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Research papers

Comparison of flood hazard assessment criteria for pedestrians with a refined mechanics-based method

G. Musolino, R. Ahmadian *, R.A. Falconer

Hydro-Environmental Research Centre, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK

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ABSTRACT

Floods have caused severe destruction and affected communities in different ways throughout history. Flood events are being exacerbated by climate change and hence it is increasingly necessary to have a more accurate understanding of various aspects of flood hazard, particularly for pedestrians. The focus of this study is therefore to investigate different criteria to assess the flood hazard for pedestrians and to propose improvements in assessing such hazards. The revised mechanics-based approach reported herein gives results based on a full physical analysis of the forces acting on a body and can be universally applied as the method can be fine-tuned for different region of the world. The results from flood hazard assessments can be used to: design evacuation plans, improve resilience of sites prone to flooding and plan more resilient future developments. Extreme flood events in the UK and documented for Boscastle (2004) and Borth (2012) were used as case studies. Two approaches were considered, including: (i) a mechanics-based approach, and (ii) an experimental-based approach, with the criteria for the stability of pedestrians in floods being compared for the criteria used by regulatory authorities in Australia, Spain, UK and USA. The results obtained in this study demonstrate that the mechanics-based methods are preferable in determining flood hazard rating assessments.

1. Introduction

Of all the natural hazards that occur world-wide, flood events are historically recognised as being one of the most devastating, often leading to significant loss of life (Bellos et al., 2020; Bracken et al., 2016; Percival and Teeuw, 2019; Svetlana et al., 2015). In specific regions of the world, climate change, in combination with an increase in population and increasing urbanisation coastal and riverside cities, has made the impact of flooding on people and economic assets even more dramatic (Guerriero et al., 2020; Milanesi et al., 2016; Wang et al., 2018). Although it is clearly impossible to reduce the flood risk of any river basin to zero (Creutin et al., 2013), it is increasingly important to minimise, so far as possible, the impact of flood events. This can be done by implementing various flood mitigation methodologies (Fox-Rogers et al., 2016) and developing preparedness and response actions such as emergency evacuation plans (Bodoque et al., 2019, 2016).

Pedestrians walking in flooded areas is one of the two major causes of death associated with flood events (Arrighi et al., 2019; Shabanikiya et al., 2014), thus one of the fundamental aspects of flood risk management is to assess the hazard posed by floods to pedestrians. Generally, pedestrians tend to underestimate the impact that a flood flow can have on the human body, especially for shallow water depths and high flow velocities, this aspect, jointly with the nature of extreme floods in specific areas (e.g. flash floods in alpine environments, steep catchments and urban environments) makes floods very dangerous for pedestrians. Moreover, most people and businesses consider flood hazard defence schemes to provide a complete safeguard against flooding when, to the contrary, the protection is often only partial (Stevens et al., 2010).

Internationally, various authorities have often adopted flood hazard assessment methods as suggested by earlier studies started in the 1970s, in providing a significant step forward to ensure the safety of pedestrians during floods. 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. In many countries, flood hazard assessment for pedestrians is not updated to recently available methods and in some 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

* Corresponding author.
E-mail address: ahmadianr@cardiff.ac.uk (R. Ahmadian).

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pedestrian protection perspective can be improved and should be considered internationally in a more unified manner.

The available literature reports different approaches and methodologies to assess the hazard to pedestrians in flooding-waters, but there is general agreement on the two main possible failure mechanisms of people stability, including: toppling and sliding (Arrighi et al., 2017; Jonkman and Penning-Rowsell, 2008). Furthermore, two main approaches have been increasingly used to assess the stability of people in floodwaters. The first is based on empirical or semi-quantitative criteria, and the second is based on formulae derived from a mechanics-based approach and supported by experimental data.

Authorities worldwide have assessed the flood hazard from the perspective of pedestrian protection using different methods available (Cox et al., 2010; Priest et al., 2016). 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 in order to identify and assess the hazard for pedestrians and houses associated with a flood event due a dam breach event and allowed hazard quantification for the following categories: passenger vehicles, adult pedestrian routes, and child pedestrians 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 depth × velocity relationships with the danger derived from floods due a dam break event and allowed hazard quantification.

Ramsbottom et al. (2003) and Ramsbottom et al. (2006) developed an empirically based 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 a report on Australian Rainfall and Runoff, by Cox et al. (2010), updated Australia's guidelines on safety of pedestrians in floodwaters. The authors reviewed their previous work and re-analysed all of the available datasets, enabling new guidelines to be produced for the safety of pedestrians in floodwaters and using depth × velocity relationships.

The main focus of this research study is to compare the performance of a revised and improved mechanics-based method (MBM) against various empirical methodologies adopted by authorities in some countries, particularly from the perspective of pedestrian protection, and to highlight the potential inconsistencies between the empirical methods. This benchmarking enables the pros and cons of the various methods to be assessed and facilitates a more universal and scientific approach to flood hazard assessment of pedestrians moving in floodwaters, with the scope of contributing to improving the flood hazard evaluation, especially for the case of flash floods and based on a pedestrian protection perspective.

Two cases studies from the UK have been considered in the benchmarking analysis. These sites include: (i) Boscastle, a tourist village in the south west of England, affected on 16th August 2004 by an extreme flash flood, which has been widely studied due to the availability of data and the impacts of the flash flood, and (ii) the Borth region, in West Wales, where on the 9th June 2012 a heavy rainfall event caused a flash flood to occur, with the site being an important tourist resort, with tourism being crucial to the local economy. For both sites pedestrians' hazard levels were important due to the nature of the sites.

The novelty of this particular study is the inclusion in the comparison of a revised and improved MBM, which considers the effects of ground slope and includes updated parameter values of the key characteristics of a typical European human body. These flood events were also considered to be significantly different in terms of their intensity, with the aim of the study being to investigate the dependency of the reliability of the results for different flood conditions and using a range of different assessment methods.

2. Case studies sites

2.1. Boscastle

Boscastle is a small touristic village, located at the end of a narrow and steep catchment in Cornwall – UK (Fig. 1). On 16th August 2004 an intense rainfall event occurred over the north coast of Cornwall with up to 200 mm of rain fell in about 5 h over a 20 km^2 catchment area (HR Wallingford, 2005; Roca and Davison, 2010). This extreme rainfall event caused a flash flood (Fig. 2) that severely affected the village and its population, causing extensive damages which were widely reported. During the event streets were inundated by over 2 m of water (Xia et al., 2011a) and people had to be rescued from cars and rooftops. The extent of the flash flood can briefly summarized as follow: 100 people were airlifted, six buildings collapsed due to the strong force of the flood water, and over 70 properties were flooded; 79 cars were washed away into the harbour, the two local bridges were blocked, the "Lower Bridge" collapsed and had to be reconstructed after the event (Environment Agency, 2004; Rowe, 2004). Damages were of the order of several million pounds, without considering psychological consequences suffered by people affected by trauma due to consequences of the flood (Rowe, 2004). Characteristics of both basin and flash flood reported above, made Boscastle an ideal case study for many flash flood modelling studies.

