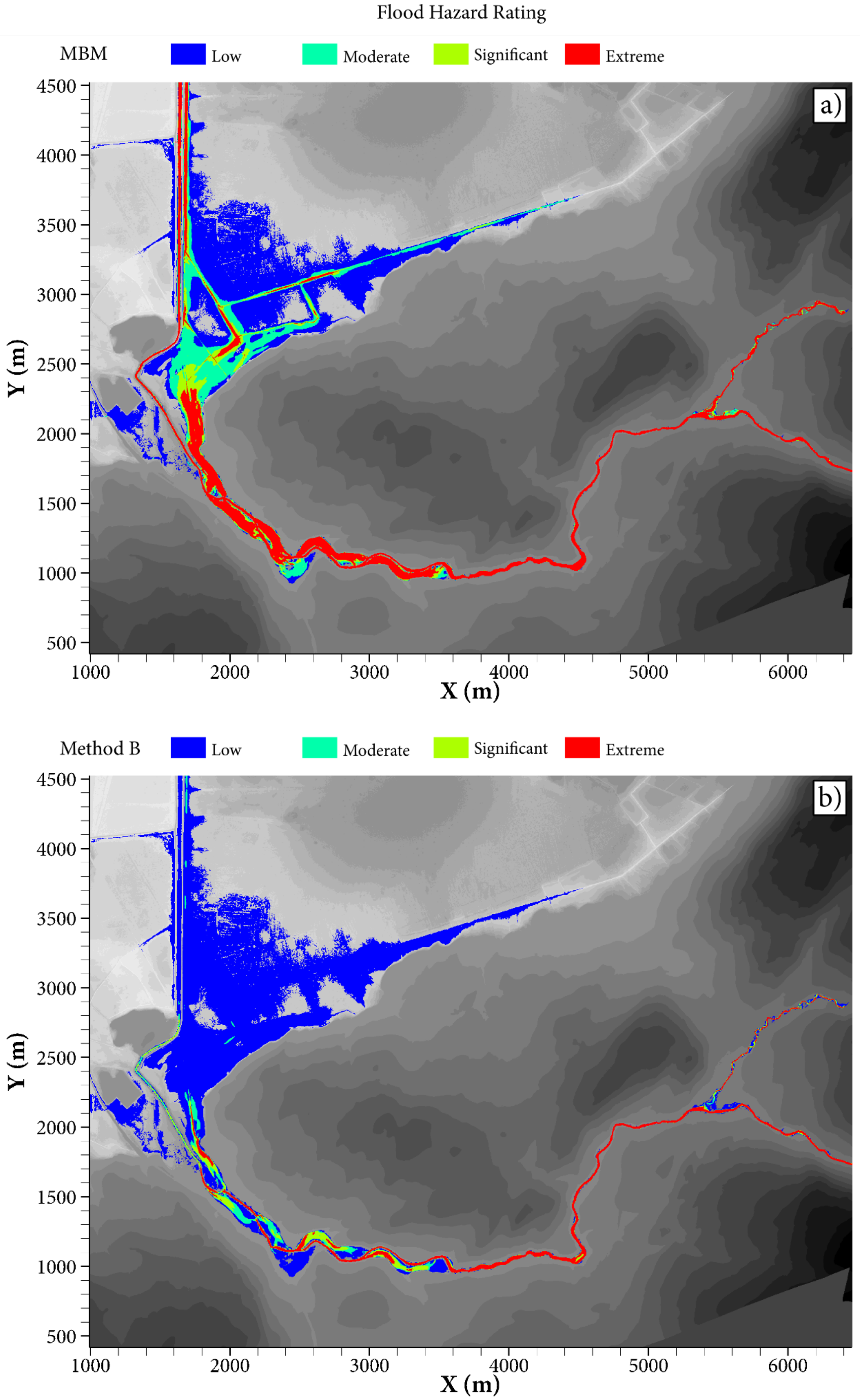


Figure 5.16 - Borth case study - FHR comparison between revised MBM and Method B – simulation time 720 min

5.3.3 Revised MBM vs Method C

In this section, a comparison between the revised MBM and the empirical methods adopted by the competent British authority is illustrated. Figures 5.17 and 5.18 show a comparison of the results between the revised MBM and Method C for Boscastle. It can be seen that when using Method C there is a reduction in the extreme FHR compared to the results obtained using the revised MBM. For Boscastle the difference is 76.93% at simulation time 200 min (Figure 5.17) and 27.04% at simulation time 340 min (Figure 5.18). For the Borth case study the difference is 83.60% at simulation time 420 min (Figure 5.19) and 81.65% at simulation time 720 min (Figure 5.20).

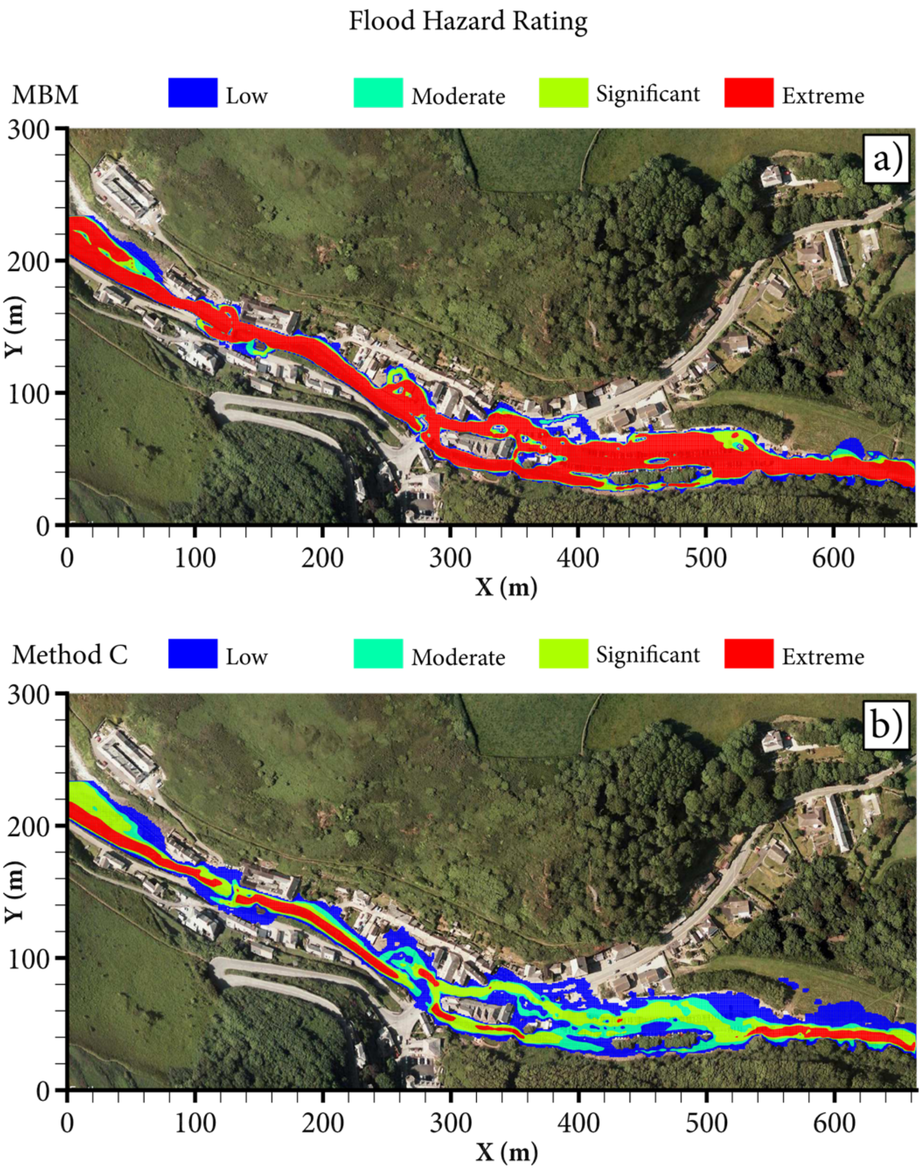


Figure 5.17 – Boscastle case study - FHR comparison between revised MBM and Method C - simulation time 200 min

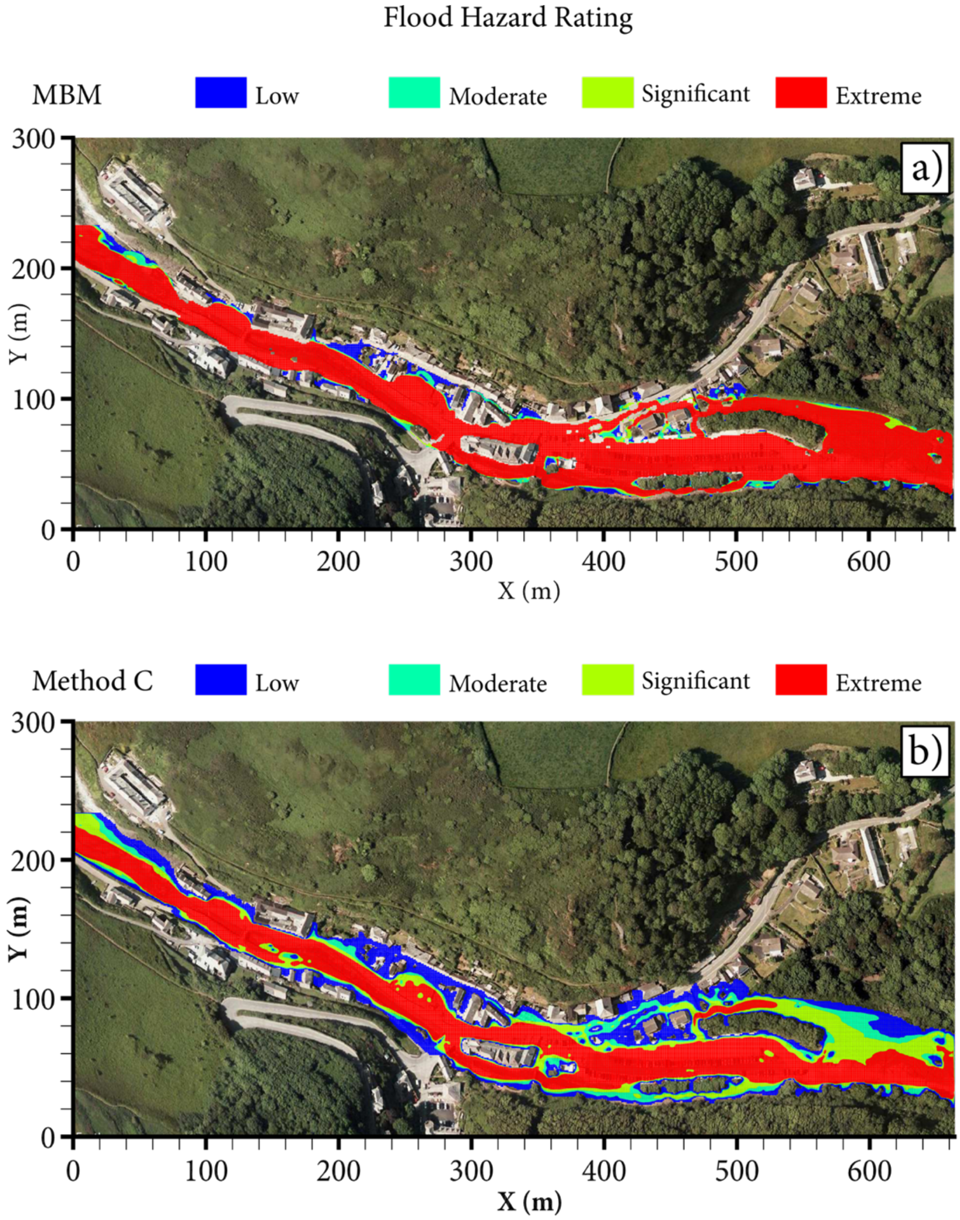


Figure 5.18 – Boscastle case study - FHR comparison between revised MBM and Method C - simulation time 340 min

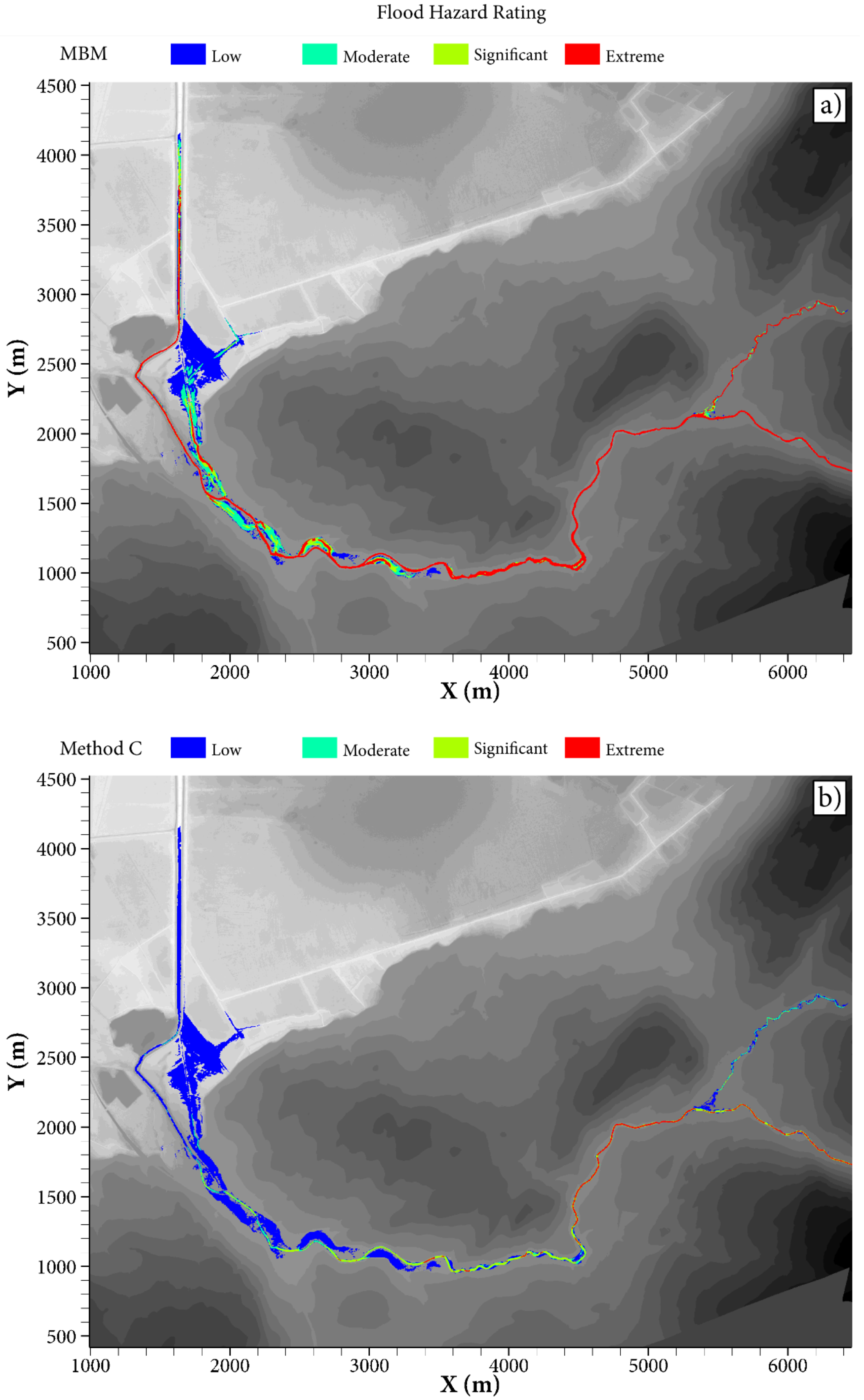


Figure 5.19 - Borth case study - FHR comparison between revised MBM and Method C – simulation time 420 min

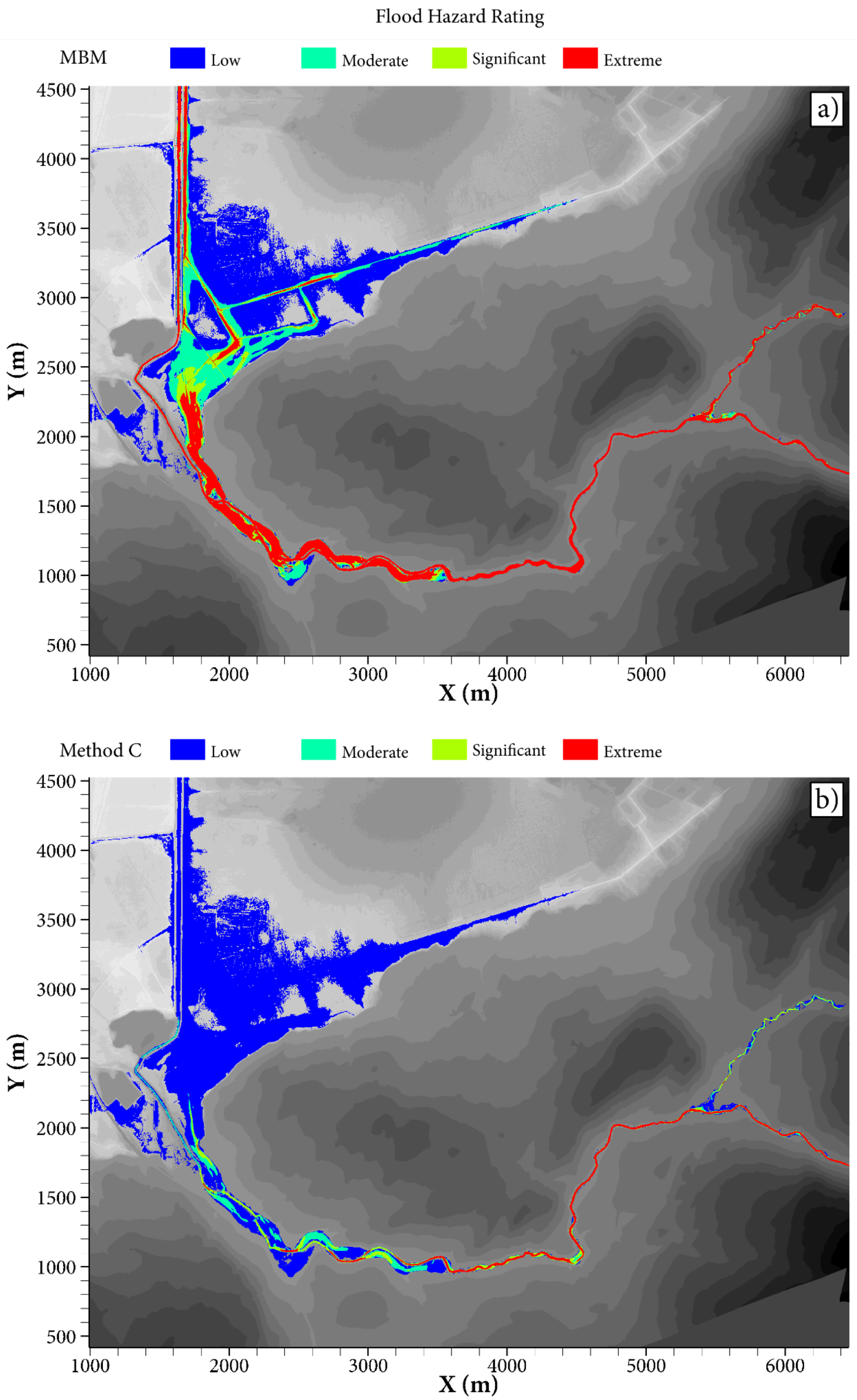


Figure 5.20 - Borth case study - FHR comparison between revised MBM and Method C – simulation time 720 min

5.3.4 Revised MBM vs Method D

This Section reports on a comparison between the revised MBM, and the empirical method adopted by the competent authority of Spain. The results of the comparison between results for the revised MBM and Method D are shown in Figures 5.21 and 5.22 for the Boscastle. In all figures it can be seen that when using the revised MBM there is a greater extension of the areas categorised as extreme FHR. For the Boscastle case study, when using Method D there are 29.69% and 3.69% less extreme FHR areas at simulation time 200 min (Figure 5.21) and at simulation time 340 min (Figure 5.22) respectively. For Borth then Method D shows 36.06% and 47.94% less extreme FHR areas at simulation time 420 min (Figure 5.23) and simulation time 720 min respectively (Figure 5.24).

