Flood Attenuation Potential of Italian Dams: Sensitivity on Geomorphic and Climatological Factors

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Flood Attenuation Potential of Italian Dams: Sensitivity on Geomorphic and Climatological Factors

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Abstract
In this work the attenuation potential of flood peaks of 265 large reservoirs all over Italy is analysed, considering a flood management that excludes gates opening and then configures strictly unsupervised attenuation effects. Key factors of dams and related basins are considered to develop a ranking method that can emphasize the interplay between dam geometry and the hydrological processes acting in the upstream watershed. To maintain a homogeneous approach in such a wide geographic area, the attenuation index is computed applying the numerical solution of the differential equation of lakes and only two different standardized hydrograph shapes have been used. An index design flood from the rational method is used as the incoming peak value for each dam, enhancing the use of the results of a recent analysis of all Italian rainfall extremes. Even with a very simple approach, twenty-four different design incoming floods are derived, by varying the shape of the incoming hydrograph and the parameters of the rational method. Exploring the ranking results in all the alternatives, the attenuation potential obtained for all dams demonstrates to be strongly sensitive to the assumptions on the time of concentration and to some rainfall features. On the other hand, the hydrograph shape seems to exert much less influence on the ranking outcome. Results obtained can be useful to studies of wide-area flood frequency analyses, as we highlighted the sensitivity of the rank of attenuation efficiency to hydrologic parameters widely used in the assessment of the design flood peaks in ungauged basins.

Keywords Reservoirs · Flood peaks attenuation · Ranking · Time of concentration · Rational method

1 Introduction

Less than 3% of the 528 large Italian dams (i.e., those having height > 15 m, or storage volume > 1.000.000 m^3) were designed for specific flood control purposes. Nevertheless, it is widely recognized that dams can have a positive effect on the hydraulic protection

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downstream, by basically storing flood volumes and contributing to flattening the incoming flood hydrograph shape. Neglecting these effects in the flood mapping and management will lead to an overestimation of flood hazard downstream the dams (Zhao et al. 2020; Boulange et al. 2021). On the other hand, flood management plans require a comprehensive assessment of the reservoir effects, with a reasoned approach that can be applied in the prediction stage.

Assessment of dam-induced alterations on flow regime, which is how this topic is typically addressed, is supported by a rich worldwide literature (e.g. Shakarami et al. 2022; Salwey et al. 2023). Some studies use analytical approaches: for instance Guo and Adams (1999) and Bacchi et al. (2008) in the field of urban drainage and Balistrocchi et al. (2013) on natural basins, developed analytical probabilistic models for flood frequency analyses, based on the derived probability distribution theory. More recently Manfreda et al. (2021) provided the distribution of the outflow peaks from in-line detention basins, highlighting how reservoir storage capacity and duration of the rainfall event are among the factors that most control the probability distribution of outgoing discharges. These approaches are, however, typically aimed at designing flood attenuation systems and therefore carried out at the scale of individual reservoirs.

To quantify the mitigation effect of reservoirs on downstream flood frequency curve, Volpi et al. (2018) showed how altered flood frequencies propagate through the river network, using an Instantaneous Unit Hydrograph-based model. They found that the mitigation of flood peaks downstream is mainly dependent on the position of the reservoir, length of the spillway crest and reservoir capacity.

Although the scientific literature is experiencing a growing interest in this topic in the last decades, the interplay between the dam and the hosting environment is still poorly understood (Chalise et al. 2021) and an established methodological framework to assess the attenuation effects performed by dams has yet to be defined. More work still needs to be done to define the “natural”, or rather “intrinsic”, attenuation capacity of dams, referring to the “average” attenuation potential that depends only on the main structural characteristics of the reservoir and on the “main features” of the flood generated by the upstream basin. This means generalizing the observed situations as much as possible, a task that requires to use a conceptual framework.

Some efforts have been made to systematically assess the impact of reservoirs on flood peaks over large areas through synthetic indices (Scarrott et al. 1999; López and Francés 2013; Xiong et al. 2019; Cipollini et al. 2022). These indices aim to roughly quantity the flood attenuation magnitude but they all provide information more in comparative terms than in absolute terms, as in many cases they lack dimensional consistency.

Another popular approach to detect the impact of reservoirs on floods is to carry out simulations that involve the stochastic generation of rainfall series and the consequent derivation of hydrographs to be routed by the reservoir system (see e.g. Montaldo et al. 2004; Noorbeh et al. 2020). This methodology is typically performed over specific case studies and is not easily reproducible on a large scale. Considering the context of a national scale, which is one of the priorities of this work, we did not find such an extensive literature available.

The work of Bocchiola and Rosso (2014) seems to be the only attempt to cover all of Italy. They focused on assessing the “actual” design return period of spillways of large dams in Italy, some of which were built about a century ago. Because their results depend on a flood regionalisation procedure that has not been published or used elsewhere, their findings are difficult to reproduce. In any case, Bocchiola and Rosso (2014) did not deal with the attenuation potential of Italian dams.

To undertake a nationwide assessment of the attenuation potential of dams, we aim to identify those elements that can be proved to exert an influence on this attenuation effect in terms of ranking of the potentials. To do so, we considered detailed infrastructure data, as well as several morphological features of the upstream basins and a specific knowledge on rainfall extremes not used before.