The domain for this study covers a surface of 0.156 km^2 (235 m wide and 665 m long), that has been divided in square cells of 1 m^2 each. LIDAR (Laser Imaging Detection and Ranging) data collected during a survey undertaken by the Environmental Agency post the flood event was used to represent the topography of the domain. A constant value of Manning's roughness coefficient equal to 0.040 been used along the whole domain (Kvočka et al., 2015; Xia et al., 2011b). Peak discharge of the event was estimated to be about 180 m^3/s as shown in Fig. 3. Therefore, based on Flood Estimation Handbook (FEH) statistical and rainfall-runoff methods the frequency of the flood event was estimated in the order of 1:400 years (HR Wallingford, 2005; Roca and Davison, 2010). Calibration and validation of the hydrodynamic model has been undertaken, in some detail and has been reported previously (Falconer et al., 2012; Kvočka et al., 2017, 2015; Xia et al., 2011b).

2.2. Borth

Borth is a coastal village located in West Wales – UK (Fig. 1) and part of the Dyfi Biosphere, which is the only UNESCO Biosphere reserve in Wales. The village it is also part of Dyfi National Nature Reserve and it is situated along the Welsh Coast Path. 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 important for the local economy. This area is suited at the final part of river Leri catchment, which is a relatively small, steep catchment. On 9th June 2012 heavy rain caused a flash flood down the Cambrian Mountains causing a severe flood in Tal-y-bont, Dol-y-bont, Borth and surrounding area (Fig. 2). About 60 properties and Caravan parks in those areas had been evacuated, this evens has been reported as: "the biggest flooding in living memory" (Foulds et al., 2012). 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 risk. The events in June 2012, highlights the need for accurate flood hazard assessment and appropriate flood defences to reduce the impact of such events or even more

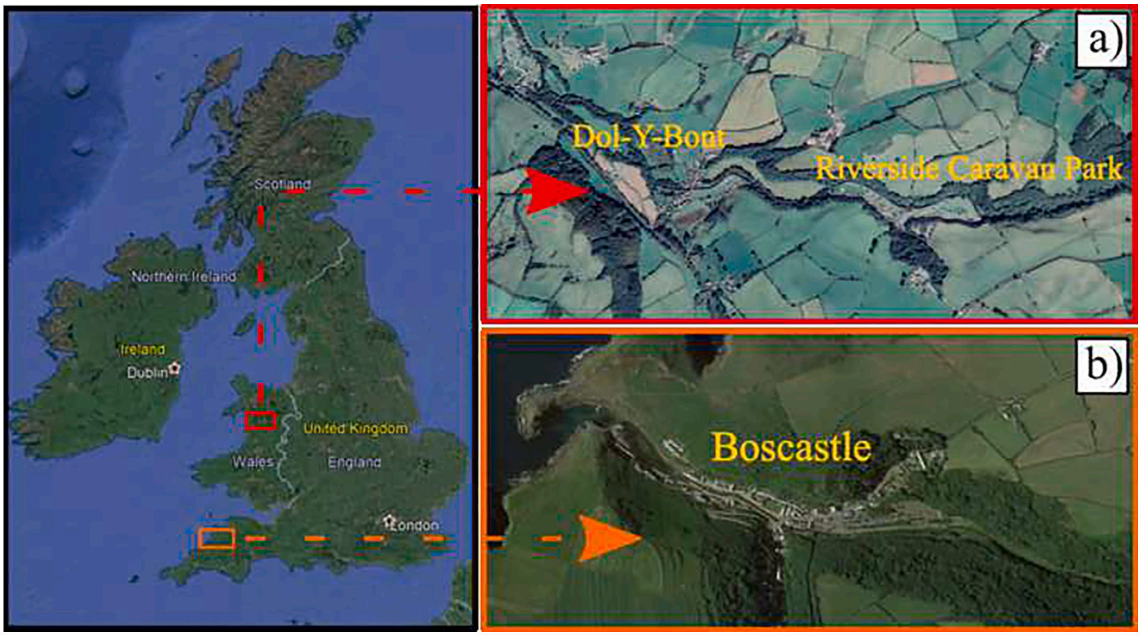

Fig. 1. Study areas: a) Dol-Y-Bont and Riverside Caravan Park; b) Boscastle.

disastrous events, similar to the one happens in Spain during a flash flood in 2007 were 87 people died in a campsite (Foulds et al., 2012).

The domain of this study covers an area of 63 km^2 (9 km long and 7 km wide) and include Borth, Tal-y-bont and Dol-y-bont areas. Topographic data used to set up the hydrodynamic model have been extracted from a 2 m LIDAR. Upstream boundary condition was flow entering the domain through two main rivers, namely River Leri and River Cuelan. 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 River Cuelan (Kvočka et al., 2018). Downstream boundary condition was set to the water levels in the Dify Estuary. Roughness parameters were assigned on the basis of Kvočka et al. (2018), to the floodplain it has been assigned the value of 0.05, the value of 0.04 was assigned for the river channel. Calibration and validation of the model has been undertaken in detail as reported by Kvočka et al. (2018).

3. Numerical modelling of flash flood events

The flood events considered as case study in this work were simulated using the DIVAST TVD model in order to obtain flood characteristics as flow depth and velocity to be used to assess flood hazard to pedestrian. DIVAST TVD was developed in the Hydro-environmental Research Centre (HRC) at Cardiff University, and has been used for a number of flood modelling studies (Ahmadian et al., 2018; Hunter et al., 2008; Kvočka et al., 2017; Liang et al., 2007a, 2007b; Neelz and Pender, 2013). DIVAST TVD is based on the finite difference scheme, the algorithm is fully conservative and is based on a standard MacCormack scheme, enhanced with a symmetric five points total variation diminishing (TVD) shock capturing algorithm (Mingham et al., 2001). The TVD algorithm allows discontinuities to be captured, as occurring for trans- and super-critical river flows, without generating spurious oscillations (Kalita, 2016). The shock-capturing feature of DIVAST TVD makes this model ideal for modelling short and steep catchments, where trans- and super-critical flows can occur for high rainfall events. Further details of the DIVAST TVD model are given in Liang et al. (2007a).

4. Assessing flood hazard to pedestrians

In this section, a brief overview of methods to assess flood hazard for pedestrians and the methods considered for benchmarking hazard analysis are presented. Especially, a revised MBM is benchmarked against methods adopted by 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 methods are summarised below and their performance in assessing the flood hazard to pedestrians have been compared and discussed in Section 5.

The methods used for the benchmarking have been selected from those available in the literature. The selection of the methods has been based on consideration of: i) the methodology adopted, with benchmark comparisons being undertaken between the different assessment methods to establish if there is any scope for improvement in the method; and ii) the validity of the method, in term of the methodology adopted by the authorities and the novelty of the analysis as reported in the literature. Methods A, B, C and D are used by government organisations, with method E being regarded as a state-of-the-art empirical approach.

4.1. Methodologies to assess flood hazard for pedestrian

Early studies of Foster and Cox (1973) showed that instability of the children in floodwaters depended on a combination of physical, dynamic and emotional factors; moreover, the results also showed that the predominant failure mechanism was sliding.

Abt et al. (1989) conducted a series of tests with human subjects and a monolith placed in a flume, their study demonstrating the importance of toppling mechanism. 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.

