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Towards the assessment of the flood attenuation potential of Italian dams: first steps and sensitivity to basic model features

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Abstract

The effect of reservoirs on downstream flood regime has been largely investigated in the literature worldwide, but there is, to date, still an insufficient elaboration on the “natural” flood peak mitigation exerted by dams.
In this work, the attenuation potential of flood peaks by the main Italian reservoirs is devised, based on a small number of objective factors that concur to the implementation of a ranking method. This can be used to select priorities in the implementation of Dam Emergency Plans in Italy, according to a legislation act of 2004.
The attenuation potential is estimated here by means of a very simple procedure, that does not require the definition a priori of a hydrograph shape and the mitigation effect is computed assuming that the dam operates as a linear reservoir, meaning that the stored volume and the outflow are linked by a linear relationship. A realistic average annual design flood peak has been estimated for each basin upstream the dams through the rational method, using for the first time the results of a countrywide analysis of rainfall extremes.
The study has been carried out using 265 dams and related watersheds throughout Italy.
Results were examined in terms of both magnitude and order position of the attenuation coefficient: a strong sensitivity to the time of concentration is apparent.

Keywords: Reservoirs; Flood attenuation; Time of concentration; Ranking

1. INTRODUCTION

The flood attenuation effect consists in the storage of the incoming flood volumes and their gradual release over time, with consequent mitigation of hydrological risk downstream. The attenuation of flood peaks performed by reservoirs is a widely discussed topic in the scientific literature; in recent years it has also been examined in relation to the increased hazards due to climate change (see Boulange et al., 2021; Ehsani et al., 2017).
Most of the available works on reservoirs and floods investigate the effect of dams in modifying the hydrological regime downstream, using both analytical approaches (Manfreda et al., 2021; Volpi et al., 2018; Guo and Adams, 1999), with different levels of simplification, and synthetic indices, to be used as covariates in flood frequency analyses (see e.g., Xiong et al., 2019). All these studies are basically carried out at the scale of individual reservoirs, while systematic assessments at a national scale are, to date, rather limited. A good (and dated) example can be taken from the Flood Estimation Handbook (Scarrot et al., 1999) where the contribution of dams on the attenuation of flood quantiles was assessed by means of a synthetic indicator, i.e. the FARL index, for several basins over the United Kingdom.
Despite the amount of work done on this subject, an established methodological framework to assess the attenuation effects performed by dams has yet to be defined. More work still needs to be done, for instance, to schematize the ‘natural’ attenuation capacity of dams, which can be considered as the ‘average’ attenuation potential that only depends on the main structural characteristics of the reservoir and on the main features of the upstream basin. The assessment of this attenuation potential is particularly relevant in a wide-area context, as can be that of an entire nation, where those approaches that assess the flood mitigation effects by simulation of long rainfall series and related hydrographs result cumbersome to be applied. In a wide-area framework there is a marked need of standardization of the forcing hydrographs and of the hydraulic conditions for the assessment of the attenuation effect, to ensure consistency of results so that they can be reliably compared. In this direction, very simple methodologies can be used to conceive an “intrinsic” attenuation potential for a set of dams, which may be useful to define a ranking among the different cases. This is the approach we follow in this paper, where a relatively large set of dams is examined in relation of their flood attenuation potential to help selecting priority cases for the implementation of Dam Emergency Plans in Italy, according to a legislation act of 2004.
While pursuing a ranking of the dams’ attenuation potentials with the simplest possible methodologies, we pay particular attention to the consistency of the hydrologic input. So, the incoming hydrograph is assumed of a simple rectangular shape and the ‘design’ discharge is obtained thought the rational method, but the ‘design’

rainfall used is specifically computed for each watershed using actual extreme rainfall values. In particular, the index areal rainfall (according to the definition of the index flood of Dalrymple, 1960) is computed for every basin using the data of the recent I^2-RED database (Mazzoglio et al., 2020) of rainfall maxima in Italy. In a search for a robust approach to rank the dams' performance, the index flood is used for the incoming hydrograph, and the routing thorough the reservoir is initially considered using the equations of a linear reservoir.
The ranking produced by this simple and standardized procedure for the assessment of the attenuation potential is subject to an inherent element of uncertainty, represented by the choice of the formulation used for the basin time of concentration. The effect of this choice on the results obtained is explicitly evaluated.
However, the (ranking) results obtained will inevitably be perturbed by whatever refinement introduced in any of the steps of the procedure. Only one case has been considered here, i.e. the application of the hydraulic routing on the incoming hydrograph in place of the simplified (linear-reservoir) routing.
In the following, a description of the structural and hydrological data used is provided, before presenting the equations used and their applications.

