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Predicting Flood Hazard Indices in Torrential or Flashy River Basins and Catchments

Davor Kvočka¹ · Reza Ahmadian¹ · Roger A Falconer¹

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Abstract Flood hazard maps are one of the main components of any flood risk management strategy. It is predicted that the degree of flood risk is going to significantly increase in the future due to climatic and environmental changes, and hence it is increasingly important that state-of-the-art methods are implemented for assessing human stability in floodwaters. Therefore, this paper focuses on proposing more accurate and detailed guidelines for predicting flood hazard indices in small and steep river basins or catchments, prone to the occurrence of flash flooding. The results obtained in this study indicate that for river basins with an average bed gradient greater than 1% (i.e. torrential or flashy river basins or catchments), then the flood hazard indices should be predicted using criteria which are based on the physical interpretation of the processes that affect the human stability in floodwaters, i.e. mechanics based and experimentally calibrated flood hazard assessment methods.

Keywords Flashy river basins · Torrential catchments · Flood hazard · Flood risk · Human stability in floodwaters · Flash floods

1 Introduction

Flooding is the most commonly occurring natural disaster, which affects the largest number of people worldwide, and can lead to thousands of fatalities and enormous economic damage. For example, since 1980 floods have resulted in nearly 220,000 fatalities and more than \$1 trillion in economic losses (Dottori et al. 2016). Moreover, the number of people affected annually by flooding is expected to increase in the future due to effects of climate change, world-wide population growth and urban development in flood-prone areas (UN 2014, 2015; HM Government 2016).

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In the case of a flood event, the flood water depth and velocity have the greatest influence on the stability (or balance) of people in floodwaters (Abt et al. 1989), and thus act as main factors in determining the degree of flood hazard risk to people. According to the Department for the Environment, Food and Rural Affairs (Defra) and the UK Environment Agency, flood hazard “describes the flood conditions in which people are likely to be swept over or drown in a flood”, with these conditions being as a result of the combined effect of the depth and velocity of the flow, the presence of debris in the flow, and the spatial and temporal dynamics of these parameters (Ramsbottom et al. 2006).

Most of the criteria used to assess the stability of people in floodwaters is derived from a mechanics based analysis linked with experiments (Abt et al. 1989; Karvonen et al. 2000; Jonkman and Penning-Rowsell 2008), or based on a simple empirical analysis of experimental data only (Keller and Mitsch 1993; Lind et al. 2004; Ramsbottom et al. 2006). However, these criteria are often based on excessive simplifications of the anatomical characteristics of a human body and the hydraulic characteristics of the flow, and are usually too dependent on the physical and psychological characteristics of the tested subjects (Xia et al. 2014). Therefore, a new type of flood hazard assessment approach has recently been developed, which is based on the physical interpretation of the processes that affect the stability of people in floodwaters (Xia et al. 2014; Milanese et al. 2015; Shu et al. 2016). The main characteristic of the mechanics based and experimentally calibrated approach is that it takes into account the buoyancy force and a detailed representation of the human anatomy. This enables more accurate predictions to be made of the flood hazard indices, which is particularly relevant for flood hazard assessment in areas prone to the occurrence of extreme flood events (Kvočka et al. 2016).

The focus of this study has been to expand on some of the main findings presented by Milanese et al. (2015) and Kvočka et al. (2016), and consequently propose more detailed guidelines for predicting flood hazard indices in small and steep river basins and catchments prone to the occurrence of flash flooding. Milanese et al. (2015) tested the effect of local slope on human stability in floodwaters by considering slopes that ranged from 0% to 30%, and clearly showed that the instability mechanisms became increasingly more restrictive with increasing inclinations of the slope. Kvočka et al. (2016) considered two different real-life extreme flood events (i.e. extreme river floods and flash floods), and showed that in areas prone to the occurrence of rapidly varying flood events, then the flood hazard indices should be predicted by using the mechanics based and experimentally calibrated flood hazard assessment approach.

With this in mind, the key objective of this study was to determine a general threshold value of the bed slope that could be used by regulatory authorities and flood risk practitioners as a guide as to when to use specific types of flood hazard assessment criteria. In order to reach the key objective of this study, two different flood hazard assessment approaches were tested, i.e. widely used empirically based approach, and mechanics based and experimentally calibrated approach. The two selected flood hazard assessment criteria were used to assess flood hazard indices for: (i) a flood wave propagating along an idealised valley, and (ii) a flash flood event in Wales, UK. The obtained results suggest that for river basins and catchments with a river or stream gradient, or bed slope, greater than 1% (i.e. torrential or flashy river basins or catchments), the flood hazard indices should be predicted using a mechanics based flood hazard assessment criteria. However, this is an orientation threshold value and thus further research is needed to propose more detailed guidelines.

2 Study Areas

2.1 Idealised River Basin

The idealised river basin consisted of a 14 m wide and 1 m deep trapezoidal channel with the side slope of 30° and two 100 m wide floodplains on the each side of the main channel (see Fig. 1a). The idealised river basin was 2000 m long and was divided into two 1000 m sections. The upper section (i.e. the first 1000 m) had a different bed slope for each test case, and with the bed slope ranging between 0.1% to 2.5% (i.e. $S = 0.001$ and $S = 0.025$). The upper limit of the bed slope range is consistent with the bed slope of River Valency at Boscastle (O'Connor 2008), the site of one of the most violent flash floods in the history of the UK (Kvočka et al. 2015). The lower section had a constant bed slope which remained nearly horizontal (i.e. $S = 0.001$) for every test case. At the end of the river basin, there was a 100 m long and 2 m deep reservoir (see Fig. 1b).

The idea behind the design of this test case was to mimic the propagation of a flood wave through a short and steep river basin, as this type of terrain is often associated with occurrence of flash floods. Even though flash flooding is generally a result of a unique combination of meteorological and hydrological conditions the steepness of the terrain is also important, since it can affect the occurrence of flash floods due to its orographic effects, and promote the rapid concentration and propagation of stream flow (Marchi et al. 2010). Examples of such topography (i.e. complex, short and steep river basins and catchments) can be found in many areas prone to flash flooding, such as much of Wales and south-east England in the UK, the Mediterranean region (e.g. Greece, France, Spain), Central Europe (e.g. Slovenia, Slovakia, Austria) etc. (Gaume et al. 2009; Marchi et al. 2010; Foulds et al. 2012).