To overcome the limitations of experimental activities involving people, various authors have proposed several conceptual modelling techniques and with differing degrees of simplification, in order to describe the complex phenomenon of pedestrian stability in floodwaters. Some of these studies and findings are summarised below.

Jonkman and Penning-Rowsell (2008) analysed their experimental results and found that the sliding mechanism was more dangerous than previous studies had suggested. Another interesting finding of their work was that sliding mechanism was the dominant mechanism of failure in shallow water depths and high flow velocities, as typically

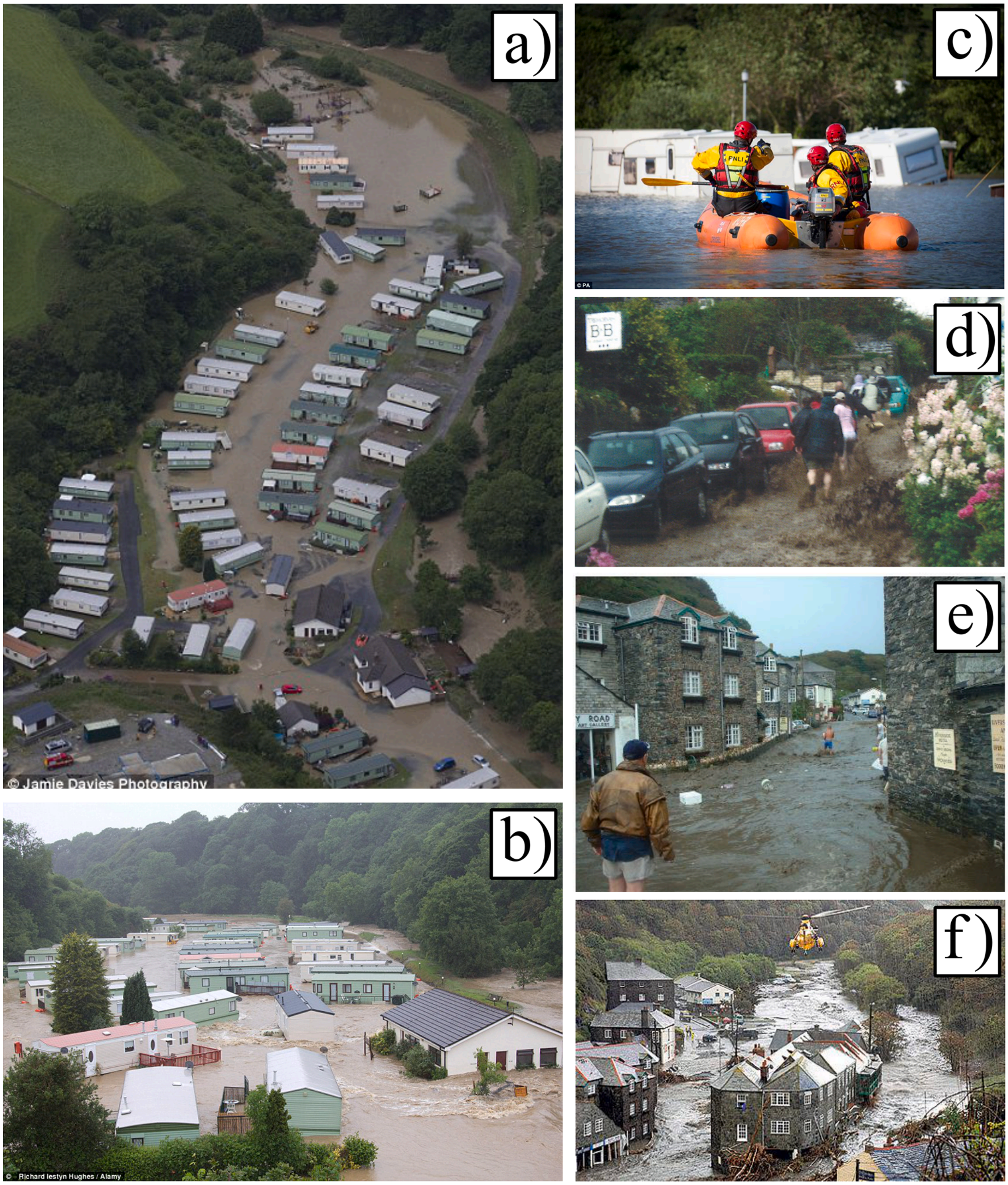

Fig. 2. a) and b) Riverside Caravan Park c) Aberystwyth Holiday village during the 9th June 2012 flood event; d), e), f) Boscastle during the 16th August flash flood event (HR Wallingford, 2005; Rowe, 2004).

occurs for the case of flash floods in urban environments. Moreover, the authors also found that the simplified approach 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.

Xia et al. (2014a) proposed a MBM, the methodology considered the failure mechanisms of both toppling and sliding and included the effects of ground slope 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., 2014b) Another important feature of this MBM approach was the inclusion of the body shape characteristics in the analysis, through the addition of coefficients describing the typical features of a human body. 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.). 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,

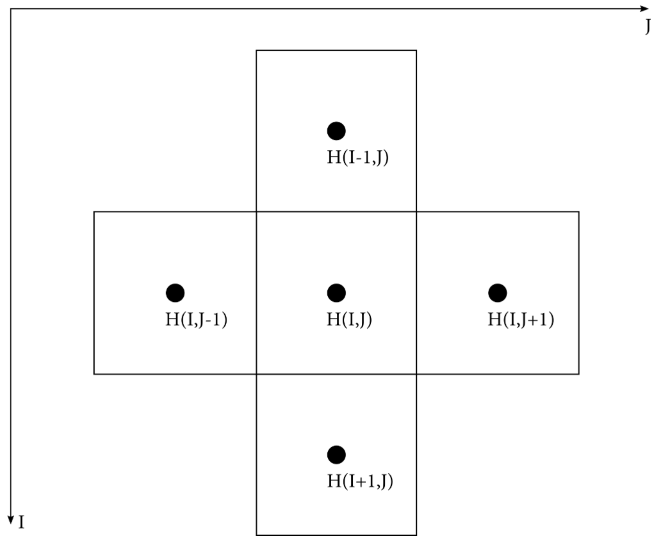

Fig. 3. The model computational cells configuration considered for the determination of ground slope angle.

proposed a methodology that identified the stability surface and relative thresholds in probabilistic terms.

Arrighi et al. (2017) 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. Recently, 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. However, the corresponding formulae were only obtained for toppling and did not include the effects of bed slope.

4.2. Mechanics based method

It is first necessary to evaluate the incipient velocity for pedestrians in order to determine their instability in floodwaters. The incipient velocity is defined in a similar manner to the incipient velocity of sediment particles in sediment transport formulation and is 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):

$$U_c = \alpha\left(\frac{h_f}{h_p}\right)^{\beta}\sqrt{\frac{m_P}{\rho_f h_p hf} - \left(a_1\frac{h_f}{h_p} + b_1\right)\left(\frac{a_2 m_P + b_2}{h_p^2}\right)} \quad (1)$$

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

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

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 (e.g. mass, height and volume of the full body and body segments, such as legs, torso, arms, etc.) as shown in Table 1, θ = angle of the sloping ground, and γ = correction constant.