Given our goal, the quantification of the attenuation effects of a large number of reservoirs requires a generalised framework and a standardization effort, aimed at reducing the dependence of the results on the operating strategies at each site. To this end, we have adopted a simple hydrological scheme for the design hydrograph estimation and a "no gates management" approach yet using a full hydraulic routing.

As will be specified in the following, the design flood hydrographs representative of each site are obtained by means of the rational formula, which depends on the design rainfall, and considering two hydrograph shapes. In a first instance we have adopted a simple rectangular incoming hydrograph; subsequently a more realistic hydrograph shape is used. By varying the parameters of the rational method, twenty-four different design hydrographs have been considered, allowing to assess the sensitivity of the intrinsic attenuation potential. We are interested in examining if, for different configurations, the rank of a given reservoir changes (ranking stability). The sensitivity analysis is conceived in terms of both the ranking stability of the flood attenuation potentials and their magnitude.

The paper is organised as follows: Section 2 defines the methods used, Section 3 introduces methods for the design flood hydrograph estimation and in Section 4 we present the rationale of the sensitivity analysis. In Section 5 the results obtained are discussed, to draw some conclusions. All details about the sample of dams investigated, the data used and the steps of the application can be found in Online Resource 1.

2 Flood Attenuation by Reservoirs: Definitions and Assumptions

The flood peak attenuation by a lake is assessed by solving the continuity and the stage-discharge equations. The continuity equation is:

$$q_i(t) - q_o(h(t)) = \frac{dV(h(t))}{dt} \tag{1}$$

where $q_i(t)$ and $q_o(t)$ are the inflow and outflow discharges respectively, V is the lake volume and h is the water level above the spillway crest.

The stage-discharge equation is generally represented by a power-law:

$$q_o(t) = \alpha h(t)^{\beta} \tag{2}$$

where α and β are constants depending on the geometry of the spillway crest.

For clarity and homogeneity of approach, the initial absolute water level in the reservoir is always considered equal to the absolute elevation of the spillway crest, H_s. Consequently, $h(t = 0) = 0$. For this reason, the term $dV(h(t))$ in Eq. (1) is intended as the change in storage volume above H_s. Based on this premise, which corresponds to the worst situation for flood attenuation, we consider the area of the lake to be constant with the lake surface elevation. The constant area value is computed at the absolute height H_s.

It follows that the term $dh(t)$ is equal to the ratio between $dV(h(t))$ and the (constant) lake area.

The attenuation coefficient η, which varies between 0 and 1, is defined as the ratio of the outgoing and the incoming peak discharges:

$$\eta = \frac{\max\left(q_o\right)}{\max\left(q_i\right)} \tag{3}$$

so that low η values correspond to good attenuation capabilities. The attenuation coefficient η is the index used to build a classification of the attenuation potential of reservoirs.

Equation (1) can be analytically solved under the hypothesis of a linear reservoir (see e.g. Evangelista et al. 2022), i.e. assuming a linear relation between $q_o(t)$ and $V(t)$. Here no simplified assumptions on the relationship between the outflow and the stored volume are invoked; therefore, the solution of Eq. (1) requires a numerical procedure.

In our evaluations, only free-surface spillways are considered; furthermore, the outflow discharge $q_o(t)$ dependence on the geometrical features of the spillway is assumed constant (i.e., no gates management is allowed). A Creager law is adopted for all spillways, i.e.

$$q_o(t) = C_d W \sqrt{2gh(t)^3} \tag{4}$$

being W the width of the spillway crest (m) and g the gravity acceleration (m/s^2). The discharge coefficient C_d is assumed to be 0.45 in all cases.

Under the above hypotheses, Eq. (1) is numerically solved by adopting a time step of 0.01 t_c, where t_c is the time of concentration of the upstream basin (see Online Resource 1).

3 Design Flood Hydrograph

In the following, the steps required to estimate the design flood peak and volume are outlined. As anticipated in Section 1, the "standardized" incoming hydrographs are obtained with a 2-steps procedure:

1. The peak value of the incoming hydrograph is calculated by means of the rational formula (Mulvaney 1851):

$$Q_{p,T} = \frac{Ci\left(d_c, T\right)A_B}{3,6} \tag{5}$$

   where $i\left(d_c, T\right)$ is the estimated extreme rainfall intensity (mm/h) for a critical duration d_c and a return period T, and C is the runoff coefficient (dimensionless).
2. The hydrograph shape is related to the flood volume in two ways: in a first instance, a rectangular incoming hydrograph is considered; in a second instance, a site-specific application of the NERC (1975) Flood Reduction Function is adopted.

The rational formula is used to simplify as much as possible the hydro-climatological factors controlling the design flood peak, including the key role of the rainfall parameters. This is particularly significant in Italy, where the knowledge of the spatial variability of rainfall extremes is supported by a richer data availability as compared to floods.

In addition, despite its simplicity, the rational formula proves to be sufficiently accurate for design, as long as the choice of the runoff coefficient is properly justified (Grimaldi and Petroselli 2015).

The subjectivity in the choice of C, as well as the strong dependence of the results on the critical duration d_c, are dealt with in this paper through a simple sensitivity analysis, as described in Section 4. As regards the runoff coefficient, no specific analysis of the surface runoff production is performed. We use two possible values for the C coefficient, i.e., 0.5 or 1 (referring respectively to low to medium permeability, and completely impermeable soil conditions). The lower value is widely referred to in the technical literature (Rossi and Villani 1994).