2. CHARACTERIZATION OF THE BASINS UPSTREAM THE (LARGE) ITALIAN DAMS

2.1 Database set up

In Italy there are today 528 large dams, i.e. those higher than 15 meters or with storage volume larger than one million cubic meters. Those are classified as "of national relevance", according to the Italian Law No. 584 of 21st October 1994.
A complete and updated database including the most relevant structural information regarding all the 528 Italian reservoirs and the geomorphological features of their upstream watersheds is currently missing. Therefore, an Italian Catalogue of "great Dams" (ICD) has been built before the analysis, thanks to the data provided by the General Directorate of Dams and Hydro-Electrical Infrastructures (GDD).
The morphological attributes of the upstream basins were computed by processing the 30-m NASA's Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (Farr et al., 2007). Only the area of the watershed directly connected to each reservoir has been considered, without reference to any indirectly connected basin.
An overview of the features available for the Italian system of large dams and related basins is provided in Table 1. It is worth stressing that to make this work possible, a systematic check of the values of the lake areas was needed. To this aim, the lake areas from the GDD to be included in the ICD have been compared with surfaces extracted at the elevation of the spillway crests from a high-resolution DEM (the TINITALY/01 DEM, 10-m spatial resolution, Tarquini et al., 2007).

Table 1. Main structural features of the Italian dams and main geomorphological attributes of the upstream basins. The median value of each parameter is also listed.

Parameter	Notation	Description	Median value
Latitude	Lat	Reference System: WGS84 (EPSG: 4326).	-
Longitude	Long	Reference System: WGS84 (EPSG: 4326).	-
Elevation of the spillway crest	H_S	In the case of several spillways located at different levels, the highest one has been considered.	650 m a.s.l.
Reservoir storage volume	V_S	Measured at the elevation H_S, according to Law No. 584 of 21st October 1994.	9.5 Mm^3
Geometry of the spillway crest	W	Total width of the spillway crest. In the case of several spillways located at the same level, they have been merged.	35 m
Lake area	A_L	Measured at the elevation H_S.	0.55 km^2
Area	A_B	The area required for channel initiation has been set to 0.02 Km^2 for basins smaller than 1 Km^2, 0.1 Km^2 for basins smaller than 10 Km^2, 1 Km^2 for basins larger than 10 Km^2.	20 km^2
Maximum elevation	H_{MAX}	-	1540 m a.s.l.
Minimum elevation	H_{MIN}	-	600 m a.s.l.
Mean elevation	H_{MEAN}	-	984 m a.s.l.
Length of the main flow channel	L	-	7.5 km
Average slope of the main flow channel	S	Calculated as $S = \frac{1}{N}\sum\frac{\Delta H_i}{L_i}$, being N the topological diameter, i.e. the number of links in which the main channel can be divided, based on the junctions.	0.05

The dams on which the assessment has been carried out have been carefully selected, excluding those for which it is not possible to obtain reasonable flood attenuation effects, i.e.:

i. officially dismissed dams;
ii. dams already used as flood detention basins;
iii. dams where no attenuation volume is available or no unsupervised management during floods is possible (this is the case, for instance, of structures regulating large natural lakes);
iv. dams with very small lake areas A_L in relation to the upstream watershed area A_B (ratios A_L/A_B lower than 1/150).

The resulting dataset, made up of 265 dams, is shown in Figure 1, where the spatial distribution of the lake area to basin area ratios for the investigated reservoirs is mapped.