It is possible to determine a Flood Hazard Rating (FHR) parameter by considering both failure mechanisms as follows:

Table 1
Revised MBM parameters used in the current study.

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

$$FHR = MIN\left(1, \frac{U}{U_c}\right) \quad (3)$$

where U = flow velocity and U_c = incipient velocity, which is the minimum velocity of either $U_{toppling}$ or $U_{sliding}$. Further details of this approach can be found in Xia et al. (2014a). Therefore, it is possible to calculate the precise threshold conditions for different age and gender groups, as well as taking account of differences in body characteristics depending on the country etc. (Milanesi et al., 2015; Xia et al., 2014b).

As noted by González-Riancho et al. (2013) slope is an important factor which can significantly affect the flood hazard assessment for pedestrians. One of the refinements of this research study has been the inclusion of the term related to the slope in Eq. (2). In previous studies this term has generally been omitted for simplicity. The term relative to the slope in Eq. (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 study the incipient velocity equations have been included in the finite difference model, outlined previously, where the bed elevation was stored at the centre of each grid cell (Ahmadian et al., 2018; Kvočka et al., 2017; Liang et al., 2007a, 2007b). 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 Fig. 3. The highest slope calculated was then selected as the slope to be used for the value of θ in Eq. (2). In this way the most adverse situation is considered in a precautionary approach.

In the proposed formulae for the stability of a pedestrian, since both case studies are located 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 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 in order to maintain stability in floodwaters, 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 using real pedestrians and dummies.

4.3. Method A

Method A uses graphs to determine the flood hazard for pedestrians. The U.S. Department of the Interior (1988) provided one graph for adults (i.e. a person over 1.5 m in height and 54 kg in weight) (Fig. 4a) and one graph for children (Fig. 4b). Details of the classifications of the hazard ratio can be founded in U.S. Department of the Interior (1988).

4.4. Method B

Cox et al. (2010), in revising the stability thresholds for the Australian guidelines, used experimental data to establish different levels of

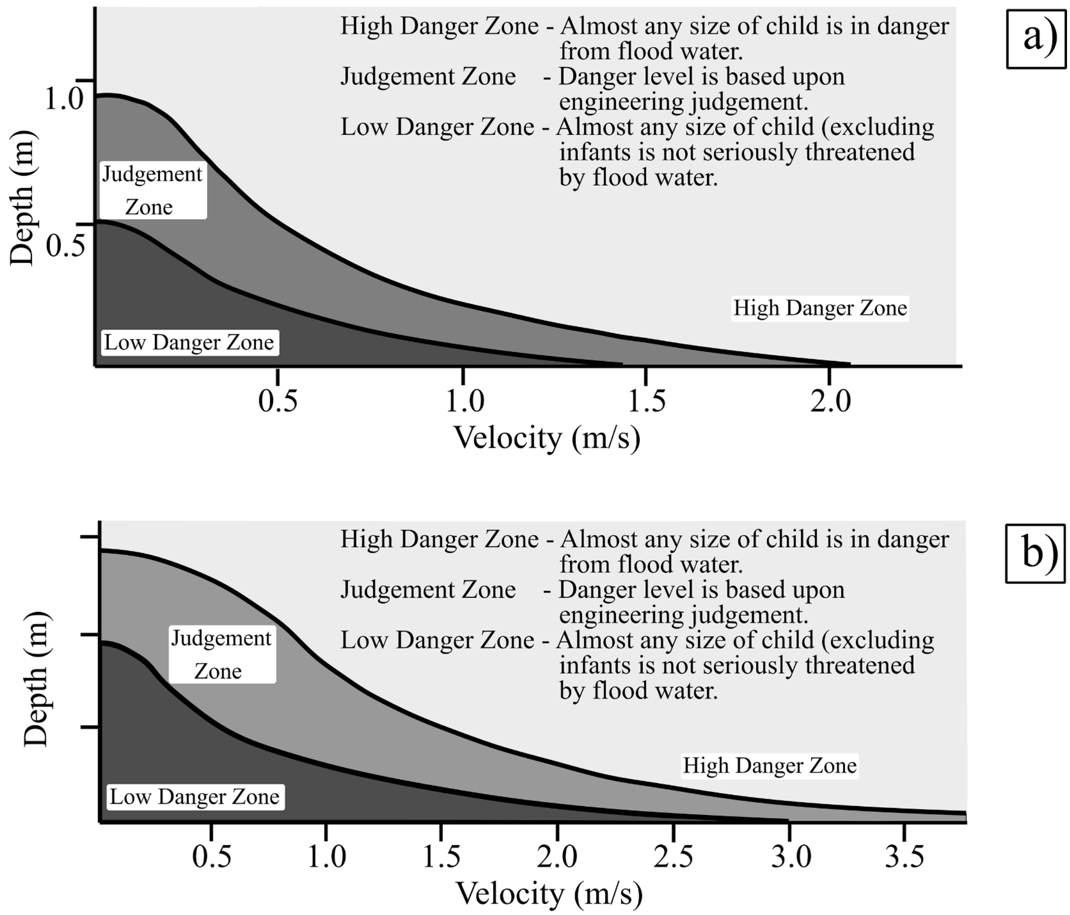

Fig. 4. Depth × velocity relationship and related FHR for (a) adults and (b) children (U.S. Department of the Interior, 1988).

hazard based on the product of depth and velocity as shown in Fig. 5.

The authors proposed four different thresholds based on different depth and velocity products. There was also a limiting depth and velocity 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

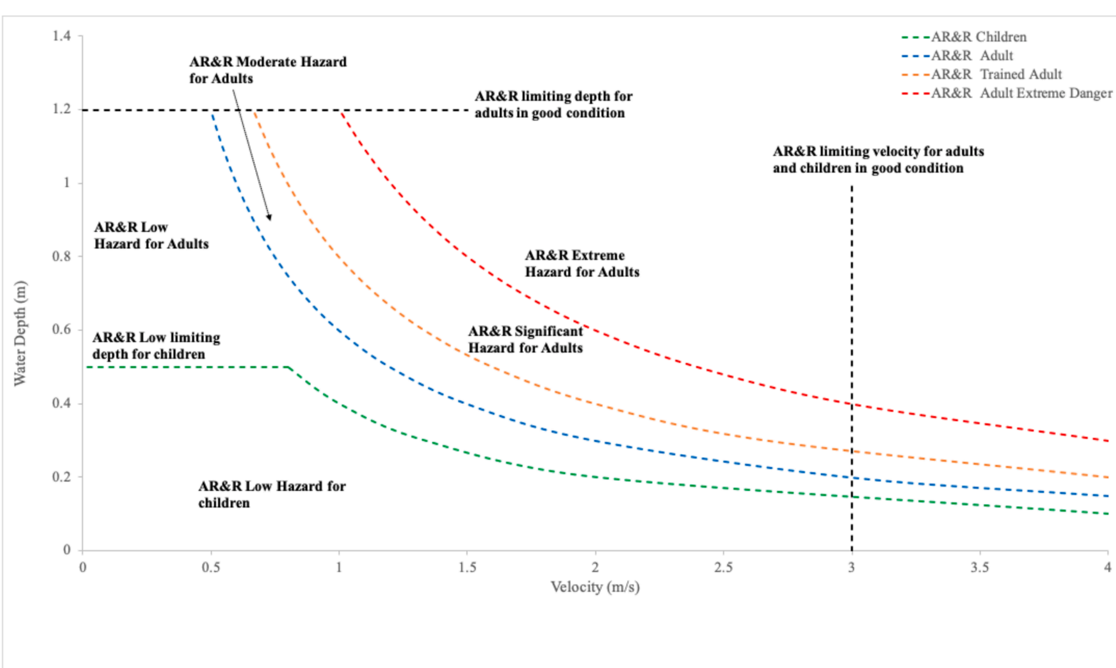

Fig. 5. Depth × velocity relationships and related flood danger levels for children and adults (Cox et al., 2010).

the depth and velocity thresholds for extreme danger.

