A SINGLE PHYSICS- AND DATA-BASED IMPACT PARAMETER TO EXPRESS FLOOD DAMAGE FUNCTIONS

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KEY POINTS

- *Flood hazard is measured using a non-dimensional physics- and data-based parameter*
- *Based on concepts of energy and momentum, the parameter accounts for flow depth and velocity*
- *It allows expressing the results from previous studies and models in a unique general form*
- *A mixed deterministic-probabilistic approach is used to obtain relative damage functions*
- *The method is applied to the case of people and vehicles in floodwaters*

1 INTRODUCTION

The estimation of flood damage is crucial for a proper risk management. Although considerable efforts made in the last decades, it remains a challenging task with several open issues (state-of-the-art reviews are *Merz et al., 2010*, *Meyer et al., 2013*).

The direct flood damage, commonly expressed in relative terms, is assessed using two kinds of tools (*Fuchs et al.*, 2019): *vulnerability curves* that relate hazard to the relative damage in case of progressive damage processes (i.e., mechanisms that allow for intermediate levels of damage, *Gerl et al.*, 2016), and *fragility curves* that describe the probability of having a certain damage in case of *on-off* damage processes (*Pita et al.*, 2021), for which only two states are possible, i.e., "fully safe" (*on-event*) or "fully damaged" (*off-event*).

This work presents a general and flexible method to estimate the relative flood damage using a common framework for progressive and *on-off* damage processes (*Lazzarin et al.*, 2022). First, a new impact parameter, *W*, is introduced to measure flood hazard when both inundation depth and water velocity play a role. Then, the relative damage is quantitatively estimated as a function of *W*, starting from physical considerations and empirical, or synthetic, damage data. The goal is extending the widely used depth-damage approach accounting for additional explicative variables, as flow velocity, yet retaining a relatively simple, intelligible, physics- and data-based structure.

2 AN APPROACH FOR THE DEFINITION OF RELATIVE DAMAGE FUNCTIONS

Flood damage can be produced by different processes, and described by many explanatory variables (*Merz et al.*, 2010). We restrict the analysis to the direct flood damage driven by mechanical processes; thus, the free variables of relative damage functions reduce to water depth and velocity (*Arrighi et al.*, 2015, 2017; *Kreibich et al.*, 2009). With respect to the traditional depth-damage curves, introducing the flow velocity as a further input parameter is expected to reduce flood damage variance (*De Moel & Aerts*, 2011).

We combine the water depth, Y, and flow velocity, U, into a single lumped parameter, W, to measure the intensity of the hydrodynamic conditions that effectively produce the damage (*Aureli et al.*, 2008), thus expressing the relative damage as a univariate function, $RD = RD(W)$. The combination of Y and U to form W depends on the exposed item and on the damage process. Noting the similarity among expressions for flow energy and momentum, a general impact parameter W can be written in the form:

$$W = \left(\frac{Y}{Y_W}\right)^{\alpha}(1+\beta F^2) \qquad \text{with} \qquad Y_W > 0,\;\; \alpha \geq 1,\;\; \beta \geq 0 \tag{1}$$

in which F is the Froude number, Y_W is a reference depth that scales the water depth Y, and α and β are two calibration factors that measure the relative importance of the static versus the dynamic component of W. The key idea is that, with suitable calibration factors α and β, iso-W lines in the U-Y plane can identify different flow conditions with equivalent damaging potentials for specific categories of items. This can be achieved since the structure of W is obtained from the physics of the damage process.

After assessing the hazard conditions, the lumped impact parameter W must be related to the damage. We use the term "relative damage functions" to denote both vulnerability functions and fragility curves. The definition of vulnerability (for progressive damage processes) and of loss probability (for *on-off* processes) are very similar each other since both vary between 0 and 1, and increase with the hazard increasing. This supports the general use of "relative damage" in both the cases. Accordingly, relative damage functions can be viewed either in a deterministic sense for progressive damage processes, or in a probabilistic sense for *on-off* events.

The method to assess the relative damage function descends from the correspondence between iso-W and iso-RD lines, being $RD = RD(W)$ a univariate function. For progressive damage processes, a set of couples (W, RD) can be found being iso-W lines matching the shape of iso-RD lines. For *on-off* processes, instead, the tuning of W is based on *off*-events hazard conditions, which corresponds to $RD = 1$. The relative damage is then given by the cumulative frequency distribution (CFD) of W associated to the *off*-events. Finally, (W, RD) couples or discrete CFDs can be suitably approximated with continuous relative damage expressions.

