Science of the Total Environment 912 (2024) 168718

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Full-length paper

Beyond flood hazard. Mapping the loss probability of pedestrians to improve risk estimation and communication

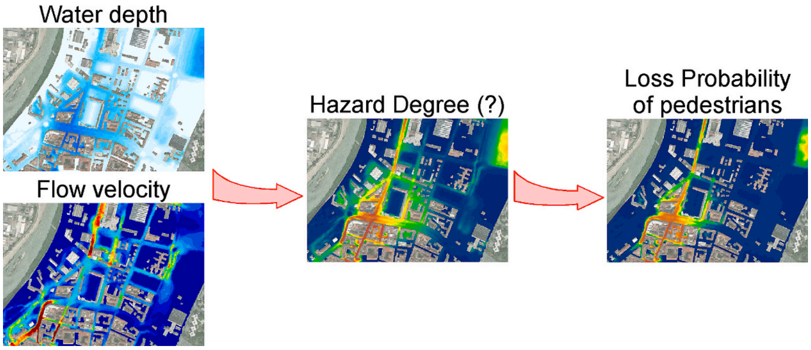
Tommaso Lazzarin [a], Albert S. Chen [b], Daniele P. Viero [a,*]

[a] Department of Civil, Environmental and Architectural Engineering, University of Padova, Italy
[b] Centre for Water Systems, Faculty of Environment, Science and Economy, University of Exeter, UK

HIGHLIGHTS

- Effective communication of flood risk to a general public is necessary to foster preparedness and resilience.
- Different attempts used to map the hazard degree of flooding events are compared to each other.
- A novel method is proposed that allows for a rigorous estimation of flood risk to pedestrians.
- The loss probability of pedestrians is mapped as an understandable measure of flood risk.
- An application shows pros and cons of the explored approaches and provides practical guidelines.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Fernando A.L. Pacheco

Keywords:
Damage
Flood
Exposure
Hazard
Vulnerability
Flood risk

ABSTRACT

The effective communication of flood hazard and risk is a necessary step to foster preparedness and resilience, hence reducing the detrimental impacts of flooding events. Classical flood maps, which show flow depth and velocity, have often proved to be incomprehensible to the majority of people. Some recent studies used color maps to convey the spatial distribution of diverse hazard indexes that, accounting for both water depth and velocity, are intended to communicate the hazard degree in a more intelligible way. It is first shown that these hazard indexes have some inherent limitations, as for example the implicit assumption of a linear relationship between flood hazard and flow velocity. As an alternative, we propose to map the loss probability (*LP*) of pedestrians exposed to floodwaters, which is a physics-based and data-consistent risk index accounting for both hazard and vulnerability. *LP* can be easily computed and allows for a sounder estimation and a more effective communication of flood risk to the general public.

1. Introduction

Awareness and preparedness to flood events are key aspects to reduce flood losses (Berghäuser et al., 2023; Fox-Rogers et al., 2016; Gersonius et al., 2016; Kreibich et al., 2017; Raaijmakers et al., 2008; Schmitt and Scheid, 2020; Thieken et al., 2007; UNDRR, 2019), and they are strongly related to a successful communication of flood risk (Acero et al., 2023; Feldman et al., 2016; Hoffmann and Muttarak, 2017;

---

* Corresponding author.
E-mail address: daniele.viero@unipd.it (D.P. Viero).

https://doi.org/10.1016/j.scitotenv.2023.168718
Received 13 September 2023; Received in revised form 13 November 2023; Accepted 18 November 2023

Intrieri et al., 2020; Maidl and Buchecker, 2015; Miceli et al., 2008; Mostafiz et al., 2022; Scolobig et al., 2012). Unfortunately, a great amount of information and knowledge on flood-related issues remains a matter of technicians, entailing a persistent gap between few experts and the general public. The identification of effective ways to communicate flood risk to different categories of people, and in particular to reach non-technicians, people that differ in age and formation, etc., is a fundamental step (Feldman et al., 2016).

The direct and active involvement of citizens and stakeholders to gather data, to analyze the issue of flooding, and to co-produce hazard maps, was shown to be very effective in communicating risk and enhancing awareness (Buytaert et al., 2014; Sanders et al., 2016; Wehn et al., 2015). The direct involvement of people on large-scale contexts requires great efforts and represents a real challenge.

Both in participative activities and in more classical one-way communication of flood-related issues, graphical representations of hazard and risk indicators (i.e., flood maps) have a fundamental role. Unfortunately, it has been evidenced that maps representing the maximum water depth and velocity have severe limits in communicating flood hazard to a wide public (Feldman et al., 2016; Houston et al., 2019; Luke et al., 2018; Sanders et al., 2020). Beyond the difficulty of interpreting the maps (Kuller et al., 2021), one can hardly identify the hazard degree associated to given values of water depth and velocity. Notwithstanding the recent advances in risk communication (e.g., 3-D visualizations of flood inundation, see Macchione et al., 2019), most people do not have a clear idea about the threat that floodwater (either shallow and fast flow, or slow and deep flow) may pose on human safety. Houston et al. (2019) proposed water depth maps in which color categories were ankle, knee, waist, and head, yet not including information on flow velocity. The Department for Environment, Food and Rural Affairs (DEFRA) and the Environment Agency of UK classified the flood risks to people as Hazard Rating (*HR*) based on the flood depth, velocity, and debris factor (Ramsbottom et al., 2003, 2006). Importantly, it has been shown that different products are needed to convey useful information to diverse users (Sanders et al., 2016, 2020). For example, crossing the spatially-distributed hazard information with the exposure of people (Koks et al., 2015) can lead to almost zero risk in heavily flooded inhabited areas; while this information is certainly relevant for environmental planning, for flood risk management, and for civil protection purposes, it can be misleading for single citizens that could be lead to consider such an area as safe.

The idea of communicating flood risk with reference to human stability in floodwater is certainly valuable. Indeed, any information, to be easily understandable to ordinary people, must be strongly connected with their practical experience and risk perception. Therefore, this is the track followed in the present study.

In the last decades, different parameters and methods have been proposed aiming at a quantitative assessment of flood hazard for pedestrians (Kreibich et al., 2009; see the also the recent review by Maranzoni et al., 2023). They usually take into account water depth and flow velocity, and sometimes other aspects as the presence of debris, etc. Hazard parameters have valuable communicative potential, as they represent a summary measure of the local hazard degree as determined by different flow conditions. For example, flood hazard maps adopted by regulatory authorities in the UK are based on the *HR* index for people in floodwaters, presented by Ramsbottom et al. (2003, 2006) and used in other several studies (e.g., Guan et al., 2023). The product number, *PN*, is another hazard parameter that found widespread applications for pedestrians and other categories of exposed items such as vehicles (Cox et al., 2010; Martínez-Gomariz et al., 2018; Russo et al., 2013; Shand et al., 2011).

The above hazard parameters were shown to suffer from a lack of proper physical foundation (Kvočka et al., 2016; Lazzarin et al., 2022b). Recent studies developed physics-based models for the stability of people in floodwaters (Arrighi et al., 2017; Chen et al., 2019; Milanesi et al., 2015; Xia et al., 2014) to provide a more robust assessment of hazard conditions by identifying threshold values of hydraulic variables (in terms of water depth, flow velocity, or non-dimensional mobility parameters) associated to the loss of stability.

Starting from Kvočka et al. (2016), a number of works appeared in the literature in which the use of physics-based thresholds was extended to rate intermediate flood hazard conditions (Dong et al., 2022a; Dong et al., 2022b; Kvočka et al., 2018; Q. Li et al., 2023; Y. Li et al., 2022; Musolino et al., 2020; Wang et al., 2021). In these works, the hazard degree was defined as $HD = \min(U/U_c; 1)$, with U the local flow velocity and $U_c = U_c(Y)$ the critical velocity at which a person loses stability in floodwaters of depth Y. Unfortunately, the underlying assumption of a linear relationship between the hazard degree and the flow velocity is not a sound hypothesis, because the instability of pedestrians in floodwaters is a matter of forces, and the hydrodynamic drag varies with the square of flow velocity. In other word, if $U_0 = U_c$ leads to a unitary hazard degree, $HD_0 = 1$, a halved flow velocity $U_1 = U_0/2$ produces an $1/4$ drag force, which is expected to generate a hazard degree far lower than the linear estimate $HD_1 = HD_0/2$.