Details of the depth × velocity relationships and the relative FHR for the different categories can be found in the classifications of the hazard ratio first given in Cox et al. (2010).

4.5. Method C

A mathematical expression using an empirically based method is widely used in the UK (Ramsbottom et al., 2006, Ramsbottom et al., 2003) and is given as:

$$HR = d(v + 0.5) + DF \quad (4)$$

where HR is the Flood Hazard Rating, d = water depth (m), v = velocity of flow (m/s), and DF is a factor which depends on the threat posed by debris, which assumes a value of 0, 0.5 or 1 (Ramsbottom et al., 2006).

Details of the classifications of the hazard ratio can be found in Ramsbottom et al. (2006).

4.6. Method D

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 (Fig. 6) to assess the flood hazard for the case of a dam failure in Spain. The graphs in Fig. 6 show the depth × velocity 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. From these results it can be seen that there is good correlation between the graphs of the pedestrian route for adults using Method A (Fig. 4 a) and the graph for the unurbanized area of Method D (Fig. 6b). From this comparison the graph for the unurbanized area will be used hereafter, rather than the pedestrian graph of Method A, since the graph for Method D is more conservative. A description and classification of the hazard level based on this method is reported in Ministerio de Medio Ambiente de Espana (1996).

4.7. Method E

Martínez-Gomariz et al. (2016) derived an empirical equation for pedestrians based on results obtained from experiments with human subjects, of different ages and gender. The authors have merged these new data, with previous data published by Russo in 2009, in order to obtain more instability conditions. This new merged dataset has been used to define the lower limit function expressed by Eq. (5) (Martínez-Gomariz et al., 2016). Thus, depending on the value of the product of the water depth (i.e. d in Eq. (5)) and the flow velocity (i.e. v in Eq. (5)) it is possible to determine the stability of a pedestrian as shown in Fig. 7.

$$(d \times v) = 0.22 m^2 s^{-1} \quad (5)$$

A classification of the hazard level can be found in Martínez-Gomariz et al. (2016).

5. Results

The results of the benchmark studies for the revised MBM and the other methods shown individually in Sections 5.1–5.5. The scope of this benchmarking study is therefore to highlight the improvements obtained using the revised MBM, as compared to previous studies. All the Figures relative to simulation time 340 min for Boscastle and 720 min for Borth are reported as supplement material.

5.1. Benchmark between revised MBM and Method A

Fig. 8 shows the benchmark results between the revised MBM and Method A in terms of predictions of the FHR for Boscastle and Borth respectively.

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 (ST) 200 min (Fig. 8b) and 3.51% less at ST 340 min. Similarly, for the Borth site, Method A assessed 28.96% and 48.71% less extreme FHR areas at ST 420 min (Fig. 8d) and ST 720 min respectively.

5.2. Benchmark between revised MBM and Method B

In Fig. 9 the results are benchmarked between the revised MBM and Method B for the sites at Boscastle and Borth respectively.

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 ST 200 min (Fig. 9b) and 340 min respectively. For Borth there are the 28.95% at ST 420 min (Fig. 9d) and 48.71% at ST 720 min less areas of extreme FHR when using Method B instead of the revised MBM.

5.3. Benchmark between revised MBM and Method C

Fig. 10 shows benchmarked results between the revised MBM and Method C for Boscastle and Borth sites respectively. 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 ST 200 min (Fig. 10b) and 27.04% at ST 340 min.

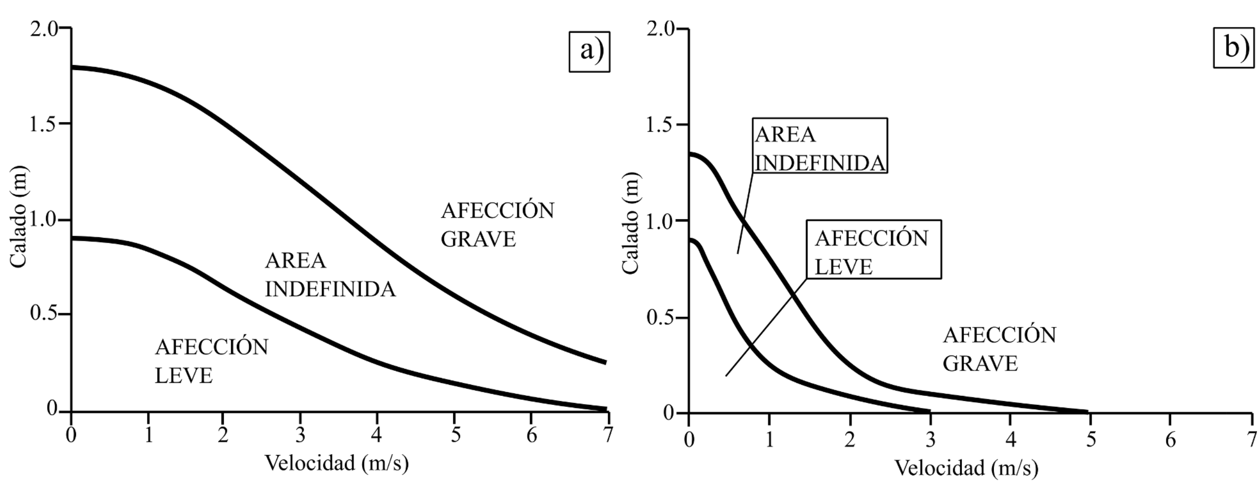

Fig. 6. Depth × velocity relationship and related flood hazard level for: (a) urban and (b) unurbanized areas (Ministerio de Medio Ambiente de Espana, 1996).