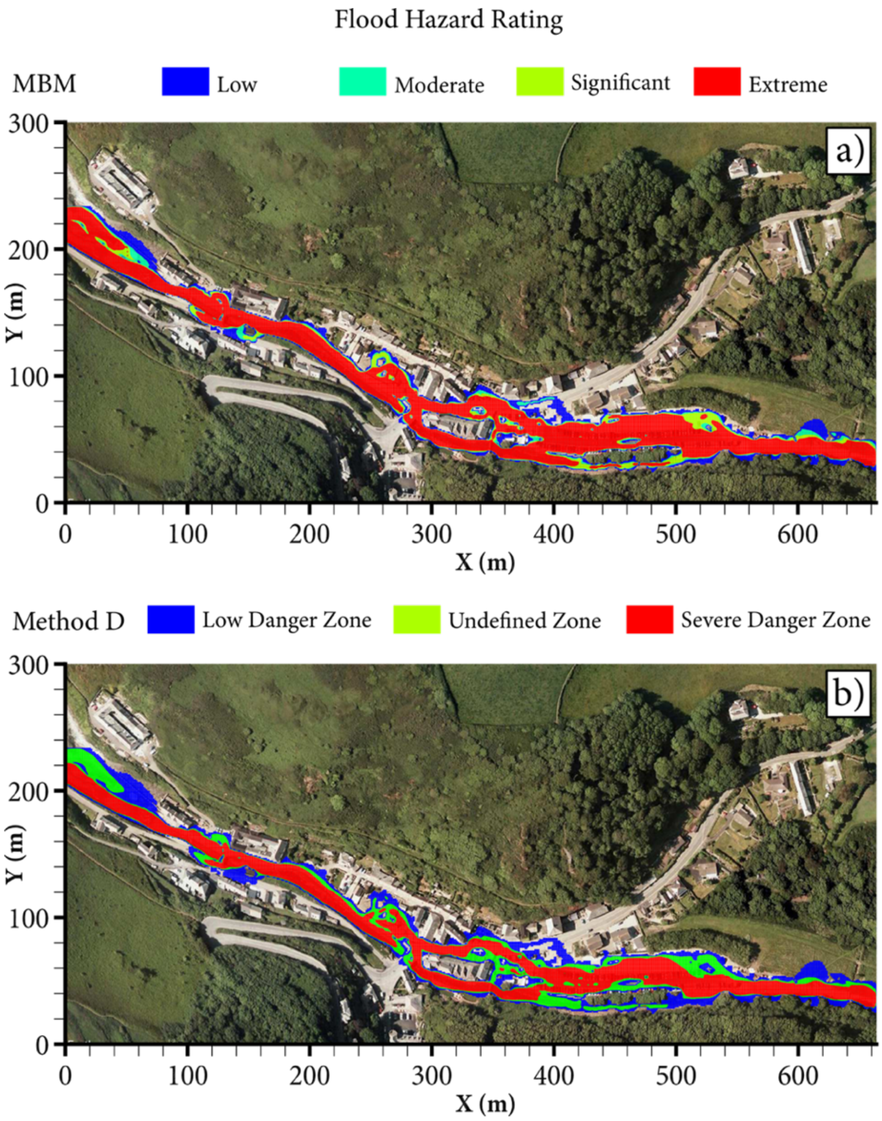


Figure 5.21 – Boscastle case study - FHR comparison between revised MBM and Method D - simulation time 200 min

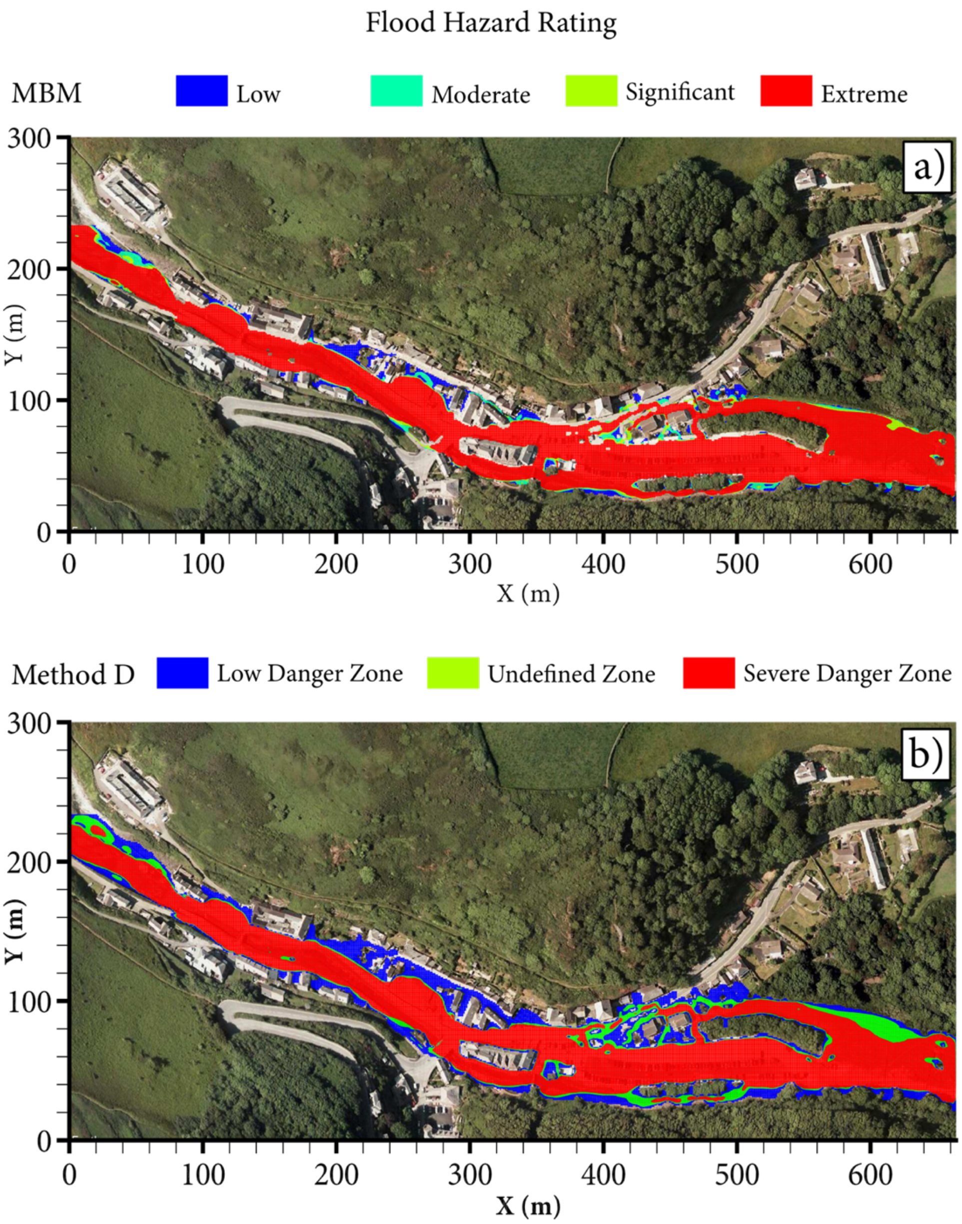


Figure 5.22 – Boscastle case study - FHR comparison between revised MBM and Method D - simulation time 340 min

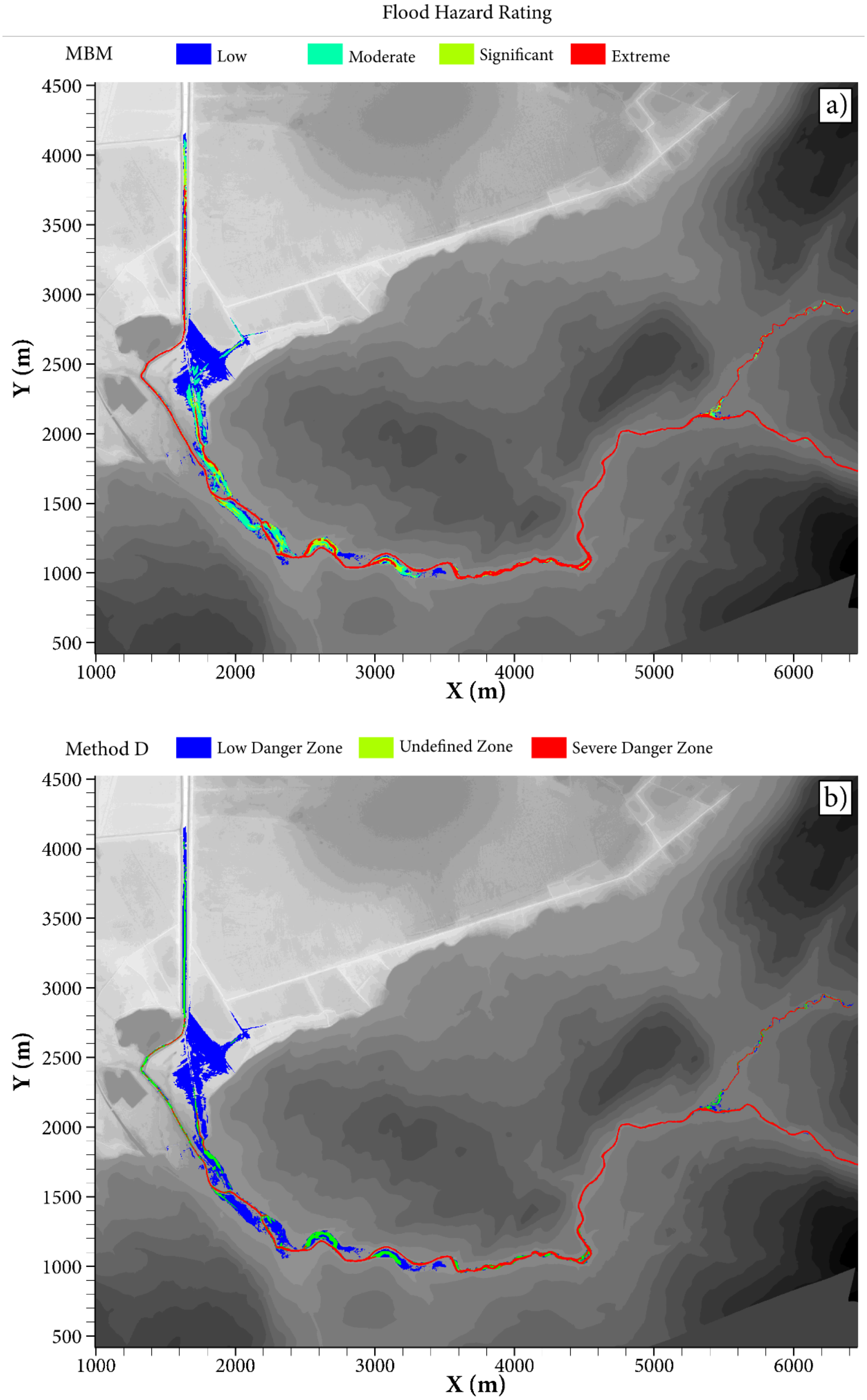


Figure 5.23 - Borth case study - FHR comparison between revised MBM and Method D – simulation time 420 min

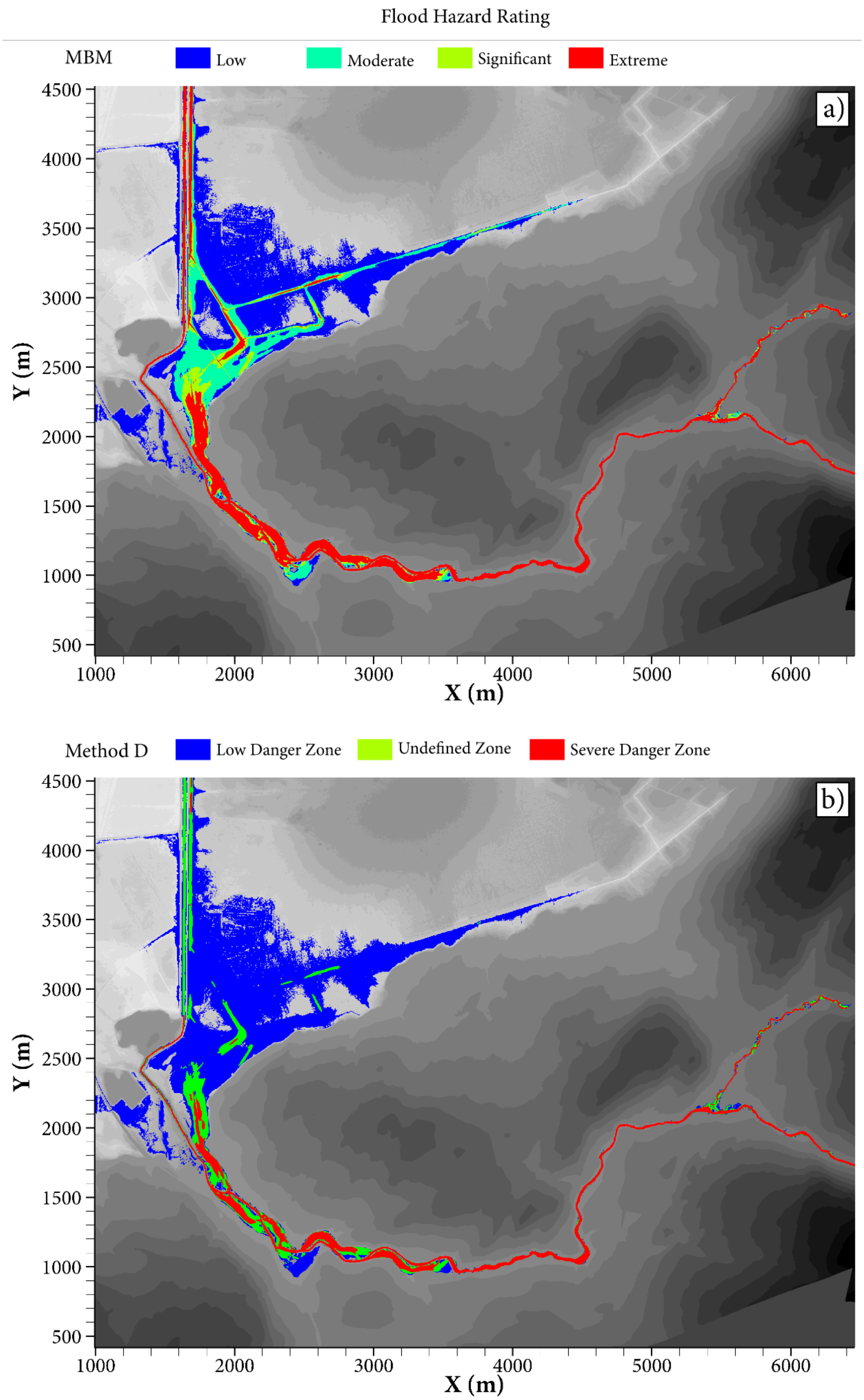


Figure 5.24 - Borth case study - FHR comparison between revised MBM and Method D – simulation time 720 min

5.4 Revised MBM vs Method E

In this section is reported a comparison between the revised MBM and the empirical method proposed by Martínez-Gomariz et al., (2016). Figures 5.25 and 5.26 show the comparison between the results of the revised MBM and Method E. The results show a greater extension of extreme FHR when using Method E. In particular, for the Boscastle site the increase in area is +10.02% at simulation time 200 min (Figure 5.25) and +6.19% at simulation time 340 min (Figure 5.26). For the Borth case study, Method E assesses increases of +15.30% at simulation time 420 min (Figure 5.27) and +11.06% at simulation time 720 min (Figure 5.28).

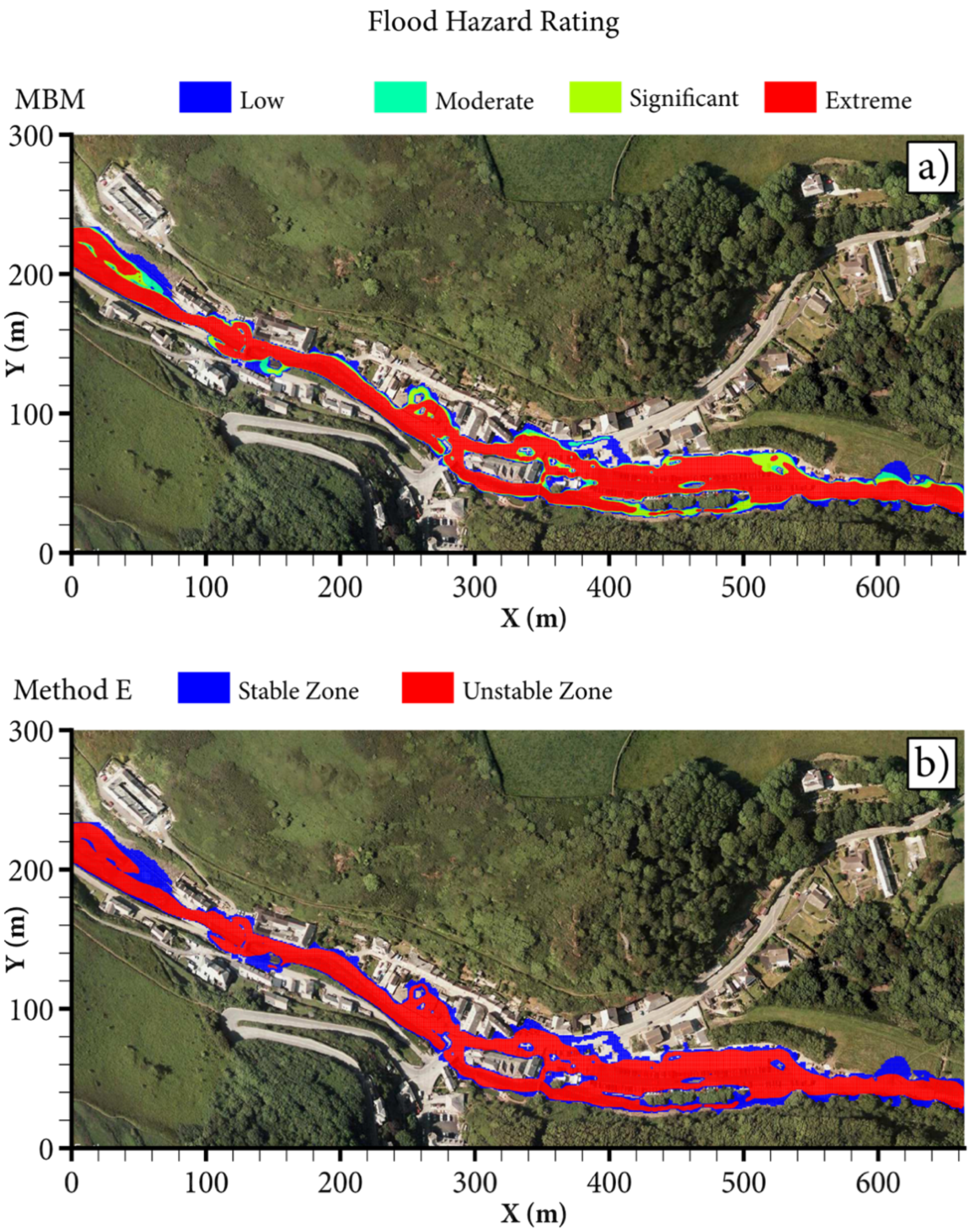


Figure 5.25 – Boscastle case study - FHR comparison between revised MBM and Method E - simulation time 200 min

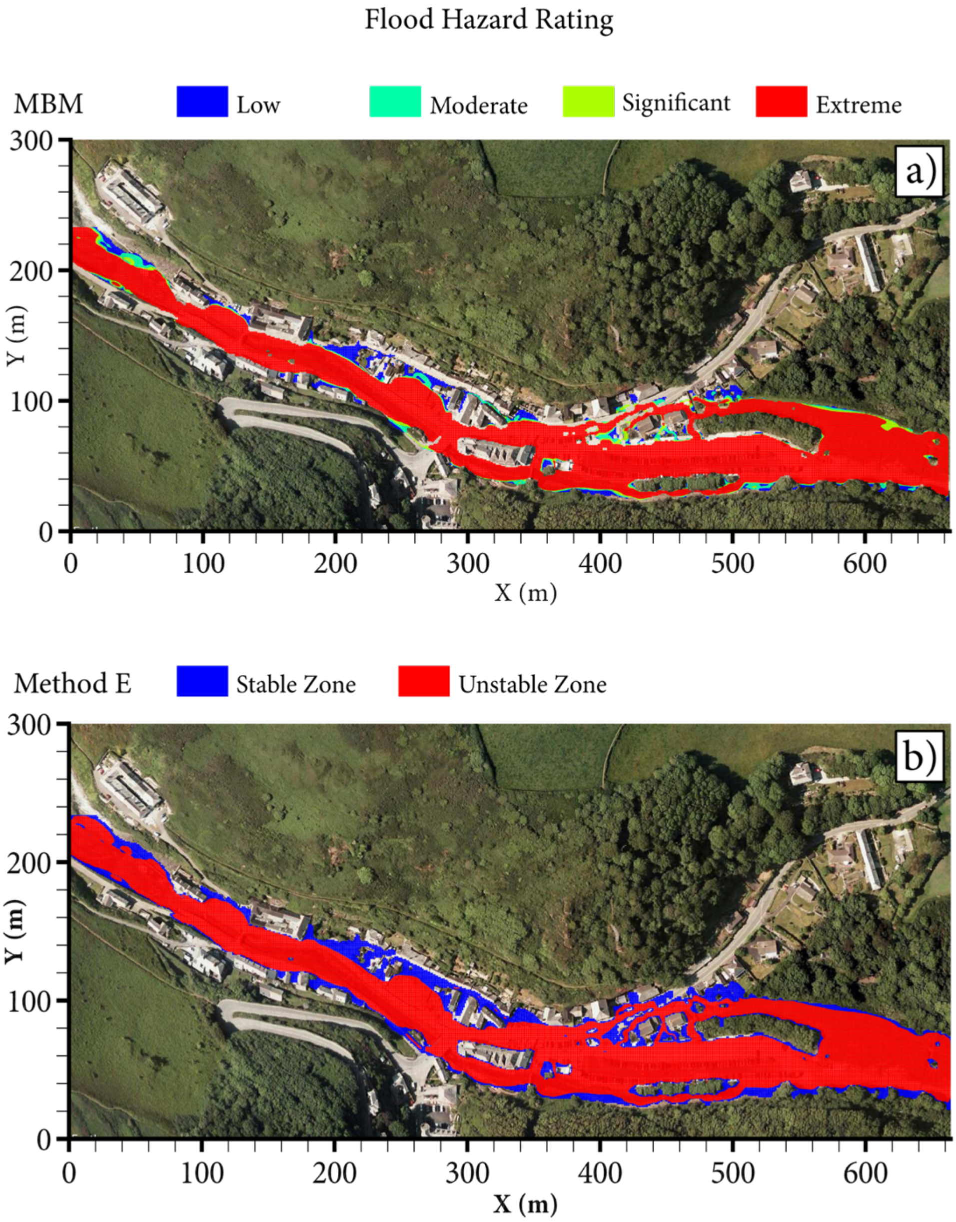


Figure 5.26 – Boscastle case study - FHR comparison between revised MBM and Method E – simulation time 340 min

