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A general formulation to describe empirical rainfall thresholds for landslides

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Abstract

In this paper, a brief description of the Generalized FLaIR Model (GFM, De Luca and Versace, 2016) is provided, that is able to reproduce all the empirical thresholds proposed in literature, aimed to forecast landslides triggered by rainfall. In particular, this paper focuses on Antecedent Precipitation (AP) schemes. The paper demonstrates that these are particular solutions of the GFM and will exemplify this using AP schemes for NE Italy[1], Seattle[2] and Nicaragua - El Salvador[3].

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Keywords: Landslides triggered by rainfall; non stationary thresholds; Antecedent Precipitation (AP) thresholds

1. Introduction

In technical literature a lot of empirical thresholds have been proposed to forecast landslides triggered by rainfall, which represents an important social-economic issue, in particular for the realization of early warning systems. Many of these empirical thresholds can be grouped in two main classes: 1) Intensity-Duration (ID) relationships[4,5,6,7,8,9,10,11]; 2) Antecedent Precipitation (AP) schemes[12,13,14,2,15,16,17,1,3,18].

ID relationships provide, for different durations, critical values of rainfall intensity that, when reached or exceeded, lead to slope failure, while thresholds belonging to the AP class define critical values of a rainfall event

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aggregated on a short duration (equal to some hours or days before a landslide event), depending on a predisposing antecedent rainfall cumulated over a long duration (equal to several days or months).

ID are usually represented by the well-known power function:

$$I = aD^n \tag{1}$$

where I is the rainfall intensity, D is rainfall duration, a and n are parameters to be estimated. However, ID thresholds assign the same weight to rain data along the time and, moreover, different precipitation patterns (increasing/decreasing along the time, etc..) with equal mean value of intensity produce the identical results (i.e. exceedance of a critical threshold or non-exceedance). It was demonstrated that FLaIR Model[19] (Forecasting of Landslides Induced by Rainfalls) is able to solve these problems, as it sets different weights to rainfall heights along the time and, furthermore, it reproduces as particular cases all ID thresholds and other schemes like Leaky Barrel[20].

Mathematical expressions, adopted for AP thresholds, are very much variable, depending essentially on the used data. Only in few cases the same analytical structure is used for analyzing different case studies, and then it is possible to investigate the dependence of parameter values on different morphological, geological and climatic contexts. Moreover, short and long durations usually assume different values from one case study to another one. Finally, in all AP schemes an equal weight is set for rain data along the time.

In order to unify this variety of mathematical expressions into an unique framework, the Generalized FLaIR Model (GFM) was proposed[21], which is based on:

- a filter $\psi(.)$, that assigns different weights to rainfall heights as a function of time;
- a function $f[.]$, that defines the relationship between predisposing antecedent precipitation and critical triggering values for a rainfall event.

GFM also reproduces FLaIR model as a particular case, and consequently all the ID thresholds. With respect to FLaIR, the following improvements are provided in GFM: i) it also considers non-stationary thresholds that depend on initial soil moisture of the slope and then on antecedent rainfall; ii) consequently, it is possible to demonstrate that it reproduces all the AP schemes as particular cases; iii) it allows for defining a more general empirical approach which not only uses non-stationary thresholds, as previously mentioned, but also considers filtered rainfall. Consequently, the influence of the rainfall heights, along the time, on landslide trigger is better reproduced, with respect to ID and AP schemes that assign the same weight to all the rainfall data in the investigated time interval; iv) GFM represents a comprehensive framework, as it permits a more rigorous approach compared to the AP schemes, reported in literature, that refer to specific case studies and then usually adopt mathematical expressions very different to each other. More precisely, GFM allows for defining a number of configurations with an increasing number of parameters, and then more and more flexible, among which an user can choose the most suitable, taking into account the need to balance the parametric parsimony and the capacity to reproduce the observed landslide occurrences; v) like FLaIR model, GFM is also suitable for regional analysis.

In this work, concerning some AP cases proposed in literature, authors demonstrated the GFM capacity to describe into a comprehensive framework any empirical scheme, characterized by non-stationary thresholds that depend on initial soil moisture of the slope. The paper is organized as follows: Sect. 2 provides a brief theoretical description of GFM, while examples of AP derivation from GFM are illustrated in Sect. 3. Conclusions are reported in Sect. 4.