The estimation of flood peaks by means of the rational formula requires the availability of spatially averaged quantiles of rainfall extremes and of some morphological data used in formulas that estimate the basin time of concentration. In Online Resource 1, these two relevant computational steps will be discussed, with particular reference to the data set under analysis.

The second step required for the estimation of the design hydrograph is the assessment of its volume and shape. Each hydrograph is characterised by scalar values, i.e. the flood peak and the volume, and by a 2D information that concerns its shape. Due to the lack of flood volumes data in the national yearbooks, to agree on reasonable assumptions about the incoming hydrograph represents perhaps the most critical part of a reliable flood attenuation assessment procedure.

The purposes of this work require a procedure for the determination of the volume and the shape of the hydrograph that is simple and scalable. The first approach we used is to adopt a rectangular input hydrograph. This shape is "simply" related to: i) the flood peak, i.e. the rainfall parameters; ii) the time of concentration.

It must be specified that, because of the lack of flood volumes data, the volume cannot be calibrated and it is oversized if compared to a data-based measure.

An alternative formulation, i.e. the NERC one, is subsequently used, in which a more complex dependence on the characteristics of the rainfall and of the basin morphology is considered. All the details about the derivation of this second hydrograph shape can be found in Online Resource 1.

It must be specified that its duration is the same as that of the rectangular hydrograph, thus it is not constrained to assume a pre-determined volume, as the flood peak is maintained for the whole duration. When using the rectangular hydrograph, an increased volume and, consequently, a degradation of the attenuation potential, will be then observed as compared to what we expect from the NERC hydrograph. The relative extent of this degradation, and thus the impact of the shape on the classification produced is, on the other hand, not predictable, and will be discussed in detail in Section 5.

4 Rationale for a Sensitivity Analysis

As mentioned above, this work is focused on estimating both the ranked efficiency of the Italian dams and the magnitude of their attenuation potentials. For an overall rank assessment, each reservoir is assigned a number (rank), which identifies its position in the ordered vector of the attenuation coefficients (from the lowest to the highest values of η).

To investigate the sensitivity of the ranking stability of the attenuation coefficients to the input parameters of the rational method, the incoming hydrograph to be routed by the reservoir is perturbed in 2 main ways (Fig. 1). First, we modify the design flood peak without varying the hydrograph time base (Fig. 1a, c). This effect can be obtained either by changing the runoff coefficient or adopting a different growth factor K_T(>1 in this case). Another, less standardized, way to obtain a variation in the flood peak can

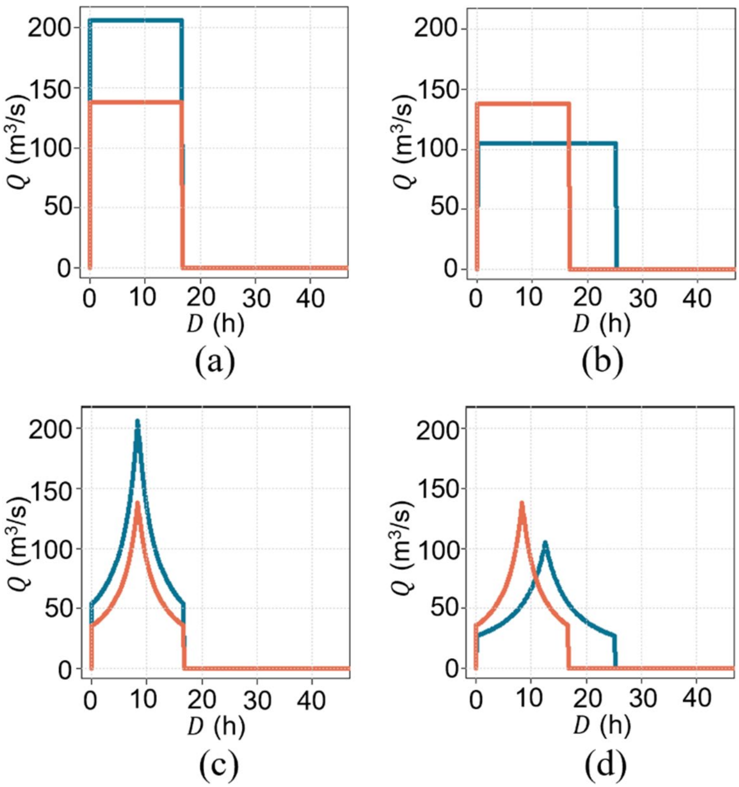

Fig. 1 Possible deformations of the inflow hydrograph for both the rectangular (**a**, **b**) and the NERC hydrographs (**c**, **d**). The orange line refers to the original hydrograph, while the blue one is the hydrograph resulting from the applied deformation

be to modify the IDF parameters a and n, which contribute to define the design rainfall (see Eq. (S1) in Online Resource 1).

The second type of modification adopted consists of changing the critical duration t_c of the design rainfall, that directly reshapes the hydrograph duration D (Fig. 1b, d), being $D = 2\,t_c$ (see Online Resource 1).

The type 1 deformation is first produced here by adopting two runoff coefficient values: $C = 0.5$ and $C = 1$. Secondly, two different rainfall scenarios are considered. They are built by varying the IDF-parameters as follows:

- Scenario 1: a constant pair (a, n) (hereafter referred to as *AVG*) is considered on all basins. This pair corresponds to $a = 27.58$ and $n = 0.32$ and is computed as the spatial average of the IDF parameters over Italy.
- Scenario 2: at-site IDF parameters (hereafter referred to as *LOC*) are used. They have been derived in each basin as described in Online Resource 1.