3 APPLICATION TO PEOPLE AND VEHICLES IN FLOODWATER

Vulnerability of people and vehicles due to stability loss in flowing water can be seen as *on-off* process, since instability occurs very quickly due to a sliding mechanism caused by drag. The resistance to flowing water depends on different aspects such as geometrical parameters and the ability to resist. This suggests that different relative damage functions should be defined according to the category (i.e., people or vehicles) and sub-categories considered. However, being the physical mechanisms of damage the same for any sub-category, a unique structure of W, given by a set (Y_W, α, β), can be defined for each category. Relative damage functions for sub-categories can then be defined by considering different values for the impact parameter. Assuming the loss of balance as a full-damage condition, the calibration factors of W are estimated starting from a physical point of view considering the stability in floodwaters through a balance of the forces acting on the item (*Lazzarin et al.*, 2022; *Milanesi et al.*, 2015; *Xia et al.*, 2010).

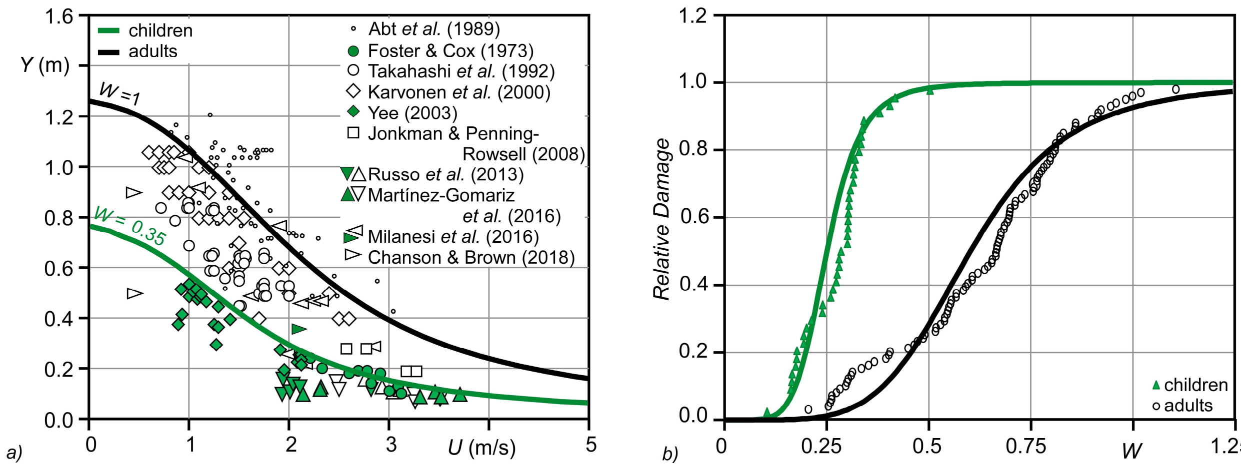

Figure 1. a) Experimental data and iso-W lines for instability of adults (black line and open symbols) and children (green line and symbols) in floodwaters. b) Cumulative frequency distributions for adults and children instability, interpolated with continuous relative damage functions by fitting Eq. (2) ($a = 0.25$ and $b = 6$ for children and $a = 0.6$ and $b = 5.0$ for adults).

For people, we consider two sub-categories, namely children and adults, where the latter is the most resistant. By comparing eq. (1) for the limit conditions $W = 1$ with the critical stability condition derived in previous studies, we find $\alpha = 2$ and a value of β that is expected to vary in the range 3.0–7.0 for adults. Then, the comparison with experimental data of *off*-conditions allows for a fine tuning of parameters, leading to $Y_W = 1.25$ m, $\alpha = 2.0$, and $\beta = 4.0$ for adults (black line in Figure 1a). The vulnerability of sub-categories should be characterized by lower values of the impact parameter, yet with the same parameter structure. Indeed, Figure

1a shows that the limit condition for children can be described by the $W = 0.35$ isoline (green line).

The second step consists in assessing the relative damage functions. Using an experimental dataset of *off*-conditions (Figure 1a), from each pair (U_i, Y_i) of the *off*-events, the associated value of W_i is computed using Eq. (1). The cumulative frequency distribution of W_i for the two sub-categories, plotted in Figure 1b, gives the relative damage curve, i.e., the probability to fail for each single individual of a given sub-category. It is convenient to interpolate the discrete frequency distributions with a continuous function to express the relative damage. A simple and effective form is:

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

Given that the hydrodynamic hazard is described by the same structure of the impact parameter W, it is possible to compare relative damage functions for different sub-categories, as shown in Figure 1b for children and adults.

The same approach is then applied to the category of vehicles. Here, we consider three different sub-categories: small-to-medium cars, medium-to-large cars, SUVs and VANs. Being the most resistant, the last category is taken as reference. Since the instability is driven by drag (i.e., a matter of forces), a reasonable choice for the parameter α is 2, so that the static contribution to W corresponds to the hydrostatic force. Suitable parameters values, needed to fit the stability condition of available data with a $W = 1$ iso-line, are $Y_W = 0.9$ m and $\beta = 0.6$ (black line in Figure 2a).