An additional and more general drawback of *HR* indexes is that they are not a direct measure of the actual risk for people in floodwaters. Indeed, the concept of risk for pedestrians is associated to the probability of being swept away by floodwaters (i.e., the loss probability, *LP*) for extreme as well as for intermediate hazard conditions. Estimating *LP*, beyond the identification of threshold (i.e., extreme) conditions, requires a further step to account for the resistance (or vulnerability) of pedestrians under lower hazard situations. As many factors contribute to the resistance of people in floodwaters, physics-based models can be conveniently tuned according to available experimental data.

To sum-up, with particular reference to intermediate flood hazard conditions, *i)* the classical flood maps can be hardly understood by most people, *ii)* previously proposed hazard indexes, which combine water depth and velocity to identify threshold conditions for human stability, suffer from a lack of proper physical foundation, and *iii)* hazard indexes are not a direct measure of the actual risk, which is intimately related with the concept of *LP*.

To overcome these limitations, we apply the method recently proposed by Lazzarin et al. (2022b). They developed a simple, physics-based and data-consistent method to assess the loss probability of pedestrian (either adult or child) in floodwaters. An impact parameter is computed from water depth and velocity, and a damage function is then used to obtain the *LP*. Given the importance of an unbiased risk perception in flood management (Birkholz et al., 2014; Kuriqi and Hysa, 2022), the *LP* of adult pedestrians, expressed as a percentage, can be seen as an intelligible measure of flood risk for the general public. Mapping its spatial distribution is then appealing to communicate flood risk to a wide audience.

In this study, we recall and compare some of the impact parameters and approaches used to determine the hazard degree for people in floodwaters, highlighting some drawbacks inherent in their use. We then show the soundness and the potential of mapping flood risk in terms of *LP* for pedestrians. We use a real-like, modelled flood event to reason about the advantages of mapping the individual loss probability as a strategy to communicate flood risk to ordinary people.

2. Materials and methods

2.1. Impact parameters expressing the hazard degree

Studies on parameters for flood hazard assessment proliferated in the recent scientific literature (Maranzoni et al., 2023). Many parameters expressing the hazard degree are based on empirical derivation. One of the most common is the so-called Product Number, $PN = U \cdot Y$, with U and Y the flow velocity and depth, respectively (Martínez-Gomariz et al., 2018; Russo et al., 2013). In general, it is assumed that hazard is small if $PN < PN_{CR}$, with PN_{CR} denoting threshold values obtained from experimental tests and collected in specific manuals (Cox et al., 2010).

Attempts were made to relate the threshold values PN_{CR} to physical characteristics of exposed items, e.g. height and weight for the case of people (Lind et al., 2004).

Another empirical parameter meant to estimate the flood hazard to people is the hazard rating HR proposed by Ramsbottom et al. (2003) and later modified by Ramsbottom et al. (2006). HR is used to produce flood hazard maps by regulatory authorities in the UK (e.g. DEFRA) and well established also outside the UK (Foudi et al., 2015; Guan et al., 2023; Kaźmierczak and Cavan, 2011; Penning-Rowsell et al., 2005; Purwandari et al., 2011). It is defined as $HR = Y(U + 0.5)$, a combination of flow depth and velocity derived from best fitting of previous formulas and experimental data. A value of $HR > 2.5$ identifies 'extreme hazard - dangerous for all' conditions.

Empirical indexes for HR suffer from some limitations. As observed by Lazzarin et al. (2022b), to provide reliable estimates, empirical criteria require additional thresholds on the main explicative variables. Otherwise, as in the case of the HR index that lacks an upper depth limit, large-depth and low-velocity flood flows are not considered as hazardous (Cox et al., 2010; Kvočka et al., 2016).

Kreibich et al. (2009) investigated the influence of water depth, Y, and flow velocity, U, on flood hazard, trying to evaluate the explanatory potential of different impact parameters expressed as combinations of these two parameters (the energy head $Y + U^2/2g$, an indicator for flow force $Y{\cdot}U^2$, and the flow intensity $Y{\cdot}U$) on various types of flood damage in five communities affected by the Elbe catchment flood in Germany in 2002. Medium-to-high correlations with all the considered categories were found with the water depth and the energy head, with the latter suggested as a suitable impact parameter. The indicators for flow force and intensity showed weaker correlations. Similarly, in relation to dam-break studies, Aureli et al. (2008) proposed the total depth $D = Y\sqrt{1 + 2F^2}$, in which F is the Froude number. The total depth D represents the water depth at rest with the same total force of the flow with velocity U. This impact parameter has been used in successive studies (Ferrari et al., 2019; Ferrari and Viero, 2020), but lacks the identification of thresholds to distinguish different hazard degrees.

In the last decade, physical models were developed to characterize the stability of people in floodwaters in terms of critical velocity, U_c, for a given water depth (Xia et al., 2014) or, alternatively, the critical depth, Y_c, for a given velocity (Milanesi et al., 2015). Based on similar considerations, Arrighi et al. (2017) introduced a mobility parameter ϑ that, compared with a Froude-dependent critical value ϑ_{CR}, allows to identify the neutral stability condition. These physics-based approaches allow accounting for hazard variables (i.e., water depth and velocity) and for the characteristics of people as well (e.g., height and weight of a person).

More recently, Lazzarin et al. (2022b) introduced a non-dimensional and flexible impact parameter, called W, that accounts for water depth and velocity, and can be tuned to match both the physics of the damaging processes and the available experimental data. It successfully described hazardous conditions for different kind of items, including pedestrians, and to allow for a dynamic representation of temporal flood damage evolutions during a flood event (Lazzarin et al., 2022a). The W impact parameter is given in the form:

$$W = \left(\frac{Y}{Y_w}\right)^{\alpha}\left(1 + \beta F^2\right) \quad (1)$$

where $F = U(gY)^{-1/2}$ is the Froude number with g the gravity acceleration, Y_W is a scale factor and α, β are two parameters that account for the mutual role of water depth and velocity in the instability or damaging mechanism. Y_W can be conveniently set to make W varying between 0 and 1. Proper values for α and β can be determined, for a given kind of exposed item, based on physical considerations and/or by calibration against available experimental data. For example, the hazard for adults exposed to floodwaters can be assessed with the impact parameter W assuming $Y_W = 1.25$ m, $\alpha = 2$, and $\beta = 4$ (further details can be found in Lazzarin et al., 2022b).

2.2. *From hazard degree to flood risk (through damage functions)*

As already mentioned, the above hazard indicators and impact parameters were typically conceived to identify the critical threshold conditions for pedestrian stability. Attempts of using such parameters to rate intermediate hazard conditions were partly qualitative, and partly not well-founded. The use of thresholds associated to hazard degree parameters, such as the PN and the HR indexes, only allowed for a qualitative description of the expected risk, which is given in classes such as 'low', 'moderate', 'significant', and 'extreme' (Cox et al., 2010; Ramsbottom et al., 2006). The abrupt changes between different classes are unlikely to be observed in reality. Similarly, the definition of an hazard degree as a linear function of the flow velocity scaled by the critical velocity for pedestrian instability, used in several recent works (Dong et al., 2022a; Dong et al., 2022b; Kvočka et al., 2016, 2018; Q. Li et al., 2023; Y. Li et al., 2022; Musolino et al., 2020; Wang et al., 2021), cannot be expected to provide consistent predictions of the real risk associated to intermediate hazard conditions (this is better explained in the next Sect. 3.1). Furthermore, even the meaning of HR cannot be defined rigorously.

These are the reasons why we prefer (and propose) to move to the concept of 'flood risk', or 'expected relative damage' that, for people in floodwaters, can be defined as the probability of being swept away (Lazzarin et al., 2022b). The passage from hazard degree to flood risk can be achieved using damage functions (sometimes referred to as fragility functions) to associate a given hazard condition with the probability of having a negative consequence such as pedestrian instability. Interestingly, the concept of 'loss probability' is a flood risk measure that can be simply understood by a wide audience, and it is thus appealing in view of communicating flood risk.