2. Brief description of GFM

A mobility function $Y(.)$, defined as a convolution (Eq. 2) between rainfall intensity $I(.)$ and a filter function $\psi(.)$, is adopted, which can be split into a predisposing function $Y_D(.)$ and a triggering function $Y_d(.)$:

$$Y(t) = \int_{t-(d+D)}^{t} I(\tau)\psi(t-\tau)d\tau = \int_{t-(d+D)}^{t-d} I(\tau)\psi(t-\tau)d\tau + \int_{t-d}^{t} I(\tau)\psi(t-\tau)d\tau = Y_D(t-d) + Y_d(t) = \frac{R_D^*(t-d)}{D} + \frac{R_d^*(t)}{d} \tag{2}$$

$R_D^*(t-d)$ and $R_d^*(t)$ represent the cumulative value of rainfall heights, filtered with $\psi(.)$, on a long duration D (related to antecedent conditions) and a short duration d (associated to a rainfall storm event), with obviously $d < D$, and evaluated at the instants $(t-d)$ and t, respectively. A landslide trigger is predicted when $Y(.)$ exceeds a critical threshold $Y_{cr}(t)$, obtained when $R_d^*(t)$ assumes a critical value $R_{d,cr}^*(t)$, for a specific value of $R_D^*(t-d)$. It is assumed that $R_{d,cr}^*(t)$ is dependent on $R_D^*(t-d)$, i.e. $R_{d,cr}^*(t) = f\left[R_D^*(t-d)\right]$, where $f[.]$ is a generic functional form; consequently, $Y_{cr}(t)$ can be written as:

$$Y_{cr}(t) = \frac{R_D^*(t-d)}{D} + \frac{R_{d,cr}^*(t)}{d} = \frac{R_D^*(t-d)}{D} + \frac{f\left[R_D^*(t-d)\right]}{d} \tag{3}$$

In Eqs. (2) – (3), the dimensions are [L/T] for $I(.)$, $Y(.)$, $Y_D(.)$ and $Y_d(.)$, [T^{-1}] for $\psi(.)$, [L] for $R_D^*(t-d)$ and $R_d^*(t)$, [T] for D and d.

Eqs. (2)-(3) are the basic equations for GFM, which is flexible as it can assume several configurations on the basis of the expressions of $f[.]$ and $\psi(.)$, which play a crucial role. In particular:

- authors discriminate three kinds of mathematical expressions that can be adopted for $f[.]$: a) Linear function; b) Linear function which induces a stationary threshold; c) Non-linear function;
- if a power function is assumed for $\psi(.)$, then any combination with a linear function $f[.]$, which induces a stationary threshold, is associated to an ID scheme[19];
- as a special case for $\psi(.)$, if a constant filter:

$$\psi(t) = \begin{cases} 1/(d+D) & 0 \le t \le d+D \\ 0 & t > d+D \end{cases} \tag{4}$$

is adopted, then it can be demonstrated[21] that $Y(.)$ and $Y_{cr}(t)$ assume the following expressions:

$$Y(t) = \frac{1}{D+d}\left[R_D(t-d) + R_d(t)\right] \tag{5}$$

$$Y_{cr}(t) = \frac{1}{D+d}\left[R_D(t-d) + R_{d,cr}(t)\right] = \frac{1}{D+d}\left\{R_D(t-d) + f\left[R_D(t-d)\right]\right\} \tag{6}$$

Any AP threshold is represented by a functional form $f[.]$ between the (not filtered) rainfall heights $R_{d,cr}(t)$ and $R_D(t-d)$; consequently, using a constant filter allows for a one-to-one correspondence in Eq. (6) between a specific AP threshold and the associated GFM configuration, and therefore AP thresholds are particular cases of the proposed comprehensive framework;