The solutions of Eq. (1) under the two hydrological scenarios produce different attenuation coefficients, defined as η_{AVG} and η_{LOC} respectively. This simplified sensitivity analysis aims to evaluate the susceptivity of any specific lake/dam configuration to the local climate.

The type 2 deformation is produced by adopting three possible values for the time of concentration. The first one is computed using the Pilgrim and McDermott's (Pilgrim and McDermott 1981) formula (referred to as PMcD), the second one is obtained by amplifying the previous value by 1.5 (referred to as 1.5PMcD), and the third comes from the adoption of the Giandotti's (1934) formula (referred to as Gi).

The combination of these different alternatives produces, for both the shapes considered, twelve possible hydrographs routed by the reservoir system. Each hydrograph is built according to the combination of basin features as summarized in Table 1. Every configuration in Table 1 can be doubled, by changing the hydrograph shape. The code of each configuration is integrated with the string 'Re' or 'NRC', for the rectangular and NERC shapes, respectively. The total number of hydrographs considered is therefore twenty-four.

The workflow for the computation of the attenuation coefficient for each of the 265 dams, as applied to the twenty-four combinations described above, is displayed in Fig. S3 (Online Resource 1).

5 Results and Discussion

The simulation framework described in the previous section, and schematized in Table 1, has produced a series of attenuation coefficients for each dam, that are analysed both in terms of their rank and their absolute value. For the sake of conciseness only selected configurations, among those presented in Table 1, are discussed below. In particular:

- Sub-section 5.1 discusses the results obtained from configurations with IDs n° 1 to 4 of Table 1;

Table 1 Working hypotheses

ID	Notation	C		t_c			(a,n)	
		0.5	1	t_c(PMcD)	1.5t_c(PMcD)	t_c(Gi)	AVG	LOC
1	C05_PMcD_AVG	✓		✓			✓	
2	C1_PMcD_AVG		✓	✓			✓	
3	C05_1.5PMcD_AVG	✓			✓		✓	
4	C1_1.5PMcD_AVG		✓		✓		✓	
5	C05_Gi_AVG	✓				✓	✓	
6	C1_Gi_AVG		✓			✓	✓	
7	C05_PMcD_LOC	✓		✓				✓
8	C1_PMcD_LOC		✓	✓				✓
9	C05_1.5PMcD_LOC	✓			✓			✓
10	C1_1.5PMcD_LOC		✓		✓			✓
11	C05_Gi_LOC	✓				✓		✓
12	C1_Gi_LOC		✓			✓		✓

As an example, the ID = 1 configuration means that we are considering a runoff coefficient equal to 0.5 (C05), a time of concentration computed using the Pilgrim and McDermott's formula (PMcD) and a single pair (a, n) for all basins (AVG)

- Sub-section 5.2 compares the results from configurations with IDs n° 2, 4 and 6;
- Sub-section 5.3 discusses configurations with IDs n°2 and 8;

Results for the configurations not addressed in this paper are shown and discussed in Online Resources 2 and 3.

5.1 Sensitivity on Runoff Coefficient and Linear Changes in the Time of Concentration

Results corresponding to the first four combinations of Table 1 are presented in Fig. 2, in terms of Empirical Cumulative Distributions (ECDs) of the four sets of η values obtained. Later on, results in terms of relative ranking displacements between the tested configurations are also represented.

The comparison of the ECD curves shows that incoming hydrographs of shorter duration, i.e., those obtained using the PMcD's time of concentration, tend to produce systematically smaller η values for both the shapes (see orange vs light blue curves in Fig. 2). This can be understood considering that a hydrograph of shorter duration introduces most of the volume in the reservoir when the water level above the spillway crest is still small. It must be clarified that the overestimation of flood volumes produced by the rectangular hydrograph shape produces in many cases attenuation coefficients close to 1. This is apparent from Fig. 2a. However, this outcome is of minor interest here because this work is not addressed to provide a specific and definitive value of the attenuation coefficient but offers a methodology to build priority ranks in different climatic and morphological conditions.