The idealised river basin computational domain was 2100 m long, 214 m wide and divided into square cells, with each cell having an area of 1 m². An inflow boundary was set as the upstream boundary condition, with a sinusoidal hydrograph being used to represent the flood wave (Lin et al. 2006):

$$Q = q_p \sin\left(\frac{\pi}{T} t\right) \tag{1}$$

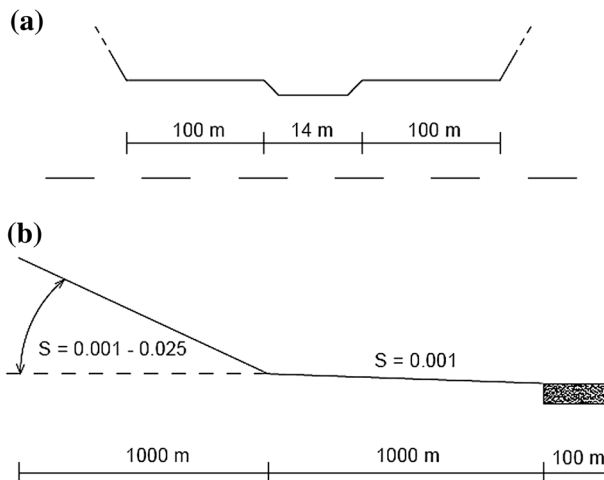


Fig. 1 Schematic presentation of the idealised river basin: (a) cross section and (b) longitudinal section

where q_p is the unit-width peak discharge, T is the duration of the flood and t is the time step with the following restriction

$$0 \leq t \leq T$$

In the conducted tests q_p was set to $300 \text{ m}^3/\text{s}$ and T was set to 4 h, which meant that the hydrograph simulated had a relatively high peak discharge (considering the dimensions of the main channel and the valley) and a short time-to-peak (i.e. 2 h). In addition, the overall flood duration was generally also short (i.e. 4 h). Also, the considered peak value of the hydrograph is consistent with the estimated peak value of the 2007 Železniki flash flood, the site of one of the most violent flash floods in the history of the Slovenia (Kvočka et al. 2016). Therefore, the considered hydrograph had all the characteristics of an extreme flash flood (Gaume et al. 2009; Marchi et al. 2010). The downstream boundary was set at the end of the reservoir, with a prescribed water level being specified as the downstream boundary condition. The main channel was assigned a Manning's roughness coefficient of 0.04, while the floodplains were assigned a Manning's roughness coefficient of 0.05.

2.2 Borth (Wales, UK)

Borth is a coastal village in west Wales, UK. It is a popular holiday seaside resort, with several caravan and camping sites nearby (see Fig. 2a). It is situated at the end of the Leri catchment. The Leri catchment is a relatively small and generally steep catchment, and is susceptible to the occurrence of flash floods (Foulds et al. 2012). The most recent flash flood occurred on 9th of June 2012, which flooded Borth and the nearby villages of Dol-y-bont and Tal-y-bont. Around 60 properties and tens of caravans were flooded around Borth, with a significant number of residents being evacuated from flooded properties in Tal-y-bont and caravan sites near Dol-y-bont as a result of the flood (Ceredigion County Council 2012; BBC 2012). Despite the general perception that the 2012 flash flood was one of the severest in history, the post-flood study revealed that the magnitude of this flood event was more common than

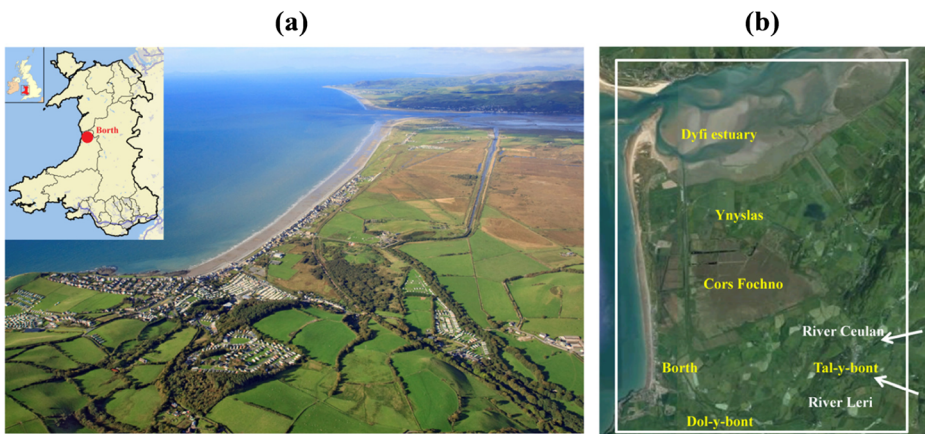


Fig. 2 The village of Borth (a) (Retrieved: November 3, 2016 from <http://www.janetbaxterphotography.co.uk>), and the Borth study domain (b) (adopted from Google Maps)

first thought. Namely, the estimated return period for this flood event was between 50 and 80 years (Foulds et al. 2012).

The Borth study domain was 9 km long, 7 km wide and covered a wider area around the villages of Borth, Dol-y-bont and Tal-y-bont (see Fig. 2b). The 2 m LiDAR (Laser Imaging Detection and Ranging) data were used to set up a computational hydraulics model. The upstream boundary was set as an inflow boundary for the River Leri and the River Cuelan near the village of Tal-y-bont. A 1:100 year flood event was simulated in this study, with the estimated peak discharge values for River Leri and River Ceulan being 64.5 m³/s and 19.1 m³/s. The downstream boundary was set in the Dyfi estuary, with a prescribed water level being specified as the downstream boundary condition. The selection of the roughness parameters was based on a site-survey conducted by the authors, and on the roughness values proposed in a study conducted for Natural Resources Wales. The floodplains were assigned a roughness value of 0.05, while both the natural river channel and the drainage channel on the Cors were assigned a roughness value of 0.04. It should be noted that there were no relevant data available to optimise these selected roughness values.