- if a mixture of constant filters:

$$\psi(t) = \begin{cases} \omega/d & 0 \le t \le d \\ (1-\omega)/D & d < t \le d+D \\ 0 & t > d+D \end{cases} \qquad \omega \in [0;1] \tag{7}$$

is used, then $Y(.)$ and $Y_{cr}(t)$ can be written as:

$$Y(t) = \frac{(1-\omega)}{D} R_D(t-d) + \frac{\omega}{d} R_d(t) \tag{8}$$

$$Y_{cr}(t) = \frac{(1-\omega)}{D} R_D(t-d) + \frac{\omega}{d} R_{d,cr}(t) = \frac{(1-\omega)}{D} R_D(t-d) + \frac{\omega}{d} f\left[R_D(t-d)\right] \tag{9}$$

Adoption of a mixture of constant functions permits a one-to-many relationship, i.e. many expressions of Eq. (9) can be related to a fixed AP threshold, as many ω values can be considered in the range [0, 1]. For this reason, the mixture of constant functions is more flexible, and then more general, as it is possible to assign different weights for event and antecedent rainfall heights. It is noteworthy that a constant filter can be derived by a mixture of constant filters by setting $\omega = d/(d+D)$.

It should be highlighted that, unlike the general case associated to Eqs. (2)-(3), Eqs. (5)-(6) and (8)-(9) use $R_D(t-d)$ and $R_d(t)$ that are the aggregated (and not filtered) rainfall amounts on D and d durations and evaluated at the instants $(t-d)$ and t, respectively.

- Any other kind of mathematical expression can be used for $\psi(.)$ (exponential, gamma, mixture of exponential filters, etc…).

3. GFM for some AP models

In this section, examples of three published AP thresholds[1,2,3] are given; in particular, for each one the specific expressions of $Y(t)$ (Eq. 2) $Y_{cr}(t)$ (Eq. 3) and $Y_{d,cr}(t) = Y_{cr}(t) - Y_D(t-d)$ are detailed, considering both a constant filter and a mixture of constant filters.

For each analyzed AP scheme, the plots of $Y_{cr}(t)$ and $Y_{d,cr}(t)$, both depending on $R_D(t-d)$, are shown in Figs. 1-6, in which only some ω values are considered as examples in the case of mixture of constant filters.

3.1. Pasuto and Silvano (1998)

Landslide trigger is predicted in NE Italy if the following conditions occur:

$$\begin{cases} R_D(t-d) \geq 200\,mm \\ R_d(t) \geq 70\,mm \end{cases} \tag{10}$$

with D = 15 days and d = 2 days.

The use of a constant filter (Eq. 4) provides:

$$Y(t)\left[\frac{mm}{day}\right] = \frac{R_D(t-d) + R_d(t)}{17} \tag{11}$$

$$Y_{cr}(t)\left[\frac{mm}{day}\right] = \begin{cases} +\infty & if\ R_D(t-d) < 200\,mm \\ \dfrac{R_D(t-d)+70}{17} & if\ R_D(t-d) \geq 200\,mm \end{cases} \tag{12}$$

$$Y_{d,cr}(t)\left[\frac{mm}{day}\right] = \begin{cases} +\infty & if\ R_D(t-d) < 200\,mm \\ \dfrac{70}{17} & if\ R_D(t-d) \geq 200\,mm \end{cases} \tag{13}$$

while, with the adoption of a mixture of constant functions for $\psi(.)$ (Eq. 7), $Y(t)$, $Y_{cr}(t)$ and $Y_{d,cr}(t)$ become:

$$Y(t)\left[\frac{mm}{day}\right]=\frac{(1-\omega)}{15}R_D(t-d)+\frac{\omega}{2}R_d(t) \tag{14}$$

$$Y_{cr}(t)\left[\frac{mm}{day}\right]=\begin{cases}+\infty & if\ R_D(t-d)<200\,mm\\ \frac{(1-\omega)}{15}R_D(t-d)+35\cdot\omega & if\ R_D(t-d)\geq 200\,mm\end{cases} \tag{15}$$

$$Y_{d,cr}(t)\left[\frac{mm}{day}\right]=\begin{cases}+\infty & if\ R_D(t-d)<200\,mm\\ 35\cdot\omega & if\ R_D(t-d)\geq 200\,mm\end{cases} \tag{16}$$

If antecedent rainfall height is larger than 200 mm, then $Y_{cr}(t)$ is linearly increasing with $R_D(t-d)$ (Fig. 1), while the critical triggering function $Y_{d,cr}(t)$ always assumes a constant behavior (Fig. 2) for any $R_D(t-d)$ value. In more detail: i) Eqs. (12)-(13) exactly reproduces the model proposed by authors; ii) Eqs. (15)-(16) allow for more flexibility and then several plots can be derived by varying ω. In particular, Eqs. (11)-(13) were obtained for $\omega = d/(d+D) = 0.12$.