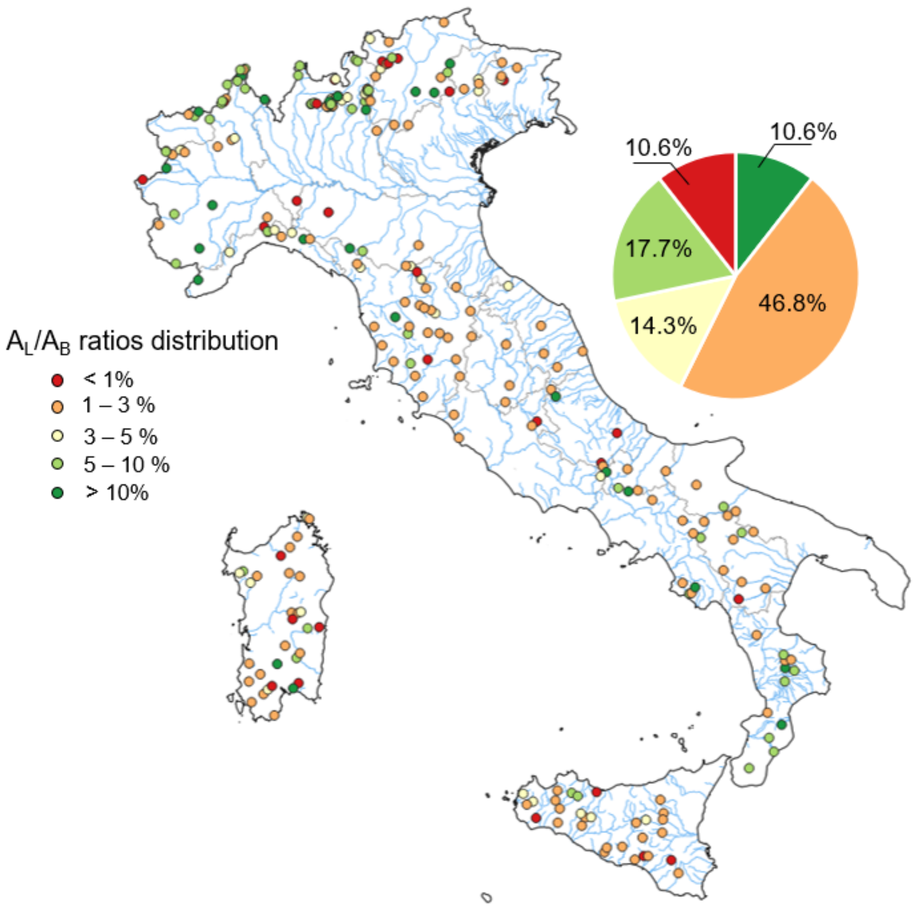

Figure 1. A_L/A_B ratios of the 265 dams considered.

2.2 Design rainfall

As outlined in the Introduction, a rectangular incoming hydrograph of constant discharge Q_{in} is considered. Q_{in} is computed by means of the rational formula (Mulvaney, 1851):

$$Q_{in} = \frac{\psi \, i_{d_c} A_B}{3{,}6} \qquad [1]$$

where i_{d_c} is the design extreme rainfall intensity (mm/h) for a critical duration d_c, A_B is the basin area (km^2) and ψ is the runoff coefficient (dimensionless). For homogeneity reasons, a unit runoff coefficient (ψ=1) has been assumed in all cases, corresponding to completely impermeable soil conditions.

According to the rational method, the average peak discharge depends on the average of the annual extremes of rainfall intensity, expressed with intensity-duration curves:

$$i_{d_c} = \frac{h_{d_c}}{d_c} = a \cdot d_c^{n-1} \qquad [2]$$

where h_{d_c} is the mean annual maximum rainfall depth for the duration d_c, and *a* and *n* are the scale factor and the scaling exponent, respectively, of the depth-duration curve.

To obtain the design rainfall for each basin, area-averaged intensity-duration curves are needed, that is quite a complex data requirement, involving the knowledge and the management of a distributed database of precipitation extremes. The rainfall data used for computing the areal intensity-duration curves come from the Improved Italian – Rainfall Extreme Dataset (I^2-RED) (Mazzoglio et al., 2020), consisting in a systematic collection of annual maximum rainfall depths in 1, 3, 6, 12 and 24 consecutive hours, recorded over Italy by 5265 rain gauges between 1916 and 2019. In the work by Mazzoglio et al. (2020), intensity-duration curves were first built at the station level. Local parameters *a* and *n* of relation [2] were calculated by means of linear regression between the duration d and the average of the annual maximum rainfall depth h_d. The at-station parameters were then spatially interpolated at a 250-meters resolution by ordinary kriging.
For the purpose of this work, the kriged maps have been clipped to basin boundaries and subsequently averaged to obtain areal average of *a* and *n*.