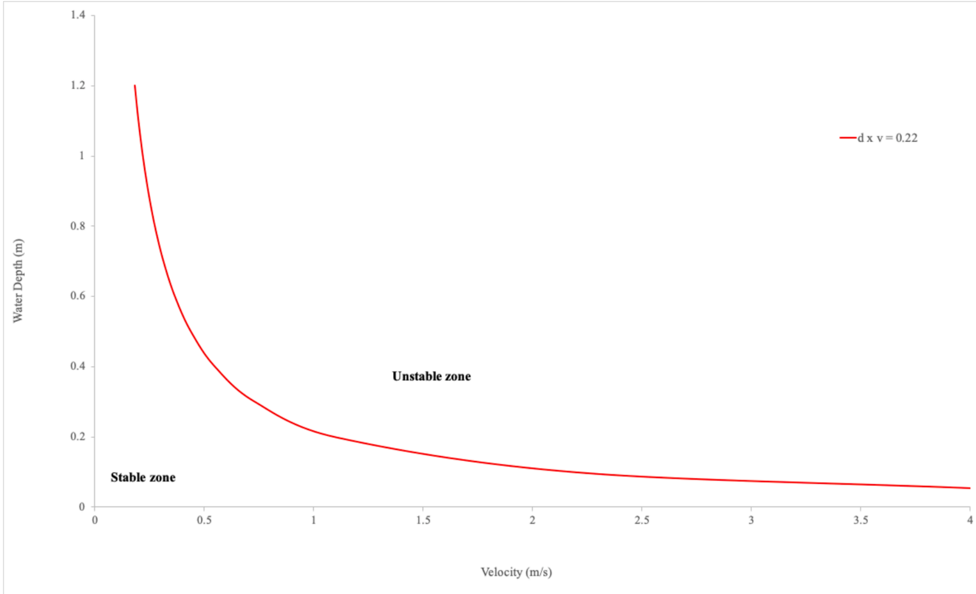

Fig. 7. Stability threshold for pedestrian in floodwaters for Method E (Martínez-Gomariz et al., 2016).

For the Borth case study the difference is 83.60% at ST 420 min (Fig. 10d) and 81.65% at ST 720 min.

5.4. Benchmark between revised MBM and Method D

The benchmark results between those for the revised MBM and Method D are shown in Fig. 11 for the Boscastle and Borth sites. 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 ST 200 min (Fig. 11b) and at ST 340 min respectively. For Borth then Method D shows 36.06% and 47.94% less extreme FHR areas at ST 420 min (Fig. 11d) and ST 720 min respectively.

5.5. Benchmark between revised MBM and Method E

Fig. 12 shows the benchmark comparisons between 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 ST 200 min (Fig. 12b) and +6.19% at ST 340 min. For the Borth case study, Method E assesses increases of +15.30% at ST 420 min (Fig. 12d) and +11.06% at ST 720 min.

6. Discussion

The results presented in this study have shown that the empirical methods, except for the Method E, generally underestimate the FHR results for extreme flood events (Musolino et al., 2020; Russo et al., 2014) when compared with the revised MBM approach (Tables 2 and 3).

In comparing the results in Tables 2 and 3 at ST 200 min and ST 420 min respectively, it can be seen that the % difference is very similar, in comparison with the results reported in Tables 2 and 3 at ST 320 min and ST 720 min respectively; when ST 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 2.1 and 2.2). Hence, 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.

In comparing the results of the revised MBM and Method E it is noted that the % differences in the FHR areas are close for both case studies. In considering the two STs, 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 STs, especially for the Boscastle case study. This observation means that the two methods give reliable results, no matter how extreme the flood event is. So far there are no data available on the instability of a pedestrian in a real flood, i.e. instability data obtained during a real flood event. Data available are only from experiments which take account of some of the most important factors leading to instability. This makes validation of different methods and – to a higher degree – comparisons of the performance of the methods, and uncertainty associated with the predictions, more difficult to assess. Moreover, different studies have highlighted that it is necessary to include the full physical characteristics of the flood in order to accurately assess the flood hazard from the perspective of pedestrian protection in events characterised by deep flood waters, high flow velocities and sudden variations in the flow regime, such those occurring in flash floods (Arrighi et al., 2017; Kvočka et al., 2016; Milanesi et al., 2015; Musolino et al., 2020). This leads to further consideration of the mechanics-based methods, such as the revised MBM presented herein. Furthermore, this study has highlighted some of the inconsistencies between the different empirical methods and the revised MBM for various physical characteristics, which confirms the caution needed in an empirical method alone.

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 later approach is inconsistent with an analysis of the hydrodynamic forces on a stationary body. Generally, the difference 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

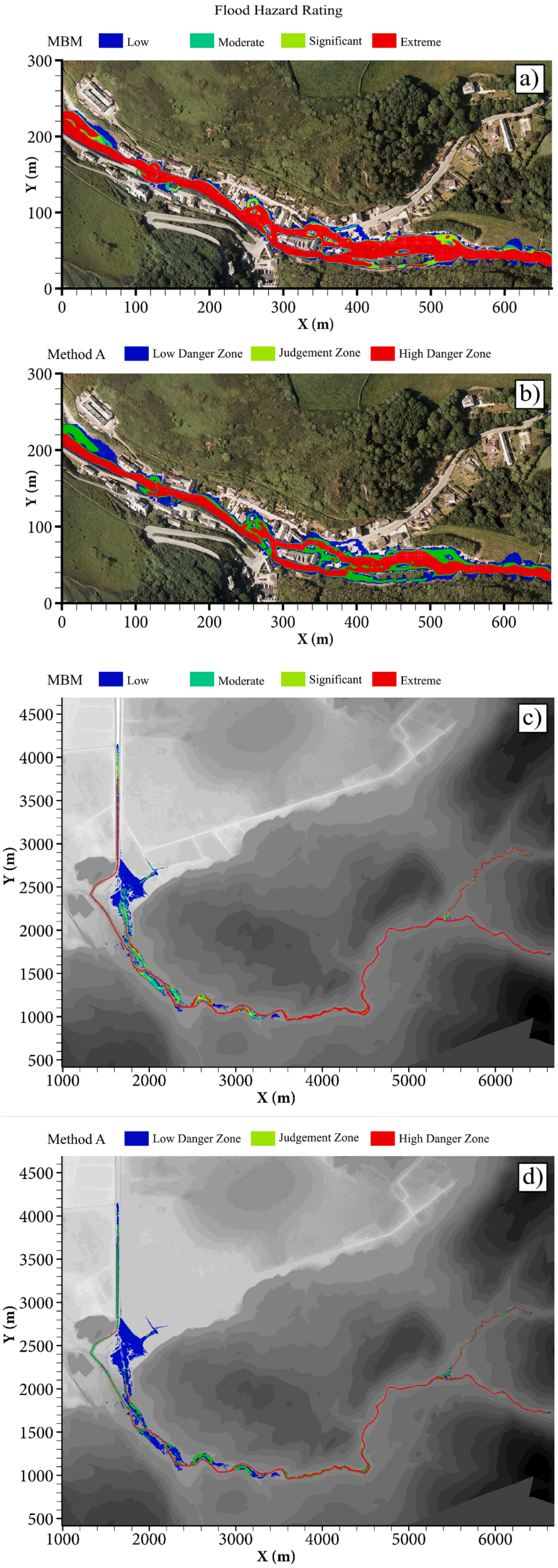

Fig. 8. FHR benchmark between revised MBM and Method A – Boscastle case study ST 200 min – Borth case study ST 420 min.