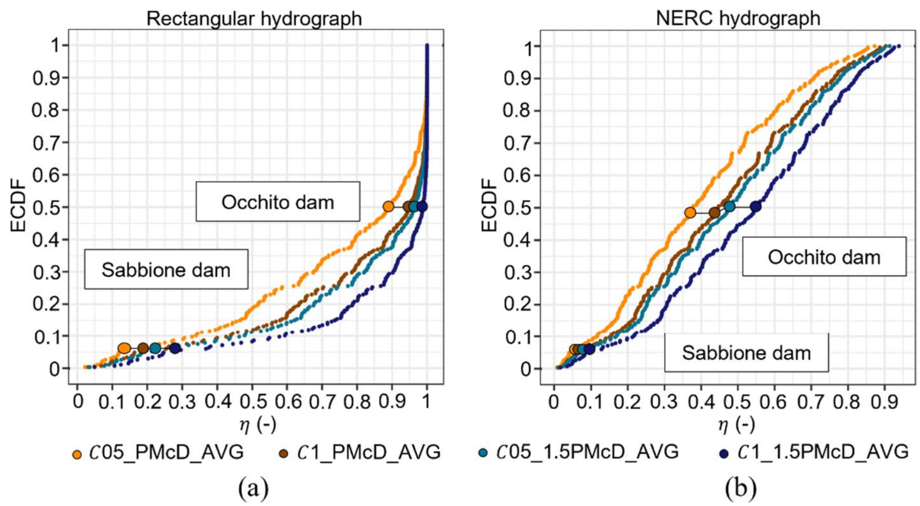

Fig. 2 ECD curves built for each of the four combinations for both the rectangular (**a**) and NERC (**b**) hydrographs. Brownish and bluish colours refer to the PMcD's t_c and 1.5 PMcD's t_c, respectively, while darker or lighter colours refer to a C equal to 1 or 0.5, respectively. The horizontal positions of results in the two highlighted dams (Occhito Dam: A_B = 1014.18 km^2, H_{MEAN} = 582.38 m a.s.l.; Sabbione Dam: A_B = 14.28 km^2, H_{MEAN} = 2766.83 m a.s.l.) show that the runoff coefficient has no influence on the ranking stability

It can also be noted from Fig. 2 that the four curves tend to become closer in the initial and in the terminal portions of the graph, indicating that η has a weak dependence on the adopted assumptions in dams with very low or very high attenuation potentials. The lower left portion of the graph includes most of the Alpine dams, which are typically characterised by high A_L/A_B ratios (see Fig. S1 in Online Resource 1) and therefore have quite good attenuation efficiencies.

An in-depth comparison of the results also reveals that the rank of η does not show major alterations as a consequence of the variation of the runoff coefficient: this can be recognized from the stable vertical position of the brownish (for t_c(PMcD)) and bluish (for $1.5t_c$(PMcD)) dots related to the two dams labelled in Fig. 2, i.e. dots lie on a horizontal line for the same t_c. For numerical reasons, some dams may be shifted by one or (maximum) two positions when changing from C = 0.5 to C = 1. (see e.g. Fig. S6 in Online Resource 3). Of course, in absolute terms the efficiency of the reservoir decreases with increasing incoming volumes, which happens when increasing C. However, the ranking stability of the attenuation coefficients implies that the runoff coefficient only works as a scale factor, and the amount of the hydrograph volume does not alter the attenuation ranking of each dam.

The above findings allow us to halve the number of working hypotheses presented in Table 1 and to use, hereafter, a single, unit, C value. Recalling the equivalence of the effects produced on the flood hydrograph by a change in the runoff coefficient and in the growth factor, we can specify that also a change in K_T would not lead to any change in the classification of the attenuation efficiency.

However, the overall picture of observed ranking shifts cannot be grasped from Fig. 2. To assess the ranking stability regarding two dimensions of hydrograph alteration, i.e. its shape and duration, a suitable way of representation is needed.

To this end, the variability of the rank R assumed by the attenuation coefficient of a given dam when changing t_c is estimated for both the shapes considered and a summary plot like the one in Fig. 3 is chosen. The relative displacements between ranks R_{Re}, obtained with the rectangular shape, and R_{NRC}, obtained with a NERC shape, are calculated as:

$$\frac{\Delta R_{Re}}{R_{Re}} = \frac{R_{Re,tc2} - R_{Re,tc1}}{R_{Re,tc1}} \tag{6}$$

$$\frac{\Delta R_{NRC}}{R_{NRC}} = \frac{R_{NRC,tc2} - R_{NRC,tc1}}{R_{NRC,tc1}} \tag{7}$$

where R_{tc1} refers to the rank of η obtained for a dam using PMcD's t_c, while R_{tc2} refers to the rank of the same dam obtained increasing PMcD's t_c by 1.5 times. We consider a relative rather than an absolute displacement to allow for a weighted analysis. In this way we assign a greater weight to the shifts that occur between the highest rankings, i.e. those corresponding to the best attenuation capacities.

As displayed in Fig. 3, a large percentage of the dams do not show any relative ranking displacement (central yellow hexagon) when modifying the time of concentration. Only for few cases, limited relative shifts can be observed. The $\Delta R/R$ range is ± 0.05 and ± 0.1 for the rectangular and the NERC hydrographs, respectively. A relatively greater sensitivity to the time of concentration can be observed when using the NERC hydrograph. This is justified by the fact that, for the NERC hydrograph, the basin t_c, not only affects the flood peak and volume, but also the overall shape of the hydrograph.

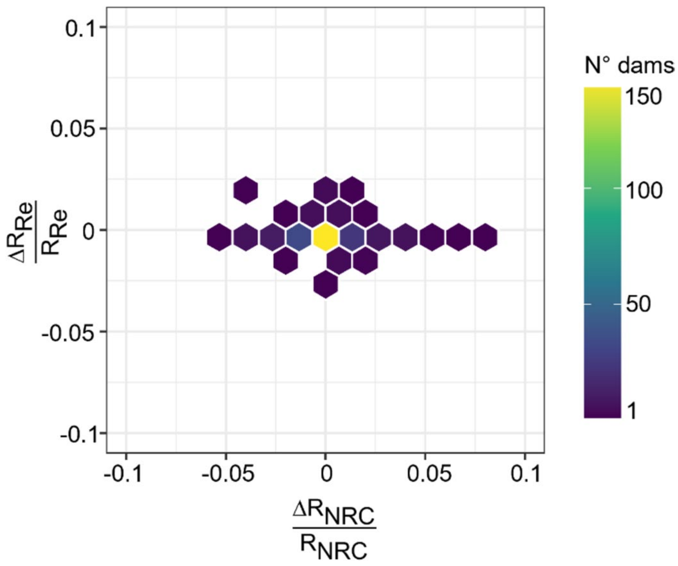

Fig. 3 Relationship between the relative ranking displacements obtained with the two hydrograph shapes considered. Both ranking configurations refer to a unit runoff coefficient and average climatic conditions

Considering the results obtained with simple alterations of the basic hydrograph scheme, we can conclude that, overall, the classification procedure is not so sensitive to a linear variation in the t_c value adopted. The maximum rank displacement is indeed of 3 positions for the rectangular hydrograph, and of 6 positions for the NERC.