To this purpose, we adopt the approach recently proposed by Lazzarin et al. (2022b), which is based on both physical reasoning and experimental data, i.e., the availability of representative samples of instability conditions for people. Lazzarin et al. (2022b) proposed a simple, quantitative estimation of the loss probability as a univariate function in the form

$$LP(W) = \frac{1}{1 + (a/W)^b} \quad (2)$$

in which the (a, b) parameters are tuned to fit the cumulative frequency distribution of W associated to the loss of people (further details in Lazzarin et al., 2022b). The parameters (a, b) depend on the characteristics of particular sub-categories (e.g., $a = 0.6$ and $b = 5.0$ for adults and $a = 0.25$ and $b = 6$ for children).

3. Results and discussion

3.1. *Shortcomings in the use of impact parameter to rate the hazard degree*

For the representative case of adult people, we compare four different approaches to rate flood hazard:

- the method by Cox et al. (2010), which is based on the product number PN. Hazardous conditions are denoted as extreme for $PN \geq 1.2$ and moderate for $PN \geq 0.6$, coherent with a linear relationship of hazard on PN. Based on Cox et al. (2010), we define $HD_{PN} = PN/1.2$. As an additional constraint, the condition $HD_{PN} = 1$ is achieved also when $U > 3.0$ m/s and/or $Y > 1.2$ m;
- the method by Kvočka et al. (2016), which identifies unstable conditions when the flow velocity exceeds the critical velocity for instability, as determined by Xia et al. (2014), and enforces a linear relationship between hazard and velocity for intermediate conditions. In this case, the hazard degree is given by $HD_U = \min(U/U_c; 1)$;

- the method by Arrighi et al. (2017), which is based on the mobility parameter ϑ, and identifies unstable conditions for $\vartheta_{CR}/\vartheta \geq 1.5$. A linear formulation to rate intermediate hazard conditions has been proposed, in the equivalent framework developed for vehicles, in Arrighi et al. (2016). Based on Arrighi et al. (2017), we define $HD_\vartheta = 0.\overline{6}\ \vartheta_{CR}/\vartheta$;
- the method by Lazzarin et al. (2022b), which assesses flood hazard with the impact parameter W defined in Eq. (1). Note that W, with $Y_W = 1.25$ m, $\alpha = 2$, and $\beta = 4$, is already scaled in a way that $W \geq 1$ indicates extreme hazard conditions.

All the above parameters (HD_{PN}, HD_U, HD_ϑ, and W) span in the interval [0,1], with the upper limit identifying extreme hazard conditions, which facilitates the comparison. For the physics-based methods that account for the characteristics of people such as body height, foot length, etc. (Arrighi et al., 2017; Kvočka et al., 2018), we refer to the average characteristics of Italian population.

The first drawback in rating the hazard is associated to the assumption of linear relationship of flood hazard on the flow velocity. Fig. 1 shows the hazard degree provided by the four methods as functions of flow velocity for different values of water depth. For the greater water depth of Fig. 1b, the $HD = 1$ conditions are reached at lower flow velocities. As regards the hazard degree at intermediate conditions, the trend associated to PN seems quite unrealistic, particularly for the evident effect of the $U > 3$ m/s threshold in Fig. 1a. The physics-based foundation of the methods by Xia et al. (2014) and Arrighi et al. (2017) determines the $HD = 1$ condition; however, even if considering a balance of forces for the upper limit condition, the rating of intermediate hazard is linear by hypothesis. The impact parameter W, introduced by Lazzarin et al. (2022b), is shaped according to the physics of the instability processes and to available experimental data, and it does not require additional thresholds as the PN-based method. It shows the most reasonable assessment of intermediate conditions (black solid lines), since the non-linear behavior of W reflects the relationship of the drag force on the squared flow velocity. It can be noted that, at intermediate hazard conditions, the three other methods overestimate the actual hazard degree because of the assumption of linearity dependence between velocity and hazard. Furthermore, for $U \to 0$, W preserves a residual hazard degree that depends on the water depth (Fig. 1b). The other methods, for $U \approx 0$, predict $HD \approx 0$ up to the limit condition in which the water depth is sufficiently large to determine the instability condition also in still water (i.e., the solid straight lines become vertical).

Fig. 2, which reports HD-isolines in the U—Y plane according to the four method here considered and a sample of experimental instability conditions (circles) taken from previous laboratory tests involving adults (see Lazzarin et al., 2022b for a complete reference of the data sources), suggests two additional drawbacks inherent in the rating of hazard.

The first drawback regards the behavior of HD in case of (almost) still water (i.e., $U \approx 0$). For increasing water depths, HD_{PN} presents an abrupt upward transition from 0 to 1 when the threshold $Y = 1.2$ m is reached. According to the method by Kvočka et al. (2016), the condition $HD_U = 1$ is reached for very high values of the water depth. The 0 to 1 transition becomes slightly smoother considering HD_ϑ, essentially because Arrighi et al. (2017) considered a more conservative threshold for the loss of stability. The depth-dependent hazard increases in case of still water is naturally handled only by the W impact parameter by Lazzarin et al. (2022b).

The second drawback, which affects all the HD indexes here considered, descends from the fact that they give an information on how far a given condition is from the limit condition triggering instability. Unfortunately, such a 'distance' is given in terms of hydraulic variables, or of hazard parameters, and it does not account for the loss probability of people subject to intermediate hazard conditions. This is clear when trying to match the distribution of circles in Fig. 2 with the HD-isolines: for all the considered methods, the $HD = 0.5$ isoline is far from dividing the sample in two equal parts. This demonstrates that the hazard degree, however computed, does not correspond to the loss probability. As a side note, the visual comparison of the $HD = 1$ isoline with the experimental data in Fig. 2 shows that the methods by Kvočka et al. (2016) and by Lazzarin et al. (2022b) better estimate the limiting condition for people safety in floodwaters (loss conditions out of the $HD = 1$ region are 50 % for HD_ϑ, 14 % for HD_{PN}, 10 % for HD_U, and 2 % for W).

Based on the same experimental data shown in Fig. 2, Lazzarin et al. (2022b) estimated the loss probability of adults exposed to floodwaters, LP, as a function of the hazard degree W, according to Eq. (2) with $a = 0.6$ and $b = 5.0$. The loss probability is plotted in Fig. 1 with dashed lines. Differences between HD and LP are evident. Considering a water depth $Y = 0.2$ m (Fig. 1a), the loss probability associated to a slide condition is almost null up to a flow velocity $U = 2$ m/s, meaning that most people can resist in such a hazard condition. Similarly, for a water depth $Y = 0.4$ m (Fig. 1b), the loss probability associated to a slide condition is almost null up to a flow velocity $U = 1$ m/s, a condition that corresponds to hazard degrees between 0.21 and 0.53 according to the different methods here considered. These important differences between the hazard degree and the loss probability reflect the human ability to cope with floodwaters of modest depth and velocity with a negligible risk, which is a key aspect to communicate flood risk realistically and effectively.