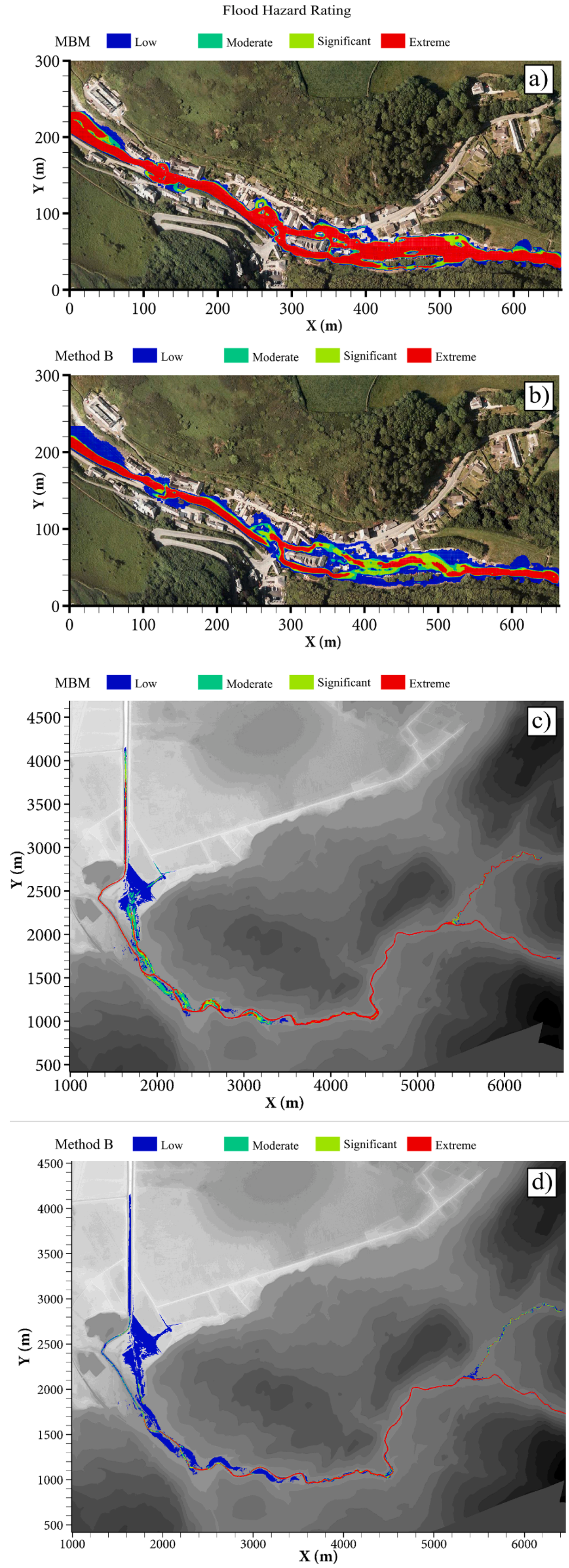

Fig. 9. FHR benchmark between revised MBM and Method B – Boscastle case study ST 200 min – Borth case study ST 420 min.

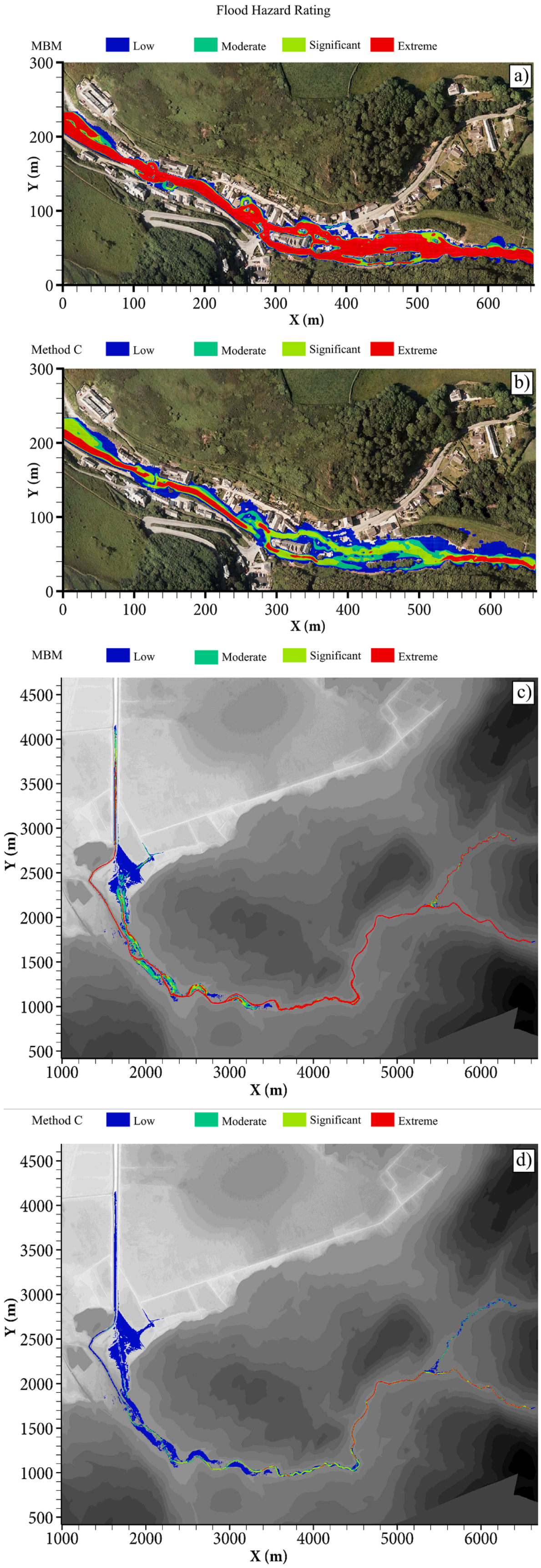

Fig. 10. FHR benchmark between revised MBM and Method C – Boscastle case study ST 200 min – Borth case study ST 420 min.