The stability conditions for the weaker sub-categories are described by isolines with lower values of W, yet using the same set of parameters (Y_W, α, β); specifically, we find $W = 0.50$ for medium-to-large and $W = 0.35$ for small-to-medium vehicles (red and green lines in Figure 2a respectively). The cumulative frequency distributions for each sub-category (Figure 2b) are evaluated using data of Figure 2a, and interpolated with continuous relative damage functions in the form of Eq. (2).

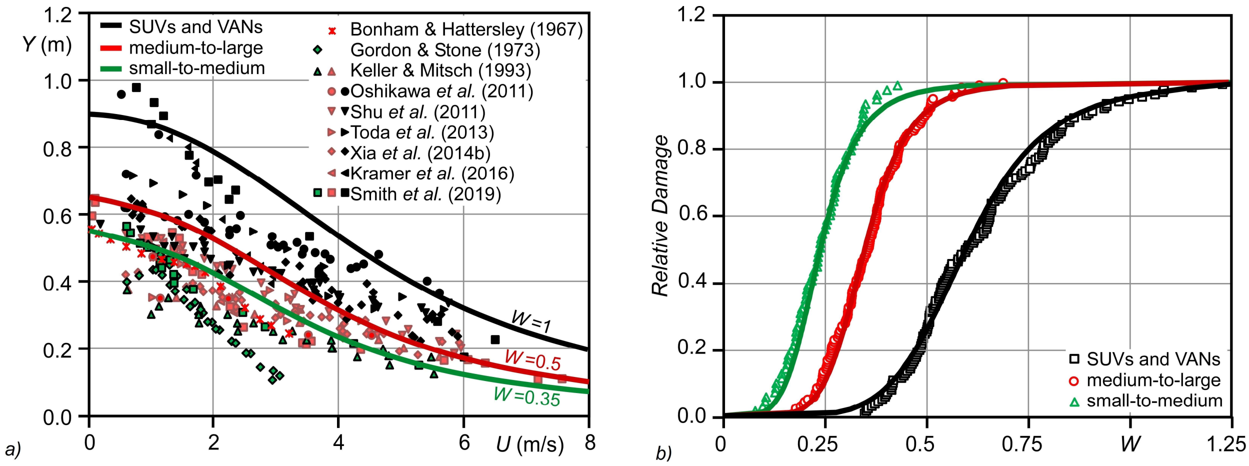

Figure 2. a) Experimental data and iso-W lines for instability of small-to-medium vehicles (green line and symbols), medium-to-large vehicles (red line and symbols), SUVs and VANs (black line and symbols). b) Cumulative frequency distributions for instability of different vehicle sub-categories, interpolated with continuous relative damage functions by fitting Eq. (2) ($a = 0.6$ and $b = 6$ for small-to-medium cars, $a = 0.35$ and $b = 6.5$ for medium-to-large cars, $a = 0.24$ and $b = 5.2$ for SUVs and VANs).

4 Discussion and Conclusions

The present study outlines a procedure to assess flood relative damage functions that use a single impact parameter to describe the hydrodynamic action.

The idea of combining water depth and velocity to express flood hazard is not new in the technical literature. However, compared to previously proposed functional relations and impact parameters, W is non-dimensional (i.e., it expresses the degree of hazard independent of specific dimensions), it is flexible, (i.e., it allows representing various damage mechanisms within a common frame), and it has a physical foundation (i.e., it extends the concept of energy and momentum to fit available experimental and field data without the need of additional thresholds).

The applications of the proposed approach demonstrate that a single set of calibration parameters allows W to describe the mechanisms of damage for objects sharing the same nature and damage mechanisms (e.g., people, vehicles, etc.). Its use becomes particularly useful when both water depth and flow velocity play a role in the damage process. Hence, the use of a given structure of W allows expressing the hazard degree as a function of a single parameter, grouping objects with different resistance and enhancing the intelligibility of hazard information. However, as a limitation, comparison between categories with different nature may be confusing in terms of hazard degree, unless $W = 1$ is assumed to represent the critical stability conditions.

Relative damage functions can be estimated considering either synthetic or experimental data providing sufficient information on flood features and on the damage of exposed items. After estimating the structure of the impact parameter W, relative damage functions are assessed in a unique framework with a probabilistic or deterministic approach, depending on the nature of the damage process. Yet, for practical applications, the relative damage functions obtained through the two approaches are equivalent.

Traditional depth-damage functions and fragility curves are enhanced by including the influence of flow velocity through the impact parameter W, and multi-variable damage functions are simplified into elegant single-variable, non-dimensional functions. Thus, damage models can be expressed with a simple, continuous form allowing clear graphical representations and simplifying damage assessment. Moreover, physics-based reasoning and available data can be merged into a unique formulation enhancing the model robustness. Experimental data, needed for a fine tuning of the W parameter structure, are difficult to find in the technical literature.

A future development concerns including other variables within the impact parameter. An example is the forcing duration, since damaging develops in time at a rate that depends on the time evolution of the forcing factors. The use of a single parameter is also expected to be valuable in describing the temporal evolution of the damage.

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