2.2.1 Event critical duration

Consistently with the assumptions behind the original concept of the rational method, the rainfall intensity in eq. [2] is assumed to be uniform over a critical duration d_c equal to the time of concentration t_c of the upstream basin.
The application of the rational formula, though robust and simple, shows a strong dependence on the critical duration d_c (Grimaldi et al., 2015). This issue is dealt with in this work through a simple sensitivity analysis, i.e. by varying t_c between two values.
Many methods to estimate the time of concentration have been developed; here we have selected two formulations, one purely empirical and one recalling the conventional Chezy formula for free-surface velocity assessment in open channels.
The first one is the Giandotti's formula (Giandotti, 1934):

$$t_c = \frac{4\sqrt{A_B}+1.5L}{0.8\sqrt{H_{mean}-H_{min}}} \qquad [3]$$

where A_B is the basin area (Km^2), L is the main flow channel (Km), H_{mean} and H_{min} are the mean elevation and the minimum elevation of the basin (m a.s.l.), respectively.
The second one has a structure of the type

$$t_c \propto \frac{L}{v} \propto \frac{L}{c\sqrt{S}} \rightarrow \; t_c = \gamma(\frac{L}{\sqrt{S}})^{\eta} \qquad [4]$$

where γ and η are constants, v is the flow velocity (m/s), L is the main flow channel (Km) and S is the average slope of the main flow channel (m/m).
The chosen formula, attributed to Picking (Silveira, 2005), has been revised according to Beven (2020), so that the time of concentration is calculated as:

$$t_c = \frac{3}{2}(0.0883\; L^{0.667} S^{-0.332}) \qquad [5]$$

The two formulations provide a sufficiently wide range of variability of the t_c values, as a region of intersection is not clearly identified; in particular, the Giandotti's formulation produces systematically longer times of concentration than the Picking's formulation.

3. SIMPLIFIED FLOOD ATTENUATION POTENTIAL

The flood attenuation by a reservoir can be described by the continuity equation:

$$q_{in}(h(t)) - q_{out}(h(t)) = \frac{dV(h(t))}{dt} \qquad [6]$$

where $q_i(h(t))$ and $q_o(h(t))$ are the inflow and outflow hydrographs respectively, V is the flood volume and h is the water level above the spillway crest. The attenuation coefficient is calculated as:

$$\eta = \frac{\max(q_{out}(h(t)))}{\max(q_{in}(h(t)))} = \frac{Q_{out}}{Q_{in}} \qquad [7]$$

If Q_{in} is known, eq. [6] can be solved after defining the volume-elevation curve:

$$V(h) = V_0(h-h_0)^{\alpha} \qquad [8]$$

and the stage-discharge curve:

$$Q(h) = Q_0(h - h_0)^{\beta} \qquad [9]$$

The V_0 and Q_0 coefficients represent the stored volume for a water level of 1 m above the spillway crest, and the outgoing discharge for a water level of 1 m above the spillway crest, respectively.
As only free-surface spillways are considered in this work, a known value β=1.5 is attributed to the exponent of eq. [9].
Denoting by h_1 a water level of 1 m, the terms V_0 and Q_0 can be then written as follows:

$$V_0 = A_L \cdot h_1 \qquad [10]$$

$$Q_0 = C_D W\sqrt{2g} \cdot h_1 \qquad [11]$$

being A_L the lake area, C_D the discharge coefficient, assumed to be 0.45 in all cases, and W the total length of the spillway crests (if more than one spillway is available).
Considering the dam system equivalent to a linear reservoir, the ratio of the outgoing discharge to the stored volume will be constant at all times, i.e. the ratio $\frac{\alpha}{\beta}$ is 1. Under these assumptions, eq. [6] can be written as:

$$q_{in}(h(t)) = \left(\frac{V_0}{Q_0}\right)\frac{dq_{out}(h(t))}{dt} + q_{out}(h(t)) \qquad [12]$$

and it can be analytically solved. The maximum outgoing discharge Q_{out} is calculated as:

$$Q_{out} = Q_{in}(1 - e^{-\frac{D}{k}}) \qquad [13]$$

In eq. [13] D is the duration of the incoming rectangular hydrograph and k, known as the “storage coefficient” [hours], is the ratio between V_0 and Q_0.
The inflow and the outflow hydrographs related to the above hypothesis are sketched in Figure 2.
The time base D of the incoming hydrograph is assumed to be $D=2t_c$, according to the framework of the rational method.