5.2 Sensitivity on Basin's Morphological Variability

This sub-section shows the effects of the variability of basin morphological features on the ranking outcomes that derive from using a more complex formula for the time of concentration. Using Giandotti's t_c, the role of main stream length and slope would become apparent. In the alternatives considered, a unit runoff coefficient and a single constant pair (a, n) are maintained for all basins. The resulting η values (and the associated rank) are compared with those obtained in the previous sub-section. The configurations tested are identified by IDs 2, 4 and 6, corresponding to the cases: C1_PMcD_AVG_Re, C1_1.5PMcD_AVG_Re and C1_Gi_AVG_Re on the one hand, and C1_PMcD_AVG_NRC, C1_1.5PMcD_AVG_NRC and C1_Gi_AVG_NRC on the other hand.

The ECD of the η values obtained in the six cases are represented in Fig. 4: the brown and blue curves are the same as in Fig. 2, while the green curve refers to the attenuation potentials obtained using the Giandotti's time of concentration. From Fig. 4 we observe that the η values obtained using the PMcD's or Gi's t_c occupy the same 'space', as the green and brown curves overlap for both the rectangular and NERC shape. However, rankings of single dams, as well as the attenuation capacity itself, can change consistently: an example is given considering the Lago Baitone Dam, having $A_B = 7.83$ km^2, $S = 15\%$, $A_L/A_B = 0.05$ and $W = 22.3$ m and the Val di Noci Dam, having $A_B = 7.45$ km^2, $S = 4\%$, $A_L/A_B = 0.027$ and $W = 25.1$ m. The two reservoirs are characterized by similar structural

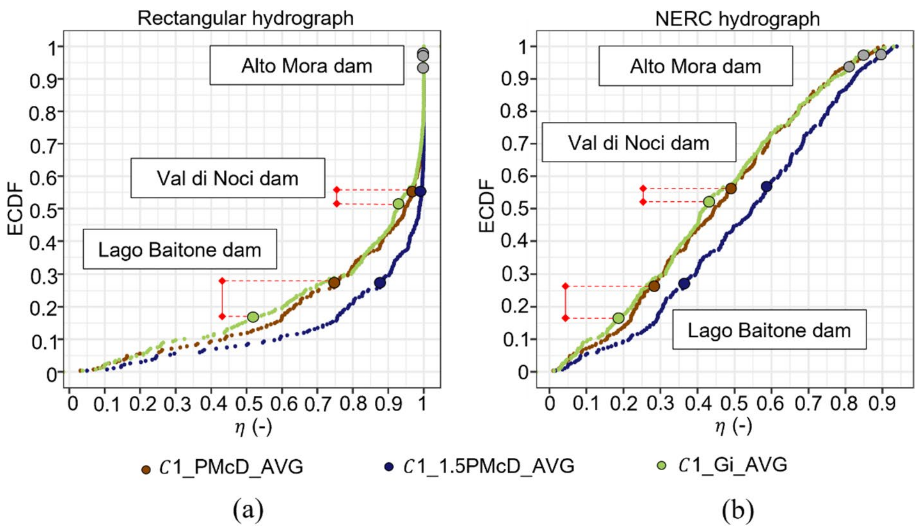

Fig. 4 ECD curves built for each of the three combinations tested for both the rectangular (**a**) and NERC (**b**) hydrographs. Brown and blue colours refer to the PMcD's t_c and 1.5 PMcD's t_c, respectively, as already shown in Fig. 2, while green colour refers to the Gi's t_c

features and upstream watershed areas. However, they strongly differ in the main channel average slopes.

It can be noted from Fig. 4 that the green dots, referring to t_c(Gi), and the brown ones, referring to t_c(PMcD), are further away when considering the Lago Baitone dam than the Val di Noci dam. This means that introducing the role of actual basin morphological features can have a major effect on the ranking outcomes (and on the attenuation capacity as well) for small mountain basins as compared to large basins with small to negligible slopes.

Of course, this sensitivity is negligible if the dam's structural features are not suitable for significant flood attenuation purposes. An example is the Alto Mora dam ($A_B = 5.67$ km^2, $S = 14\%$, $A_L/A_B = 0.007$ and $W = 32.3$ m, gray dots in Fig. 4) for which the attenuation coefficient does not vary significantly even considering the morphological characteristics of the upstream basin.

As in previous sub-section, the relative ranking displacements obtained when changing the time of concentration are again computed for both the shapes, according to Eqs. (6) and (7). In this case, the R_{tc1} and R_{tc2} refer to the ranking produced with PMcD's and Giandotti's time of concentration, respectively. Results are shown in Fig. 5. The performances associated with the two shapes are not clearly different as those observed in Fig. 3, since the hexagons in Fig. 5 are aligned along a 1:1 line. The same result is obtained if local climatic conditions are used for each basin, instead of average climatic conditions over the whole Italy, as shown in Fig. S22 of Online Resource 2.

