A FLOOD DAMAGE MODEL ACCOUNTING FOR TIME-EVOLVING HAZARD, EXPOSURE, AND VULNERABILITY AT THE EVENT-SCALE

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KEY POINTS

- *Flood damage models typically ignore how hazard, exposure, and vulnerability vary during a single flood event, which can significantly impact the final damage.*
- *The proposed model allows computing the time-evolution of flood damage in the course of single flood events.*
- *A simple yet realistic application to rice crops demonstrates the model effectiveness and potential for flood risk management and assessment.*

1 INTRODUCTION

The importance of accurately estimating flood damage has grown during last years. While flood damage models have evolved to cover various assets (e.g. buildings, infrastructures, see the review in *Gerl et al.*, 2016), they often overlook the time-evolution of damaging processes in the course of single flood events. This is important as the flood damage is the outcome of dynamic processes evolving throughout the event (*Maranzoni et al.*, 2023). Yet, current models for damage assessment rely on summary indicators that represent the worst conditions occurred during the flood event (e.g., maximum water depths or flow velocity), and sometime on some kind of duration of the flood event, but neglect the temporal evolution of the damage determinants (i.e., hazard, exposure, and vulnerability).

We propose a model that shifts this paradigm, allowing to estimate the flood damage by explicitly considering the temporal evolution of the key factors that cause the flood damage. The approach involves computing the flood damage by integrating the rate at which damage progresses over time, which depends on time-evolving hydraulic conditions, exposure levels, and vulnerability. The model introduces additional complexities (e.g., increased number of model parameters, with associated uncertainties) but allows for promising applications, particularly when the interplay of flood duration and intensity is important in shaping the final damage and to gain insights on the effects of civil protection measures to be undertaken in the course of a flooding event (*Lazzarin et al.*, 2023).

2 MATERIALS AND METHODS

2.1 Model variables

For a single item category and generic point $\mathbf{x} = (x, y)$ within the flooded area, we introduce the following definitions:

- $W(t)$ is a lumped impact parameter which describes the hydrodynamic forcing as a function of the water depth, Y, and velocity, U (*Lazzarin et al.*, 2022a):

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

  where $F = U(gY)^{-1/2}$ is the Froude number (g is gravity), Y_W is a scaling factor, α and β are two parameters reflecting the relative importance of water depth and velocity in the instability or damaging mechanism.
- $\mathbb{E}_0$ is the quantity, or value, of potentially exposed items, belonging to a single homogeneous category, present in a unit area at the initial time t_0;
- $\mathbb{E} = \mathbb{E}(t)$ is the quantity/value of potentially exposed items during the flooding event ($\mathbb{E}$ can reduce in time due to countermeasures and rescue activities undertaken in the course of the flood event);

- $V(W)$ is the fraction of $\mathbb{E}$ that can be damaged if subject to a constant hydrodynamic forcing, W, lasting for a reasonably long period of time. It represents the vulnerability of exposed items;
- $D = D(t)$ is the damaged fraction of $\mathbb{E}$ at time t.

2.2 Model equations

The key idea is to evaluate the flood damage by integrating in time (during the flooding event) the rate at which damaging progresses. The damaging rate is evaluated by means of a logistic-type function that depends on the hydrodynamic forcing and on the exposure (both of them vary in time):

$$\frac{d}{dt}(D\mathbb{E}) = \mathbb{E} \cdot cD^{1-\gamma}\left(1 - \frac{D}{max(V,D)}\right)^{1+\gamma} \quad (2)$$

where c is the damage rate factor and γ a calibration parameter in the range $0 \le \gamma \le 1$.

If the potential exposure, $\mathbb{E}$, is constant in time (i.e., $\mathbb{E}(t) = \mathbb{E}_0$, no rescuing activities), Eq. (2) reduces to:

$$\frac{dD}{dt} = cD^{1-\gamma}\left(1 - \frac{D}{max(V,D)}\right)^{1+\gamma} \quad (3)$$

3 CALIBRATION PROCEDURE

In the calibration procedure, the parameter γ and the functions $V(W)$ and $c(W)$ are evaluated using available experimental data, information, and/or phenomenological models. The analytic solution of the logistic-type equation (3), when W is constant in time, can be used for the model calibration as it reduces to:

$$D(t) = \frac{V}{1+V\cdot(c\gamma\, t)^{-1/\gamma}} \quad (4)$$

where c controls the speed at which the damage progresses and γ controls the delay after which damage starts increasing fast. The role of c and γ is highlighted in Fig. 1 and can be of help in the calibration procedure.