3.2. Chleborad (2003)

For Seattle, critical conditions for landslide trigger are:

$$R_{d,cr}(t)=\begin{cases}88.9-0.67\cdot R_D(t-d) & if\ R_D(t-d)\leq 132.7\,mm\\ 0 & if\ R_D(t-d)>132.7\,mm\end{cases} \tag{17}$$

with D = 15 days and d = 3 days.
Adoption of a constant filter (Eq. 4) implies:

$$Y(t)\left[\frac{mm}{day}\right]=\frac{R_D(t-d)+R_d(t)}{18} \tag{18}$$

$$Y_{cr}(t)\left[\frac{mm}{day}\right]=\begin{cases}\frac{R_D(t-d)\cdot(1-0.67)+88.9}{18} & if\ R_D(t-d)<132.7\,mm\\ \frac{R_D(t-d)}{18} & if\ R_D(t-d)\geq 132.7\,mm\end{cases} \tag{19}$$

$$Y_{d,cr}(t)\left[\frac{mm}{day}\right]=\begin{cases}\frac{-0.67\cdot R_D(t-d)+88.9}{18} & if\ R_D(t-d)<132.7\,mm\\ 0 & if\ R_D(t-d)\geq 132.7\,mm\end{cases} \tag{20}$$

while the use of a mixture of constant functions for $\psi(.)$ (Eq. 7) provides:

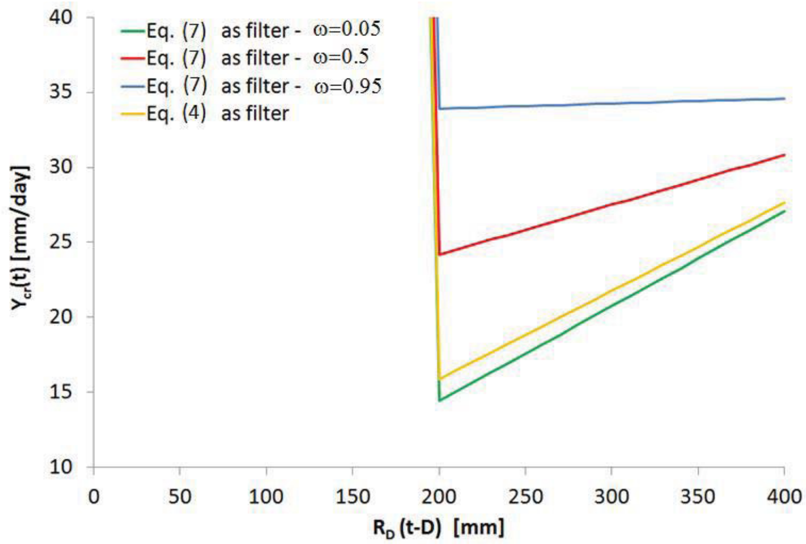

Fig. 1 Plot of $Y_{cr}(t)$ for AP scheme proposed by Pasuto and Silvano (1998)