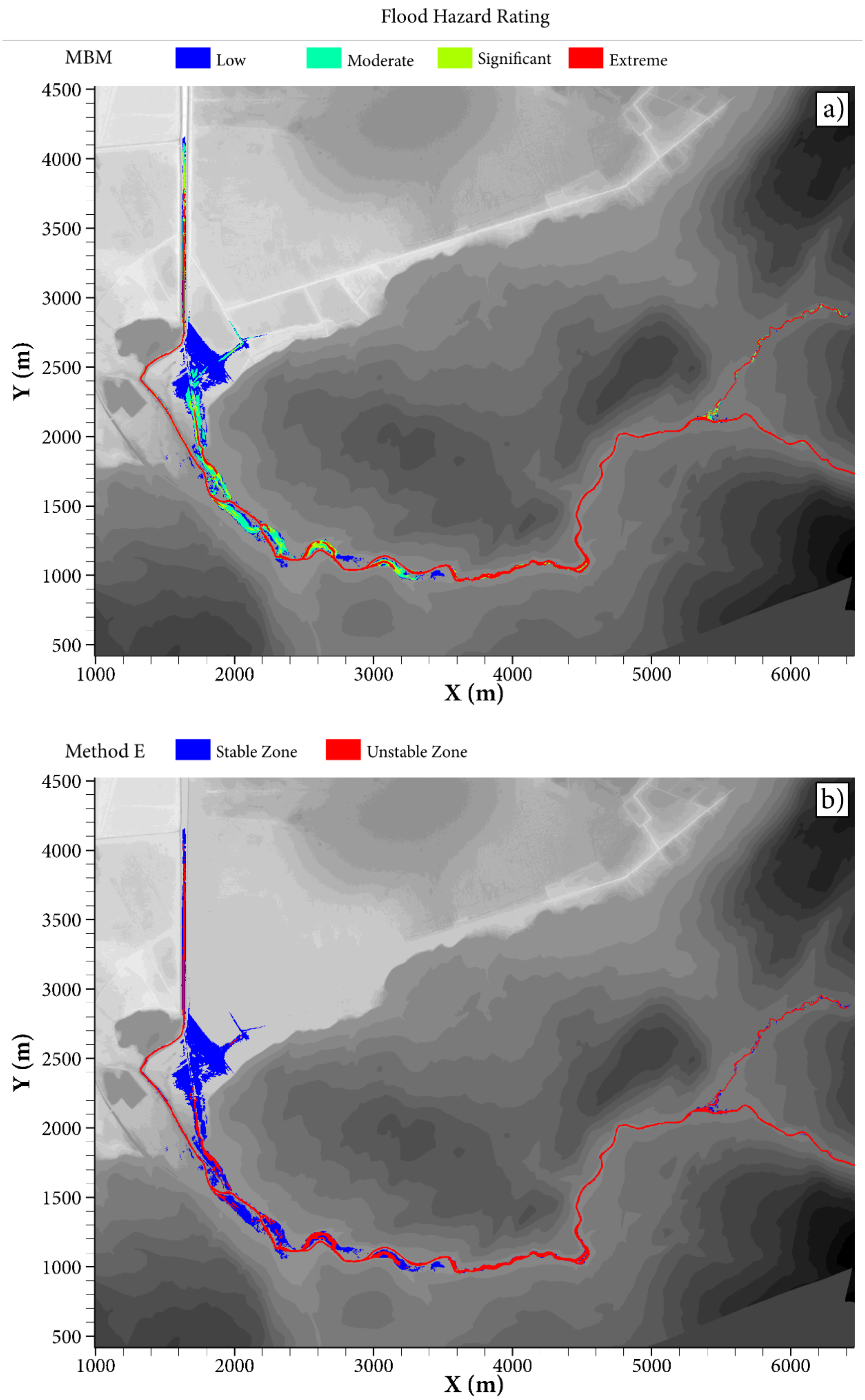


Figure 5.27 - Borth case study - FHR comparison between revised MBM and Method E – simulation time 420 min

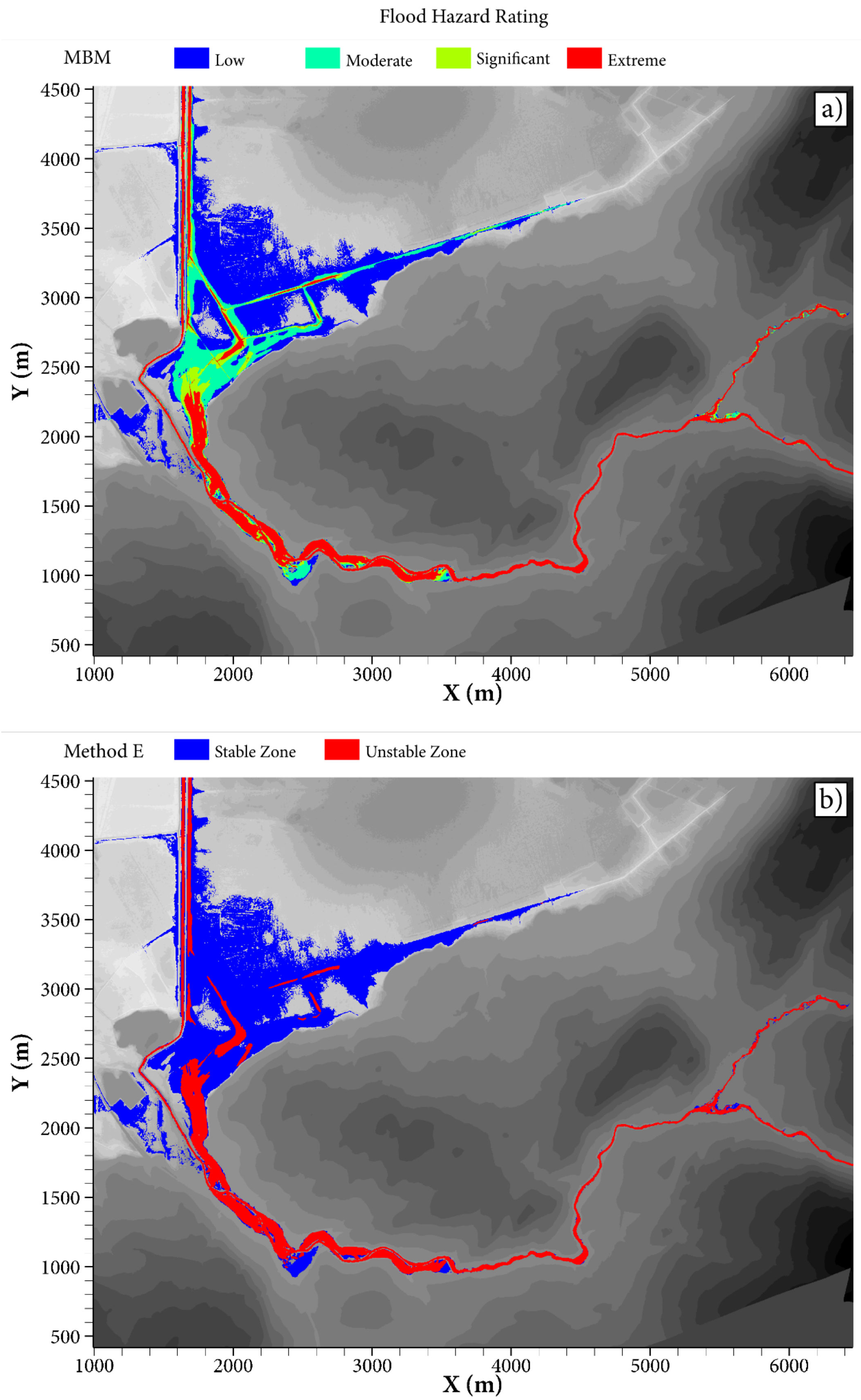


Figure 5.28 - Borth case study - FHR comparison between revised MBM and Method E – simulation time 720 min

5.5 Discussion

In this section the results presented in the previous Sections are discussed, strength and weakness of each method are illustrated to show if there is still margin for improvement in flood hazard assessment for pedestrians. With this being one of the objectives of this research work.

The results presented in section 5.2.1 to 5.2.5 have shown that the empirical methods, except for the Method E, generally underestimate the flood hazard rate results for extreme flood events when compared with the revised MBM approach (Table 5.8 and Table 5.9).

Table 5.8 – Boscastle case study - comparison between the revised MBM and the other methods in terms of % difference of extreme FHR areas

Boscastle case study	% difference simulation time 200 min	% difference simulation time 320 min	|% difference|
Method A vs revised MBM	-29.54%	-3.51%	26.03%
Method B vs revised MBM	-55.60%	-15.25%	40.35%
Method C vs revised MBM	-76.93%	-27.04%	49.89%
Method D vs revised MBM	-29.69%	-3.69%	26%
Method E vs revised MBM	+10.02	+6.19	3.83%

Table 5.9 – Borth case study - comparison between the revised MBM and the other methods in terms of % difference of extreme FHR areas

Borth case study	% difference *simulation time* 420 min	% difference *simulation time* 720 min	|% difference|
Method A vs revised MBM	-28.96%	-48.71%	19.75%
Method B vs revised MBM	-60.10%	-70.41%	10.31%
Method C vs revised MBM	-83.60%	-81.65%	1.95%
Method D vs revised MBM	-36.06%	-47.94%	11.88%
Method E vs revised MBM	+15.30%	+11.04%	4.26%

In comparing the results in Tables 5.8 and 5.9 at simulation time 200 min and simulation time 420 min respectively, it can be seen that the % difference is very similar, in comparison with the results reported in Tables 5.8 and Table 5.9 at simulation time 320 min and simulation time 720 min respectively; when simulation time is close to the peak of the flood event then the % differences are noticeably different. This is explained by the fact that the two flood events are different in terms of intensity, with the Boscastle flood event being a 1:400 years flood event and Borth being a 1:100-years flood event (See Sections 4.3 and 4.4). Hence, the more extreme conditions lead to the assessment close to the peak of the event being similar using the different methods, as the value of the water depth and/or flow velocity will be greater. In other words, if the value of the water depths and flow velocities are relatively large then all of the assessment methods tend to give similar assessments of the stability thresholds – which have been already largely exceeded (Musolino et al., 2020a).

In comparing the results of the revised MBM and Method E, it is noticed that the % differences in the FHR areas are close for both case studies. In considering the two simulation times, the difference between the revised MBM and Method E is 3.83% for Boscastle and 4.26% for Borth, with no such big differences when considering the benchmark with the other methods at different simulation times, especially for the Boscastle case study. This observation means that the two methods give reliable results, no matter how extreme the flood event is.

Thus, it is important to use an appropriate assessment method, since if an emergency evacuation plan needs to be activated for local residents, then it is important to undertake the planning as soon as possible in order to implement the safest evacuation pathways. In contrast, if the FHR predictions are not reasonably accurate, then any evacuation plans can be erroneous and could have serious consequences.

The difference in the predictions is thought to be due to the following reasons: the revised MBM approach is defined as being a product of the submerged depth and the square of the free stream velocity, while the empirical methods are based on the product of the depth and velocity. This latter approach is inconsistent with an analysis of the hydrodynamic forces on a stationary body. Generally, the differences in the results are covered by experimental coefficients at low velocities. However, for these case studies, and similar extreme flood events, the difference in the hazard assessment is expected to be considerably higher when the velocity is well in excess of unity, as is generally the case for most extreme flood events. Thus, when assessing extreme flood events, which are often also characterised by deeper floodwaters, higher flow velocities and sudden variations in the flow regime necessitate the inclusion of a full physical analysis, as for the revised MBM approach. In this approach more physics is included in the analysis and hence the FHR values predicted are deemed to be more reliable (Arrighi et al., 2017; Milanesi et al., 2015; Musolino et al., 2020). Furthermore, the revised MBM approach considers all the forces acting on a pedestrian moving in floodwaters, including the effects of the ground slope. Both velocity and slope are relevant factors to be considered when assessing flood events, especially in steep catchments.

Methods A and D assess the FHR to produce very similar graphs and hence the results are similar. Method A allows a characterization between the thresholds for adults and children, whereas Method D does not include this distinction. Moreover, both methods have been developed for dam failures and therefore consider very specific flood characteristics (i.e., a rapid change in depth, as well as velocity). Moreover, the graphs leave some areas to the judgment of the individual, which could be misleading. Furthermore, considering that the key flood characteristics are velocity and water depth, then a distinction between the urban and non-urban areas may not be adequate (Russo et al., 2014). This suggests that the methods A and D need to be updated as also reported by Martínez-Gomariz et al. (2016) and Russo et al. (2014).

When using Method B, further explanation of the lower FHR threshold is explained by the fact that Cox et al. (2010), in updating the previous thresholds, used a database which included extensive scatter in the data. The data were obtained from experimental campaigns, which were conducted with inconsistent protocols, thereby increasing the potential for errors, such as gaining experience of the tested subjects, use of safety equipment, not including slope effects, etc. (Arrighi et al., 2017; Russo et al., 2013).

The differences of the predicted FHR values using Method C, as highlighted in Figures 5.17 to 5.20, and the revised MBM can be explained by the fact that the revised MBM approach considers the square of the velocity in its formulation as mentioned previously. The differences in the results are also explained by the following limitations, highlighted by Cox et al. (2010): (i) the available datasets have been averaged, regardless of the influence of the training that the subjects gained repeating the same task during the tests. Due to the averaged data, the final formula includes the effects of training in formulating the results. Since most pedestrians would not have any experience in moving in floodwaters, then the assumption of any form of training cannot be considered as valid. (ii) there is no experiment supporting the proposed values for the debris factor. (iii) the authors did not include any upper depth limit, which means that a large depth and a low velocity would not necessarily be considered as dangerous, but this may be the case, since once a pedestrian starts to float then the person becomes unstable. Moreover, Milanesi et al., (2015) pointed out that by considering the nature of the empirical approximation function as purely regressive, it is not possible to truly connect hazard level and physical effects, so there is no relationship between hazard levels with physical aspects of pedestrians (e.g., no different thresholds for age, body size and shape).

The authors of Method C also pointed out in their work that the expression they proposed "is based on experience of flood hazard estimation". It is recognised that the expression appears rather arbitrary, and refinement of this relationship is proposed in Phase 2, based on a more detailed assessment of previous work together with possible new research" (Ramsbottom et al., 2003). In Phase 2, Ramsbottom et al. (2006) refined the expression, but only for the part relative to the debris factor, since at the time studies relative to the use of the square of the velocity were not available.

For Method E, despite the good results obtained when using this method, some limitations are present. Firstly, the experimental method does not offer the possibility to characterise different body features. This means that the method needs to be tailored for different areas in the world, where body characteristics can be very different by repeating the experiments. Similarly, it is not possible to obtain thresholds for different categories (i.e., adults and children) within specific geographic group. Secondly, the authors focused their attention on flow cases with a high velocity and shallow depth, so neglecting the toppling failure mechanism, which occurs more frequently in deeper flows.

The limitations and results reported herein for all the methods compared against the revised MBM suggest that the existing frameworks can be improved using a more physic-based methodology as presented in this study. This method is based on the laws of fluid mechanics and considers all the forces acting on a pedestrian in floodwaters, takes into account the effects of the ground slope and also considers the body characteristics, which makes it possible to characterize the threshold level for different body types.

5.6 Summary

Nowadays, climate change and increasing in urbanisation rise the chances, for a person, to face a flood event in streets and urban environments. Moreover, people for very different reasons, walk in the streets at any hour of the day and with bad weather conditions. Thus, these two aspects make of extreme importance to assess flood hazard for pedestrians in a scientific and more reliable way. At today, evolution of technology, experimental procedure, and computational power allow us to use improved methodologies based more on full forces analysis jointly with experimental procedures. In this Chapter the methods that are used to quantify the flood hazard for pedestrian in this research work are illustrated. For each method, a description of the principal features and of the methodology used is given.

The comparisons reported herein have highlighted that the empirical methods, have limitations in acquire reliable thresholds of human stability in flood waters. Although, the method used by Martínez-Gomariz et al., (2016) have shown very similar predictions to the revised MBM method, the method lacks the capability to include human body characteristics in calculating the threshold velocity and/or depth. This means that the method needs to be calibrated by extensive experiments, in different regions, and it cannot be used for different groups of people with different body types and capabilities (e.g., adults, children and less mobile senior citizens). Moreover, the approaches widely used by authorities were considered not to be sufficiently accurate in terms of assessing human stability thresholds in floodwaters and a revision to these methods should be considered in using most recent methodologies, as for the revised MBM approach.

The revised MBM herein proposed, considers all the physical forces acting on a human body, interacting with flood waters, also it has included the most recent available body shape parameter values and the effects of the ground slope in the formulation. These additional parameters have allowed improved accuracy in the determination of the physics-based threshold levels, which lead to enhanced safety of pedestrians moving through evacuation routes during extreme flood events.

Another benefit in assessing flood hazard with the revised MBM is that it allows the analysis to be tailored to include the characteristics of a specific body type. As shown in the results reported herein, the planning of flood escape routes needs to be considered and adapted for different body types, particularly since the characteristics of the human body can vary significantly from one country to another, often leading to different stability thresholds. Furthermore, a more specific characterisation can be undertaken when considering adults, children, and elderly adults, etc. As can be seen from the results reported in chapter 6, to guarantee safety for all in planning the preferred escape route the most critical pedestrian class must be considered.

Although various formulations conclude that deep water would always be dangerous, in contrast shallow, fast flowing flood water can be just as dangerous and even potentially more dangerous, especially in urban environments. This aspect must be kept in mind in the design of evacuation plans, but also it is important to raise awareness of this aspect with flood planners etc., since the hazard of fast flowing shallow flood waters can often be underestimated. Being aware of flood escape routes and the most appropriate response of people in extreme flood events should ensure a reduced risk of serious injury or even fatality during such events.

This study has demonstrated that there is still scope to improve on the formulations for assessing flood hazard, especially for the MBM with the human body characteristics being included; with this aspect not having previously being included

6 Vulnerability and Evacuation Plans

6.1 Introduction

This chapter is dedicated to vulnerability and to evacuation plans. As it will be shown these two aspects are interconnected especially when considering flood hazard assessment in pedestrian perspective. As pointed out by many works in the literature and by this research work, it is necessary not only to consider flood characteristics, but also human characteristics do determine reliable FHR and design evacuation plans to be used in case of flood events. Moreover, in this chapter it is presented, a cost-effective resilient mitigation scheme which benefits pedestrian evacuation during flood events. This approach aims to increase the resilience of our environment with minimum interference and cost and hence can be adopted in small villages where more fundamental structural solutions may not be financially feasible, or in urbanised areas as part of bigger and more complex alleviation schemes.

6.2 Social Vulnerability

6.2.1 Introduction

Flood Risk is determined from the combination of three elements: flood hazard, exposure and vulnerability, the first two have been largely explored and improved in recent years, but vulnerability has been somehow neglected (Armenakis et al., 2017; Berndtsson et al., 2019; Koks et al., 2015). The social dimension of flooding which is mainly associated to emotional feelings and people's risk perceptions is usually not considered into flood risk management (Bodoque et al., 2019). Moreover, urbanization of floodplains areas joint with climate change effects are increasing vulnerability of communities (S. Chen et al., 2018).

Vulnerability expresses the capacity to deal with the event and this is not only referred to defence structures, properties, and services in general, but it has a very broad meaning, which also include people's capacity to deal with a flood event in terms of a correct behaviour, preparedness and psychologically as well. In the past a lot of focus was posed on the technological development of flood hazard assessment which gained huge benefit from the development through the years of numerical modelling applied to floods. This aspect without doubt increases the capacity to better understand floods phenomenon and the ability to plan adequate defences to flood events. However recently appears clear to researchers and predictionaries that a technocratic approach alone it is not sufficient, as flood risk assessment have to keep into account not only the territory and flood dynamics but also the social context as this aspects can largely influence people response to a flood events (Bodoque et al., 2019). Emotional feelings of individuals in relation to flood events can determine people' s risk perceptions and reactions to the flood events, thus, it is very important to integrate this aspect with a numerical approach in order to improve mitigation actions and people preparedness (Bodoque et al., 2016).

As reported by Koks et al. (2015) the ability of households to adapt and respond to hazard is very important for the assessment of hazard's impacts and the successful implementation of policy measures. This capacity to adapt and respond is a function of households' socio-demographic status which is related to their social vulnerability. Thus, social characteristics can be considered relevant factors in determining the feasibility of flood risk management policies (Koks et al., 2015)

6.2.2 Methodology

Considering what just reported in 6.2.1, flood hazard maps should not keep into account only factors as water depth and flow velocity, but they should be "corrected" using a social vulnerability index which keeps into account different social factors relevant for a flood event.