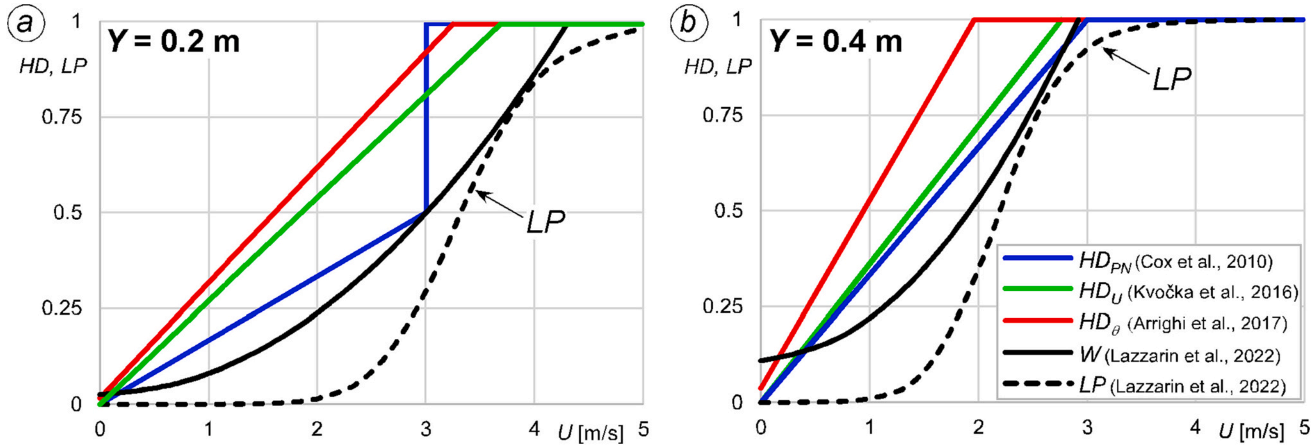


Fig. 1. Hazard degree, HD, predicted by different approaches (solid lines) as a function of the flow velocity, for a water depth $Y = 0.2$ m (a) and $Y = 0.4$ m (b). The dashed lines indicate the loss probability, LP, according to Lazzarin et al. (2022b).

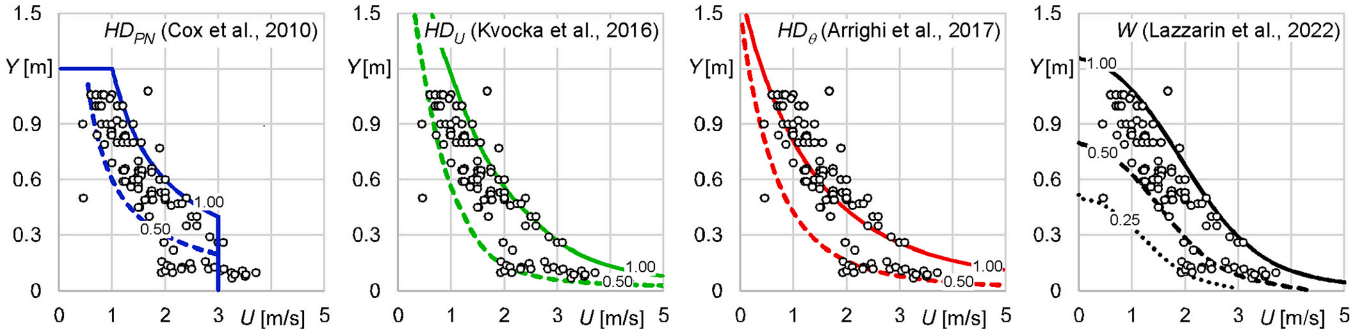


Fig. 2. Experimental data for instability of adults in floodwaters and isolines for hazard degree $HD = 1$ (solid lines), $HD = 0.5$ (dashed lines), and $HD = 0.25$ (dotted line in rightmost panel) according to the four different approaches considered in this study.

3.2. *Using the loss probability of people to map the flood risk*

To assess the different indexes for flood hazard and risk mapping, we consider a real case study and, specifically, the flooding in the city center of Alessandria (northwest of Italy). Alessandria is a medium-size city of about 90,000 inhabitants, located at the confluence of the Tanaro and the Bormida Rivers (Fig. 3). The Tanaro River inundated part of the city center during the 1994 flood event.

The spatial distribution of maximum water depth and velocity, shown in Fig. 4, was obtained using the two-dimensional, depth-averaged, 2DEF hydrodynamic model (D'Alpaos et al., 2007; Defina, 2000, 2003; Defina et al., 1994; Lazzarin and Viero, 2023; Viero, 2019; Viero et al., 2014; Viero and Valipour, 2017), which has been applied to several similar case studies in the last decades (Lazzarin et al., 2023; Mel et al., 2020a, 2020b; Viero et al., 2013, 2019). The presence of buildings was accounted for explicitly by using a sufficiently refined mesh to represent the locations of buildings, and by removing the computational elements overlapping the building footprint (Schubert and Sanders, 2012) to prevent water movement across buildings.

In the course of the flooding event, floodwaters overflowed the right levee of the Tanaro River in the southwest corner of the investigated area, moved northward to cross the city center, and finally ponded in the northeastern part of the city, which is characterized by lower elevations and by a lower building density (Fig. 3). Due to the quite irregular distributions of both terrain elevation and building density, the maximum water depth and velocity present a noticeable variability in space. The flow concentration in relatively narrow streets led to maximum flow velocities in the order of 2 m/s.

Fig. 5a–d shows the spatial distribution of the hazard degree computed with the four considered methods; the approaches provide coherent classifications for both very low and extreme degrees of hazard, which is indeed a positive result.

The main discrepancies among the different methods emerge for intermediate hazard conditions, as suggested by the analysis presented in Sect. 3.1. For example, in regions characterized by moderate depths (~1 m) and by relatively low velocities (e.g., those pointed out by cyan arrows in Fig. 5), relatively lower hazard degree values are obtained using HD_{PN} and HD_U, and higher values are obtained using HD_ϑ and W (see the large inundated region at North-East). Such a behavior is a direct consequence of the second drawback evidenced in Sect. 3.1.

The effects of the linearity assumption inherent in the HD_{PN}, HD_U, and HD_ϑ methods appear in the central part of the settlement (e.g., those

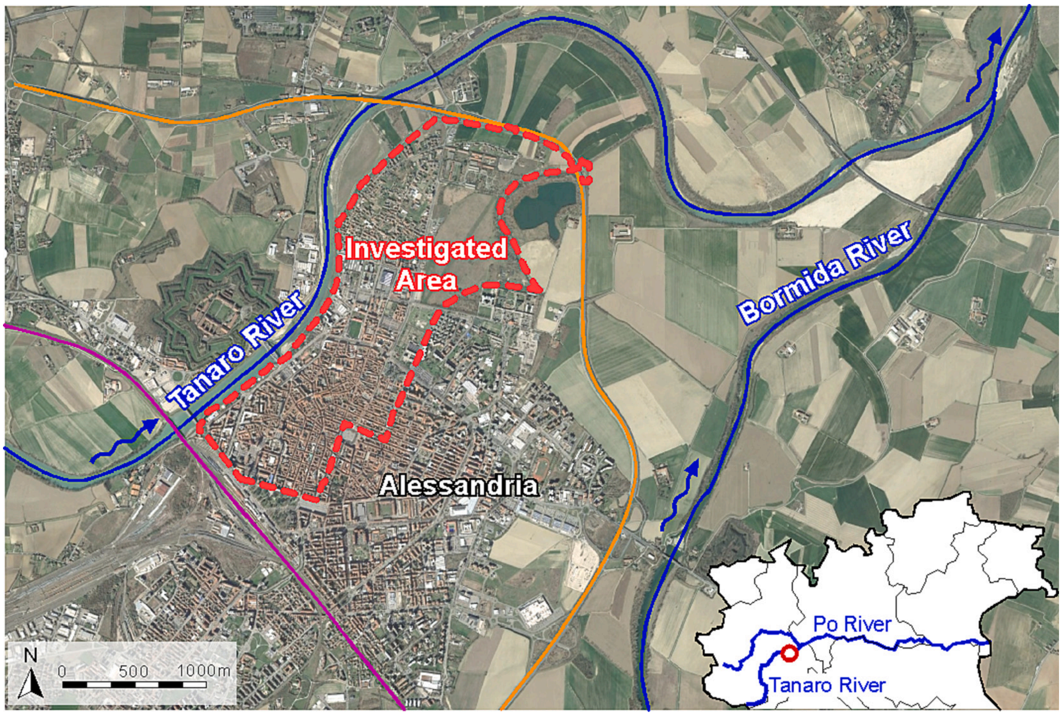


Fig. 3. Location of the study area in the center of Alessandria (northwest of Italy), between the rivers Tanaro and Bormida.