3 Flood Hazard Assessment Methodologies

3.1 Empirically Based Method

The empirical flood hazard assessment methodology proposed by Ramsbottom et al. (2006) was developed for the Department for Environment, Food and Rural Affairs (DEFRA) and the UK Environment Agency. Ramsbottom et al. (2006) tested various empirical formulae by comparing the predictions to experimental datasets obtained from laboratory studies conducted by Abt et al. (1989) and Karvonen et al. (2000). The formula adopted to undertake hazard rating analysis is given as follows:

$$HR = d(v + 0.5) + DF \quad (2)$$

where HR is the flood hazard rating (m²/s), *d* is the water depth (m), *v* is the velocity of the flow (m/s) and DF is a debris factor (m²/s), which can have a value of 0, 0.5 or 1, depending on the place of the flood and on the features of the flow. Four flood hazard classifications were proposed, which are summarised in Table 1.

The empirical expression presented by Ramsbottom et al. (2006) has some shortcomings, such as incorporation of the ability of the test subject to learn how to manoeuvre in the flow with time (i.e. training), inclusion of a debris factor without any prior experimental testing, and

Table 1 Flood hazard classification proposed by Ramsbottom et al. (2006)

HR	Degree of flood hazard	Description
< 0.75	Low	Caution
0.75–1.5	Moderate	Dangerous for some (i.e. children)
1.5–2.5	Significant	Dangerous for most people
> 2.5	Extreme	Dangerous for all

exclusion of any upper depth limit, which means that large depth/low velocity flood flows are not necessarily considered as hazardous (i.e. floating is not automatically classified as dangerous) (Cox et al. 2010). Nonetheless, the criterion proposed by Ramsbottom et al. (2006) is well established, both within and outside of the UK (Purwandari et al. 2011; Porter and Demeritt 2012; Foudi et al. 2015), and is therefore regarded as a reliable criterion for assessing and mapping flood hazard risk to people.

3.2 Mechanics Based and Experimentally Calibrated Method

The formulae presented by Xia et al. (2014) is based on the physical interpretation of the processes that affect the stability of people in floodwaters. The proposed formulae considers: (i) all forces acting on a human body in floodwaters, i.e. drag, bed frictional, gravity, buoyancy and the normal reaction force, (ii) the effect of a non-uniform upstream vertical velocity profile on the stability of a person standing in floodwaters, and (iii) the impact of the net buoyancy force on the body for rapidly varying water depths.

The formulae proposed by Xia et al. (2014) are based on the mechanisms of toppling and sliding instability, which are the two main instability mechanisms for a human body in floodwaters. The incipient velocity for a human body in floodwater experiencing toppling instability is written as:

$$U_c = \alpha \left(\frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_f^2} - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p} \right) (a_2 m_p + b_2)} \quad (3)$$

where U_c is the incipient velocity, h_f is the water depth (m), h_p is the height of the person (m), m_p is the weight of the person (kg), ρ_f is the density of water (kg/m^3), α and β are empirical coefficients and a_1 , a_2 , b_1 and b_2 are coefficients based on the general characteristics of the human body.

The incipient velocity for a human body in floodwater experiencing sliding instability is written as:

$$U_c = \alpha \left(\frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_p h_f} \left(a_1 \frac{h_f}{h_p} + b_1 \right) \frac{(a_2 m_p + b_2)}{h_p^2}} \quad (4)$$

where U_c is the incipient velocity, h_f is the water depth (m), h_p is the height of the person (m), m_p is the weight of the person (kg), ρ_f is the density of water (kg/m^3), α and β are empirical coefficients and a_1 , a_2 , b_1 and b_2 are coefficients based on the characteristics of the human body.

The initially proposed criteria were further refined in order to take into account the effect of different slopes. For example, the formula for the incipient velocity at toppling instability that considers the effect of slope is given as (Xia et al. 2016):

$$U_c = \alpha \left(\frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_f^2} (\gamma \sin \theta + \cos \theta) - \left(a_1 \left(\frac{h_f}{h_p} \right)^2 + b_1 \left(\frac{h_f}{h_p} \right) \right) \times (a_2 m_p + b_2) \left(\frac{\gamma \sin \theta}{h_p h_f} + \frac{\cos \theta}{h_f^2} \right)} \quad (5)$$

where U_c is the incipient velocity, h_f is the water depth (m), h_p is the height of the person (m), m_p is the weight of the person (kg), ρ_f is the density of water (kg/m^3), α and β are empirical coefficients, a_1 , a_2 , b_1 and b_2 are coefficients based on the characteristics of a human body, θ is the angle of the ground slope and γ is the ratio defined as

$$\gamma = \frac{a_{gx}}{a_{gy}}$$

where a_{gx} is the correction coefficient for the distance between the centre of gravity of the body and the bed and a_{gy} is the correction coefficient for the distance between the position of the centre of gravity of the body and the heel.

The degree of flood hazard risk according to the criteria proposed by Xia et al. (2014) can be quantified by mimicking the principle of bivalence, and is given as:

$$HR = \text{MIN} \left(1, \frac{U}{\text{MIN}(U_{\text{toppling}}, U_{\text{sliding}})} \right) \tag{6}$$

where HR is the flood hazard rating, U is the mean velocity of the flow, U_{toppling} is the toppling incipient velocity and U_{sliding} is the sliding incipient velocity.

The main difference between the empirical approach and the mechanics based approach is in the way they take into account forces induced by flow conditions. The overturning force on the human body in floodwaters according to the empirical approach (see Eq. (2)) is proportional to the water depth times the velocity (i.e. h_v), whereas in the mechanics based approach (see Eqs. (3), (4) and (5)) the overturning force is proportional to the water depth times the velocity squared (i.e. h_v^2). Therefore, the mechanics based criteria can be much more influenced by higher velocities and momentum, as compared to the empirically based criteria, and thus can quickly adapt to rapidly varying flood events with abrupt changes in the flow regime (e.g. hydraulic jumps). This characteristic enables a more accurate assessment to be made of the flood hazard indices in a short time period, which is a particularly important feature for flood hazard assessment of rapidly varying flood events, such as flash floods (Kvočka et al. 2016).

4 Methodology

In order to enable an equitable comparison between the two methods, two considerations were applied. Firstly, any external factors that present a risk to people in floodwaters (e.g. floating debris) were omitted from the flood hazard assessment process. Therefore, the predictive ability of both methods was based solely on the overturning force of the flow. Secondly, both methods assessed flood hazard risk in each computational cell as if the cell was horizontal (i.e. no local effect due to the bed slope). Even though there are mechanics based methods that can take into account the effect of the bed slope (Milanesi et al. 2015; Xia et al. 2016), these were not considered within this study due to the inability of the empirical method to consider different inclinations of the bed slope. Therefore, Eq. (2) (i.e. empirically based method), and Eqs. (3) and (4) (i.e. mechanics based method) were used for predicting the flood hazard

indices in this study. This meant that neither of the methods had any evident advantage over the other, which enabled a generally objective comparison to be made between the principal prediction methods of the considered criteria.