Among the several factors that can be considered, the most important are age, nationality, education level, wealth, previous experience with flood events, place attachment and tendency of the local population to walk along a flooded area.

Age is relevant because households with young children can take more time to evacuate and as well elderly persons can have mobility problems that can influence their evacuation time during a flood event. Moreover, both age groups can increase the burden to care to both relatives and rescue teams. For young children it is possible to consider people under 14 and for elderly person it is possible to consider people above 65.

Nationality can influence vulnerability because eventual language, cultural and religious barriers may cause problems during flood evacuations, with this aimed to be an inclusive approach which considers everybody needs and respectful of all.

Education level and wealth are good indicators of the capacity of a person to deal with the negative effects of a flood events. Usually, people with limited financial resources have problems to deal with the devasting effects of a flood and this indicate scarce resilience. Moreover, people with limited economic resources tend not to leave their houses/belongings during an evacuation due to a flood events or to have risky behaviours to try to save their properties during a flood and in this way increasing their vulnerability. In addition, people with low level of education/ low income tend to live in flood prone areas as these areas offer cheaper houses. This mean that more vulnerable persons live in more dangerous areas.

Previous experience in dealing with flood event allow people to know to some extent what the correct behaviour is to have during a flood event, or evacuation, so people with such experiences tend to be more aware and prepared to face such events. People with no experience with flood events or not aware of dangers by floods are more prone to take risky behaviours, to not follow instructions by authorities with this obstructing the role of emergency institutions. But it is also important to constantly remember to people who already faced effects of a flood what the danger is, as people tend underestimate flood hazard again after few years that the event took place (De Dominicis et al., 2015).

Information relative to what extent people are attached to a place and how they perceive the territory are also very important, because they will influence people's reactions during an emergency. It has been proven that place attachment play a relevant role in people's decision to evacuate during a disastrous event (De Dominicis et al., 2015).

Defining social characteristics to a local level it is very important. As pointed by Koks et al. (2015) population is usually very heterogeneous which is an aspects usually not considered by traditional flood risk management approaches. Thus, it is very important to include a local characterization in terms of social vulnerability when designing and implement measures to mitigate flood impacts such as evacuations, individual mitigation, and flood insurances. This means that mitigation measures should not be applied homogenously across large areas but tailored to local socioeconomics characteristics. In this approach it is possible to see a parallelism between the tailored approach to assess flood hazard based on human characteristics presented in Musolino et al. (2020) where flood hazard is determined considering different human categories based on body characteristics representative to the population living in the studied area.

To characterise the study to a specific place, demographic data will be needed. Ideally can also be used a specific questionnaire which allow to know people's tendency to walk in flooded streets, leave the place where they live with no hesitations, and other behaviours during a flood event.

In this way in designing mitigation measures it is possible to know where to do specific actions related not only to flow characteristics but also keeping in account social characteristics of people living in that specific area.

Seven Factors has been considered, namely 1) age, 2) nationality, 3) education level, 4) wealth, 5) previous experience of flood events, 6) place attachment, 7) likeness to walk along a flooded area.

For each of these factors, a value will be obtained, all the values will be added with sign (positive is the factor will increase the hazard, negative otherwise) and the final value will be the Social Vulnerability Factor.

Proposed values:

If more 50% of population of the study area has

-An age not 14<age<65: +0.25, 0 otherwise

-A nationality: Not British +0.25, 0 otherwise

-An education Level: Not degree +0.25, 0 otherwise

-A wealth: (define a threshold for medium wealth of the study area) and -0.25 if over the threshold; +0.25 otherwise

-Previous experience with floods in the last 5 years: -0.25; +0.25 otherwise

-Place attachment: Low +0.25, Medium +0.5, High +0.75

-Likeness to cross a flooded street/wandering around: Very Unlikely +0.25, Likely +0.5, Very Likely +0.75.

Once a Social Vulnerability Factor has been determined considering the factors previously described, it can be used to create a vulnerability maps to be used in conjunction with the maps obtained using the improved MBM illustrated in Chapter 6. Integrating flood hazard results obtained with a method which considers both flood and human body characteristics relative to the study area with a vulnerability based on social characteristics relative to the study area, it provides a more holistic approach and reliable results to be used in assessing flood risk for pedestrians.

As future study this methodology will be tested for the two locations presented in Chapter 4. A questionnaire will be redacted to get the data relative to the seven factors afore mentioned. Through interviews to the local population of the study areas, the data will be collected and successively statistically analysed to keep into account the social vulnerability in assessing flood risk for pedestrians. This methodology represents early-stage research on the topic and will be further developed and tested as part of future studies.

6.3 Determining Evacuation routes

6.3.1 A Novel Method for Determining Evacuation Routes

Generally, evacuation issues can be categorized into two main classes. Depending on the distance, it is possible to have small scale evacuations and long-distance evacuations. Small scale evacuations are related to emergency located in a relatively small area and evacuation is mainly done on foot. Instead, long-distance regional evacuation implies appearance of multiple emergencies and/or extended over a big area and requires vehicle for transport. It is also possible to have hybrid situations where the first part of the evacuation process is done on foot and after arrived at the designed safe point the process is done with vehicles. Evacuations can also be categorized in autonomous, recommended, and mandatory. Autonomous and recommended evacuation happens when people get warnings regarding disasters. In this case alert time is relatively longer compared with mandatory evacuations, which are generally with short notice and commanded by governments or competent authorities (Li et al., 2014). The methodology showed in this research work is focused on small scale evacuations and can be applied to both autonomous, recommended, and mandatory evacuations.

Evacuation plans require a multilevel analysis of different factors since many different elements are involved such as flood hazard, evacuation routes, safe points (shelters, safe meeting areas), population (including both physical and behavioural characteristics) and evacuation modelling. As seen in Chapter 2 (Literature Review) different approaches have been proposed focusing mainly on road/transport system characteristics or on flood hazard aspects, other authors instead prefer to focus on the evacuation process itself, analysing evacuation time, safe and critical areas, warning procedures, and behavioural aspects as crowd behaviour and dynamics.

The methodology here proposed is focused only on evacuation of pedestrians and can be expanded in future works including evacuation using also transport systems. In considering pedestrians as subject of an evacuation plans, two approaches can be adopted: macroscopic or microscopic (Mukherjee et al., 2015). The macroscopic modelling approach considers groups of individuals as a whole entity, thus characteristics of the motions (i.e., average velocity, average acceleration direction of the motion), behavioural and preferences of the individuals are averaged, and the result will be a broad picture of the phenomenon. This modelling method is more inclined to adopt an Eulerian approach of analysis where the number of individual being in the study domain (or present in the grid box in which the domain can be subdivided) is considered and taking also into account the concepts of centre of mass and density (Helbing, 1998; Hughes, 2002; Maury et al., 2010; Treuille et al., 2006).

Instead, the microscopic modelling approach has a single individual as the main subject which forms the crowd. Interactions between individuals and with the surrounding environment, as well their own motion, are simulated in this approach. Thus speed, acceleration, and direction of motion of the individual are the main focus in the model. Moreover, the collective behaviour is derived from the knowledge of the motion behaviour of the single individual. This modelling approach is then more inclined to use a Lagrangian analysis approach in which individual and their characteristics in terms of motions and interactions are tracked trough the domain. (Antonini et al., 2006; Hughes, 2002; Mukherjee et al., 2015; Singh et al., 2009).

In this research work a microscopic based approach has been adopted for the analysis of the individual. Crowd interaction and modelling of crowd behaviour at the moment are not considered and will be included in future work.

The main focus of this research work is the man-environment (in this case the pavements/roads system that the pedestrian can use) and the man-floodwater interactions. As pointed out by Bartolucci and Magni, (2016); Bernardini et al. (2017); Chanson et al. (2014); Cox et al. (2010); and Xia et al. (2011) these interactions affect pedestrians behaviour in abandoning hazardous areas and not making any decision that can affect the conservation of safe conditions during the evacuation process to reach a safe point.

Thus, key aspects of the methodology here proposed are i) flood hazard characteristics, ii) human physical characteristics, iii) identification of safe areas/shelters, and iv) identification of safest paths to move from a hazardous area to a safe zone.

As suggested by Musolino et al. (2020a) a Lagrangian-based flood hazard assessment approach, which put flood and human body characteristics in relationship, has been used in this research work to determine the safest evacuation routes to design the evacuation plan.

The author believes that psychological factors, crowd interaction and behaviour are very important aspects to be considered in designing evacuation plans. However, this work is mainly focused on the physical aspects of evacuation planning. The inclusion of psychological factors will be considered in future work.

The methodology used to evaluate the safest evacuation/access route for a flood event is illustrated in Figure 6.1 and summarised as follows:

- **1) Identification of the flood characteristics:** Since FHRs depend on the interaction between the flood and the person being exposed to the flood, the starting point of this methodology is to evaluate the flood's characteristics. In this research, DIVAST 2D TVD is used for hydrodynamic modelling and evaluating the flood's characteristics. Details of this model are reported in Section 3.

- **2) Identification of the pedestrian critical class**: The pedestrian's critical class is selected based on the main user of the area by the managing authorities, while considering the most vulnerable. For instance, in designing evacuation route for a school, general characteristics of the youngest children using the school will be selected, or in the same manner, for access to the flooded region by emergency services the general body characteristics of emergency services personnel will be used in this section. In this way, specific thresholds for human stability for a specific geographic area can be acquired. The Body Mass Index (BMI) for different age groups has been defined by the WHO Expert Committee on Physical Status (1995) is used to acquire height and weight. For this study, an average British person was considered as the critical class. It is crucial that appropriate evacuation plans for the most vulnerable groups of people, including people with disability or the elderly, are considered.
- **3) Calculation of the FHR for the pedestrian critical class:** Considering both mechanisms which lead to the instability, namely sliding and toppling as described in detail in Chapter 5, it is possible to determine the FHR for the pedestrian critical class. FHR is then determined for the entire area that can be used to access the potential safe/assembly points, referred to here as Safe Points (SPs). Monitoring Points (MPs) are used to monitor the FHR and how it changes over time along the routes. A MP is a critical point which is characterised by the highest FHR on each possible path which leads to the SPs. It is also essential to place MPs in proximity of the access routes to SPs for designing evacuation routes and potential retrofitting schemes as illustrated in Section 6.
- **4) Identification of Safe Points:** SPs identify areas that are not flooded during the design floods, thus are suitable to find shelter and await rescuers. SPs can be horizontal and/or vertical places (González-Riancho et al., 2013). Horizontal places are SPs which are outside the hazard zone (i.e., areas not flooded) or accessible high grounds. Vertical places are SPs located inside the hazard zone but in a building's higher floors, or other vertical structures

that are high enough to guarantee safety in case of extreme flood events. To avoid extreme densities as one of the key issues concerning evacuation planning, the whole domain can be divided into sub-areas, and for each of these sub-areas a specific SP is identified (Helbing et al., 2005, and Marques et al., 2020).

- **5) Classification of roads depending on their Flood Hazard Rate**: Once both MPs and SPs are located, it is possible to check the suitability of each road by observing the FHR. In other words, the maximum FHR for each route is recorded using the MPs and then the routes with the lowest maximum FHR are selected as the safest route.
- **6) Design the flood evacuation plan:** In the context of Lagrangian modelling, people were considered to move from each point in all possible directions towards SPs. The routes with the lowest maximum FHR selected in the previous stage are used to design paths which leads to the SPs.

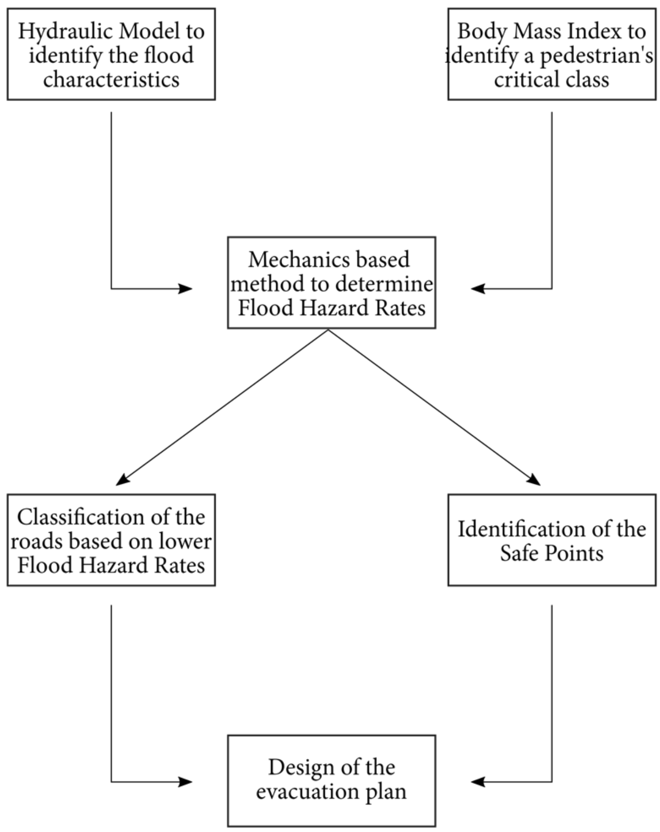


Figure 6.1- Schematics of evacuation/access route identification process.

Since FHRs depend on the interaction between the flood and a person, the starting point of this methodology is to evaluate the flood's characteristics. In this research work the hydrodynamic model used to evaluate flood's characteristics is DIVAST-TVD 2D, and details about this model are reported in Chapter 3. Once water depth and flow velocity are calculated the following step is to identify the pedestrian's critical class. In evaluating this critical class firstly, the most representative body shape and relative body characteristics, for the study area, have to be determined. Relatively to body characteristics, the Body Mass Index (BMI) is used to have reliable categories of height and weight to be used as input data. In this way specific and truthful thresholds for human stability can be determined according to the geographic area object of the analysis. Consideration relative to the BMI are reported in Section 6.3.3.

Once the flood area and stability thresholds for pedestrians are determined, it is necessary to identify where people can go to be safe from the flood. Thus, it is necessary to identify SPs (described previously in point 4) which people can reach following the evacuation plan and find shelter from the flood or meet the rescue teams. For this reason, the whole domain will be divided in subareas, and for each of these sub areas will be identified a specific SP. Dividing the study area in sub areas with different safe points allow to avoid too many persons in the same streets or going to the same location, one of the main point in designing is to avoid extreme densities (Marques et al., 2020) which is one of the main problems during an evacuations (Helbing et al., 2005).

The following step is to calculate the FHRs for all the streets of the studied area. Again, this is achieved by using the revised and improved MBM which is fully described in Section 6.2.1. Once the FHR for all the streets of the study area is determined, it is possible to determine the suitability of each road by observing the FHR. The maximum FHR for each route is recorded using the MPs (described previously in point 3) and then the routes with the lowest maximum FHR are selected as the safest route. In this way it is possible to immediately locate the safer streets to be used for the evacuation plan. A road with a lower FHR has to be preferred also if the final path to arrive to a safe point is longer.

In Figure 6.2 is reported an idealised scheme of roads that allows to reach a safe point. There are different options to reach the safe point from the pedestrian location, objective of this methodology is to provide the safest path among the available ones considering both flood and pedestrian characteristics. Once FHR has been calculated considering the pedestrian critical class for all the streets it is possible to organise the different alternative paths in a table. All the alternatives are ranked by their FHRs, in this way the safest route can be determined choosing the alternative which presents the lowest maximum FHR. In case two or more alternatives have the same o very similar level of safety the shortest one is then selected as the ideal safe path for the evacuation plan, since minimising evacuation time means minimise exposure to potential hazards (Shekhar et al., 2012).

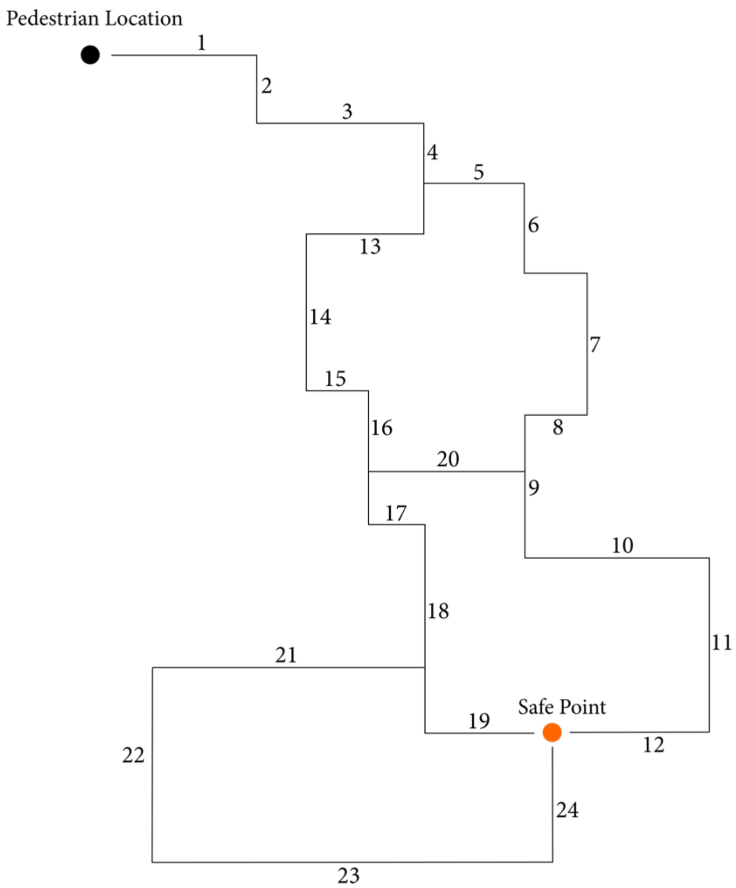


Figure 6.2 – Idealised roads scheme

Pedestrians can be informed about the path to follow with different methods, for example maps located in strategic points, local community engagement, periodic flood evacuations drills, messages on mobile phones integrated with mobile applications which can give to the user the best path to follow depending on their position during the events.

6.3.2 Role of Body Mass Index (BMI)

In this section the role of BMI is examined in determination of the parameters h_p (height in m) and m_p (weight in kg) necessary to evaluate the flood hazard by using the mechanics-based method. This extension to this method will enable the design of evacuation routes best suited to meeting the needs of the most vulnerable users, (e.g., elderly adults or children). Using the BMI to determine the parameters h_p and m_p is another novelty of this work and allows for the determination of more realistic evacuation routes, tailored for the population living in the study area. Using this approach, it is possible to have a medical/scientific based approach in the choice of the weight of a person once their height is defined according to the country and population sub-category. In Section 6.3.3 the analysis relative to the influence of height and weight parameters is reported in determining the evacuation routes.

The BMI is defined by WHO as the person's weight in kg divided by the square of the person's height in metres (kg/m^2) (WHO Expert Committee on Physical Status, 1995). The lowest BMI for a healthy adult over 20 years of age is 18.5. Thus, the BMI chosen for adults is 18.5 to consider the most vulnerable person in the normal weight category. In other words, ensuring the safety of the most vulnerable person in this category will ensure the safety for other persons of the same category.

For children and teenagers, the BMI values are different even though the definition of the parameter is the same. This difference is due to the rapidly changing weight and height of children, particularly during the puberty. In this case, the necessary data are extracted from the growth chart (Figure 6.3) provided by the Royal College of Pedestrian and Child Health (using the 50th line, which indicates that the value has exceed 50% of the entire data series). Data are available online at WHO Global Database on BMI.

Adult and children weight/height values are reported in Tables 6.1 and 6.2 respectively.