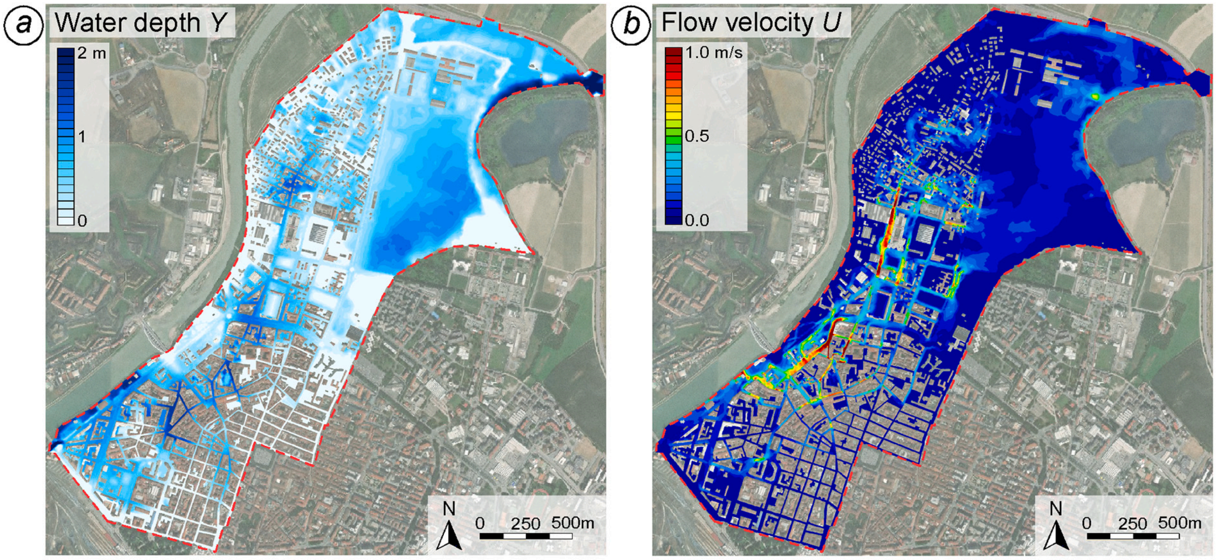


Fig. 4. Maximum water depth (a) and flow velocity (b) in the flooding of Alessandria (northwest of Italy) due to the overflowing of the Tanaro River.

pointed out by white arrows in Fig. 5), where relatively high flow velocities are observed along with low water depths. Here, compared to the *W*-based method developed by Lazzarin et al. (2022b), the three linear methods provide sensibly higher hazard degrees.

As suggested by the analysis of Sect 3.1, the hazard degree does not represent the loss probability, with a larger difference for lower hazard degrees. The results in Fig. 5 show how this difference impacts the risk perception that emerges when mapping a flooding event at a city scale. Fig. 5e shows that the loss probability, *LP*, computed with Eq. (2) assuming $a = 0.6$ and $b = 5.0$, is almost zero in large portions of the city where the hazard degree is modest ($HD < 0.25$). Areas subject to extreme values of both hazard and loss probability almost coincide to the ones obtained using the *W*-based method by Lazzarin et al. (2022b). However, the HD_{PN}, HD_U, and HD_ϑ methods provide very low hazard degrees in large areas characterized by relatively high loss probability; this occurs in low-velocity areas, a problem already evidenced and discussed above.

Trying to look at the maps shown in Figs. 4 and 5 with the eyes of the general public, the representation of maximum water depths retains a definite value; being easily understandable, it provides a general picture of the flooded area in terms of both the extent and severity (possibility of entering the ground floor of buildings, reaching the door frame of vehicles, etc.). The values of maximum flow velocity remain difficult to be interpreted in terms of hazard; this supports the use of summary indicators which integrate the effect of flow velocity with that of water depth. The information conveyed by the hazard indicators of Fig. 5a–d has been shown to be partly biased; moreover, the definition (and understandability) of intermediate hazard degrees remains quite vague. The loss probability of pedestrians is again an intelligible information, which has an enhanced potential to discriminate a harmless nuisance flooding (Moftakhari et al., 2018) from a dangerous situation, which can be ascribed either to deep or fast flowing floodwaters.

As concerns the limitations of the proposed method, it is stressed that the *LP* refers to adult people. This is not representative of the risk condition for different categories of pedestrians (e.g., child, elder, etc.), which can have a different resistance to the destabilizing force of floodwater. Furthermore, the present approach evaluates the flood risk locally per unit exposure, with the specific purpose of evaluating the danger of facing floodwater at a given location. To evaluate the expected damage in terms of loss of lives, this information should be complemented with the number (and kind) of people potentially present in the flooded area during the flood event. Finally, it is worth noting that plotting the *LP* alone does not allow to distinguish between (almost) dry from harmless nuisance flooding areas, in which floodwaters can still produce severe damages (to buildings, infrastructures, etc.).

4. Conclusions

In this work, mapping the loss probability for people (pedestrians) in floodwater is proposed as an effective index to estimate and communicate flood risk to a wide audience. Indeed, the loss probability of people, given as a percentage and plotted in colormaps, is a simple and understandable measure of flood risk also for non-technicians and non-expert ordinary people.

It is shown that the use of *LP* of people can entail substantial advantages with respect to some hazard indicators that have been proposed and applied in the recent scientific literature. In particular, the *LP* is negligible in regions where pedestrians can safely stand (e.g., slow shallow floodwaters), for which hazard indicators typically overestimate the risk perception. In addition, the *LP* is correctly high in low-velocity deep waters, where the hazard degree indexes generally produce a dangerous underestimation of the flood risk perception. This is particularly important because deep floods are widespread in lowland areas.

The *LP* maps of pedestrians provide an immediate picture of areas that are subject to dangerous flooding conditions for humans, which is useful to conduct disaster preparedness campaigns and to foster awareness of people living in flood-prone areas.

As a further guideline for a proper communication of flood risk, the loss probability maps should not be presented alone, but always accompanied with maps of maximum water depth. This is to avoid the wrong perception that ‘no risk’ means ‘no damage’, i.e., to avoid generating false confidence in areas of low loss probability, where slow shallow waters can still produce extensive damage.

As a future development, it could be considered to complement the picture of flood risk with maps of relative damage to the ground floor of buildings (again expressed as a percentage), another measure that is well connected with the practical experience of people. The damage functions provided by Lazzarin et al. (2022b) can be useful in this view.