The mechanics based criteria (i.e. Eqs. (3) and (4)) are calibrated using two sets of parameters. The coefficients a_1 , b_1 , a_2 and b_2 are used to adjust the mechanics based and experimentally calibrated methods for a specific body type. These coefficients form part of an expression that represents the effect of the buoyancy force in Eqs. (3) and (4), as a function of the height and weight of the body for a given water depth. For example, a human prototype of 1.71 m in height and 68 kg mass was considered in this study. The coefficients a_1 , b_1 , a_2 and b_2 are constant, and thus the same values of these coefficients were applied for both mechanisms of toppling and sliding instability. The values of the coefficients a_1 , b_1 , a_2 and b_2 used in this study can be seen in Table 2. A more detailed explanation on how to determine these coefficients a_1 , b_1 , a_2 and b_2 from the characteristics of a human body can be found in previous studies in the literature (Xia et al. 2014; Kvočka et al. 2016).

The parameters α and β can be evaluated from the relevant experimental data. These two parameters are used to adjust the mechanics based method to the experimental conditions, e.g. friction, drag force, the effect of a non-uniform velocity distribution, training etc. The empirical criteria considered in this study were derived using the experimental data of Abt et al. (1989) and Karvonen et al. (2000), which were based on experiments using real human test subjects. Therefore, the parameters α and β used to calibrate the mechanics based method in this research were also based on the same datasets, and are outlined in Table 2. This meant that neither of the considered methods had an advantage over the other in terms of being able to predict more accurately the flood hazard indices due to a better fit to the calibration datasets. The detailed explanation on how to evaluate the parameters α and β from experimental data can be found in the literature (Xia et al. 2014; Kvočka et al. 2016).

The empirically based method categorises flood hazard into four flood hazard classifications (see Table 1), whereas the mechanics based method quantifies flood hazard by mimicking the principle of bivalence (see Eq. (6)). This means that the mechanics based method has only one flood hazard classification, i.e. extreme. Therefore, the quantifying flood hazard criteria of the mechanics based method were divided into three additional flood hazard classifications, with these new classifications corresponding to the flood hazard classifications of the empirically based method. The subdivision was conducted in such a way that the ratio of the threshold values that separate the subdivided flood hazard classifications of the mechanics based method were identical to the ratio of the threshold values that separate the flood hazard classifications of the empirically based method. The threshold values in the empirical method were 0.75, 1.5 and 2.5; therefore, the corresponding values for the mechanics based method

Table 2 The values of parameters used to calibrate the mechanics based method (Xia et al. 2014; Kvočka et al. 2016)

Parameter	Toppling instability (i.e. Eq. (3))	Sliding instability (i.e. Eq. (4))	Unit
α	7.867	10.253	$\text{m}^{0.5}/\text{s}$
β	0.462	0.139	/
a_1	0.633		/
b_1	0.367		/
a_2	1.015×10^{-3}		m^3/kg
b_2	-4.927×10^{-3}		m^3

would be 0.3, 0.6 and 1. The subdivision of the mechanics based method into additional flood hazard classifications enabled a more comprehensive comparison between the considered criteria.

The numerical flood simulations conducted in this study were characterised with relatively high Froude number flows and abrupt changes in the flow regime (e.g. hydraulic jumps). It was shown previously that only models which include techniques to solve the shallow water flows with discontinuities (e.g. shock-capturing techniques, discontinuous Galerkin methods etc.) generally produce numerically accurate predictions of flood depths and velocities when simulating rapidly varying flood events, such as flash flood scenarios (Kvočka et al. 2015, 2017). Therefore, a two-dimensional DIVAST-TVD flood inundation model with a shock-capturing capability was used for predicting flood depths and velocities in all test cases. The DIVAST-TVD model combines the standard MacCormack scheme with a symmetric five-point total variation diminishing (TVD) term, and was originally developed by Liang et al. (2007). The DIVAST-TVD model is applicable to cases that could involve discontinuities in the model solution (e.g. flash floods, dam breaks etc.), and has been extensively verified for such scenarios in several benchmarking studies (Hunter et al. 2008; Neelz and Pender 2013).

5 Results and Discussion

5.1 Idealised Test Case

Figure 3 shows a comparison between the empirically based and the mechanics based flood hazard assessment methods for the idealised river basin test case. It can be seen in Fig. 3 that both criteria generally assessed a similar degree of flood hazard risk when the upper gradient was below 1% (i.e. $S = 0.01$). This was as expected, since the formulae based on empirical or quasi-theoretical studies are as accurate as mechanics based criteria for flood events that are characterised with generally low velocities (i.e. less than 1 m/s) and a low Froude number (Kvočka et al. 2016). However, the prediction of flood hazard risk indices in the upper part of the valley started to differ more significantly between both methods when the gradient became steeper, i.e. when the gradient was greater than 1%. This again is not surprising, as the mechanics based method can be much more influenced by the forces induced by flow conditions, and where the dynamic force on a body is proportional to the square of the mean velocity.

For example, Figs. 4 and 5 show the predicted maximum velocities and Froude number values for the idealised river basin test case. It can be seen in Figs. 4 and 5 that both velocities and Froude number values in the upper part of the valley are higher with the increase in the bed slope, and with the Froude number being particularly high (i.e. near or above 1) when the slope was greater than 1%. On the other hand, the velocities and Froude number values were similar in the nearly horizontal lower part of the valley for all test cases. When these values are compared to the results presented in Fig. 3, it can be seen that the mechanics based and experimentally calibrated method is much more influenced by the higher velocities and momentum of the flow when compared to the empirically based method. This confirms that the mechanics based approach can better adapt to higher or rapidly changing velocities, and thus can more realistically predict the flood hazard risk indices for flood events characterised by high-velocity and high-Froude number flows, such as flash floods.