This result show that, unless we refer to a very simplified scheme as in the previous case, where t_c depends only on the basin area and its variability is constant for each basin, the stability of the classification is not so sensitive to the shape variability of the incoming hydrograph. These outcomes confirm the findings of Marone (1964, 1971), who pointed out that for relatively simple, single-peak hydrographs, the adopted shape has relatively little influence on the attenuation capacity. Also the work by Miotto et al. (2006), where 20 real reservoirs in Italy are considered, shows that their position in the classification of attenuation efficiencies

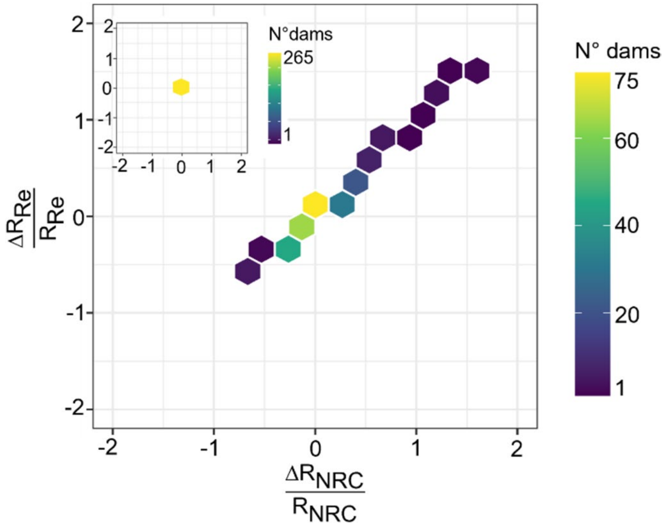

Fig. 5 Relationship between the relative ranking displacements obtained with the two hydrographs considered. Both ranking configurations, i.e. C1_PMcD_AVG and C1_Gi_AVG, refer to an average climatic condition and a unit runoff coefficient. Figure 3 with the same range of variability of the x- and y-axes (±2) is given in the top left corner for comparison

basically remains the same as the hydrograph shape varies. NERC and triangular shapes were tested in that case.

Confirmation of the little influence of the hydrograph shape would greatly simplify the approach to the flood attenuation assessment, even because methods for its objective definition are not yet well established (see e.g. Tomirotti and Mignosa 2017; Brunner et al. 2017).

Still looking at Fig. 5, it should be noted that the relative ranking displacements $\Delta R/R$ show strongly different magnitudes from those found in the previous sub-section. For both shapes, about 25% of the dams do not experience any relative ranking displacement (central yellow hexagon), but both $\frac{\Delta R_{Re}}{R_{Re}}$ and $\frac{\Delta R_{NRC}}{R_{NRC}}$ can reach (positive) values of up to 200%, as a consequence of a non-linear (and more realistic) variation of the time of concentration for the same basin (i.e. changing from PMcD's t_c to Gi's t_c).

5.3 Sensitivity on Climate Variability

The aim of this section is to explore the effect of using input hydrographs built according to the actual climatic conditions at each site. The combinations tested are the following: C1_PMcD_AVG_Re, C1_PMcD_LOC_Re, C1_PMcD_AVG_NRC and C1_PMcD_LOC_NRC. The attenuation coefficients η_{LOC} and η_{AVG} have been computed as described in Section 4 and the deviation $\Delta\eta/\eta$ between the tested configurations has been estimated as:

$$\frac{\Delta\eta}{\eta} = \frac{\eta_{C1\_PMcD\_LOC} - \eta_{C1\_PMcD\_AVG}}{\eta_{C1\_PMcD\_AVG}} \tag{8}$$

The distribution of $\Delta\eta/\eta$ in the plane given by the values of pairs $(a, n)_{LOC}$ is depicted in Fig. 6, where each reservoir is associated to a point. The colour and size of each point identify the sign and the value of $\Delta\eta/\eta$, respectively.

It can be first noted that the NERC hydrograph induces greater variations in the η values when modifying the design rainfall intensity, i.e. $\Delta\eta/\eta$ of up to 50%, compared to a maximum variation of 10% in the rectangular case. This is because, in the NERC case even the IDF parameters, as well as the basin t_c, affect the flood peak and volume and the shape of the hydrograph limbs too.

It is interesting to note that the rainfall parameter a discriminates the reservoirs' efficiency in real climate conditions if considering the rectangular hydrograph (Fig. 6a), while n controls the attenuation coefficients in the case of a NERC shape (Fig. 6b). As the parameter a represents the average maximum rainfall in 1-h duration, this result shows that, if adopting a constant incoming hydrograph, the higher the average intensity of storms, the lower tends to be the intrinsic dam's attenuation efficiency in analogous configurations.

On the other hand, where the parameter n assumes high values, which means that the rainfall intensity decreases slowly with the duration, the use of an average IDF curve and a more complex hydrograph shape such as the NERC one, may lead to an overestimation of the attenuation potential of the reservoir by up to 50%.

Referring to Fig. 6a, the greatest climatic influence on $\Delta\eta$ (percentage up to 10%) for the rectangular hydrograph lies in the region corresponding to low a values and high n values. This behaviour is typical of high-altitude areas, such as the alpine region, consistently with the maps reported in Mazzoglio et al. (2020). Alpine dams are also those that show the highest η values in all cases, i.e. those located at the bottom of the curves shown in Figs. 2 and 4. The efficiency of this category of reservoirs for flood control purposes can be then partly attributed to "favourable" climatic conditions.