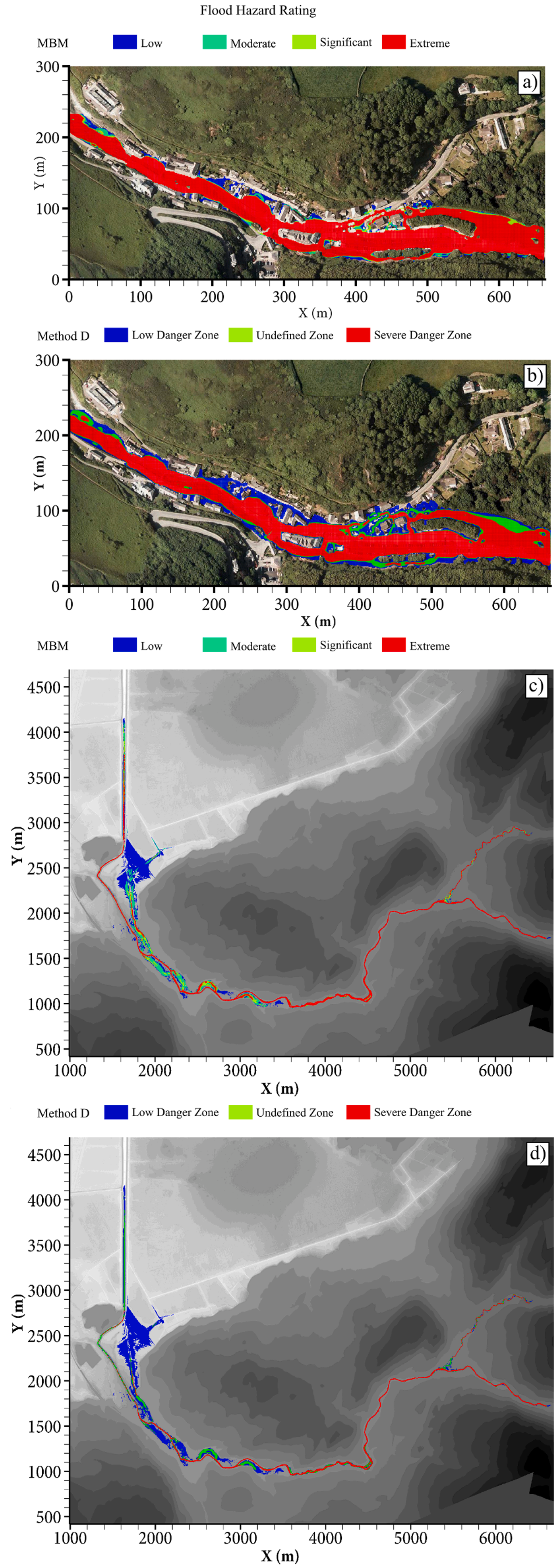

Fig. 11. FHR benchmark between revised MBM and Method D – Boscastle case study ST 200 min – Borth case study ST 420 min.

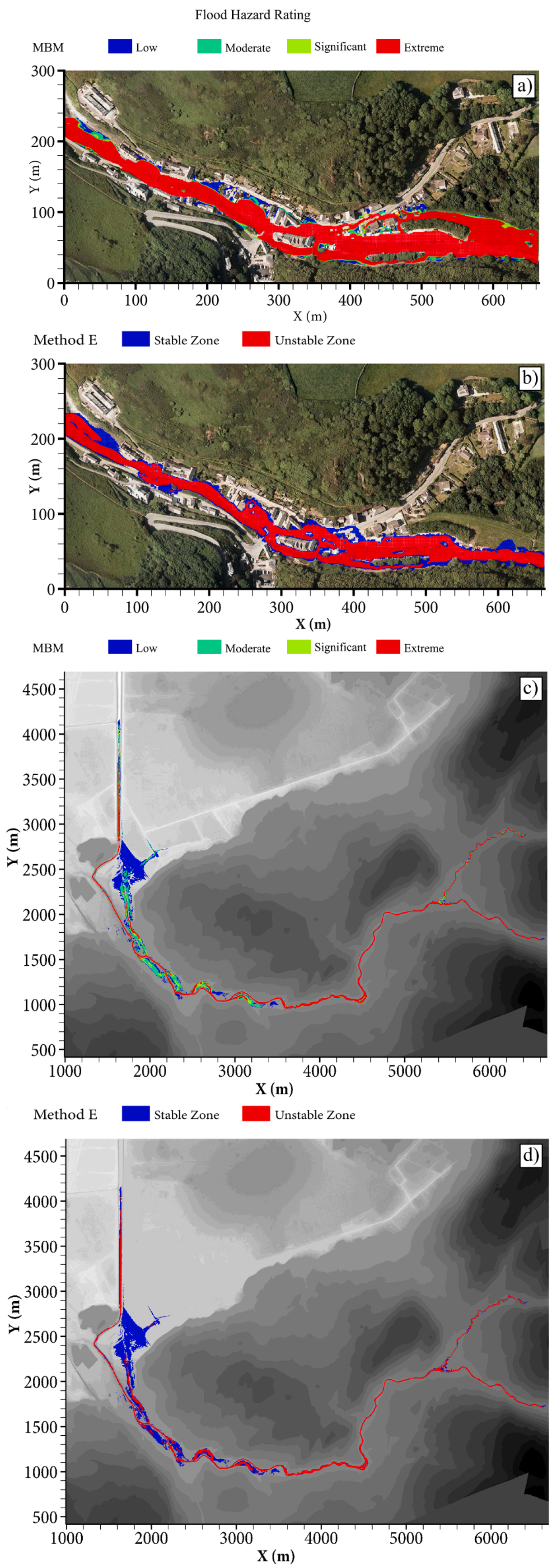

Fig. 12. FHR benchmark between revised MBM and Method E – Boscastle case study ST 200 min – Borth case study ST 420 min.

Table 2
Boscastle case study – Benchmark between the revised MBM and the other method in terms of % difference of extreme FHR areas.

Boscastle case study	% difference – ST 200 min	% difference – ST 320 min	|% difference between ST|
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 3
Borth case study – Benchmark between the revised MBM and the other method in terms of %difference of extreme FHR areas.

Borth case study	% difference – ST 420 min	% difference – ST 720 min	|% difference between ST|
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%

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 as aforementioned. Furthermore, the revised MBM approach considers all of 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 considered (i.e. 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 suggested 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 procedures, 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 in of the predicted FHR values using Method C, as highlighted in Fig. 10, 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 difference 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 the majority of 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 particular 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 is 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 characteristics. 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) inside a 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 of the methods benchmarked against the revised MBM suggest that the existing frameworks widely used can be improved using a more physics-based methodology as presented in this study.

The historical case studies reported in this study were related to two specific return period flood events, namely 1in 400 years for Boscastle and 1 in 100 years for Borth. However, in assessing the flood hazard of a specific area from a pedestrian protection perspective, different return periods should be considered. Creating multiple aggregated scenarios considering different return periods offers more insight (Dankers and Feyen, 2009; Menne and Murray, 2013; Yin et al., 2013) in pedestrian protection perspective and can better support the design optimisation of evacuation plans, based on multiple aggregated scenarios. In order to undertake this improvement, floods with different return periods should be simulated and multiple flood hazard scenarios considered for pedestrian protection, based on a different set of characteristics for each return period. Finally, the evacuation plans could then be aggregated and produced as a function of the return period. This is beyond the scope of this paper and is recommended to be considered in future studies.

7. Conclusions

In this study the main methods used internationally and reported in the literature have been benchmarked against the mechanics-based approach, with the aim of investigating the scope for improving the FHR from a pedestrian protection perspective when considering extreme flood events, such as flash floods.

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.

This study proposed a revised MBM, which 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 should lead to enhanced safety of pedestrians moving through evacuation routes during extreme flood events.

The revised MBM approach proposed herein has a key limitation in terms of the availability of data relating to the body shape parameters. If these data are not available then a detailed characterization for the study area cannot be undertaken with a relatively high degree of accuracy, particularly since generic body shape data then has to be used. Moreover, the impact on the flood hazard assessment due to psychological and behavioural response has been not considered in the formulation, with these aspects being recommendations for future works.

Further research is also required on developing new flood hazard maps based on the most critical pedestrian category for the study area and considering different flood return periods, as proposed in Section 5.

CRediT authorship contribution statement

G. Musolino: Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing, Visualization, Data curation. **R. Ahmadian:** Supervision, Conceptualization, Methodology, Project administration, Funding acquisition, Resources, Writing - review & editing. **R.A. Falconer:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2020.100067.

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