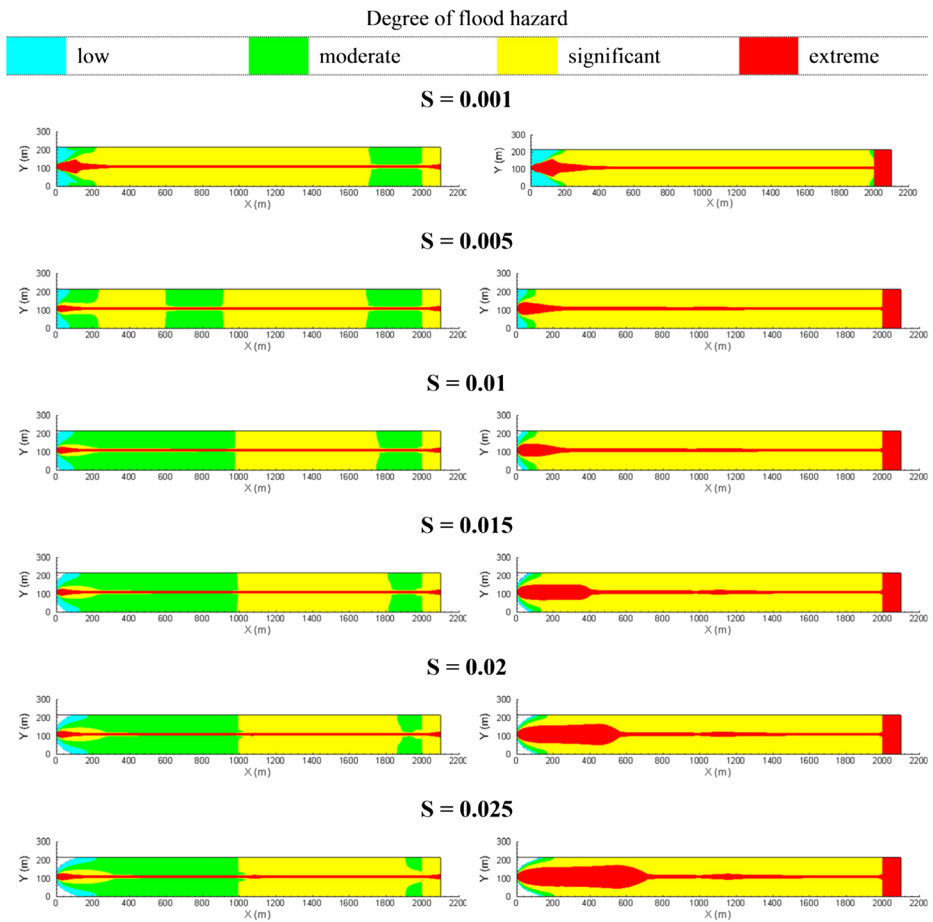


Fig. 3 Maximum flood hazard rating according to the empirically based method (left) and the mechanics based and experimentally calibrated method (right) for the idealised river basin test case

Even though this is a simple idealised test case, the results indicate that the mechanics based approach should be used when the river basin (or catchment) gradient is above 1%. This is particularly interesting when one considers how river basins or catchments are generally divided according to the value of the bed slope. In general, *river*s are defined as basins having a bed slope that is less than 1%, *torrential river*s are defined as basins having a bed slope ranging from 1 to 6%, and finally streams are referred to as *torrents* when the bed slope is greater than 6% (Ancey 2013). This means that the value of the bed slope, which indicates when it would be more accurate to use a mechanics based flood hazard risk assessment approach, is very similar to the threshold value of the bed slope that is used to distinguish between a river and torrential river.

Moreover, torrential catchments are typically small (i.e. less than 100 km² in size), characterised by a steep terrain and being susceptible to the occurrence of sudden, short and violent flood events (Ancey 2013). However, these characteristics are also characterising features of catchments prone to flash flooding (Marchi et al. 2010), with a mechanics based flood hazard risk assessment approach already being identified as the most appropriate method