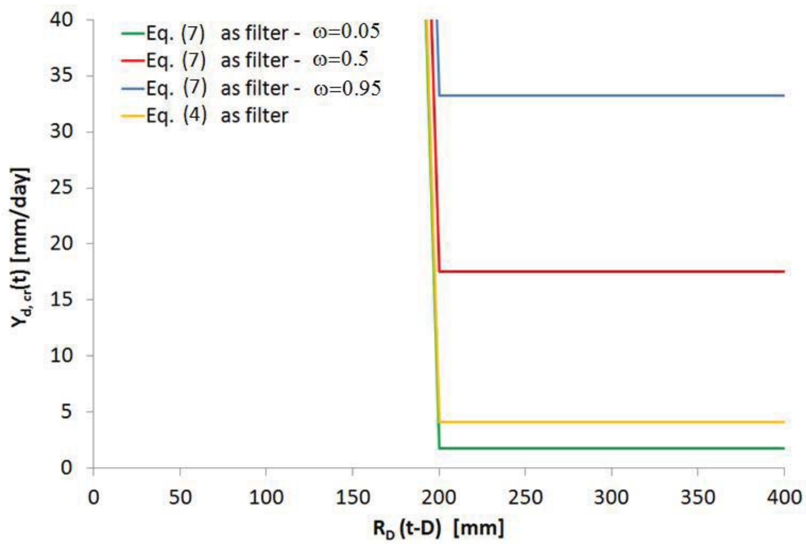

Fig. 2 Plot of $Y_{d,cr}(t)$ for AP scheme proposed by Pasuto and Silvano (1998)

$$Y(t)\left[\frac{mm}{day}\right]=\frac{(1-\omega)}{15}R_D(t-d)+\frac{\omega}{3}R_d(t) \tag{21}$$

$$Y_{cr}(t)\left[\frac{mm}{day}\right]=\begin{cases} R_D(t-d)\cdot\left[\frac{(1-\omega)}{15}-0.67\cdot\frac{\omega}{3}\right]+\frac{\omega}{3}88.9 & if\ R_D(t-d)<132.7\,mm \\ R_D(t-d)\cdot\left[\frac{(1-\omega)}{15}\right] & if\ R_D(t-d)\geq 132.7\,mm \end{cases} \tag{22}$$

$$Y_{d,cr}(t)\left[\frac{mm}{day}\right]=\begin{cases}-0.67\cdot\frac{\omega}{3}\cdot R_D(t-d)+\frac{\omega}{3}88.9 & if\ R_D(t-d)<132.7\,mm\\ 0 & if\ R_D(t-d)\geq 132.7\,mm\end{cases} \tag{23}$$

If $\omega \leq 0.23$, limit for which the factor multiplying $R_D(t-d)$ in the first expression of Eq. (22) is null, then the threshold $Y_{cr}(t)$ is piecewise linearly increasing with $R_D(t-d)$; if $\omega > 0.23$ then $Y_{cr}(t)$ linearly decreases when $R_D(t-d)<132.7\,mm$, while it linearly increases when $R_D(t-d)\geq 132.7\,mm$ (Fig. 3). The critical triggering function $Y_{d,cr}(t)$ is always linearly decreasing with $R_D(t-d)$, and it is equal to zero when $R_D(t-d)\geq 132.7\,mm$ (Fig. 4). From a mixture of constant filters, Eqs. (18)-(20) are obtained for ω = 0.17.

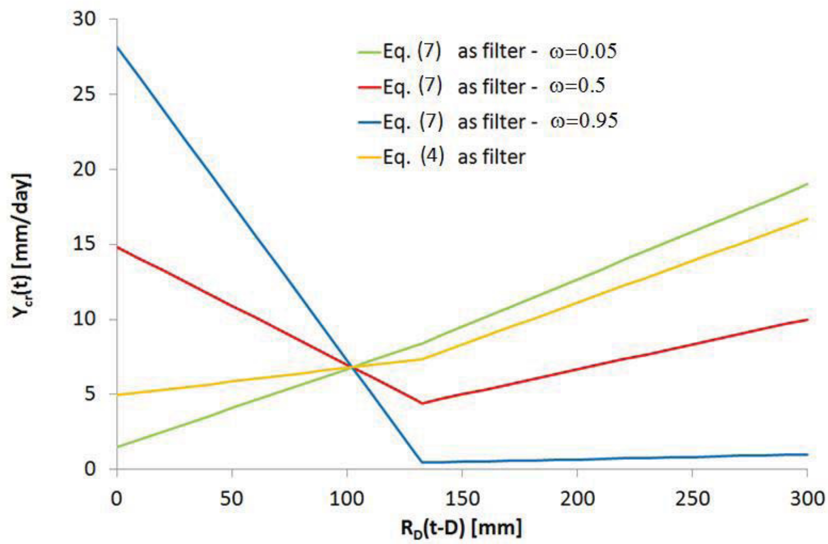

Fig. 3 Plot of $Y_{cr}(t)$ for AP scheme proposed by Chleborad (2003)