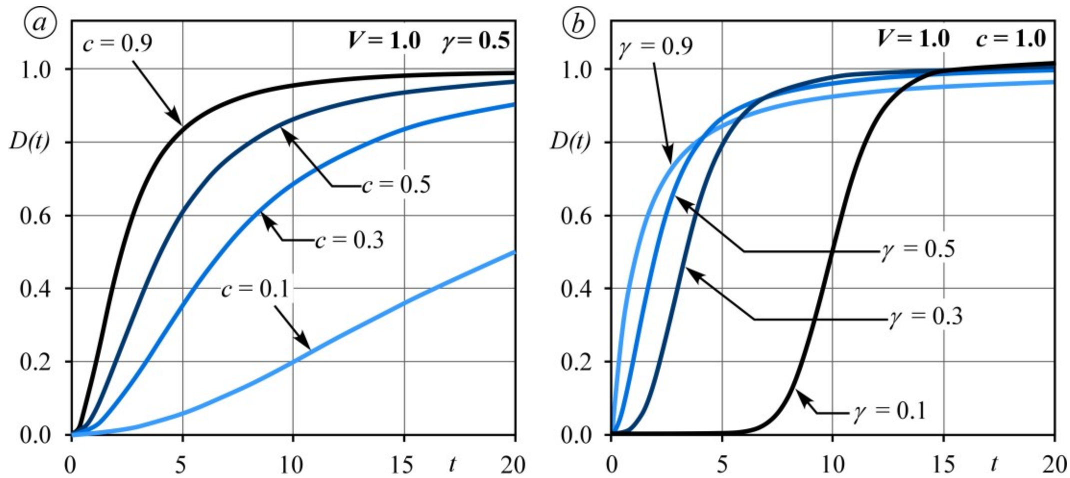

Figure 1. Time evolution of the specific damage, $D(t)$, according to Eq. (4), for $V = 1$ and: a) for different values of the damaging rate, c (with $\gamma = 0.5$); b) for different values of γ (with $c = 1$).

4 FLOOD DAMAGE TO CROPS

The temporal evolution of the flood and its duration affect crop damage significantly, as demonstrated in previous studies (e.g., *Forster et al.*, 2008). Existing models for flood damage to crops incorporate flood duration as an explicative parameter, along with the maximum flow depth (e.g., *Molinari et al.*, 2019), but with an unclear definition of duration (indeed, the water depth is not constant in time, and the same duration with different water depth can produce a different damage). The present model explicitly computes the evolution of damage in time, without the need of defining a "flood duration".

In the following, an application to rice crops is presented to exemplify the calibration procedure and to illustrate the model ability in evaluating the time evolution of damage, forced by varying hazard conditions simulated by a synthetic flooding event. We considered rice in maturity stage using damage functions provided by *Shrestha et al.* (2016) and pictured in Fig. 2a for different duration, τ. For the definition of the parameter W, we assumed $\alpha = 1$, $\beta = 0$, and $Y_W = 1.0$ m, so that W exactly corresponds to the water depth.

For some constant values of W, points on the curves of Fig. 2a are extracted, and then plotted in the graph of Fig. 2b that shows the relative damage $D(\tau)$ for different values of W. This set of iso-W data is then interpolated using Eq. (4) (dashed lines in Fig. 2b) to calibrate the model in the case of rice. We found $\gamma = 0.6$ and the couples (V,W) and (c,W) pictured in Figs. 2c and 2d. Proper continuous expressions have been used to interpolate these data (see also *Lazzarin et al.*, 2022b) in the form:

$$V(W) = \frac{1}{1+(a/W)^b} \qquad c(W) = pW^q \tag{5}$$

with $a = 0.85$ and $b = 7$ (Fig. 2c), and $p = 0.4$ d^{-1} and $q = 1.5$ (Fig. 2d), for rice in the maturity stage.