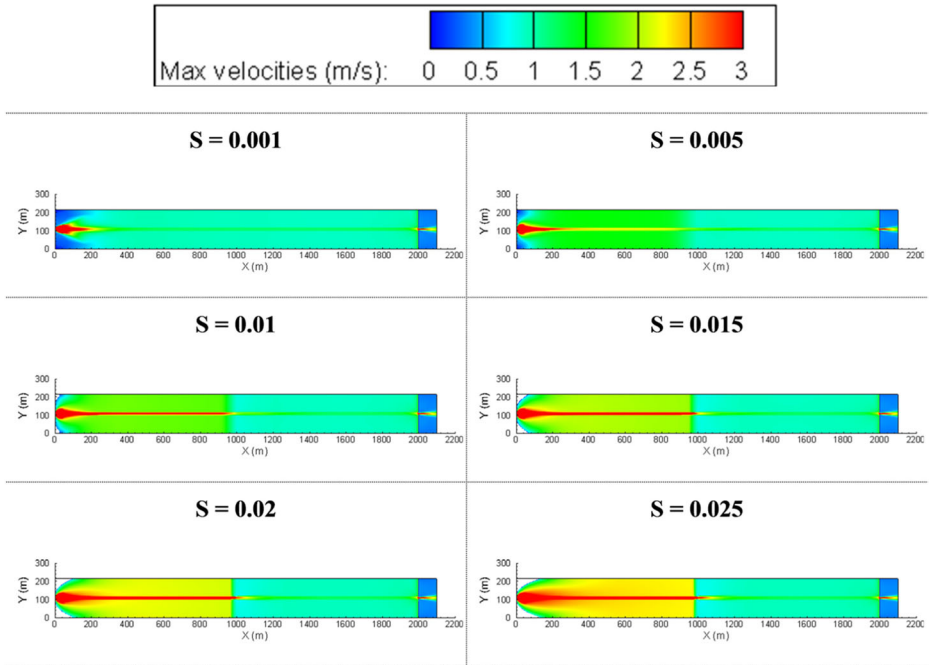


Fig. 4 Maximum velocities for the idealised river basin test case

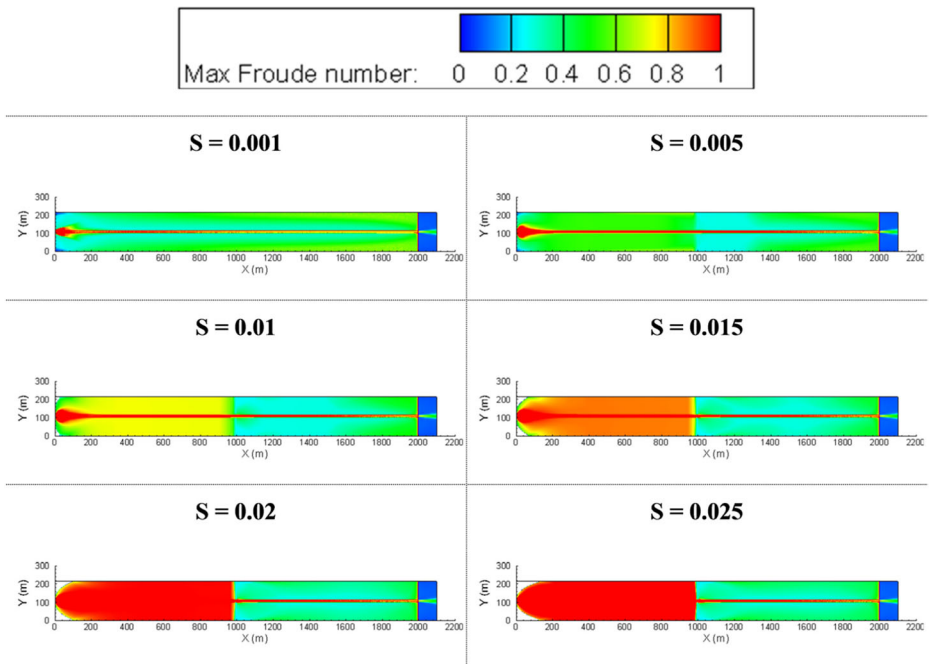


Fig. 5 Maximum Froude number values for the idealised river basin test case

for predicting flood hazard indices in areas susceptible to the occurrence of flash floods (Kvočka et al. 2016). All in all, the aforementioned considerations and obtained results suggest that for a torrential or flashy river basin or catchment, the flood hazard indices should be predicted using the mechanics based and experimentally calibrated approach.

5.2 Flood Hazard Mapping in the Vicinity of Borth

Figure 6 shows a comparison between the empirically based and the mechanics based flood hazard assessment methods in the wider area around Tal-y-bont. In Fig. 6, it can be seen that the mechanics based method generally assessed a higher degree of flood hazard risk when compared to the empirically based method. This is not surprising as the mechanics based approach was much more influenced by the flows conditions, i.e. particularly higher velocities and changes in the flow regime. The flow characteristics can be seen in Fig. 7, which shows the predicted maximum velocities and Froude numbers in the wider area of Tal-y-bont. It can be seen in Fig. 7 that both velocity and Froude number values were generally higher in this area, with the maximum velocities generally being well above 1 m/s and maximum Froude number values generally being near or above 1.

Based on the results presented in Figs. 6 and 7, it again appears that the mechanics based method is more accurate in representing the higher degree of risk associated with the high-velocity and high-Froude number flows when compared to the empirically based method. Consequently, the mechanics based approach generally predicts higher flood hazard indices for higher Froude number flood events, and therefore provides a more accurate flood hazard risk assessment in areas prone to the occurrence of flash floods. In addition, the average local bed slope in the wider area around Tal-y-bont is typically 2%, which means that the results obtained agree well with the previous results obtained for the idealised river basin test case. All this suggests that the mechanics based approach should be used for flood hazard risk

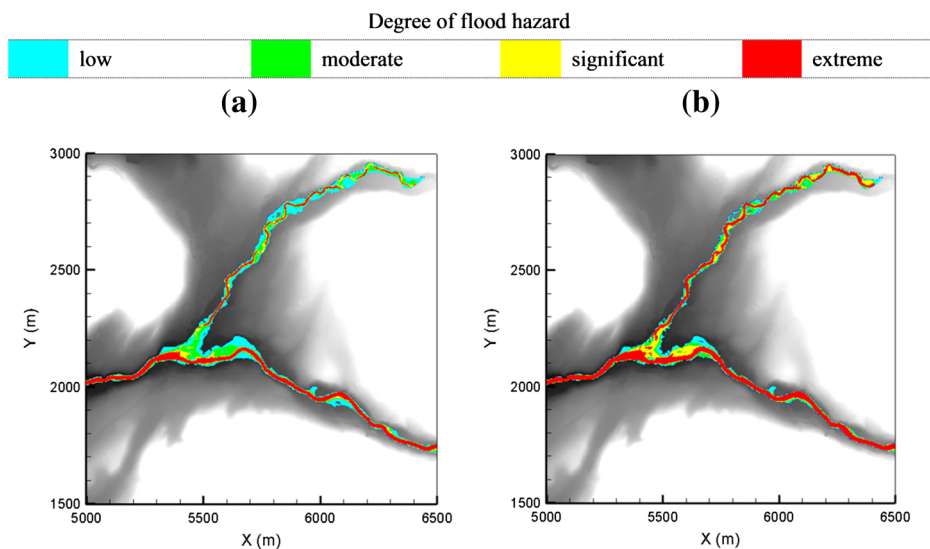


Fig. 6 Maximum flood hazard rating in the wider area around Tal-y-bont according to: (a) the empirically based method and (b) the mechanics based and experimentally calibrated method

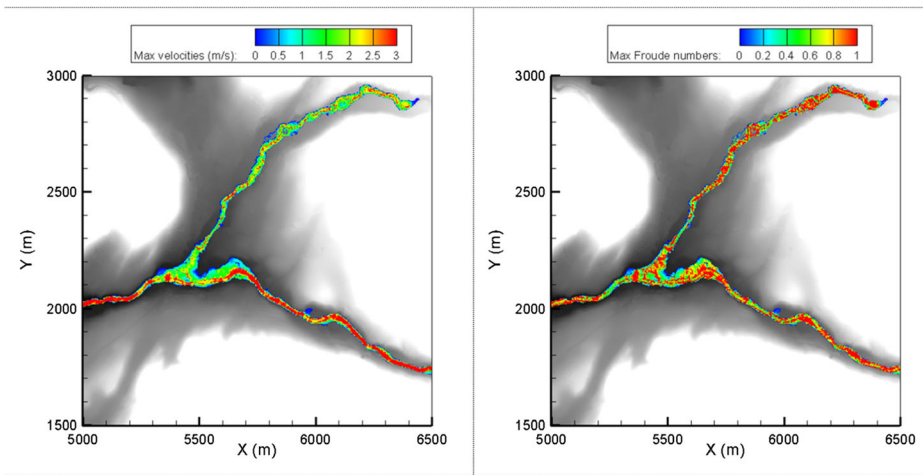


Fig. 7 Maximum velocities (left) and Froude numbers (right) in the wider area around Tal-y-bont

assessment in areas characterised with a steep terrain (i.e. with a bed slope in excess of 1%), which are prone to the occurrence of sudden, short and extreme flood events (e.g. flash floods).