Table 6.1 - Weight/Height Values for Adults

Adults class	1	2	3	4	5	6	7
Height (cm)	160	165	170	175	180	185	190
Weight (kg)	47.36	50.37	53.47	56.66	59.94	63.32	66.79

Table 6.2 - Weight/Height for Children and Young People

Children/teenagers class		1	2	3	4	5	6
Boys	Height (cm)	109	127	143	161	176	177
	Weight (kg)	16.2	26	35	50	67	69.5
Girls	Height (cm)	109	127	144	159	163	163
	Weight (kg)	17.2	26	36	50	57.5	58
Age	Years	5	8	11	14	17	20

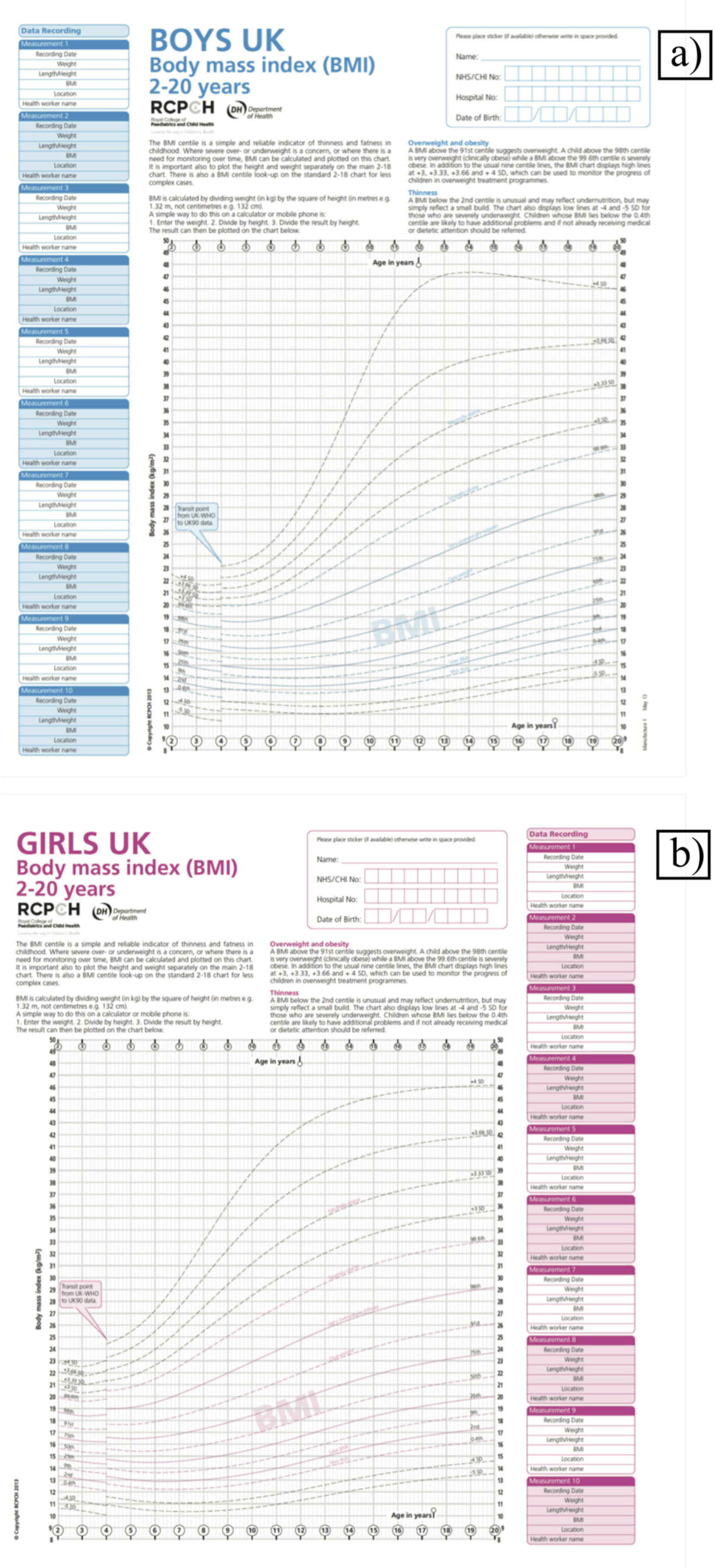


Figure 6.3 - BMI charts for children/teenager

6.3.3 Evacuation Plan: results and discussion

In this section, results relative to evacuation plans for the two case studies showed in Chapter 5 are presented and discussed. The results have been obtained applying the methodology illustrated in Section 6.3.1 and the aspects relative to the BMI (See 6.3.2) for determining the critical pedestrian class to be considered when using the proposed methodology.

Considering the case study of Boscastle, Table 6.3 highlights the results of the FHR at the peak flood time, based on data from 17 monitoring points that are representative of the paths which lead to the safe points, located in places which are not affected by the flood. Location of the monitoring and safe points is showed in Figure 6.4

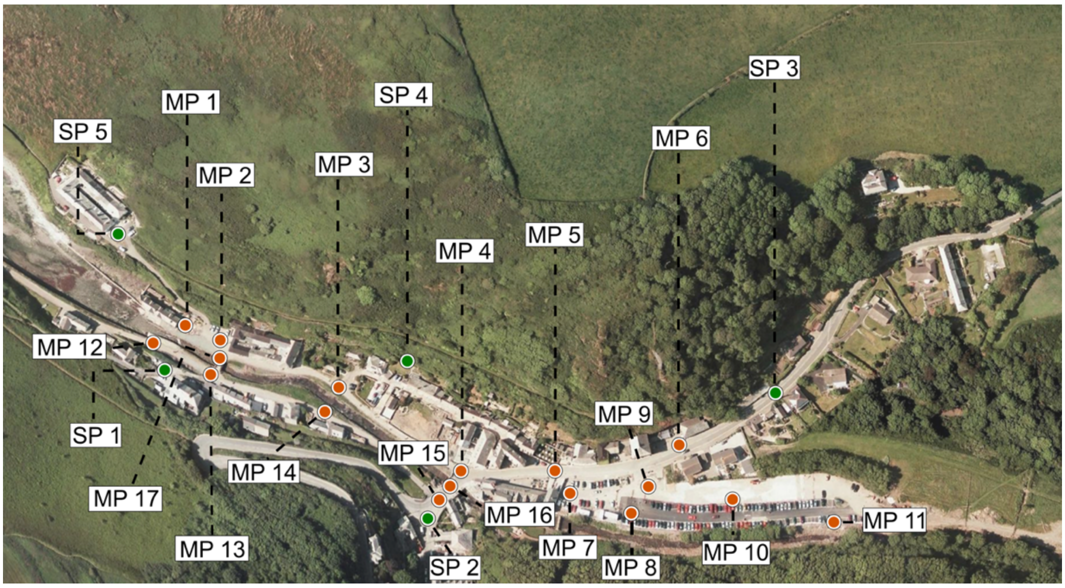


Figure 6.4 – location of Monitoring Points (in orange) and Safe Points (in green)

The characteristics related to pedestrian categories are shown in Table 6.1 and 6.2 of Section 6.3.2 where only 3 sets of results are reported herein to avoid repetition, with similar results having been obtained for all of the Monitoring Points, for the whole simulation period, and for the various human categories (Musolino et al., 2020b). Human categories reported are Adults1, Average Adults and Boys 2, these categories represent the most critical adult category (i.e., Adults1), the average adult category (i.e., Average Adults), which is characterized by height equal to 1.75m and weight equal to 83.7 kg (ONS - Office for National Statistics (UK), 2010), and the most critical children category among boys and girls (i.e. Boys2). The values may seem high, but the data reported are the maximum values for the entire event for the Boscastle flood and were expected to be high at the peak of the event.

The results, reported in Table 6.3, underline the influence of the height and weight of a person in terms of the FHR for the most representative categories. In Table 6.3, a Monitoring Point is coloured in green if it has the same rank for two or more human categories, otherwise it is shown in orange. If the Monitoring Points for two or more human categories have the same rank position, but have different values of FHR, then the cell is coloured in light-blue (Musolino et al., 2020b). The results in terms of the FHR are reported from the highest to the lowest, for all the 17 Monitoring Points. Between the categories of Boys 2 and the two adult categories there is rank agreement only for Monitoring Points 4, 6, 9, 11, and 15. Also, the Monitoring Points 6, 9, 11, and 15 have the same rank in terms of hazard rate, but they show different values of the hazard rate when the influence of weight and height is considered. This shows the importance of the body characteristics in determining the FHR and consequently the evacuation route.

The two adult categories are almost in agreement in terms of rank. Monitoring Points 2, 6, 9, 11, 12, 15, 16, and 17 show the same rank, but different values for the hazard rate due to the influence of weight and height are observed, as mentioned above.

Table 6.3 - Variability of flood hazard rate with height and weight, simulation time 390 min.

Rank	Monitoring Point	Flood Hazard Rate - Boys 2	Monitoring Point	Flood Hazard Rate - Adults 1	Monitoring Point	Flood Hazard Rate - Average Adult
1	4	44.31	4	44.31	4	44.31
2	2	43.22	10	32.58	10	32.58
3	10	32.58	13	31.63	13	31.63
4	13	31.63	7	26.68	7	26.68
5	7	26.68	3	26.59	3	26.59
6	3	26.59	8	26.59	8	26.59
7	8	26.59	1	23.2	1	23.2
8	1	23.2	5	19.93	5	19.93
9	5	19.93	14	17.5	14	17.5
10	16	18.94	2	16.69	2	11.57
11	12	18.81	16	10.62	16	7.61
12	14	17.5	17	9.06	17	6.86
13	11	12.49	11	8.59	11	6.37
14	17	12.12	12	8.26	12	6.05
15	6	7	6	4.37	6	3.18
16	15	2.6	15	1.97	15	1.5
17	9	0.78	9	0.38	9	0.24

Figure 6.5 shows optimal evacuation plan for the categories of: "Boys 2" (Figure 6.5 a), "Adults 1 (Figure 6.5 b), and "Average adults" (Figure 6.5 c).

Figure 6.7 shows detailed results for Monitoring Point 2 as an example, reporting the incipient velocity for toppling instability and the relative flood hazard. With these results governing the critical conditions for this case as the value of incipient velocity for toppling are lower than the one for sliding as is possible to observe from the results reported in Figure 6.6. Which reports the incipient velocity for toppling and sliding for the Monitoring Point 2.

In all cases it can be noted that as the weight/height value increases then the critical velocity also rises, thereby leading to a corresponding reduction in the flood hazard. Figures 6.7 a, c, e shows that at the same location (i.e., Monitoring Points 2) there is a difference of approximately 1 m/s between the incipient velocity for adults and children or young people. This relatively large difference between children and adults should be carefully considered, since at Monitoring Points 2 the incipient velocity for the adults (Figure 6.7 a) never reaches the critical state (i.e., a value of 0.5). Therefore, this point is expected to be safe for this category. However, when children and teenagers are considered, this point becomes unsafe for the first two classes, (i.e., for both boys (Figure 6.7 c) and girls (Figure 6.7. e)), as the velocity is higher than the critical velocity for these categories. As reported in Table 6.4, for the category Boys 2, Monitoring Point 2 is ranked as the 2nd highest FHR, while the rank of this point drops to 10th for the two adults' categories.

For this case study, the ideal evacuation routes were therefore calculated for children since children were expected to live in the village. Considering the age of Boys2 category (8-year-old), they are supposed to walk without the help of their parents in case of flood evacuation.

The results reported and discussed in this section show that attention needs to be particularly focused on these findings where they are at, or close to, more vulnerable categories, such as where schools, sport centres, etc. exist, and where children are more likely to be present. This is because the threshold of incipient velocity is lower than the corresponding value for adults. For elderly people the same consideration would apply as for children (Milanesi et al., 2015; Xia et al., 2014b).

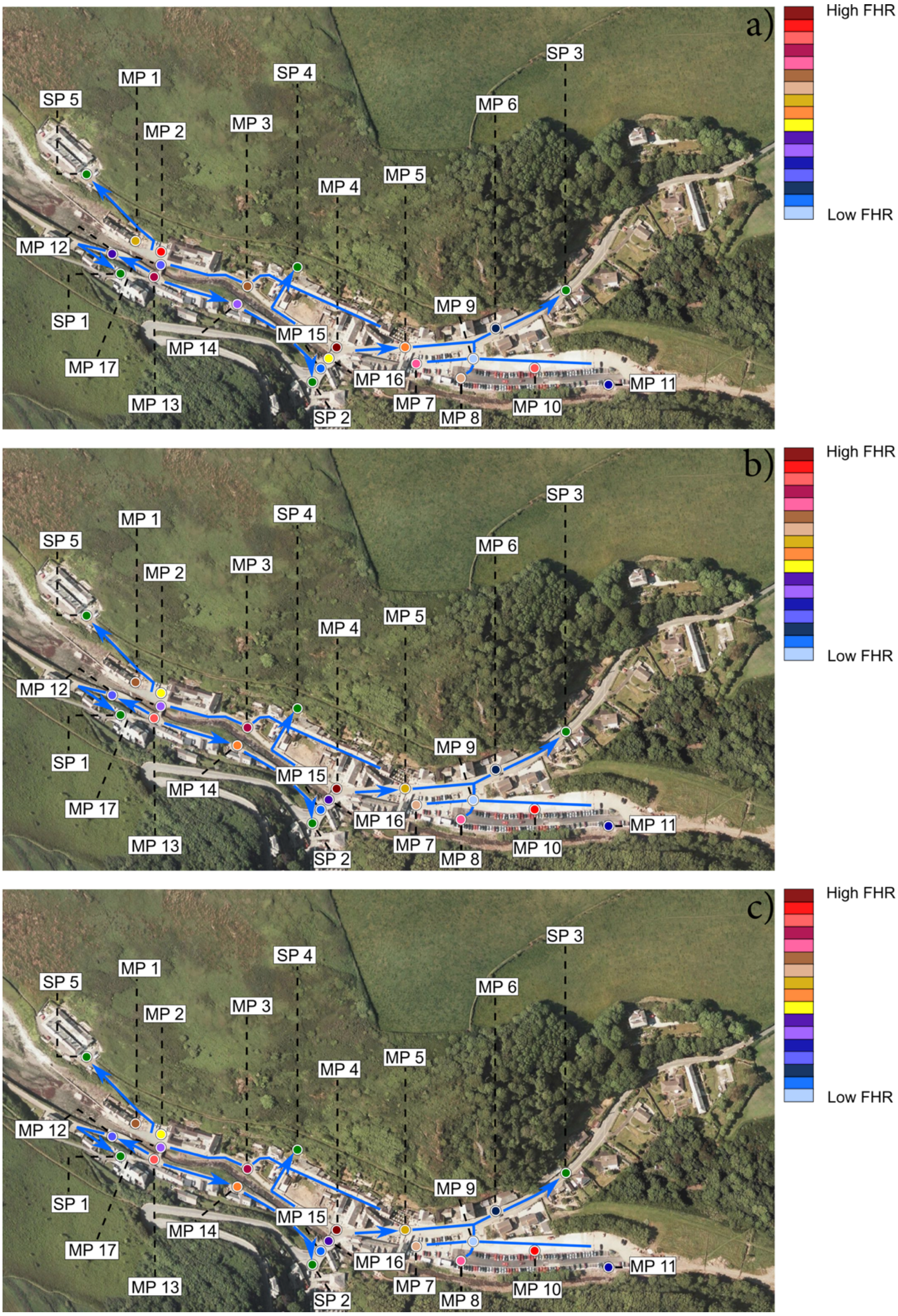


Figure 6.5 - Location of Monitoring Points (MP), Safe Points (SP), and Evacuation Routes (blue lines) for: a) "Boys2", b) "Adult 1", and c) "Average Adult".

Monitoring Point 2

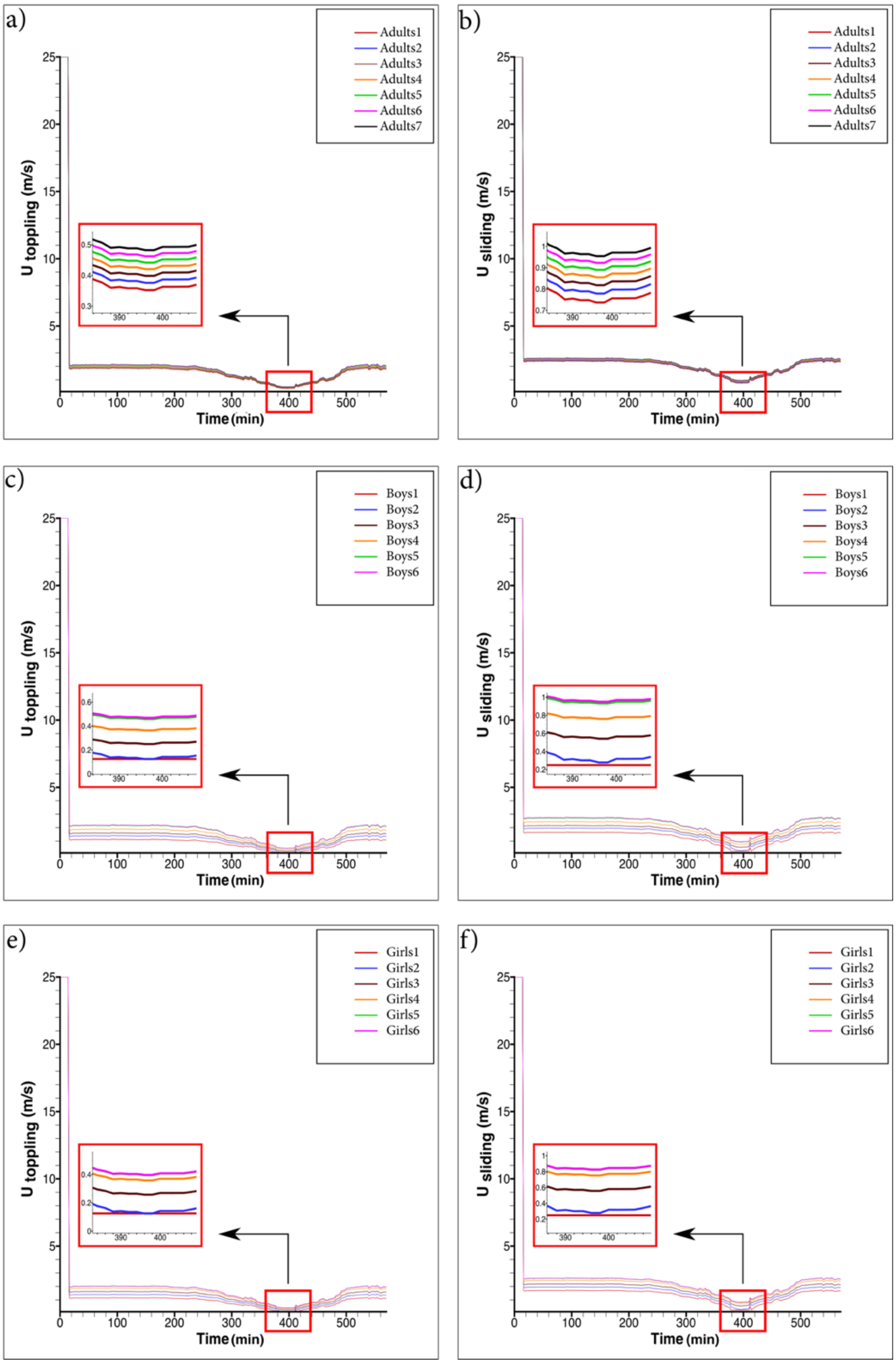


Figure 6.6 - Velocity for Toppling and Sliding Mechanisms at Monitoring Point 2

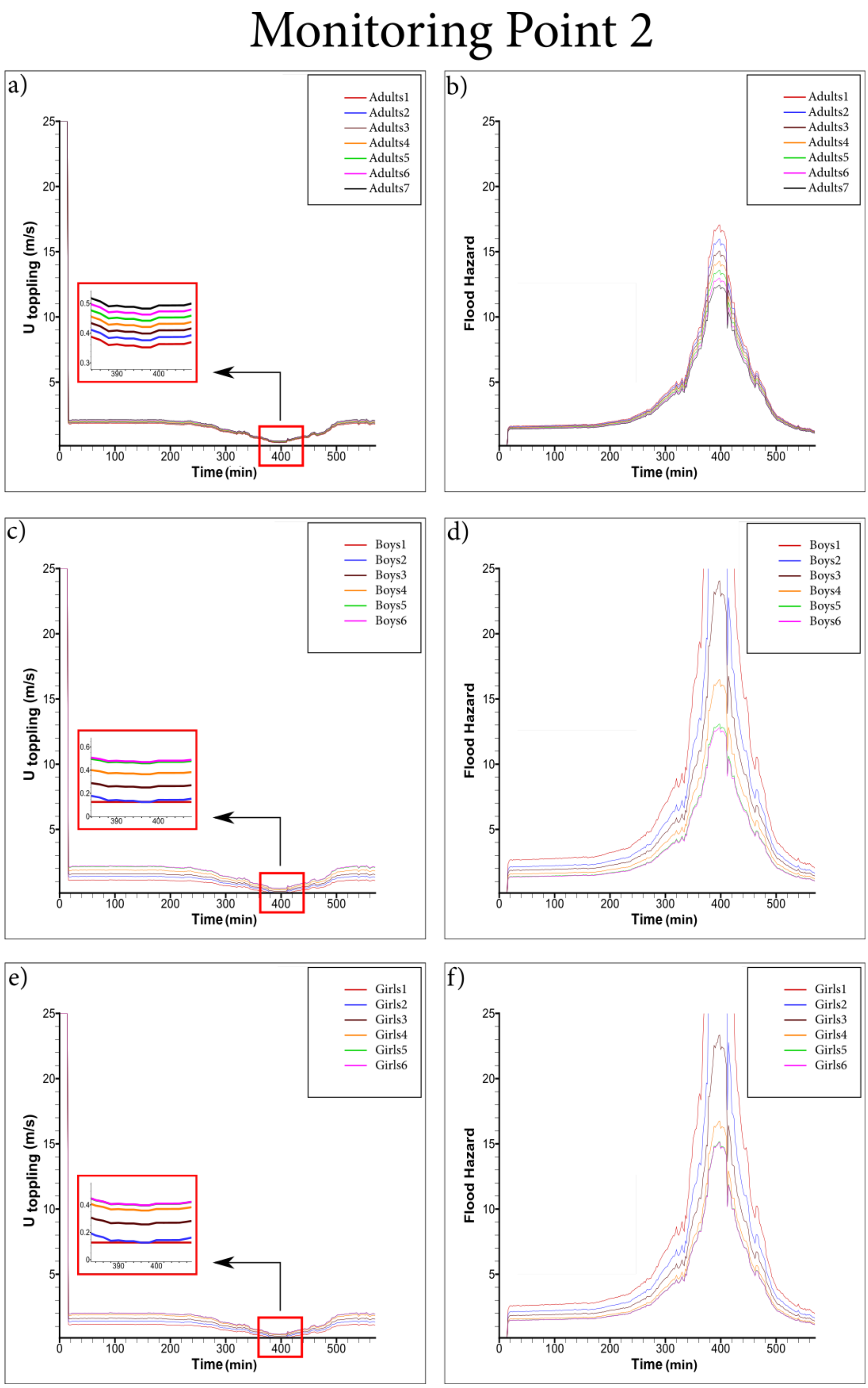


Figure 6.7 - Velocity for Toppling Mechanism and Flood Hazard for Monitoring Point 2

For the Borth case study main focus has been put on the Riverside Caravan Park area. As seen in Chapter 5 this area has been heavily affected by the flood of the 9th June 2012 herein chose as flood modelling case study. Considering this specific caravan park and the surrounding area, 6 MPs and 1 SP have been selected (Figure 6.8).