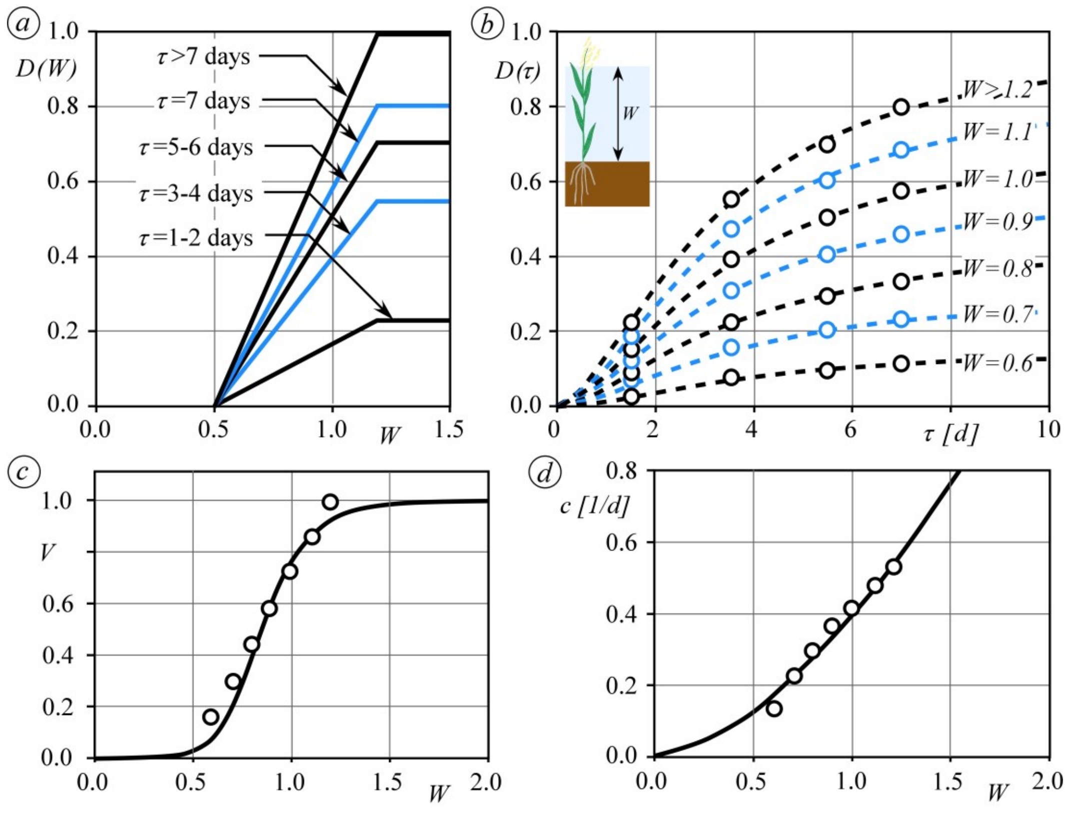

Figure 2. Specific damage to rice during the maturity stage: relative yield loss as a function of the impact parameter W, for different flood durations t (a, adapted from *Shrestha et al.*, 2016), and of the flood duration, t, for different values of W (b); vulnerability, $V(W)$, (c), and damage rate, $c(W)$, (d), where dots denote the (V, W) and (c, W) couples for the chosen values of W.

The calibrated model is then used to estimate the damage to a rice crop, induced by synthetic flooding events, by integration of Eq. (3). For the flooding hydrographs in Fig. 3a, the results in terms of relative damage to crop are shown in Fig. 3b. Flood damage to rice increases gradually during the rising phase of the flood, peaking below 20% when W_{MAX} is reached. During the receding phase, the damage stabilizes earlier for steeper hydrographs (e.g., blue lines in Fig. 3), while for longer hydrographs (e.g., grey lines in Fig. 3), the damage continues to rise for a longer time. For the grey-lined hydrograph, the final damage is approximatively two times larger than the damage predicted for the blue-lined hydrograph due to persistently high water levels.

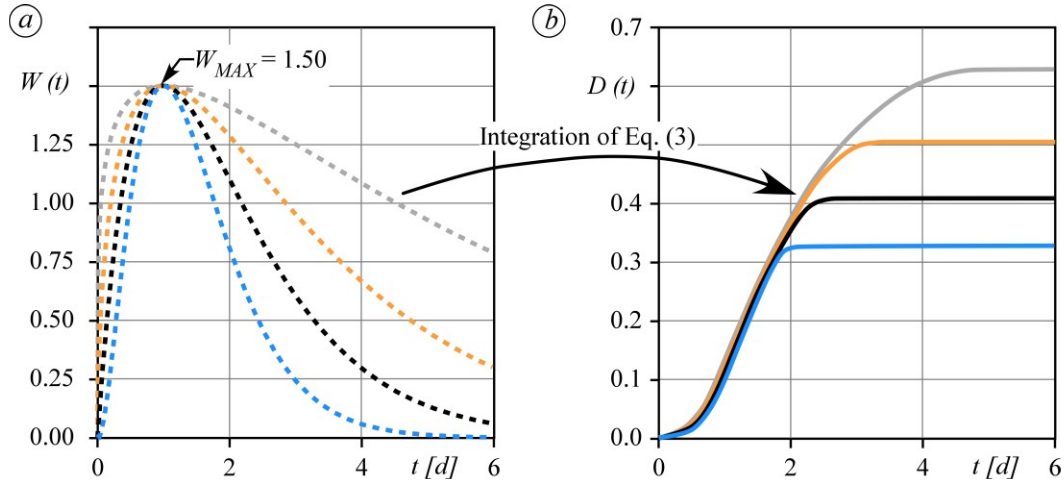

Figure 3. Temporal evolution of the specific damage to rice during the maturity stage, $D(t)$, (b), for the flood conditions $W(t)$ pictured in (a).

5 CONCLUSIONS

The present work applies a novel framework for flood damage assessment, which considers the time evolution of damaging processes within a single flood event, to the case of rice crops. Unlike existing models, which correlate flood damage to summary indicators of hazard and exposure, this approach predicts the expected damage at each point within the flooded area using a logistic-type equation that describe the temporal evolution of the damage. The model application to rice crops demonstrates its advantages, including the ability to assess damage generated by different flow hydrographs and the same peak value.

Importantly, the model implicitly accounts for flood duration, thus relaxing the hypothesis that the final damage depends solely on the maximum water depth and, possibly, on flow velocity and/or an unclear concept of “flood duration” which is typically independent of the hazard degree. Compared to traditional approaches, the model is characterized by a larger number of parameters (which imply larger uncertainties). However, the fact that its components have a precise physical meaning can be of help in case of scarce data.

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