Figure 8 shows a comparison between the empirically based and the mechanics based flood hazard assessment methods in the wider region around Dol-y-bont. In Fig. 8, it can be seen that the mechanics based method generally predicted higher flood hazard indices in the wider region around Dol-y-bont. The terrain around Dol-y-bont is generally less steep than around Tal-y-bont, with the average local bed slope being around 0.6%. Nonetheless, the flow conditions in this area were still characterised with relatively high-velocity flows (i.e. above 1 m/s) and Froude number values reaching up to 1 (see Fig. 9). This indicates that the mechanics based method is more suitable for assessing flood hazard indices in torrential or flash flood response river basins and catchments. These areas are often characterised with a complex terrain and steep bed slopes (generally greater than 1%), which can significantly change in relatively small areas (e.g. from 2% around Tal-y-bont to around 0.6% in Dol-y-bont). This further suggests that in steeper torrential or flashy river basins and catchments the flood hazard indices should be predicted using flood hazard criteria based on the

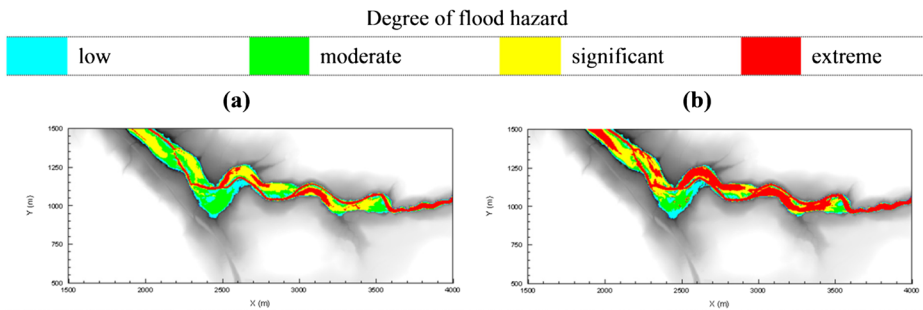


Fig. 8 Maximum flood hazard rating in the wider area around Dol-y-bont according to: (a) the empirically based method, and (b) the mechanics based and experimentally calibrated method

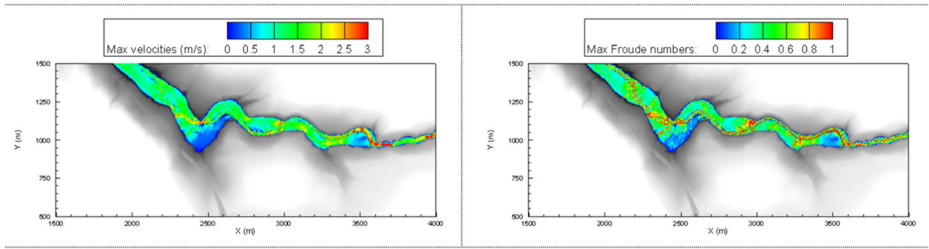


Fig. 9 Maximum velocities (left) and Froude numbers (right) in the wider area around Dol-y-bont

hydrodynamic interpretation of the processes, such as the mechanics based and experimentally calibrated method considered in this study.

Figure 10 shows a comparison between the empirically based and the mechanics based flood hazard assessment method in the wider region around Borth. In Fig. 10, it can be again seen that the mechanics based method generally assessed higher degrees of flood hazard risk in the areas characterised with higher velocities and Froude number values (see Fig. 11). Figure 10 also shows that in the areas where the velocities were smaller (i.e. 0.5 m/s or less), both methods predicted similar degrees of flood hazard risk indices. This is not surprising since the area around Borth is nearly horizontal and therefore the effect of the terrain on the flow characterises is relatively small, i.e. the rapid concentration and propagation of flood flow is minimised due to the flat ground. For example, similar results were observed for the idealised test case hazard risk when the upper gradient was below 1% (see Section 5.1). However, it can be also seen in Fig. 10 that the empirically based method predicted a higher degree of flood hazard index in areas where the velocities are smaller (see Fig. 11), but the floodwater is generally deeper (see Fig. 12).

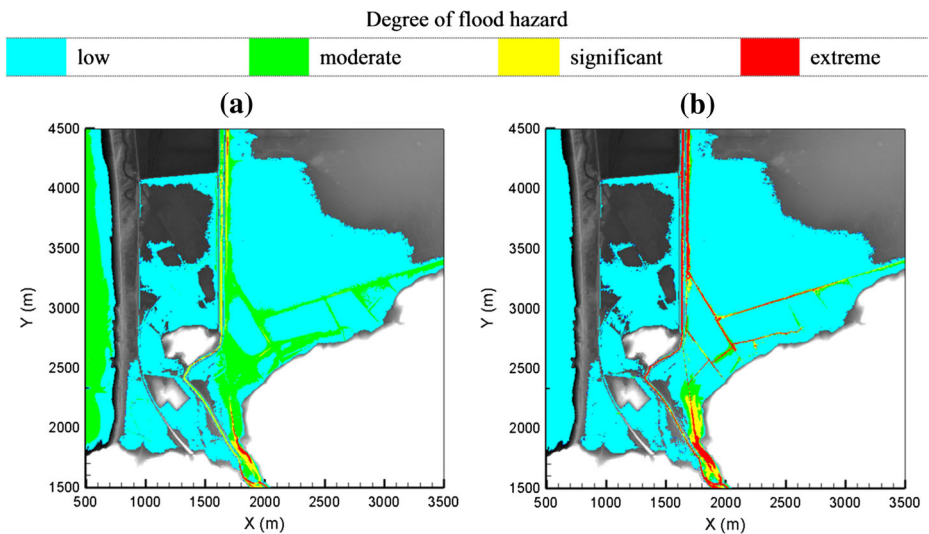


Fig. 10 Maximum flood hazard rating in the wider area around Borth according to: (a) the empirically based method and (b) the mechanics based and experimentally calibrated method