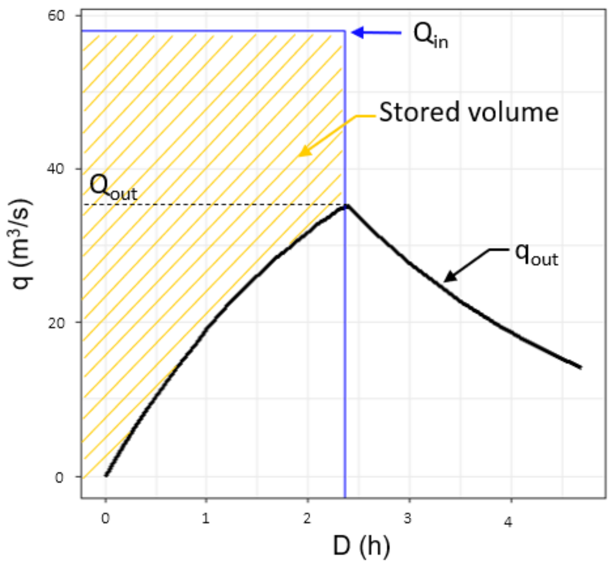

Figure 2. Example of flood attenuation for the Agaro dam (Piedmont region, A_B = 11 km^2, A_L = 0.06 km^2, W = 36m).

In order to identify the bias of this simplified method, it has been compared to a more complete one, i.e. the numerical integration of eq. [7].
The numerical solution of eq. [7] has been performed by considering the initial water level in the reservoir equal to the elevation of the spillway crest H_s. For this reason, the term dV(h(t)) in eq. has been intended as the change in volume above H_s.

This hypothesis is based on the assumption that the area of the lake is constant with the water level above the spillway crest and equal to the area of the lake measured at the H_s level. It follows that the term dh(t) has been estimated as the ratio between dV(h(t)) and the lake area.
Under the above simplifications, eq. [7] has been numerically integrated by adopting a time step of $0.01t_c$.
The attenuation coefficient η, determined as described above, is the index used to formulate a classification of the attenuation potential of Italian reservoirs.

4. RESULTS AND DISCUSSION

Results have been analyzed both in terms of the magnitude and the order position of the attenuation coefficient η. For the purpose of rank assessment, each reservoir is assigned a number, hereafter called rank, which identifies its position in the vector that orders the attenuation coefficient in an increasing sense (from the lowest to the highest value of η). For each of the four classifications produced in this work, using two different methods and two different formulas for the time of concentration, the number of order permutations for each dam between the different configurations has been computed.
The ranking stability has been assessed through the Spearman's footrule (Alvo et al., 2014), whereby the spread between two individual permutations μ and ν can be quantified by means of a distance function based on absolute deviations.

$$d_F(\mu,\nu) = \sum_{i=1}^{N} |\mu(i) - \nu(i)| \quad [14]$$

In Figure 3 the ranking stability between the applications proposed in this work is depicted. In particular, Figure 3a shows the boxplot of the distribution of the variations in the order position for each dam, obtained by ordering the η_G and the η_P values, for the hydraulic routing.
While only a few reservoirs (around 2%) show variations in the order of 50 places, the median number of permutations is lower than 15 places. Despite the number of rank permutations is higher in the simplified method compared to the hydraulic one, as well as the total number of variations d_F, the overall sensitivity of the ranking structure to the time of concentration remains the same in both cases.
It is worth stressing that the greatest variability in terms of ranking occurs for intermediate values of the attenuation potential, indicating a weak dependence on the adopted assumptions for very low or very high attenuation potentials. Alpine reservoirs are in the first positions of the classification for both the formulation adopted for t_c and both the methods used.
On the other hand, Figure 3b displays the variations in the order position for each dam between the hydraulic routing and the simplified one for a fixed time of concentration (in the given example, t_c is estimated using the Giandotti's formulation, but a similar boxplot is found for the Picking's time of concentration).
In this case, the simplified and the complete methods provide very different classifications, as reflected in the significant growth in the total number of rank permutations d_F.