As done for Boscastle case study, the methodology presented in 6.3.1 and 6.3.2 has been used, the results in terms of the evacuation plans are reported in Figure 6.9. Since there is a single street inside the caravan park and the area is relatively limited, no alternative routes are possible, so the evacuation plan will be designed considering just the available route. Therefore, this case represents a different situation compared to Boscastle where multiple choices are available. Thus, this case study has been chosen mainly to demonstrate how it is possible to deal with situations where no alternatives are present to consider different scenarios and thus demonstrate the benefits of applying the holistic retrofitting methodology presented in Sections 6.4. Benefits offered by retrofitting routes are presented in Section 6.5.

Figure 6.8 – Displacement of the Monitoring Points (in orange) and Safe Points (in Green) for Riverside Caravan Park cases study

Figure 6.9 – Evacuation plan for Riverside Caravan Park cases study

6.4 Improving evacuation plans

Walking in flood water is seriously dangerous and it should be avoided whenever it is possible. However, people and authorities can be surprised by floods severity, and it could be necessary to evacuate people or access vulnerable people during a flood event. FHR can be used to identify safe evacuation routes (Musolino et al., 2020b). However, it is not always feasible to identify safe enough paths, or paths that give enough time to arrive to a safe place. In most cases, the route is considered unsafe because of high FHR in limited segment(s) of the route.

As an alternative to building hard engineering flood defences to reduce the FHR in an area, we propose targeted retrofitting evacuation and access routes to reduce flood hazard to a safe level. This will enhance people's safety during evacuation and transform our existing living environment into a more flood-resilient environment at a minimum cost. It is important to emphasise that author recommend people avoiding venturing through flood waters as much as possible and the proposal for retrofitting is to ensure safety when evacuation is necessary.

There are historical examples of different solutions used to create safe paths to escape flood waters as showed in Figure 6.10a which shows a flooded street in Pompeii (Italy). Most efforts in the modern built environment are focused on eliminating flood risk, however this is not always possible which sometimes leads to rudimentary solutions to create safe passages through flooded areas, as depicted in Figure 6.10b. This figure from Wuhan (China) illustrates people using an improvised bridge to cross a flooded street, which is definitively not a safe solution.

As Illustrated in Figure 6.11a in the streets of Pompeii during the Roman period, blocks of stone were put at a regular distance to allow people to walk safely in case of flooded streets. The height and the spacing of the blokes allow carriages to go through the streets in normal conditions without any interference. This type of passage may not be safe and suitable for everyone in the modern built environment. However, the concept of permanent flood evacuation passages as used in Pompeii can be part of modern flood risk management. Figure 6.11b illustrates the retrofitted scheme being discussed in this research work to create a safe path. It should be noted that Figure 6.11b is only produced for illustration, and the flow regime after retrofitting has to be modelled in order to ensure it does not exacerbate the impact of flooding on other places by producing a blockage.

The retrofitting scheme herein proposed consists in increasing the elevation of the path over a necessary length to provide a safe passage for evacuation of people when necessary, or as an access route for rescuers to access the flooded areas. The final step is repeated until the path is safe, until the evacuation route is safe based on FHR or the increase required is beyond acceptable. The retrofitted path will be selected as the evacuation route if the flood hazard post-retrofitting is within the safe zone. In this way, the passage can be used for more time before the peak of the event and after the peak.

The retrofitting scheme can be implemented as follows: firstly, potential SPs in the vicinity of public places (e.g., schools, offices, hotels, museums, car parks, residential complexes, etc.) that may require evacuation have to be identified using flood inundation and extent simulations and other criteria required by SPs previously described. Secondly, all the routes connecting the evacuation location and the SPs are highlighted. It is important that all the routes not only the shortest routes are considered at this stage. Thirdly, determining the FHR along the path for all possible routes linking evacuation and safe locations. This allows to identify the critical points in the routes, (i.e., locations along the route with high flood hazard), where the rest of the route is safe. Fourthly, selecting the potential evacuation routes where the path is safe based on the FHR, with no or minimum interventions. Finally, repeating the flood simulation including the proposed retrofitting, slightly raising the topography at the location of the critical point in the model to identify post-retrofitting impact and avoid any adverse impact of the retrofitting.

To demonstrate the benefits of this retrofitting scheme when designing evacuation plans with a pedestrian perspective, for both the case studies the road level has been increased, starting from 0.5 cm until the values of FHR were good enough to guarantee safety, thus the road level has been raised up to 25 cm for the necessary length in the identified locations. This allows a reduction of both water depth and flow velocity, and consequently reducing FHR to a safe level. In determining the FHR, the MBM illustrated in Chapter 5 is applied here due to the flexibility of the method in taking in account human characteristics. This provides the opportunity to consider the body characteristics of the critical users' category of the route in the planning process of evacuation or access routes, (e.g., children's body type for the school evacuation path, or healthy adults for emergency services access planning).

Figure 6.10 – a) retrofitted street in Pompeii (Italy) photo by Giorgio Cosulich / Getty Images b) flooded street in Wuhan (China) 2012 photo by the Guardian

Figure 6.11 – Pompeii Italy – a) not retrofitted, b) with retrofitting scheme – photo by Giorgio Cosulich / Getty

It is important to emphasise that this method of retrofitting does not reduce the risk to zero but will increase the safety of the route for more time during a flood event. Moreover, not all the roads can be retrofitted, and scrupulous hydrodynamic analysis must be done to quantify the benefits gained from the retrofitting in order to check which area is more suitable to be retrofitting. This approach aims to increase the resilience of our environment with minimum interference and cost and hence can be adopted in small villages where more fundamental structural solutions may not be financially feasible or in urbanised areas as a part of bigger and more complex alleviation schemes.

Generally, this retrofitting scheme can be deployed in the following situations:

- Cases where the degree of flood hazard coupled with limited time to undertake incident management activities, in other words in cases where the rapid onset of the flood event permit little or no time for warning the public or evacuating, example of this situation in the 2004 Boscastle flash flood (Penning-Rowsell et al., 2013).
- Locations where people could be exposed to flood waters those that provide little or no shelter from flooding waters (e.g., camping sites, caravan parks as in Borth case study), building damaged by the flood or buildings with no elevated floors. In all these cases it is better to find shelter in proper areas using evacuation paths.
- To mitigate circumstances where people take risky behaviours, ignoring instructions or misjudging the danger of the flood, including walking, or driving through flooded areas.

6.5 Benefit from Retrofitting Roads

The results obtained for the two case studies are presented and discussed in this section. First, the model was run for each case study and the maximum FHR across the domain was calculated. Figure 6.12 and Figure 6.13 illustrate the results relative to the maximum FHR for the case studies of Boscastle and Riverside Caravan Park respectively. These represent the worst-case scenario that can be addressed when designing an evacuation plan.

The case studies considered here are major events and most routes do not stay safe during the peak of the floods as shown in Figure 6.12 and 6.13. It is expected in such cases that the evacuation would be carried out before the peak condition. In this study, the most critical condition is considered for demonstration of the methodology. The design of evacuation plans in practice requires multi-parameter analysis considering a wide range of variables, which is beyond the scope of this work.

As the scope of this section is to demonstrate the benefits of the proposed scheme, only one human category is considered, namely the average adult category (i.e. Average Adults), which is characterised by height equal to 1.75 m and weight equal to 83.7 kg (ONS - Office for National Statistics (UK), 2010). Of course, all the consideration discussed relatively to the influence of height and weight in designing evacuation plans showed in 6.3.3 are valid, but for simplicity only a category is considered in this specific application.

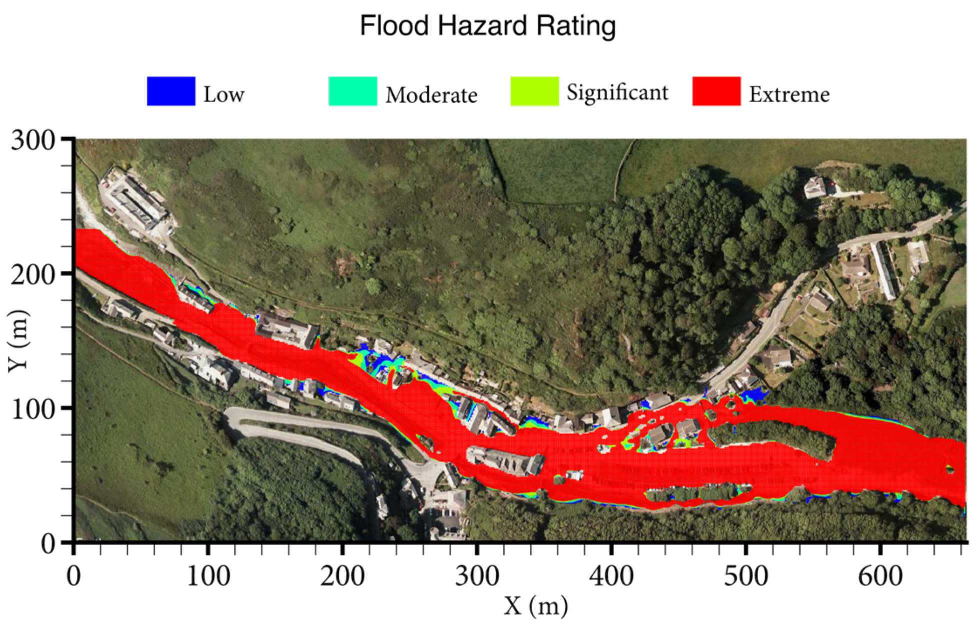


Figure 6.12– maximum FHR for pedestrians, Boscastle case study

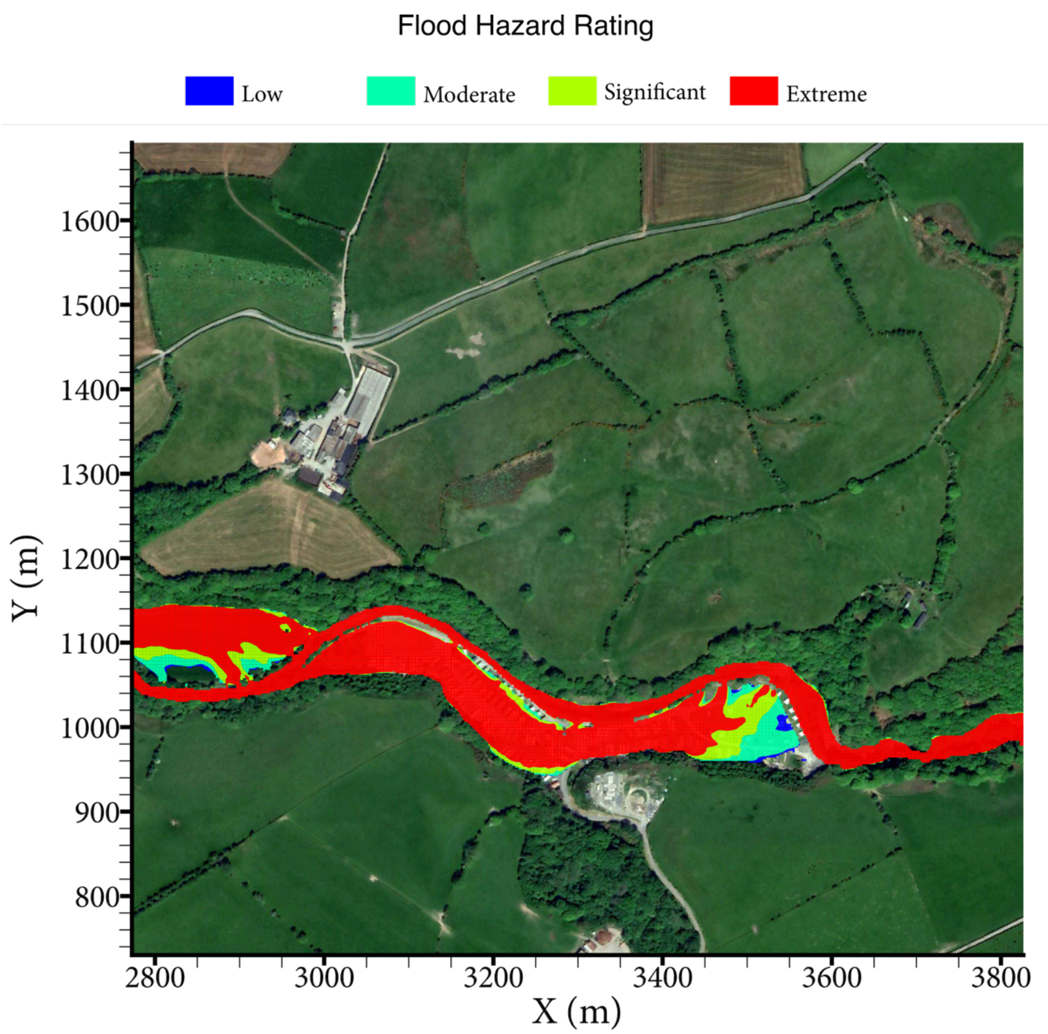


Figure 6.13 - maximum FHR for pedestrians, Riverside Caravan Park case study

As reported in detail in Section 6.3 once the FHR is determined for the considered flood event and pedestrian critical class, it is possible to determine SPs and classify the road depending on their FHR though the MPs, in Table 6.4 are reported the maximum FHR for the 17 MPs for Boscastle case study. At this point it is possible to design the evacuation plan using the routes with the lowest maximum FHR which lead to the SPs.

Figure 6.14 shows the evacuation plan for Boscastle. An important finding derived from this type of analysis is that the suitable SPs are not necessarily the closest ones. In other words, the shortest path to the SP is not always the most appropriate route to be selected as the evacuation route. This is because pedestrians may face higher flood hazard through the shortest path, which makes it unsafe. Example of this situation is shown in Figure 6.14, considering a pedestrian which is on the right side of MP 13 he/she should go to SP 2 and not to SP 1 since MP 14 and MP 15 have a lower FHR value compared to MP 13, so crossing this latter MP to reach SP 1 is more dangerous. Similarly, for a pedestrian which is on the left of MP 3, since MP 1 and MP 2 have a lower FHR than MP3 is better to not cross this last MP and direct towards SP 1 instead of SP 4.

Table 6.4 – Maximum FHR for the 17 MPs for Boscastle case study

Monitoring Point	FHR - Average Adult
4	44.27
10	41.81
8	32.64
13	30.84
3	26.46
5	24.91
1	24.01
2	23.26
7	20.56
14	15.89
12	15.47
17	14.71
16	13.45
11	12.99
6	6.841
15	3.82
9	1.3

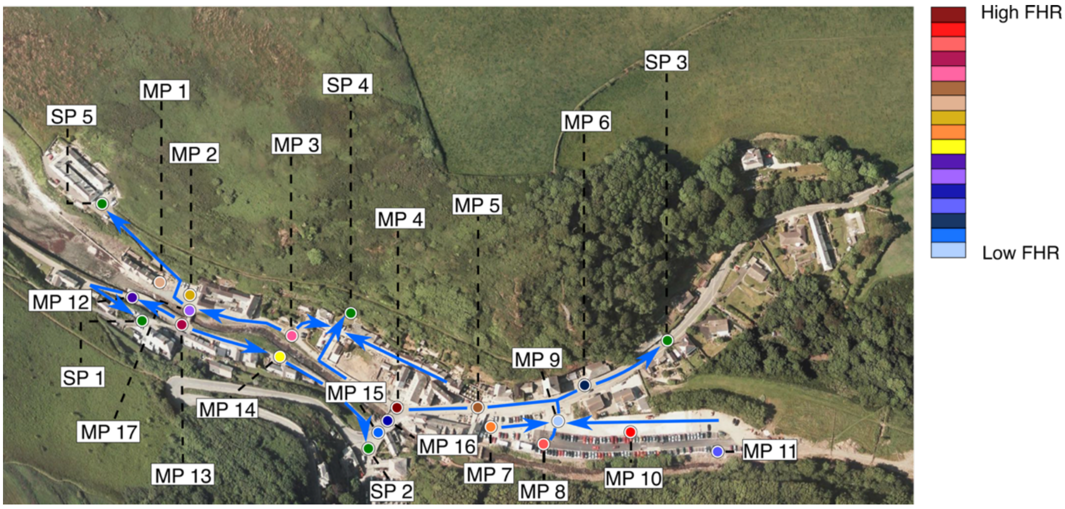


Figure 6.14 – FHR for the Monitoring Points and evacuation routes (blue lines) for Boscastle case study

As aforementioned, for Riverside Caravan Park the choice of evacuation route is exclusive. With this case study chosen mainly to demonstrate the benefits of retrofitting roads when no alternative are presents. Figure 6.15 shows the evacuation plan for Riverside Caravan Park.

Figure 6.15 – Evacuation routes (blue lines) for Riverside Caravan Park case study

As previously discussed, retrofitting existing roads and paths can be used to improve people's safety during flood events by providing a safe evacuation or access route. Such retrofitting has been implemented in the case study sites to demonstrate their potential application alongside FHR. To achieve that, specific zones in each case study sites have been selected and to enhance evacuation route, retrofitting has been applied to the chosen roads in the selected zones.

To demonstrate the potential for pedestrians' safety enhancement during a flood evacuation, two areas in the Boscastle case study linked to publicly used buildings in the area have been considered: Zone 1 (Figure 6.16 inside the black rectangle) is the area relative to the Cobweb Inn a Free House/Bed & Breakfast, Zone 2 (Figure 6.19 inside the black rectangle) is relative to the Bridge House a Tea Room/Hotel.

The unsafe passage window was from the last instant where the path is still safe before the peak of the event, until the first instant after the peak of the event where the path becomes safe again based on the FHR predicted by the numerical simulations (i.e., 332 minutes and 460 minutes from the start of the simulation, respectively). In this way, it is possible to know i) up to when it is possible to evacuate in safe conditions, and ii) the first available moment after the peak of the event when it is possible to evacuate people who were not available to evacuate from the area before the peak and find shelter in buildings.

Figure 6.16 shows the FHR over the Zone 1 evacuation route for Boscastle during the times that define the unsafe passage window with and without the retrofitting scheme. Figures 6.17 and 6.18 illustrate a comparison of FHR for Zone 1 with and without retrofitting for the two times that define the unsafe passage windows. The retrofitting option here was to increase the topography of the selected area by 25 cm, lower values do not give safe enough values of FHR.

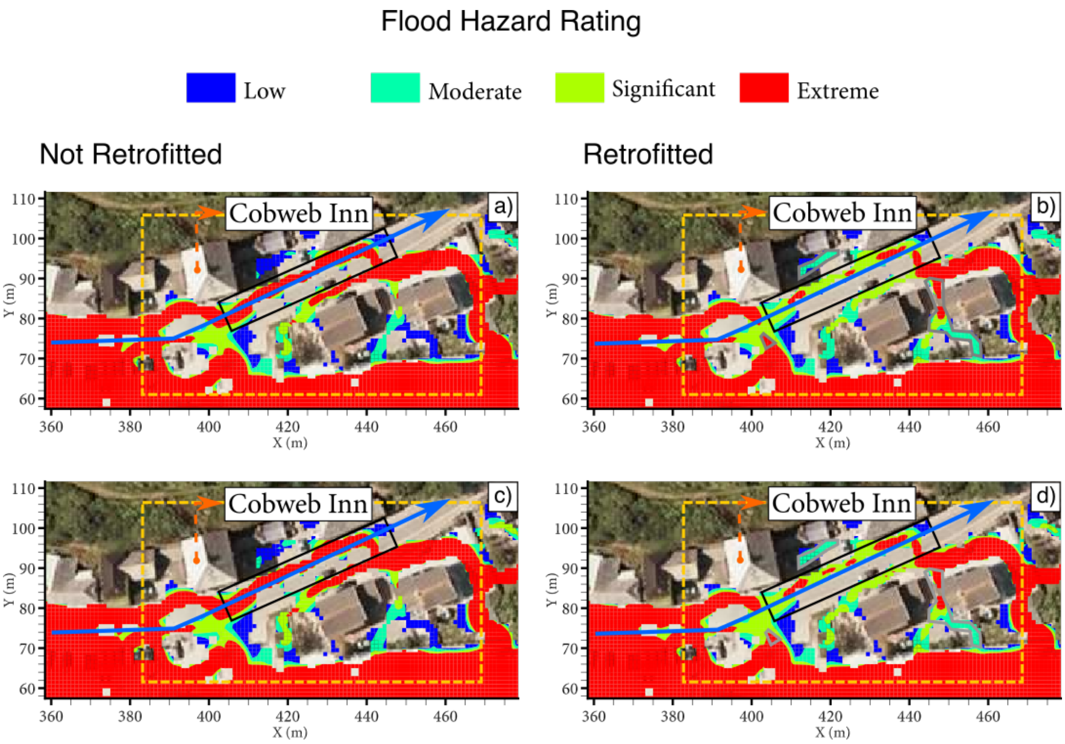


Figure 6.16 – FHR comparison between not retrofitted a) and retrofitted b) sim. time 332 min (before the peak) and not retrofitted c) and retrofitted d) sim. time 460 min (after the peak) in Boscastle zone 1. The blue line indicate the evacuation route.