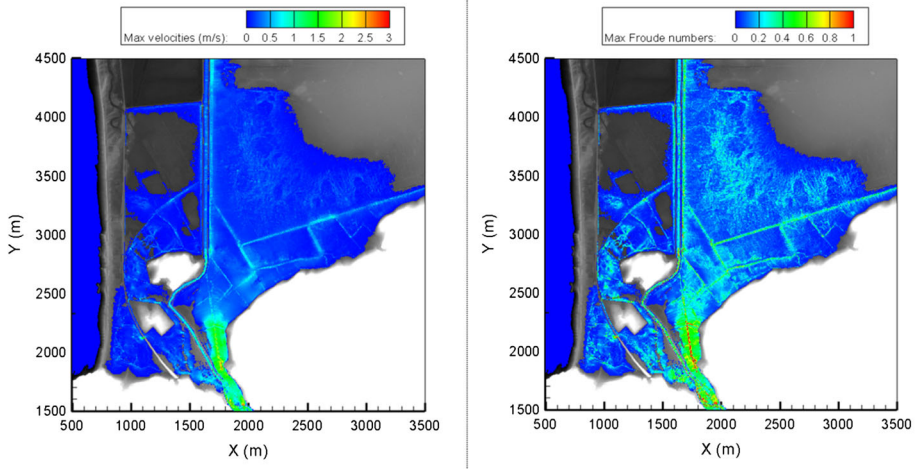


Fig. 11 Maximum velocities (left) and Froude numbers (right) in the wider area around Borth

This later finding is due to the different nature of both methods. The empirically based method considered in this study defines the flood hazard risk as being a function of the product of the depth and velocity. Consequently, the empirically based approach in this example defines a large depth/low velocity flow as hazardous (although this is not always the case, see Section 3.1). In contrast, the mechanics based method is based on the laws of fluid mechanics (or physics), and takes into account the characteristics of a human body (e.g. height

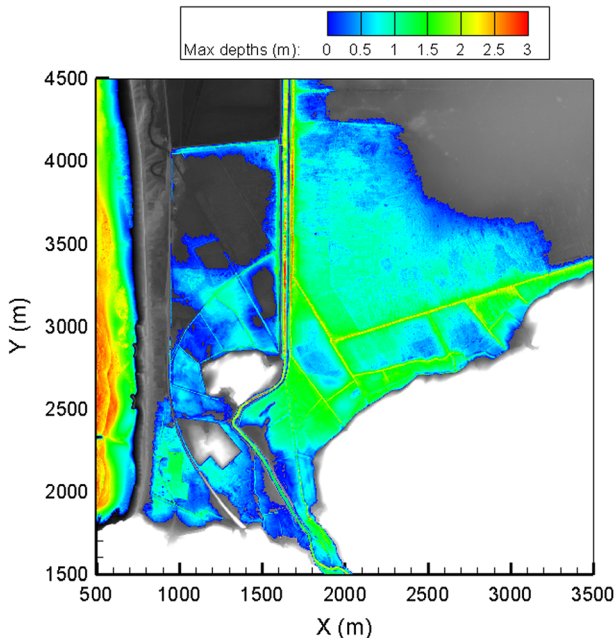


Fig. 12 Maximum water depths in the wider area around Borth

and weight). Thus, the mechanics based approach defines the flood hazard index as being primarily related to a critical velocity of the flow that leads to the loss of a person's stability in floodwaters. However, the critical velocity is calculated for a specific water depth, which means that a person will lose stability at a specific depth only if the velocity of the flood flow is higher than the critical velocity. Therefore, the mechanics based method will not automatically classify a large depth/low velocity flow as being hazardous, and particularly if the velocity of the flow is below the critical velocity.

6 Conclusions

In this paper, we have investigated the threshold value of the bed slope that could stand as a guide as to when to use a specific type of flood hazard risk assessment criteria. Two very different flood hazard assessment methods were considered: (i) a widely used empirically based method presented by Ramsbottom et al. (2006), and (ii) a mechanics based and experimentally calibrated method proposed by Xia et al. (2014). The two different flood hazard assessment criteria were used to predict flood hazard indices for two different test cases, i.e. a flood wave propagating along an idealised river basin, and a flash flood event in a short and steep river basin in Wales, UK.

The results obtained suggest that for river basin or catchment areas with a stream gradient, or bed slope, greater than 1% (i.e. torrential or flashy river basins or catchments), the flood hazard indices should be predicted using the criteria that consider the hydrodynamic processes of the flow, such as those dynamic and static forces included in the mechanics based and experimentally calibrated method considered in this study. The mechanics based equations are much more influenced by higher velocities and the momentum of the flow in comparison with other types of flood hazard assessment criteria (e.g. empirical criteria). Therefore, they are therefore highly adaptable to complex hydrodynamic processes associated with flood events occurring in steeper river basins and catchments. Thus, the mechanics based and experimentally calibrated criteria can more accurately assess the danger to people stability due to flooding in (i) areas prone to the occurrence of sudden, short and violent flood events (i.e. torrential or flashy river basins and catchments), and (ii) in conditions where the Froude number is either supercritical or trans-critical. In addition, the implementation of the mechanics based equations into the flood risk modelling software is straightforward and does not cause any additional computational cost as well.

The intention of this paper is not to criticise specific flood hazard assessment methodologies or past research work. In contrast, the scope of this paper is to raise awareness of the limitations of flood hazard assessment methodologies currently used by regulatory authorities and flood risk practitioners. For example, Chanson et al. (2014) outlined that the instability thresholds for real-life flood situations should be much lower than the instability thresholds based on the criteria derived from the analysis of the experimental data due to the complex hydrodynamic conditions in real-life flood events. Therefore, there is a need to more efficiently implement state-of-the-art modelling techniques to the practical hydro-environmental engineering community. Finally, this paper proposes only a rough estimation of a general threshold value of the bed slope that could be used as a guide as to when to use specific types of flood hazard assessment criteria. Therefore, further extensive research is needed in order to specify more detailed modelling guidelines that could be used by regulatory authorities and flood risk practitioners.

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