3.3. Heyerdahl et al. (2003)

In Nicaragua and El Salvador, the critical event rainfall height assumes the following expression:

$$R_{d,cr}(t)=258\cdot[R_D(t-d)]^{-0.32} \tag{24}$$

where D = 96 h and d = 1 h.
With the adoption of a constant filter (Eq. 4), $Y(t)$, $Y_{cr}(t)$ and $Y_{d,cr}(t)$ become:

$$Y(t)[mm/h]=\frac{R_D(t-d)+R_d(t)}{97} \tag{25}$$

$$Y_{cr}(t)[mm/h]=\frac{R_D(t-d)+258\cdot[R_D(t-d)]^{-0.32}}{97} \tag{26}$$

$$Y_{d,cr}(t)[mm/h]=\frac{258}{97}\cdot[R_D(t-d)]^{-0.32} \tag{27}$$

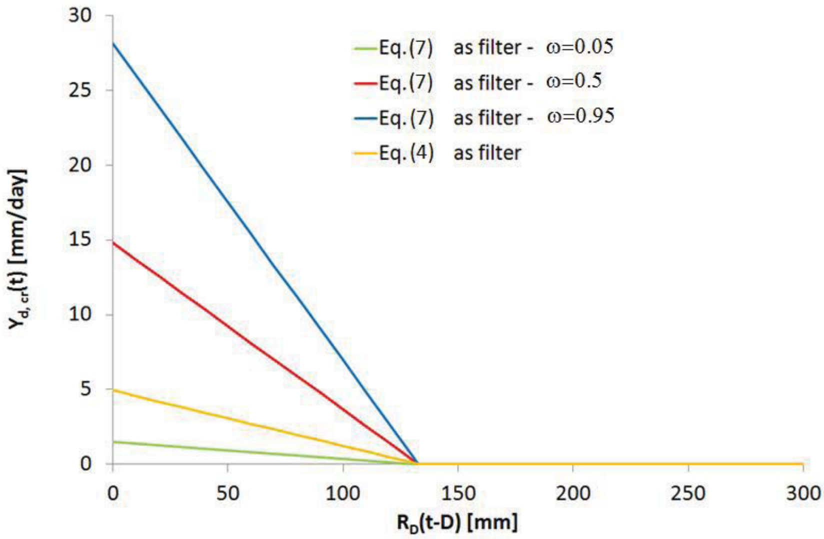

Fig. 4 Plot of $Y_{d,cr}(t)$ for AP scheme proposed by Chleborad (2003)

while, with a mixture of constant functions (Eq. 4), we obtain:

$$Y(t)[mm/h] = \frac{(1-\omega)}{96} R_D(t-d) + \omega \cdot R_d(t) \tag{28}$$

$$Y_{cr}(t)[mm/h] = \frac{(1-\omega)}{96} R_D(t-d) + \omega \cdot 258 \cdot [R_D(t-d)]^{-0.32} \tag{29}$$

$$Y_{d,cr}(t)[mm/h] = \omega \cdot 258 \cdot [R_D(t-d)]^{-0.32} \tag{30}$$

Figures 5 and 6 show, respectively, the plots of $Y_{cr}(t)$ and $Y_{d,cr}(t)$, by considering particular values of ω for the mixture of constant filters. From a mixture of constant filters, Eqs. (25)-(27) are obtained for ω = 0.01. The parameter ω influences the values of $Y_{cr}(t)$ and $Y_{d,cr}(t)$: an increase of ω produces a significant rise of thresholds in one or more orders of magnitude.

4. Conclusions

The described GFM (Generalized FLaIR Model) is extremely flexible as it can assumes several configurations on the basis of $f[.]$ and $\psi(.)$; moreover, all the ID (Intensity-Duration) and AP (Antecedent Precipitation) thresholds, reported in technical literature, are particular cases of GFM if specific mathematical expressions for $f[.]$ and $\psi(.)$ are adopted.