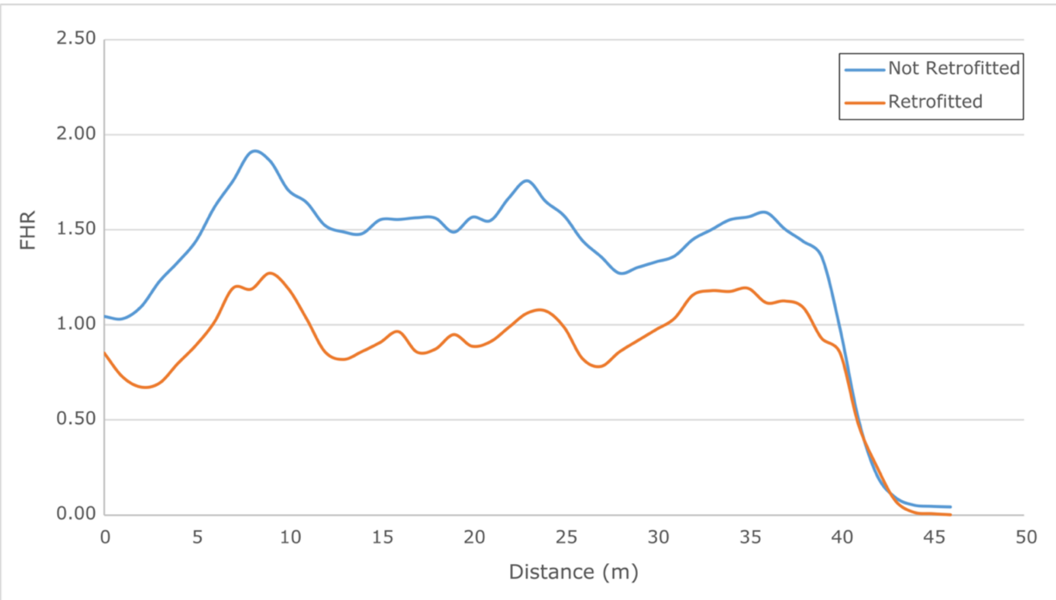


Figure 6.17 – FHR comparison between retrofitted and not retrofitted in Boscastle zone 1 – simulation time 332 min

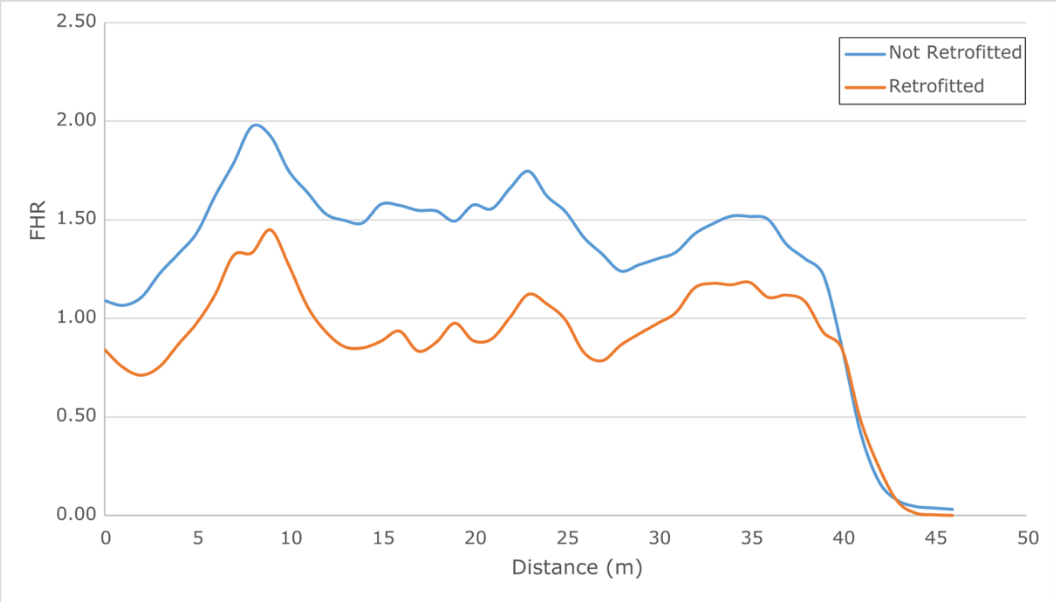


Figure 6.18 - FHR comparison between retrofitted and not retrofitted in Boscastle zone 1 – simulation time 460 min

Similarly, to Zone 1, the FHR over Boscastle Zone 2 evacuation routes during the times that define the unsafe passage window (i.e., 8 minutes and 570 minutes from the start of the simulation) with and without the retrofitting scheme is shown in Figure 6.19. Figures 6.20 and 6.21 show a comparison of FHR for Zone 2 with and without retrofitting for the two times which define the unsafe passage windows. The retrofitting option here was to increase the topography of the selected area by 25 cm, lower values do not give safe enough values of FHR.

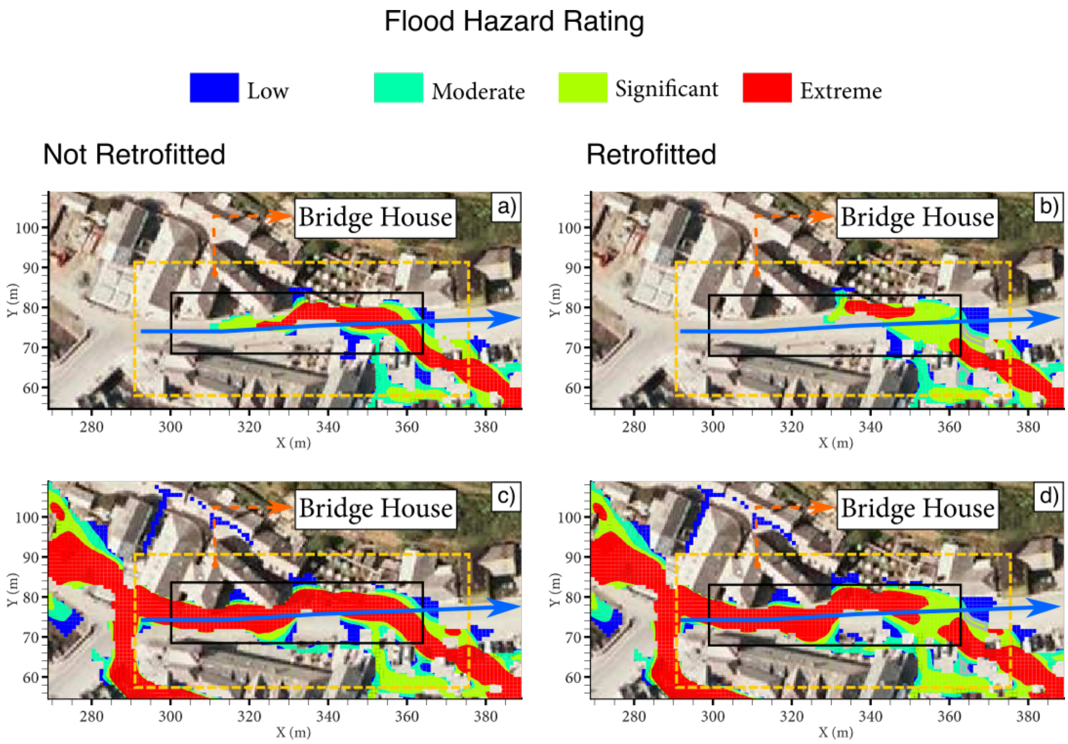


Figure 6.19 - FHR comparison between not retrofitted a) and retrofitted b) simulation time 8 min (before the peak) and not retrofitted c) and retrofitted d) simulation time 570 min (after the peak) in Boscastle zone 2. The black rectangle represents the retrofitted area the blue line indicates the evacuation route, the grey polygons indicate the areas where the FHR is negatively affected by the retrofitting, and the yellow rectangle represent the zoom area.

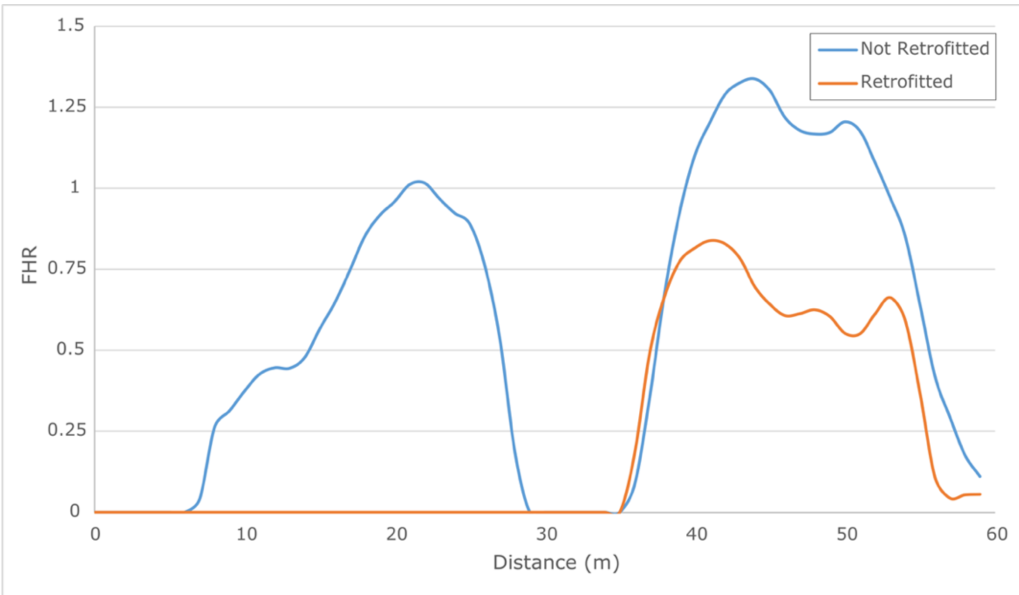


Figure 6.20 - FHR comparison between retrofitted and not retrofitted in Boscastle zone 2 – simulation time 8 min

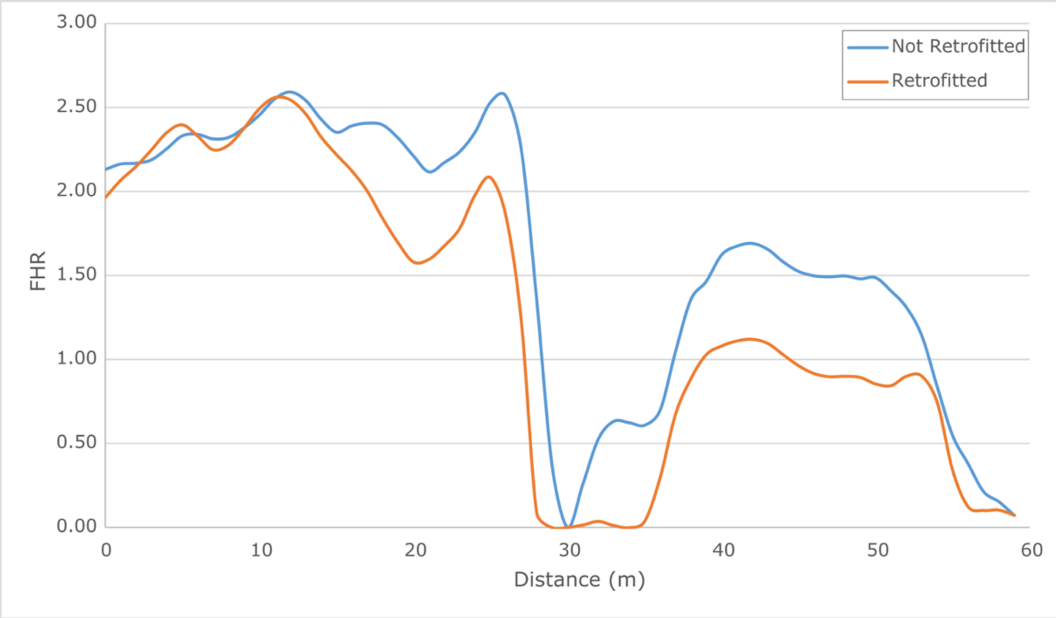


Figure 6.21 – FHR comparison between retrofitted and not retrofitted in Boscastle zone 2 – simulation time 570 min

As showed in Figures 6.16 and 6.19 the change in FHR is not significant in the domain, there are very limited areas nearby the retrofitted zone where the FHR is slightly increased. As it is showed in detail in Figures 6.22 and 6.23 the areas where this negative change happens (i.e., area delimited by grey polygons) are not on the evacuation routes. As well the variation is almost everywhere in the safe FHR range (i.e., FHR < 1 or FHR not Extreme in the Figures legend), thus it is believed that this retrofitting option does not adversely affect the FHR in the domain.

Further improvement can be obtained by rising more the height of the retrofitting scheme, this of course will require more tests and simulations. This is not included here since the main scope of this study is to demonstrate the potential for retrofitting in increasing pedestrian safety during evacuation.

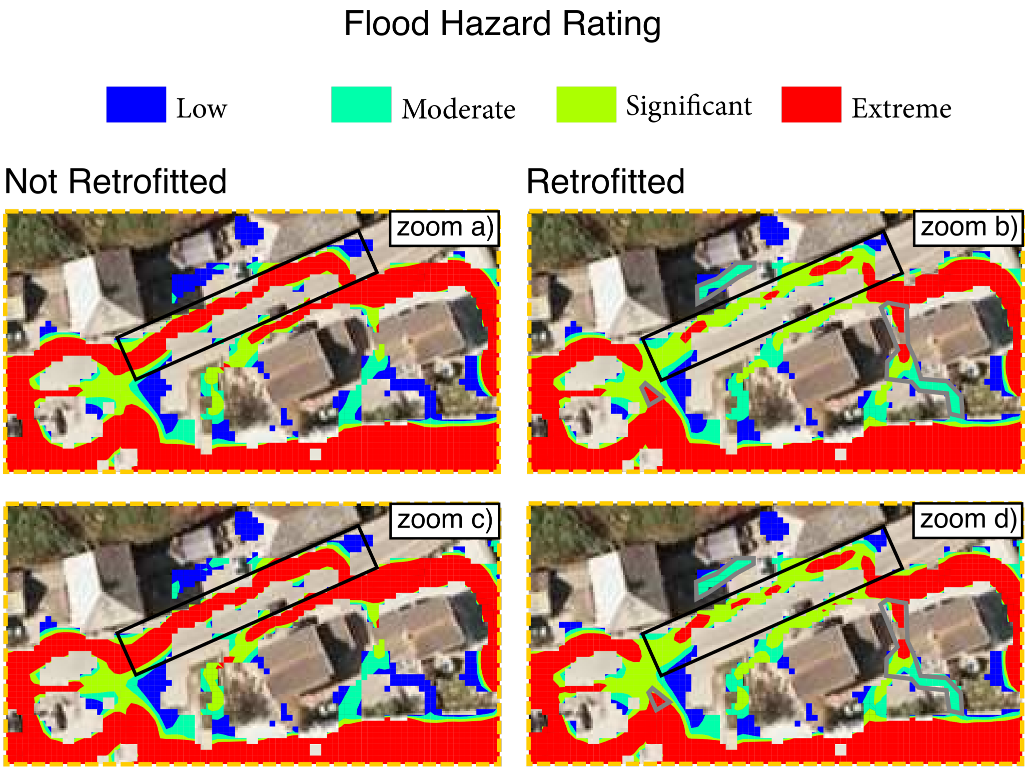


Figure 6.22 – Details of FHR comparison between not retrofitted a) and retrofitted b) simulation time 332 min (before the peak) and not retrofitted c) and retrofitted d) simulation time 460 min (after the peak) in Boscastle zone 1.The grey polygons indicate the areas where the FHR is negatively affected by the retrofitting.

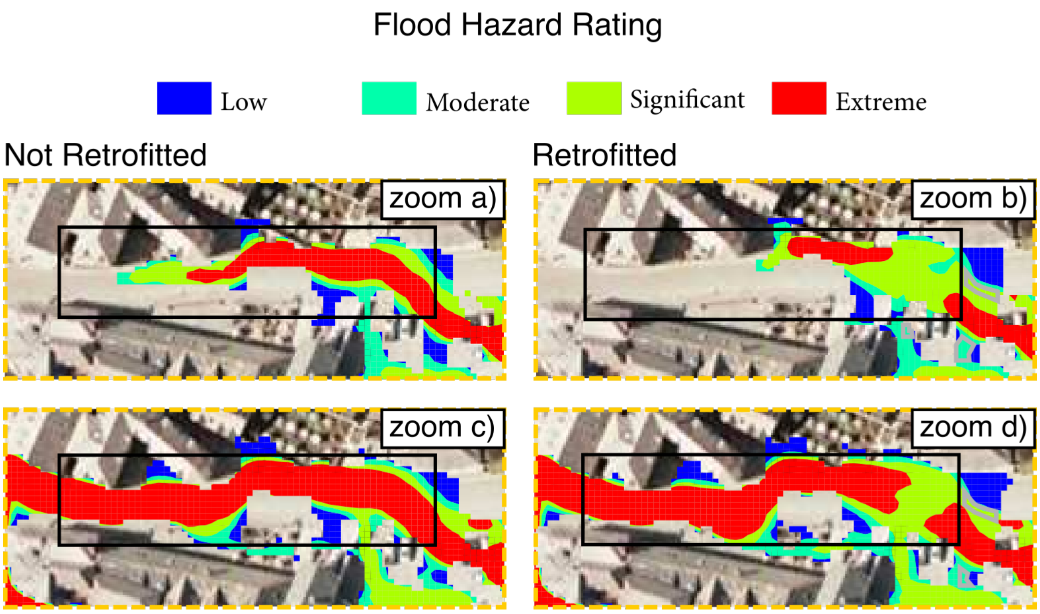


Figure 6.23 – Details of FHR comparison between not retrofitted a) and retrofitted b) simulation time 8 min (before the peak) and not retrofitted c) and retrofitted d) simulation time 570 min (after the peak) in Boscastle zone 2. The grey polygons indicate the areas where the FHR is negatively affected by the retrofitting.

There is only one route to evacuate the Riverside Caravan Park in Borth, as can be seen in Figure 6.15. As was highlighted earlier, the area was previously flooded (Figure 6.13). Due to the nature of caravan park, with potential new visitors who are not familiar with the area, and in the absence of any flood reduction measure, availability of a safe and accessible evacuation route is crucial for the site. For this case study the unsafe passage window was from, 300 and 1020 minutes from the start of the simulation, respectively.

Figure 6.24 a and c illustrates the FHR over the evacuation route during the times which define the unsafe passage window (i.e., 270 and 1050 minutes from the start of the simulation, respectively) with and without the retrofitting scheme. Different retrofitting option were examined and retrofitting a selected location of 25 cm was chosen as the option for this site, this being the value which gives a significative reduction of the FHR for that area, lower values do not give enough safe value of FHR. Figure 6.24 b and d depicts the FHR over the evacuation route at the same time as Figure 6.24 a and c. Furthermore, Figures 6.25 and 6.26 demonstrate FHR along the evacuation route for the extreme temporal values of the unsafe passage windows, respectively. The FHR has been significantly reduced along the Riverside Caravan Park evacuation path and provides a safe passage over a longer period. Moreover, the peak values have also been reduced significantly which makes the evacuation route safe for that condition.