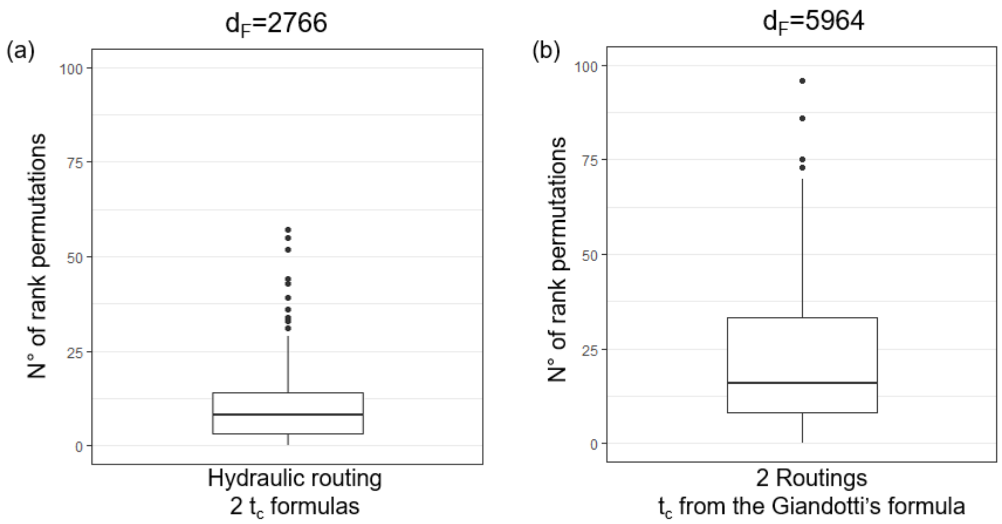

Figure 3. Boxplots of the distribution of rank permutations for each dam. Panel (a) refers to different formulations for the time of concentration within the complete method, panel (b) refers to the difference between the two methods, for the same time of concentration (i.e. the one by Giandotti).

In order to investigate the results from the ranking comparison, some insights are provided below.
Results from the application of the linear method are illustrated in Figure 4. Specifically, Figure 4a shows the relationship between the η values computed by adopting the Giandotti's or the Picking's formulations for the

time of concentration, η_G and η_P respectively, for the linear routing. As expected, the longer the time base of the incoming hydrograph, the lower the attenuation effect (i.e. the higher the η values). This can be understood considering that increasing D values correspond to increasing flood volumes, computed as $Q_{in} \cdot D$. This is indeed a side effect which will take place also if other hydrograph shapes are considered.
About 10% of the reservoirs considered shows a η=1 result, i.e. no reduction of the flood peak, for both the formulations adopted for the time of concentration. These dams are those with a particularly low ratio between the V_0 coefficient of eq. [8] and the flood volume.
By coupling eqs. [7] and [13], it is possible to derive an analytical relationship between η and the ratio between the storage coefficient and the time of concentration, henceforth referred to as δ. It results as:

$$\eta = 1 - e^{-\frac{2}{\delta}} \quad [15]$$

The exponential relationship expressed by eq. [15] is depicted in Figure 3b, where high values of the δ parameter correspond to high capacities of flood peaks attenuation. Bearing in mind how δ is defined, its highest values are found for the Alpine reservoirs, which are characterized by large A_L/A_B ratios, consistently to what arises from the analysis of ranking.