It should be specified that Fig. 6 refers to one of the combinations investigated, i.e. that related to the PMcD time of concentration. However, a similar behaviour is found if increasing the t_c value by 1.5 times, as shown in Fig. S28 in Online Resource 2.

A minor influence of the climatic features, as compared to that exerted by the time of concentration, is observed in terms of ranking. The maximum recorded position shifts are 26 and 40 places for the rectangular and NERC hydrographs respectively, but 80% of the 265 dams considered experience variations of less than 8 positions in the former case, less than 20 positions in the latter.

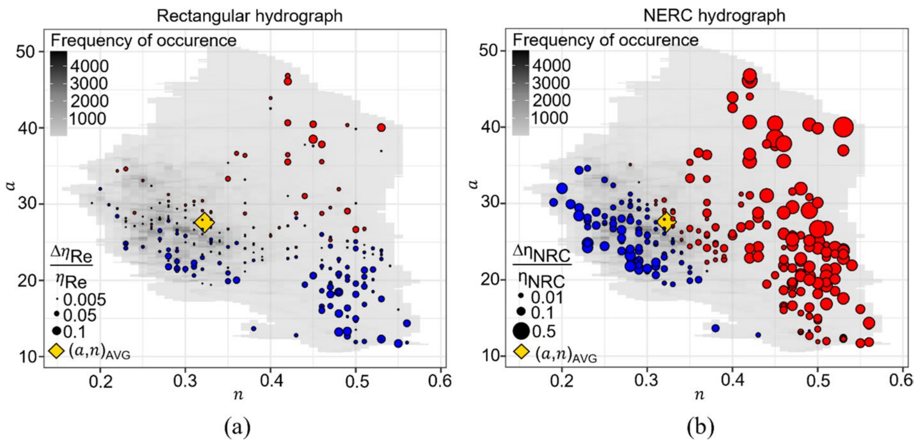

Fig. 6 Range of variability of the IDF-parameters a and n over Italy (grey shaded area), with average values (yellow square). Colour of points stands for the sign of $\Delta\eta$ (blue for negative values, red for positive values), while the size refers to the entity of $\Delta\eta$. **a** rectangular hydrograph, **b** NERC hydrograph

Although this finding may appear misleading, it points out that the variability related to local climatic conditions is not the main governing factor in identifying target reservoirs to be adopted for attenuation purposes. This allows us to provide a classification that is quite robust, i.e., stable over time. In other words, there will be no need to repeat the classification procedure over the years as the available rainfall data increases since the ranking stability is mainly due to the geomorphological attributes of the basin upstream the dam.

For the sake of comparison, the relationship between $\frac{\Delta R_{Re}}{R_{Re}}$ and $\frac{\Delta R_{NRC}}{R_{NRC}}$ is provided in Online Resource 3 (Fig. S27). Again, a slight influence of the adopted hydrograph shape is observed.

6 Conclusions

In this work, an approach to a comprehensive assessment of the intrinsic flood attenuation potential of Italian large dams has been proposed, aimed at identifying, as objectively as possible, the reservoirs best fitted for their flood mitigation efficiency. In building a classification approach, we have appraised the role of basic morphological and hydrological features of each considered case, by using a simple modelling framework (i.e. the rational formula). Twenty-four possible configurations of the incoming hydrograph have been derived from the variations of the main parameters needed to apply the rational formula and the hydrograph shape, obtaining a sensitivity analysis framework. Variations in the absolute value and in the ranking of the flood attenuation coefficients for 265 dams have been examined.

For every incoming hydrograph, the attenuation index has been computed by solving the hydraulic equations of the lakes.

The main conclusions emerged from the above-mentioned simulations are the following:

(i) A change in the runoff coefficient C modifies the absolute amount of the dam attenuation efficiency, i.e. lower C values, corresponding to lower input flood volumes, result in higher attenuation. On the other hand, no significant effect is observed on ranking stability. As a proportional increase in the flood peak is also determined by changing the reference return period, according to the index flood paradigm, this result is quite significant when the objective of the analysis is the dam efficiency classification.

(ii) The attenuation coefficients η show a strong sensitivity to the variability of the time of concentration, both in terms of their magnitude and of their rank. We found that the shorter the time of concentration t_c, the greater the attenuation efficiency. Therefore, just a simple amplification of t_c from the same formula already modifies (even if in a small degree) the ranking of the attenuation efficiencies. In addition, the largest number of order position variations is observed when changing the t_c formula, e.g. by introducing the role of morphological features of the basin drainage network. This means that apparently similar configurations of dams and upstream basins can produce different results if the basin morphology is rather different.

(iii) No significant changes in the ranking are observed when considering different IDF curves, from which the design rainfall is obtained. However, consideration of the actual variability of the rainfall features on the Italian territory has allowed to recognize ideal combinations of rainfall parameters and geometrical characteristics of the reservoirs with respect to the dams' flood mitigation efficiency. The best combination resulted to be the one that is common in the Alpine dams.

(iv) The choice of the hydrograph shape is not crucial for classification purposes, i.e. it does not have very significant effects on the ranking of the most efficient dams. This finding does not imply that one should not make efforts in estimating a reasonable hydrograph shape to assess the absolute attenuation capacity. If the problem lies with a single reservoir, the selection of the design shape is still an essential step.

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Declarations

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Consent to Participate Not applicable.

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