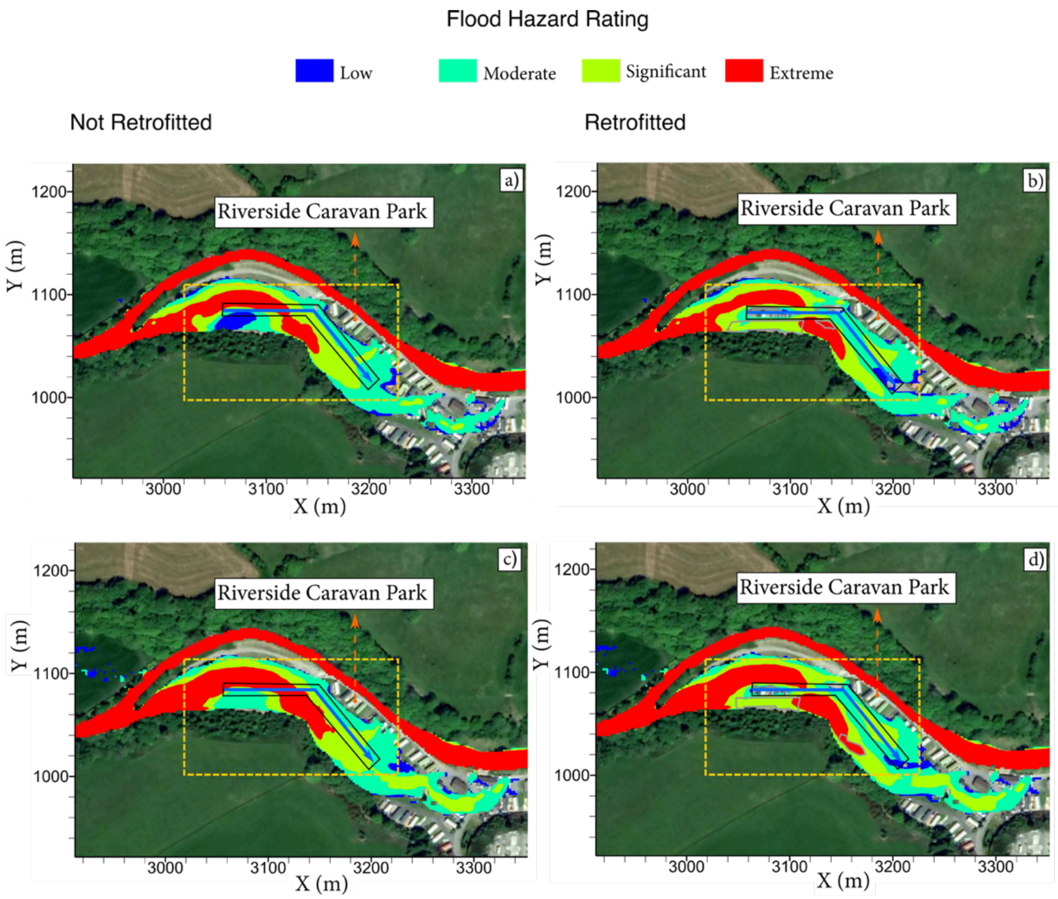


Figure 6.24 - FHR comparison between not retrofitted a) and retrofitted b) simulation time 270 min (before the peak) and not retrofitted c) and retrofitted d) simulation time 1050 min (after the peak) in Riverside Caravan Park. The black rectangle represent the retrofitted area , the blue line indicate the evacuation route, the yellow rectangle represent the zoom area.

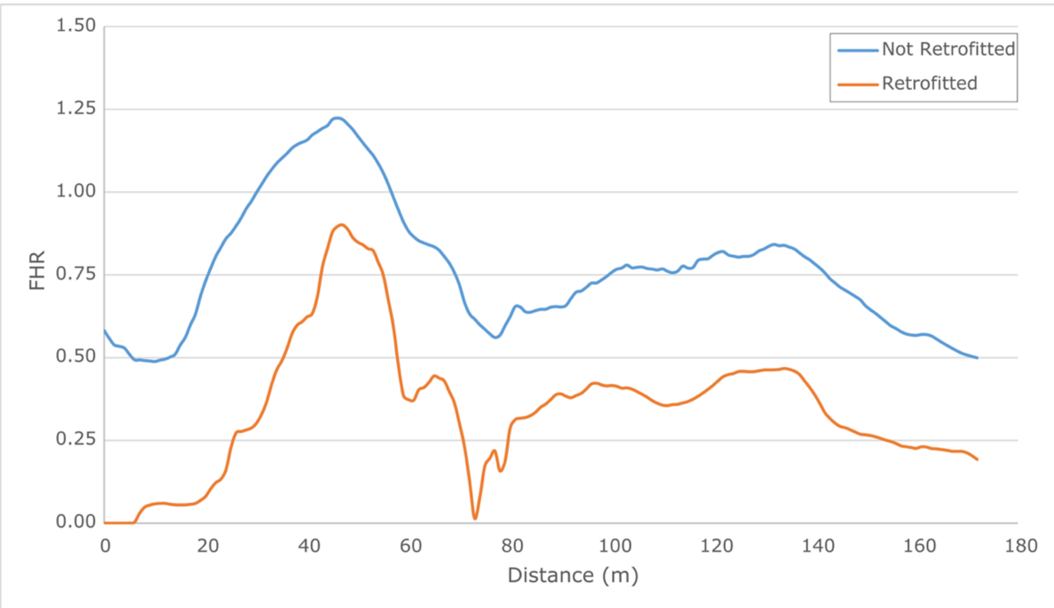


Figure 6.25 – FHR comparison between retrofitted and not retrofitted in Riverside Caravan Park – simulation time 270 min.

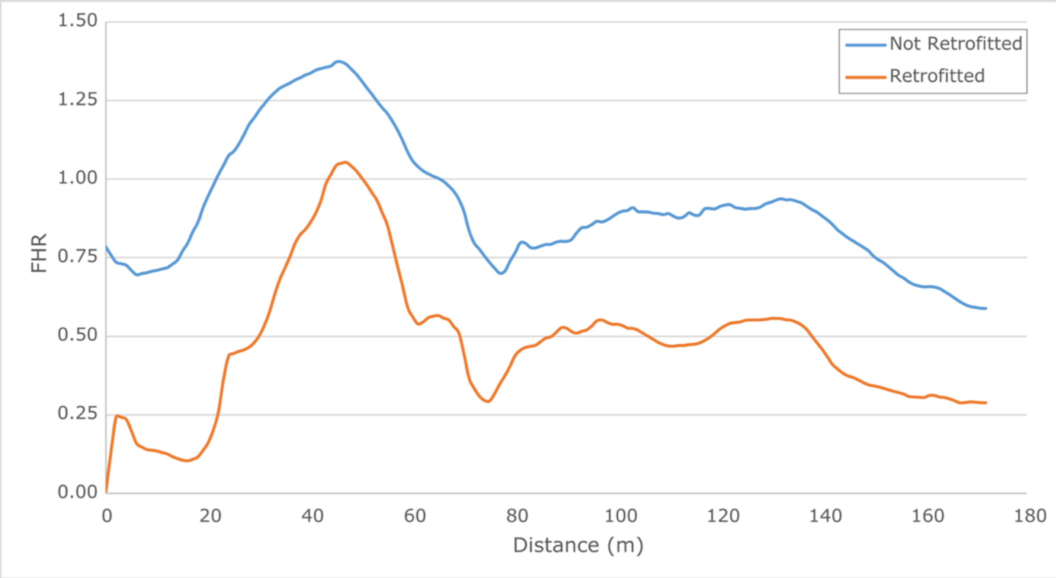


Figure 6.26 – FHR comparison between retrofitted and not retrofitted in Riverside Caravan Park – simulation time 1050 min

As showed in Figure 6.24 the change in FHR is not significant in the domain, there are very limited areas nearby the retrofitted zone where the FHR is slightly increased, but as it is showed in detail in Figure 6.27 the areas where this negative change happens (i.e., area delimited by grey polygons) are not on the evacuation routes and as well the variation is almost everywhere in the safe FHR range (i.e., FHR < 1 or FHR not Extreme in the Figures legend), thus it is believed that this retrofitting option does not adversely affect the FHR in the domain.

Further improvement can be obtained by further rising the height of the retrofitting scheme, this of course will require more tests and simulations. This is not included here since the main scope of this study is to demonstrate the potential for retrofitting in increasing pedestrian safety during evacuation. This highlights the significance of the retrofitting in providing a resilient solution for our living environment.

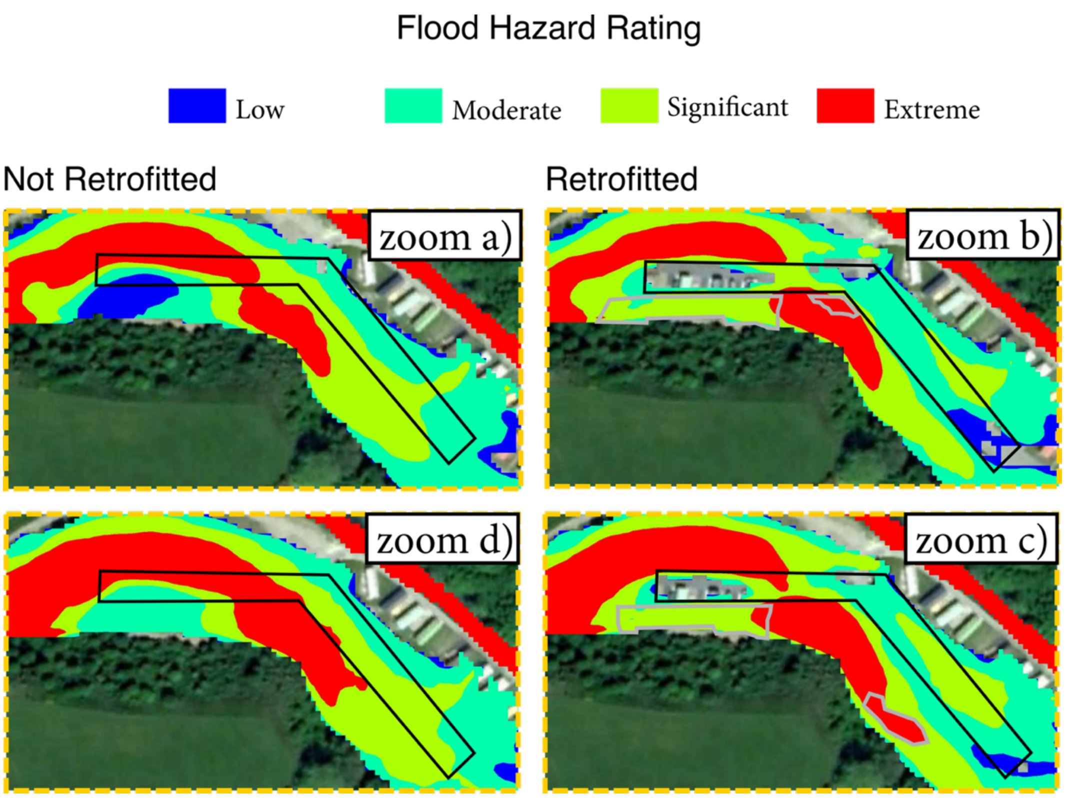


Figure 6.27 – Details of FHR comparison between not retrofitted a) and retrofitted b) simulation time 270 min (before the peak) and not retrofitted c) and retrofitted d) simulation time 1050 min (after the peak) in Riverside Caravan Park. The grey polygons indicate the areas where the FHR is negatively affected by the retrofitting.

People need to be evacuated before flood conditions become too challenging and therefore evacuation time is one of the key factors (Pel et al., 2012). Retrofitting and consequently lowering the FHR will delay the challenging conditions along the evacuation route and therefore create a longer evacuation window. Results reported in Table 6.5 show the evacuation window for the case studies and highlight the benefits of retrofitting proposed for the selected roads. Particularly, there is a remarkable increase in the safe evacuation window in the Riverside Caravan Park. Considering that getting trapped in a caravan surrounded by floodwater can be a very dangerous situation, having an extra 30 minutes evacuation time could be crucial in reducing risk to lives. As shown, retrofitting a road not only lowers the FHR, but also allows extra safe evacuation time.

Table 6.5 - time gained using the retrofitting scheme in selected areas.

	Last safe moment before the peak	First safe moment after the peak	Safe evacuation window due to retrofitting before the peak	Safe evacuation window due to retrofitting after the peak
Boscastle zone 1 Not Retrofitted	332 min	460 min	+10 min	+10 min
Boscastle zone 1 Retrofitted	342 min	450 min		
Boscastle zone 2 Not Retrofitted	8 min	+570 min *	+2 min	+18 min
Boscastle zone 2 Retrofitted	10 min	552 min		
Riverside Caravan Park Not Retrofitted	270 min	1050 min	+30 min	+30 min
Riverside Caravan Park Retrofitted	300 min	1020 min		

* at the end of sim. still is not safe

6.6 Summary

In this chapter a novel methodology has been proposed for designing evacuation plans in case of flood events. Key point of this methodology is to put the attention on both flood and pedestrian characteristics. Moreover, pedestrian characteristics are evaluated considering physics based/medical aspects (i.e., BMI consideration), In this way, the most critical pedestrian class can be individuated for the specific case study, considering the geographical study area, and a more detailed analysis can be done considering sub areas in the domains such as touristic areas, industrial areas, city centres, parks, etc. In this way FHRs for all the streets of the study area can be evaluated considering the most critical pedestrian class specifically determined. This is necessary because as pointed by some authors in the literature not all people are equally vulnerable at the same flooding waters' depths and velocities, vulnerability depends on both person's and flow characteristics and situational characteristics as well. To create a more holistic approach a methodology to keep into account a social vulnerability factor has been introduced to consider not only physical aspects related to the human body, but also phycological/behavioural aspect related to pedestrians.

In this research work is also proposed a novel approach to increase the resilience of our living environment against flooding by retrofitting the existing infrastructure to enhance evacuation safety. Slight changes in the elevation of part of the roads and/or footpaths through retrofitting existing infrastructures will allow not only to have safer routes by reducing the Flood Hazard Rate, but to also increase the safe evacuating window time before and after the flood peak. This demonstrates that retrofitting existing schemes can be a valid low-cost flood management tool to enhance people's safety. It can be deployed independently or in conjunction with other flood defences as part of a more articulate and holistic flood mitigation scheme.

Another important finding, showed by results herein presented, is that in some specific cases the shortest path is not always the safest. Previous works determined the evacuation plan based only on the shortest path possible, but when considering pedestrians evacuations during a flood event also the FHRs associated to all the possible evacuation routes alternatives have to be considered in conjunction with the evacuation time. Nowadays people move around urban environment for different reasons at any hour of the day and with any weather conditions, so they can be surprised by flood events when on the streets Reason why it is very important to promote the concept of safe behaviour during flood events and as well to offer safe evacuation plans as in case on fire drills or similar events.

Further research is needed in designing resilient flood defence schemes and evacuation plans as well. Important aspects that should be considered in future works are the "human" factors, such as psychological and behavioural factors. It is very important to integrate these aspects into engineering works to design a suitable evacuation route with a more holistic approach.

7 Conclusions and Future Work Recommendations

7.1 Conclusion

The main aim of this thesis is to improve flood risk management, through enhancing pedestrian safety during flood events. A particular focus of this research work has been flood hazard and vulnerability assessment. Moreover, it contributes to non-structural flood mitigation schemes, presenting a “human-based” flood evacuation design process and retrofitting scheme for roads which can make roads and streets safer for pedestrians in case of flood events and potential flood evacuation actions.

As reported in the Introduction, river flooding is considered as one of the most devastating and frequently occurring natural hazards, with this being true not only in economic terms but also in terms of loss of lives. Furthermore, it is not possible to reduce the flood risk of all river basins to zero, even if nowadays we can rely on different tools, strategies, and engineering solutions, which make a huge contribution to mitigating the negative impacts of river flooding. Thus, it is imperative for researchers to continue to develop all these tools and strategies to improve our predictive abilities, but also to give effective holistic and resilient mitigation schemes which allow us to live as safely as possible with natural phenomena such as flooding.

Considering improving our predictive tools and mitigation strategies is even more important considering that, as pointed out by many researchers, flooding related problems are expected to be even more concerning due to the effects of various drivers such as climate change, population growth, increasing levels of urbanisation into flood prone areas, inappropriate land use and inadequate planning.

Flooding can affect areas worldwide, and every world region has very peculiar characteristics in terms of environment, but also in terms of human characteristics. Thus, it is very important to consider people’s body characteristics and cultures, otherwise the assessment of flood hazard can be unreliable for a specific area/local population. Bearing this in mind, a key aspect is to try to have a more universal assessment method based on physical rather than empirical aspects while allowing for the method to have the capability to be fine-tuned for specific characteristics of local environment and population.

The aim of this thesis is to make a contribution to the improvement of flood hazard assessment for pedestrians, A methodology is proposed in this research work for selecting evacuation and access routes and so designing evacuation plans for pedestrians in case of flood events. This methodology brought together flood characteristics (classic approach) and human characteristics. Lastly, a resilient solution for improving the safety of evacuation routes is also provided.

In relation to the key objectives (i) and (ii) reported in Section 1.2 in this thesis, several methods used to assess people's stability in floodwater have been selected, namely a mechanics-based method which has been further developed and improved as part of this thesis, and also empirical methods, some of which are used even today by national authorities of various developed countries. As it has been shown in Chapter 5, the empirical methods herein considered inherit limitations in returning reliable thresholds of human stability in floodwaters and also do not offer the user the ability to adapt them to different situations, such as different body characteristics. This latter aspect is very relevant since the characteristics of the human body can vary significantly from one country to another, often leading to different stability thresholds. Furthermore, a more specific characterisation can be undertaken when considering adults, children, and elderly adults, etc. for the determination of the critical class to be considered for the design of emergency plans and measures such as evacuation plans.

The results of the comparison between the empirical methods and the mechanics-based method herein proposed, clearly shows that the latter method gives more physics-based results which are more robust and generic in comparison with empirical predictions. This is because the mechanics-based method accounts for all factors necessary to describe the highly complex phenomenon of human instability in floodwaters, especially in the case of flash floods.

The improved mechanics-based method herein proposed considers all the physical forces acting on a human body and interacting with floodwaters, meaning a more universal approach. It has also included the most recent available body shape parameters, the body mass index methodology to determine height and weight in a more medical/scientific way, and the effects of ground slope in the formulation. These improvements of the method have allowed better accuracy in the determination of the physical-based threshold levels, and the capability to be adapted for different human body characteristics which lead to a more physical-based flood hazard assessment from a pedestrian perspective.

Key objective (iii) of this thesis (see Section 1.2) is presented in Chapter 6. This includes a novel methodology for designing evacuation plans, as well as reporting an early study on a novel methodology for including social factors in assessing flood hazards for pedestrians; this methodology has to be further developed and tested in future works.

Regarding the methodology to design evacuation plans, two aspects have been considered:

Firstly, determining evacuation routes from a pedestrian perspective, meaning that the most critical pedestrian category for a specific area has to be considered. The results reported in Chapter 6 show clearly the importance of considering the most appropriate pedestrian category when designing an evacuation plan as people are not equally vulnerable. Another important finding shown by the results presented in Chapter 6, is that in some specific cases the shortest path is not always the safest. Previous works determined the evacuation plan based only on the shortest path possible, but when considering pedestrian evacuations during a flood event, the flood hazard rates associated with all possible evacuation routes have to be considered in conjunction with the evacuation time.

Secondly, as part of improving the design of evacuation routes, a novel approach which consists of retrofitting the existing infrastructure to enhance evacuation safety is presented. Retrofitting roads allows not only to have safer routes by reducing the flood hazard rate, but also increases the safe evacuating window time before and after the flood peak. This demonstrates that retrofitting existing schemes can be a valid low-cost flood management tool to enhance people's safety. It can be deployed independently or in conjunction with other flood defences as part of a more articulate and holistic flood mitigation scheme.

All the findings here summarised were tested with two well-documented real cases studies, namely Boscastle's 2004 flash flood and Borth's 2012 flash flood events. These two case studies have been selected considering location, data availability, and the opportunity to have results from different environment and flood conditions to ensure more general results being produced.

7.2 Future works

Flood risk management is a broad field which includes many different disciplines such as mathematics, physics, engineering, and psychology, among others. Thus, it is not possible to consider all the different areas of interests. In addition to this, there are also limitations to this work due to software, data availability, time constraints, and the COVID-19 pandemic to be considered. For these reasons, some considerations and suggestions for future works are reported in this section.

Mechanics-based methods have demonstrated to be powerful tools for assessing flood hazards for pedestrians that can be used within different applications to ensure and enhance safety for people in case of flood events. Thus, more research in this field is needed. Firstly, it is necessary to develop databases of human body characteristics for people of different nationalities so that methods can be fine-tuned for every study area around the world. Today there is a lack of data that does not allow to release the full potential of the method. This can be achieved through further data collection on one hand, and on the other hand performing more experiments with human beings and dummies to get the calibration data relative to human body characteristics which are necessary for using the mechanics-based method. In performing more experiments with people, it is necessary to improve experimental protocols. As seen in the literature, reliability of results depends on the data collected during the experimental campaign. Therefore, it is necessary to develop procedures that can be representative of more realistic conditions to overcome the limitations of present experimental campaigns such as excessive use of safety equipment, gaining experienced in performing the task, laboratory set-ups that are not fully representative of the real environment conditions, and not considering physiological aspects etc.

For a modern approach to flood risk management, it is very important to consider a holistic approach that integrates different disciplines to consider not only engineering aspects but also the “human factor”. This means including psychological and behavioural aspects among others. As shown in the Literature Review chapter, today only fragmentary studies have been done, each of which is related to a specific topic, but a global overview that includes engineering, psychological, and behavioural consideration is missing. For more insight relative to the “human factor” the methodology relative to the social vulnerability presented in Section 6.2.2 has to be further developed and tested; in this way behavioural and psychological aspects can be included in flood hazard assessment.

Another important aspect to consider is to better promote awareness of flood-related problems among the population. As seen in the Literature Review chapter, one of the causes that leads to danger for people when moving in urban environments during flood events, relates to the decisions of people to undertake risky behaviours. This is mainly connected to the fact that they misjudge flooding-related problems and they also overestimate their ability, especially among people that face the effects of flooding for the first time. In conjunction with this aspect there is the development of flood evacuation plans which are today only marginally considered by authorities worldwide, and also the development of flood drills similar to how it has happened for many years with fire drills, which have proved to be very effective and help to reduce death rates in the case of fire alarms.

Other fields of ongoing research which need more development are improving the accuracy of flow velocity, and inundation extent predictions during flash floods. While many highly accurate flood models have been developed, 1D/2D linked models that allow fast and more accurate results still require further improvements. In particular, the development of fully conservative 1D/2D linked models is recommended which include shock capturing features in order to be able to give reliable results also in cases of flash floods and other extreme flood events. In this way, it will be possible to further develop early warning and real-time systems to enhance people’s safety, especially when considering flash floods.

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