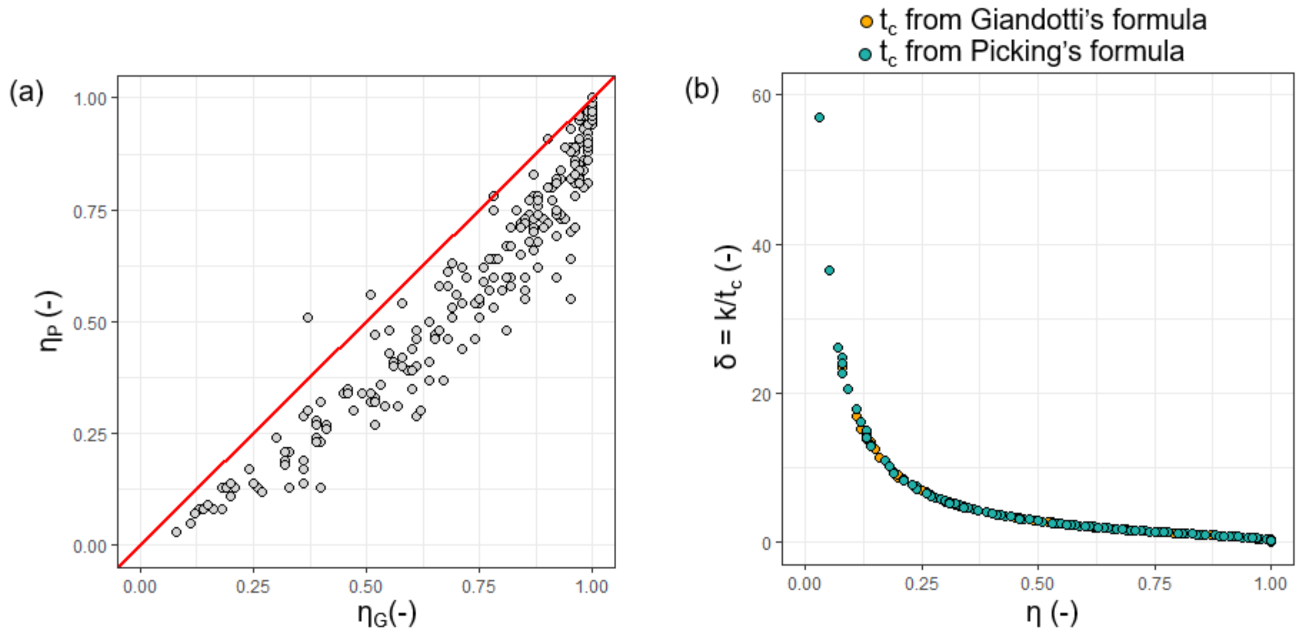

Figure 4. (a) Comparison between the η values computed with different formulation for the time of concentration. (b) Analytical relationship linking η to the δ parameter.

Figure 5 shows the attenuation coefficients obtained with the two different routing methods, for both the times of concentration used. Regardless of the t_c value adopted, it is not possible to identify a univocal relationship between the results produced with the two approaches.
These findings lead to consider that, while at present it is not possible to identify a preferred method, it is certainly worth investing in as accurate a formulation for the time of concentration as possible.
It is also interesting to point out that the behavior shown in Figures 5a and 5b can be attributed to the value of the A_L/A_B ratio. Figure 6 shows how a threshold of A_L/A_B=0.075, above which the hydraulic routing produces higher attenuation coefficients (i.e. lower attenuation potentials), can be drawn. This threshold is the same for both the t_c values adopted.

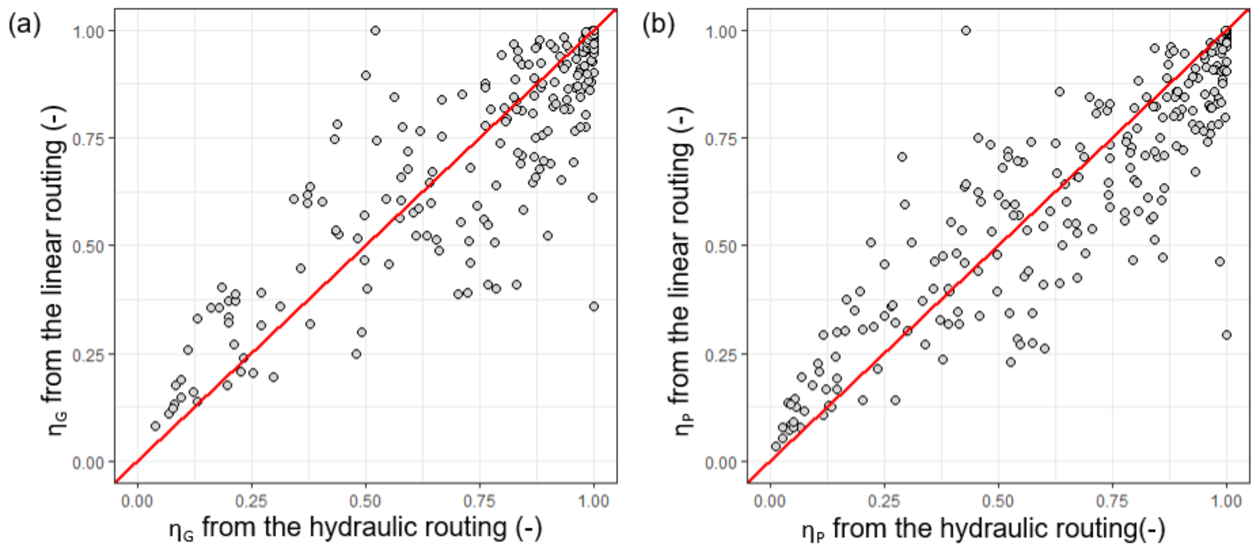

Figure 5. Results from the linear routing compared with those from the integration of the differential equation of the lakes, for the Giandotti's (a) and the Picking's (b) time of concentration.