In details, this paper focuses attention on the second class, and authors demonstrate that all the AP thresholds, proposed in literature, can be reproduced with a GFM configuration in which the filter $\psi(.)$ is constant (or, in an equivalent way, it is a mixture of constant filters with the parameter ω set equal to $d/(d+D)$), and $f[.]$ assumes a specific form proposed by the authors. With GFM it is possible to generalize progressively this formulation:

- by adopting a mixture of constant filters for $\psi(.)$ and by assuming ω as a parameter to be estimated;
- by considering for $\psi(.)$ other mathematical expressions, different from a mixture of constant filters, in order to assign different weights to rainfall heights as a function of time. As an example, the use of a mixture of

exponential filters allows for decreasing weights related to rainfall data which are distant in time from the current instant.

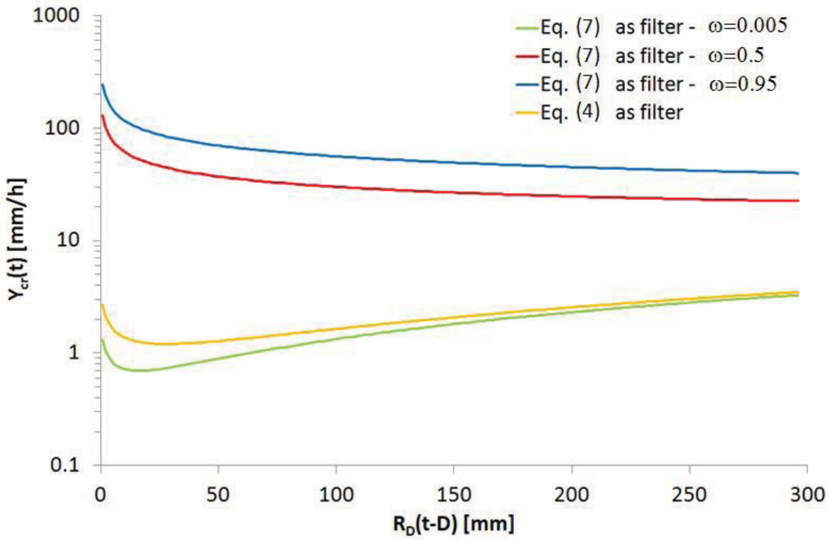

Fig. 5 Plot of $Y_{cr}(t)$ for AP scheme proposed by Heyerdahl et al. (2003)

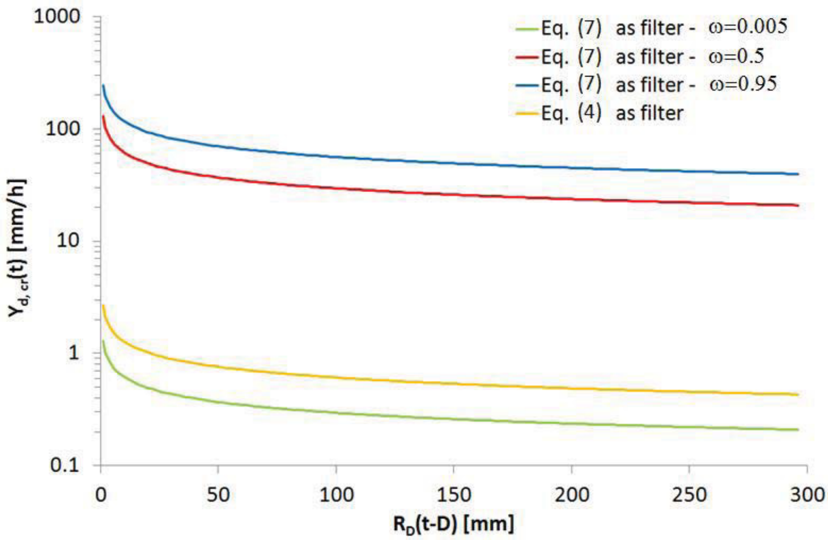

Fig. 6 Plot of $Y_{d,cr}(t)$ for AP scheme proposed by Heyerdahl et al. (2003)

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