List of symbols/nomenclature

Y	water depth
U	flow velocity

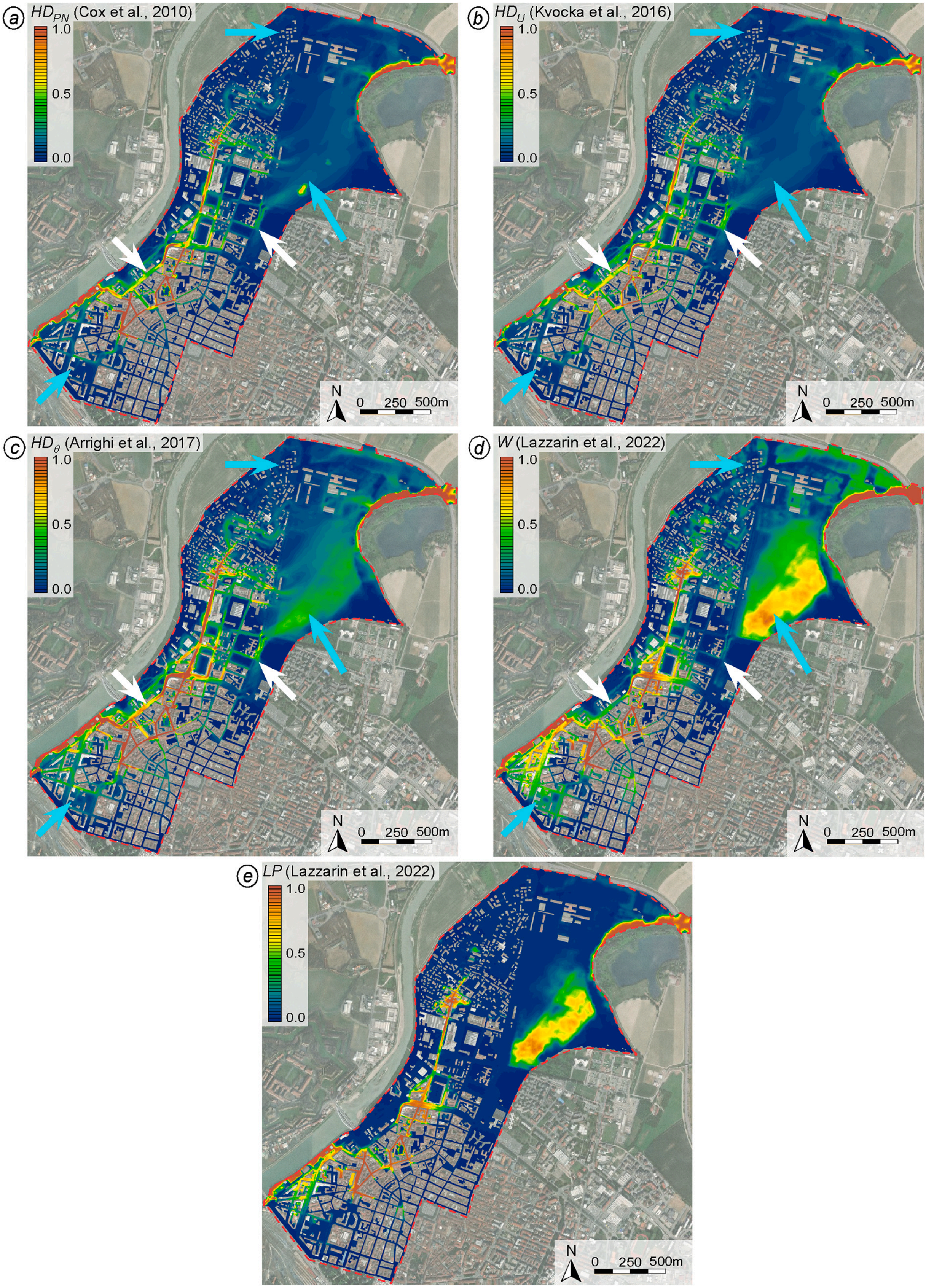


Fig. 5. Flood hazard degree *HD* (a-d) and loss probability *LP* (e) for adult people associated to the overflowing of the Tanaro River in Alessandria.

U_c	critical flow velocity determining the loss of stability
HR	hazard rating used by DEFRA and UK Environment Agency (Ramsbottom et al., 2003, 2006)
PN	product number (Martínez-Gomariz et al., 2018; Russo et al., 2013)
HD	generic index expressing the hazard degree
HD_{PN}	hazard degree according to Cox et al. (2010)
HD_U	hazard degree according to Kvočka et al. (2016)
HD_ϑ	hazard degree according to Arrighi et al. (2017)
W	impact parameter for the hazard degree (Lazzarin et al., 2022b)
LP	loss probability (Lazzarin et al., 2022b)

Funding

D.P.V. was supported by the RETURN Extended Partnership funded by the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

A.S. Chen's involvement in the work was supported by the project ARSINOE: climAte ReSIlient-regioNs thrOugh systEmic solutions and innovations funded by the EU H2020 Programme (GA 101037424).

CRediT authorship contribution statement

Tommaso Lazzarin: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **Albert S. Chen:** Writing – review & editing. **Daniele P. Viero:** Conceptualization, Methodology, 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.

Data availability

Data will be made available on request.

Acknowledgements

Dr. Francesco Carraro is gratefully acknowledged for carrying out preliminary, large-scale flood simulations of the Tanaro River case study.

References

Acero, B., Díaz, R., Behr, J.G., 2023. Flooding perception and its impact on hurricane evacuation intentions. Int. J. Disas. Risk Reduct. 95, 103892 https://doi.org/10.1016/j.ijdrr.2023.103892.

Arrighi, C., Huybrechts, N., Ouahsine, A., Chassé, P., Oumeraci, H., Castelli, F., 2016. Vehicles instability criteria for flood risk assessment of a street network. Proc. Int. Assoc. Hydrol. Sci. 373, 143–146. https://doi.org/10.5194/piahs-373-143-2016.

Arrighi, C., Oumeraci, H., Castelli, F., 2017. Hydrodynamics of pedestrians' instability in floodwaters. Hydrol. Earth Syst. Sci. 21 (1), 515–531. https://doi.org/10.5194/hess-21-515-2017.

Aureli, F., Maranzoni, A., Mignosa, P., Ziveri, C., 2008. 2D numerical modelling for hydraulic hazard assessment: a dam-break case study (A c. Di). In: Altinakar, M., Kokpinar, M.A., Darama, Y., Yegen, B., Harmancioglu, N.B. (Eds.), River Flow 2008, Proceedings of the International Conference on Fluvial Hydraulics. Kubaba, pp. 729–736.

Berghäuser, L., Bubeck, P., Hudson, P., Thieken, A.H., 2023. Identifying and characterising individual flood precautionary behaviour dynamics from panel data. Int. J. Disas. Risk Reduct. 94 (June), 103835 https://doi.org/10.1016/j.ijdrr.2023.103835.

Birkholz, S., Muro, M., Jeffrey, P., Smith, H.M., 2014. Rethinking the relationship between flood risk perception and flood management. Sci. Total Environ. 478, 12–20. https://doi.org/10.1016/j.scitotenv.2014.01.061.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., De BiÃ¨vre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D.M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., Zhumanova, M., 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. Front. Earth Sci. 2 (October), 1–21. https://doi.org/10.3389/feart.2014.00026.

Chen, Q., Xia, J., Falconer, R.A., Guo, P., 2019. Further improvement in a criterion for human stability in floodwaters. J. Flood Risk Manag. 12 (3), e12486 https://doi.org/10.1111/jfr3.12486.

Cox, R.J., Shand, T.D., Blacka, M.J., 2010. Revision Project 10: Appropriate Safety Criteria for People (In Australian Rainfall & Runoff).

D'Alpaos, L., Defina, A., D'Alpaos, L., Defina, A., 2007. Mathematical modeling of tidal hydrodynamics in shallow lagoons: a review of open issues and applications to the Venice lagoon. Comput. Geosci. 33 (4), 476–496. https://doi.org/10.1016/j.cageo.2006.07.009.

Defina, A., 2000. Two-dimensional shallow flow equations for partially dry areas. Water Resour. Res. 36 (11), 3251. https://doi.org/10.1029/2000WR900167.

Defina, A., 2003. Numerical experiments on bar growth. Water Resour. Res. 39 (4), 1–12. https://doi.org/10.1029/2002WR001455.

Defina, A., D'Alpaos, L., Matticchio, B., 1994. A new set of equations for very shallow water and partially dry areas suitable to 2D numerical models (A c. Di). In: Molinaro, P., Natale, L. (Eds.), Modelling Flood Propagation Over Initially Dry Areas. American Society of Civil Engineers, pp. 72–81.

Dong, B., Xia, J., Li, Q., Zhou, M., 2022a. Risk assessment for people and vehicles in an extreme urban flood: case study of the "7.20" flood event in Zhengzhou, China. Int. J. Disas. Risk Reduct. 80 (August), 103205 https://doi.org/10.1016/j.ijdrr.2022.103205.

Dong, B., Xia, J., Zhou, M., Li, Q., Ahmadian, R., Falconer, R.A., 2022b. Integrated modeling of 2D urban surface and 1D sewer hydrodynamic processes and flood risk assessment of people and vehicles. Sci. Total Environ. 827, 154098 https://doi.org/10.1016/j.scitotenv.2022.154098.

Feldman, D., Contreras, S., Karlin, B., Basolo, V., Matthew, R., Sanders, B., Houston, D., Cheung, W., Goodrich, K., Reyes, A., Serrano, K., Schubert, J., Luke, A., 2016. Communicating flood risk: looking back and forward at traditional and social media outlets. Int. J. Disas. Risk Reduct. 15, 43–51. https://doi.org/10.1016/j.ijdrr.2015.12.004.