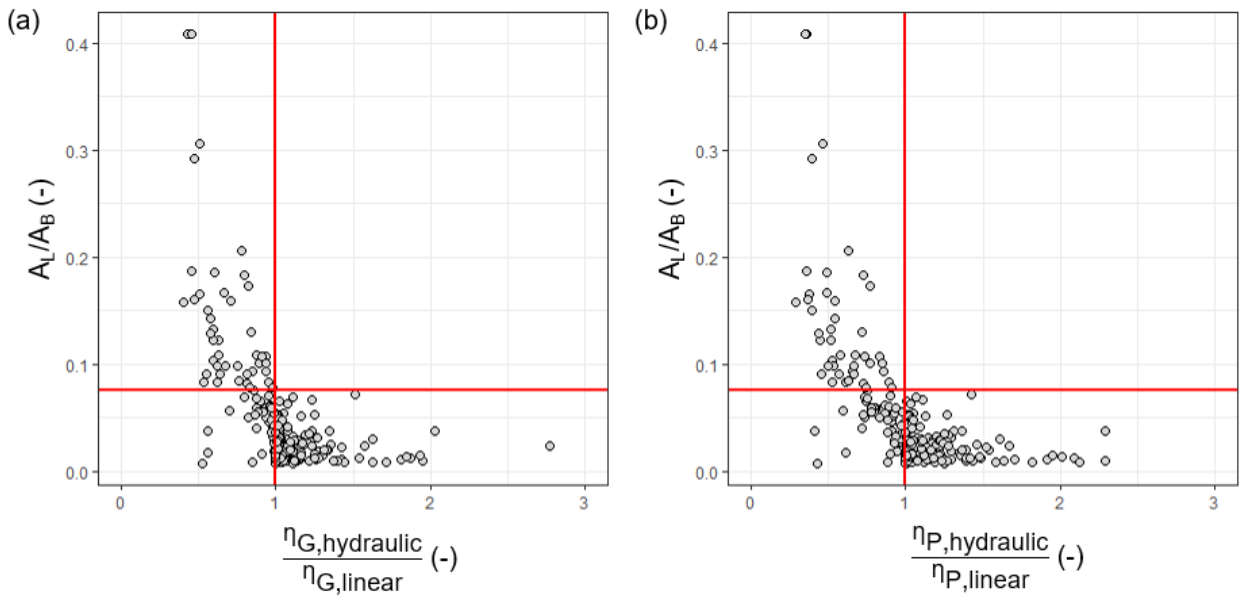

Figure 6. Ratio between the attenuation coefficients obtained with the two routing methods with the Giandotti's (a) and the Picking's (b) time of concentration.

5. CONCLUSIONS

In this work an intrinsic flood attenuation potential for 265 Italian large dams has been examined in two main ways. On the one hand, there is the need to identify, as objectively as possible, target reservoirs to be used for attenuation purposes, according to the Italian decree of 27th February 2004. At the same time, the classification methodology adopted may be useful to a systematic and large-scale assessment of those elements that most influence the efficiency of reservoirs in flood mitigation.
The flood attenuation coefficient has been computed here using a simple and standardized method, in order to ensure a homogeneous approach. The dam system has been treated as a linear reservoir, using a rectangular incoming hydrograph and a flood peak coming from the rational formula. Sensitivity of the attenuation potential has been investigated in terms of time of concentration and routing method.
The main conclusions outlined in this work are summarized in the following.

i. The magnitude of the attenuation coefficient shows a strong sensitivity to the time of concentration. As expected, the shorter the time of concentration, i.e. the time base of the incoming hydrograph, the greater the attenuation efficiency.

ii. The attenuation coefficients obtained from this simplified procedure appear to be different from the ones coming from a more detailed routing method, i.e. the numerical integration of the continuity equation; however, no systematic shift can be observed between the results produced with the two methods.
iii. The classifications of the attenuation coefficients produced by implementing the linear routing, on one hand, and the hydraulic routing, on the other hand, show globally a very similar sensitivity to the time of concentration.

The methodology used in this work may appear overly simplified. However, this work should be seen as a first step in the process of building a robust procedure of classification of the attenuation potential, to highlight the typical features responsible for the attenuation phenomenon. To date, it is certainly clear that particular attention must be paid to the choice of formulation for time of concentration. Further studies are ongoing on this topic.

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