Ferrari, A., Viero, D.P., 2020. Floodwater pathways in urban areas: A method to compute porosity fields for anisotropic subgrid models in differential form. J. Hydrol. 589, 125193 https://doi.org/10.1016/j.jhydrol.2020.125193.

Ferrari, A., Viero, D.P., Vacondio, R., Defina, A., Mignosa, P., 2019. Flood inundation modeling in urbanized areas: A mesh-independent porosity approach with anisotropic friction. Adv. Water Resour. 125, 98–113. https://doi.org/10.1016/j.advwatres.2019.01.010.

Foudi, S., Osés-Eraso, N., Tamayo, I., 2015. Integrated spatial flood risk assessment: the case of Zaragoza. Land Use Policy 42, 278–292. https://doi.org/10.1016/j.landusepol.2014.08.002.

Fox-Rogers, L., Devitt, C., O'Neill, E., Brereton, F., Clinch, J.P., 2016. Is there really "nothing you can do"? Pathways to enhanced flood-risk preparedness. J. Hydrol. 543, 330–343. https://doi.org/10.1016/j.jhydrol.2016.10.009.

Gersonius, B., van Buuren, A., Zethof, M., Kelder, E., 2016. Resilient flood risk strategies: institutional preconditions for implementation. Ecol. Soc. 21 (4), art28. https://doi.org/10.5751/ES-08752-210428.

Guan, M., Guo, K., Yan, H., Wright, N., 2023. Bottom-up multilevel flood hazard mapping by integrated inundation modelling in data scarce cities. J. Hydrol. 617 (PC), 129114 https://doi.org/10.1016/j.jhydrol.2023.129114.

Hoffmann, R., Muttarak, R., 2017. Learn from the past, prepare for the future: impacts of education and experience on disaster preparedness in the Philippines and Thailand. World Dev. 96, 32–51. https://doi.org/10.1016/j.worlddev.2017.02.016.

Houston, D., Cheung, W., Basolo, V., Feldman, D., Matthew, R., Sanders, B.F., Karlin, B., Schubert, J.E., Goodrich, K.A., Contreras, S., Luke, A., 2019. The influence of hazard maps and trust of flood controls on coastal flood spatial awareness and risk perception. Environ. Behav. 51 (4), 347–375. https://doi.org/10.1177/0013916517748711.

Intrieri, E., Dotta, G., Fontanelli, K., Bianchini, C., Bardi, F., Campatelli, F., Casagli, N., 2020. Operational framework for flood risk communication. Int. J. Disas. Risk Reduct. 46, 101510 https://doi.org/10.1016/j.ijdrr.2020.101510.

Kaźmierczak, A., Cavan, G., 2011. Surface water flooding risk to urban communities: analysis of vulnerability, hazard and exposure. Landsc. Urban Plan. 103 (2), 185–197. https://doi.org/10.1016/j.landurbplan.2011.07.008.

Koks, E.E., Jongman, B., Husby, T.G., Botzen, W.J.W., 2015. Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. Environ. Sci. Pol. 47, 42–52. https://doi.org/10.1016/j.envsci.2014.10.013.

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B., Thieken, A.H., 2009. Is flow velocity a significant parameter in flood damage modelling? Nat. Hazards Earth Syst. Sci. 9 (5), 1679–1692. https://doi.org/10.5194/nhess-9-1679-2009.

Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J.C.J.H., Apel, H., Aronica, G.T., Arnbjerg-Nielsen, K., Bouwer, L.M., Bubeck, P., Caloiero, T., Chinh, D.T., Cortès, M., Gain, A.K., Giampá, V., Kuhlicke, C., Kundzewicz, Z.W., Llasat, M.C., Mård, J., Matczak, P., Merz, B., 2017. Adaptation to flood risk: results of international paired flood event studies. Earth's Future 5 (10), 953–965. https://doi.org/10.1002/2017EF000606.

Kuller, M., Schoenholzer, K., Lienert, J., 2021. Creating effective flood warnings: a framework from a critical review. J. Hydrol. 602, 126708 https://doi.org/10.1016/j.jhydrol.2021.126708.

Kuriqi, A., Hysa, A., 2022. Multidimensional aspects of floods: nature-based mitigation measures from basin to river reach scale (A c. Di). In: In, C.S.S., Ferreira, Z., Kalantari, Hartmann, T., Pereira, P. (Eds.), Nature-based Solutions for Flood Mitigation: Environmental and Socio-economic Aspects. Springer International Publishing, pp. 11–33. https://doi.org/10.1007/698_2021_773.

Kvočka, D., Falconer, R.A., Bray, M., 2016. Flood hazard assessment for extreme flood events. In: Natural Hazards, 84, pp. 1569–1599. https://doi.org/10.1007/s11069-016-2501-z. Fascicolo 3.

Kvočka, D., Ahmadian, R., Falconer, R.A., 2018. Predicting flood hazard indices in torrential or flashy river basins and catchments. Water Resour. Manag. 32 (7), 2335–2352. https://doi.org/10.1007/s11269-018-1932-6.

Lazzarin, T., Viero, D.P., 2023. Curvature-induced secondary flow in 2D depth-averaged hydro-morphodynamic models: an assessment of different approaches and key factors. Adv. Water Resour. 171 (November 2022), 104355 https://doi.org/10.1016/j.advwatres.2022.104355.

Lazzarin, T., Viero, D.P., Molinari, D., Ballio, F., Defina, A., 2022a. A new framework for flood damage assessment considering the within-event time evolution of hazard, exposure, and vulnerability. J. Hydrol. 615 (PA), 128687 https://doi.org/10.1016/j.jhydrol.2022.128687.

Lazzarin, T., Viero, D.P., Molinari, D., Ballio, F., Defina, A., 2022b. Flood damage functions based on a single physics- and data-based impact parameter that jointly accounts for water depth and velocity. J. Hydrol. 607 (January), 127485 https://doi.org/10.1016/j.jhydrol.2022.127485.

Lazzarin, T., Defina, A., Viero, D. Pietro, 2023. Assessing 40 years of flood risk evolution at the micro-scale using an innovative modeling approach: the effects of urbanization and land planning. Geosciences 13 (4), 112. https://doi.org/10.3390/geosciences13040112.

Li, Q., Xia, J., Dong, B., Liu, Y., Wang, X., 2023. Risk assessment of individuals exposed to urban floods. Int. J. Disas. Risk Reduct. 88 (February), 103599 https://doi.org/10.1016/j.ijdrr.2023.103599.

Li, Y., Zhou, W.-H., Shen, P., 2022. Pedestrian danger assessment under rainstorm-induced flood disaster for an artificial island. Int. J. Disas. Risk Reduct. 78 (November 2021), 103133 https://doi.org/10.1016/j.ijdrr.2022.103133.

Lind, N., Hartford, D., Assaf, H., 2004. Hydrodynamic models of human stability in a flood. J. Am. Water Resour. Assoc. 40 (1), 89–96. https://doi.org/10.1111/j.1752-1688.2004.tb01012.x.

Luke, A., Sanders, B.F., Goodrich, K.A., Feldman, D.L., Boudreau, D., Eguiarte, A., Serrano, K., Reyes, A., Schubert, J.E., AghaKouchak, A., Basolo, V., Matthew, R.A., 2018. Going beyond the flood insurance rate map: insights from flood hazard map co-production. Nat. Hazards Earth Syst. Sci. 18 (4), 1097–1120. https://doi.org/10.5194/nhess-18-1097-2018.

Macchione, F., Costabile, P., Costanzo, C., De Santis, R., 2019. Moving to 3-D flood hazard maps for enhancing risk communication. Environ. Model Softw. 111, 510–522. https://doi.org/10.1016/j.envsoft.2018.11.005.

Maidl, E., Buchecker, M., 2015. Raising risk preparedness by flood risk communication. Nat. Hazards Earth Syst. Sci. 15 (7), 1577–1595. https://doi.org/10.5194/nhess-15-1577-2015.

Maranzoni, A., D'Oria, M., Rizzo, C., 2023. Quantitative flood hazard assessment methods: a review. J. Flood Risk Manag. 16 (1), 1–31. https://doi.org/10.1111/jfr3.12855.

Martínez-Gomariz, E., Gómez, M., Russo, B., Djordjević, S., 2018. Stability criteria for flooded vehicles: a state-of-the-art review. J. Flood Risk Manag. 11, S817–S826. https://doi.org/10.1111/jfr3.12262.

Mel, R., Viero, D.P., Carniello, L., D'Alpaos, L., 2020a. Multipurpose use of artificial channel networks for flood risk reduction: the case of the waterway Padova–Venice (Italy). Water 12 (6), 1609. https://doi.org/10.3390/w12061609.

Mel, R., Viero, D.P., Carniello, L., D'Alpaos, L., 2020b. Optimal floodgate operation for river flood management: the case study of Padova (Italy). J. Hydrol. Reg. Stud. 30 (C), 100702 https://doi.org/10.1016/j.ejrh.2020.100702.

Miceli, R., Sotgiu, I., Settanni, M., 2008. Disaster preparedness and perception of flood risk: a study in an alpine valley in Italy. J. Environ. Psychol. 28 (2), 164–173. https://doi.org/10.1016/j.jenvp.2007.10.006.

Milanesi, L., Pilotti, M., Ranzi, R., 2015. A conceptual model of people's vulnerability to floods. Water Resour. Res. 51 (1), 182–197. https://doi.org/10.1002/2014WR016172.

Moftakhari, H.R., AghaKouchak, A., Sanders, B.F., Allaire, M., Matthew, R.A., 2018. What is nuisance flooding? Defining and monitoring an emerging challenge. Water Resour. Res. https://doi.org/10.1029/2018WR022828.

Mostafiz, R.B., Rohli, R.V., Friedland, C.J., Lee, Y.-C., 2022. Actionable information in flood risk communications and the potential for new web-based tools for long-term planning for individuals and community. Front. Earth Sci. 10 https://doi.org/10.3389/feart.2022.840250.

Musolino, G., Ahmadian, R., Falconer, R.A., 2020. Comparison of flood hazard assessment criteria for pedestrians with a refined mechanics-based method. J. Hydrol. X 9 (November 2020), 100067. https://doi.org/10.1016/j.hydroa.2020.100067.

Penning-Rowsell, E., Floyd, P., Ramsbottom, D., Surendran, S., 2005. Estimating injury and loss of life in floods: a deterministic framework. Nat. Hazards 36 (1–2), 43–64. https://doi.org/10.1007/s11069-004-4538-7.

Purwandari, T., Hadi, M.P., Kingma, N.C., 2011. A GIS modelling approach for flood hazard assessment in part of Surakarta City, Indonesia. Indones. J. Geogr. 43 (1) https://doi.org/10.22146/ijg.2296.

Raaijmakers, R., Krywkow, J., van der Veen, A., 2008. Flood risk perceptions and spatial multi-criteria analysis: an exploratory research for hazard mitigation. Nat. Hazards 46 (3), 307–322. https://doi.org/10.1007/s11069-007-9189-z.

Ramsbottom, D., Floyd, P., Penning-Rowsell, E., 2003. Flood Risks to People: Phase 1. R&D Technical Report FD2317.

Ramsbottom, D., Wade, S., Bain, V., Hassan, M., Penning-Rowsell, E., Wilson, T., Fernandez, A., House, M., Floyd, P., 2006. Flood Risks to People – Phase 2. R&D Technical Report FD2321/IR2.

Russo, B., Gómez, M., Macchione, F., 2013. Pedestrian hazard criteria for flooded urban areas. Nat. Hazards 69 (1), 251–265. https://doi.org/10.1007/s11069-013-0702-2.

Sanders, B.F., Luke, A., Schubert, J.E., Moftakhari, H.R., AghaKouchak, A., Matthew, R.A., Goodrich, K., Cheung, W., Feldman, D.L., Basolo, V., Houston, D., Serrano, K., Boudreau, D., Eguiarte, A., 2016. Co-development of coastal flood models: Making the leap from expert analysis to decision support. In: Sustainable Hydraulics in the Era of Global Change - Proceedings of the 4th European Congress of the International Association of Hydroenvironment engineering and Research, IAHR 2016, 104, p. 3. https://doi.org/10.1201/b21902-3 (1).

Sanders, B.F., Schubert, J.E., Goodrich, K.A., Houston, D., Feldman, D.L., Basolo, V., Luke, A., Boudreau, D., Karlin, B., Cheung, W., Contreras, S., Reyes, A., Eguiarte, A., Serrano, K., Allaire, M., Moftakhari, H., AghaKouchak, A., Matthew, R.A., 2020. Collaborative modeling with fine-resolution data enhances flood awareness, minimizes differences in flood perception, and produces actionable flood maps. Earth's Future 8 (1). https://doi.org/10.1029/2019EF001391.

Schmitt, T.G., Scheid, C., 2020. Evaluation and communication of pluvial flood risks in urban areas. WIREs Water 7 (1), e1401. https://doi.org/10.1002/wat2.1401.

Schubert, J.E., Sanders, B.F., 2012. Building treatments for urban flood inundation models and implications for predictive skill and modeling efficiency. Adv. Water Resour. 41, 49–64. https://doi.org/10.1016/j.advwatres.2012.02.012.

Scolobig, A., De Marchi, B., Borga, M., 2012. The missing link between flood risk awareness and preparedness: findings from case studies in an Alpine Region. Nat. Hazards 63 (2), 499–520. https://doi.org/10.1007/s11069-012-0161-1.

Shand, T.D., Cox, R.J., Blacka, M.J., Smith, G.P., 2011. Appropriate safety criteria for vehicles. In: Australian Rainfall & Runoff.

Thieken, A.H., Kreibich, H., Müller, M., Merz, B., 2007. Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002. Hydrol. Sci. J. 52 (5), 1016–1037. https://doi.org/10.1623/hysj.52.5.1016.

UNDRR, 2019. Global Assessment Report on Disaster Risk Reduction (GAR).

Viero, D.P., 2019. Modelling urban floods using a finite element staggered scheme with an anisotropic dual porosity model. J. Hydrol. 568, 247–259. https://doi.org/10.1016/j.jhydrol.2018.10.055.

Viero, D.P., Valipour, M., 2017. Modeling anisotropy in free-surface overland and shallow inundation flows. Adv. Water Resour. 104, 1–14. https://doi.org/10.1016/j.advwatres.2017.03.007.

Viero, D.P., D'Alpaos, A., Carniello, L., Defina, A., 2013. Mathematical modeling of flooding due to river bank failure. Adv. Water Resour. 59, 82–94. https://doi.org/10.1016/j.advwatres.2013.05.011.

Viero, D.P., Peruzzo, P., Carniello, L., Defina, A., 2014. Integrated mathematical modeling of hydrological and hydrodynamic response to rainfall events in rural lowland catchments. Water Resour. Res. 50 (7), 5941–5957. https://doi.org/10.1002/2013WR014293.

Viero, D.P., Roder, G., Matticchio, B., Defina, A., Tarolli, P., 2019. Floods, landscape modifications and population dynamics in anthropogenic coastal lowlands: the Polesine (northern Italy) case study. Sci. Total Environ. 651, 1435–1450. https://doi.org/10.1016/j.scitotenv.2018.09.121.

Wang, N., Hou, J., Du, Y., Jing, H., Wang, T., Xia, J., Gong, J., Huang, M., 2021. A dynamic, convenient and accurate method for assessing the flood risk of people and vehicle. Sci. Total Environ. 797, 149036 https://doi.org/10.1016/j.scitotenv.2021.149036.

Wehn, U., Rusca, M., Evers, J., Lanfranchi, V., 2015. Participation in flood risk management and the potential of citizen observatories: a governance analysis. Environ. Sci. Pol. 48, 225–236. https://doi.org/10.1016/j.envsci.2014.12.017.

Xia, J., Falconer, R.A., Wang, Y., Xiao, X., 2014. New criterion for the stability of a human body in floodwaters. J. Hydraul. Res. 52 (1), 93–104. https://doi.org/10.1080/00221686.2013.875073.