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EFFECTS OF RESERVOIRS ON DOWNSTREAM FLOOD FREQUENCY CURVES

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Abstract

Along with other risk mitigation measures, artificial flood storage has been considered as a smart way to tackle the problem, since it help reducing flood peaks. Dams embedded into the river network are able to modulate the flood wave propagation, given their 'natural' flood attenuation potential driven by the portion of volume available above the spillway crest level. Usually the 'natural' effects that these dams exercise on the flood peak values is not considered when assessing the Flood Frequency Curves (FFCs) of the river reaches downstream. This can become a significant issue in areas where the presence of relatively large reservoirs must be taken into account to provide a correct Flood Hazard estimation. In this study we first use a regional statistical method for flood frequency estimation to assess the 'undisturbed' FFCs at the cross section of several dams in the North West of Italy. The procedure adopted here does not require the definition a priori of an analytic form of the FFC, because the regionalization applies on the three first L-moments, that are allowed to smoothly varying in the space. Then, we correct the 'original' FFCs taking into account the presence of reservoirs. The correction proposed is based on the assessment of the reservoir attenuation effect that has been computed, on all dams, with two different methods: i) by using a simplified and constant attenuation index named SFA (Synthetic Flood Attenuation) and ii) by solving numerically the continuity equation to compute the maximum outgoing peak discharge. Results are examined and compared, first to assess if a single index can be useful to this goal and, secondly, to look for factors responsible of the variability of the actual attenuation effect with the return period. The study has been carried out using all 57 large artificial reservoirs located in the Northwestern part of Italy, for which a comprehensive set of hydrological and structural data has been collected, also with the help of the Italian Dams Authority (Registro Italiano Dighe, RID).

Keywords: Flood Frequency Curves; Reservoirs; Flood Attenuation; Hydrologic Safety.

1. Introduction

In the scientific literature not very many methods for the systematic assessment of the effect of attenuation produced by dams can be found, as most papers are mainly directed to the study of real-time management of floods (Sordo-Ward et al., 2012). In other words, little importance has been given so far to the evaluation of the reservoir attenuation effect on Flood Frequency

Curves (FFC) over large regions, where the curves are determined using regional methods of statistical analysis.

The role of dams on the attenuation of flood quantiles in the river sections downstream was, for example, considered by Robson and Reed (Flood Estimation Handbook, 1999) by means of synthetic indicators as the FARL index, empirically built using the ratios between lake and basin areas. Subsequently, Miotto et al (2007) have shown that there exists the possibility of obtaining, through dimensional analysis, more significant indicators, still based on geometrical factors easy to determine. In particular, Miotto et al. (2007) refer to the need to explicitly take into account at least one indicator relative to the geometry of the spillway crest. Indeed, one of the problems that make non-unique the methodologies to evaluate the attenuation effect on the FFC is the difficulty of identifying standard operational rules, during floods, that apply to the various kind of spillway gates available in the reservoirs. These operation schemes should be able to appear as 'neutral ' with respect to the possible effects resulting from the different states that the stored water volume can assume in the reservoir. In many cases, moreover, gates that partly close surface spillway crests involve additional degrees of freedom in the management during floods, as operation rules, e.g. for the case of hydropower uses, can involve the goal of keeping the water level at its maximum, to maintain a high power production.

On the basis of these premises, we set up a database on the structural features of 57 reservoirs located in Piedmont and Valle d'Aosta, with the aim of integrating the results of a study on regional Flood Frequency analysis carried out for the North West of Italy (Laio et al., 2011). The advancement over that study will be represented by the systematic reconstruction of the FFC curves downstream the reservoirs, as a result of the evaluation of the attenuation effect of flood peaks corresponding to different return periods.

The reconstruction of the so-called “attenuated FFC” (AFFC) is pursued by evaluating the attenuation attitude of dams in “unsupervised” conditions, corresponding to assuming initial volume at the maximum allowed level without surface spillways activation, and assuming no management of the gates possibly obstructing the spillway crests. The gates are always considered fully opened. The volume available for attenuation is then represented as the product of the maximum surface of the reservoir lake times the height reached above the spillway crest when the maximum discharge is being spilled.

The reconstruction of the AFFC is obtained with two methods: in the first instance the synthetic index SFA (Syntethic Flood Attenuation, Miotto et al., 2007) is used. SFA is obtained through a simplified solution of the continuity equation of the dams and provides a constant attenuation coefficient for all return periods.

Subsequently, the effect of unsupervised attenuation is determined by numerically solving the continuity equation over the dam on a large number of flood hydrographs, characterized by having peaks that follow the FFC. For this second case a clear dependence of the result from the shape of the hydrograph curve is well known. For this reasons, some authors used rectangular flood hydrograps (Pianese Rossi, 1986). In our case, we considered that the search of typical features of the attenuation should provide elements for a comparative assessment of the extent of the attenuation that can exist on different reservoirs. To this end, it was decided to use standard forms of the flood hydrograph entering the reservoir lake, even because a thorough investigation on the relationship between the distribution of the peaks and volumes (De Michele et al., 2005; Kottegoda & Rosso, 1997) cannot be afforded without having available several flood hydrograph measures, and appears out of the scope of a large-area assessment.

Results obtained with the two methods were compared to see if the simpler ones allows to recognize a correct ranking of the attenuation effects. Subsequently, variation of the attenuation coefficient with the return period was connected to some specific features of the dams under study.

2. Case study

The 57 reservoirs considered in this study are classified as "of national importance" by the Italian regulations that encompass dams higher than 15 m or with volume at the crest level larger than 10^6 m^3. Among these reservoirs, 50 are located in the Piemonte Region and 7 fall in the nearby Valle d'Aosta Region, as shown in Figure 1.

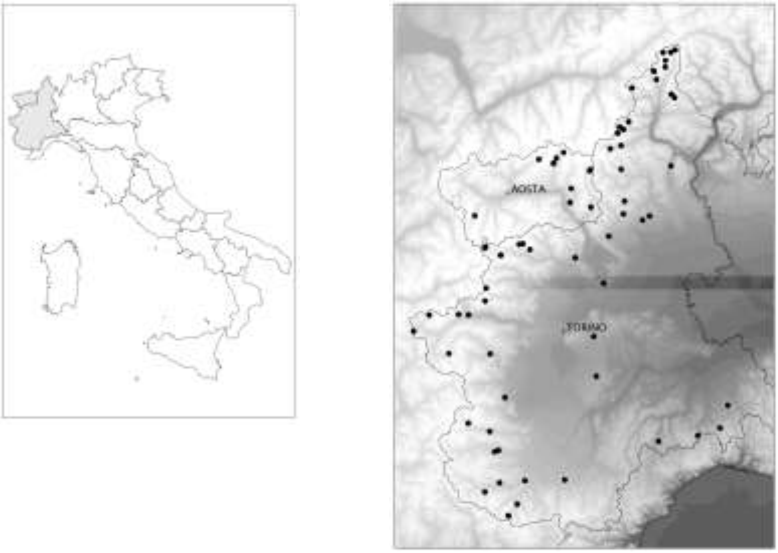

Figure 1: Area of the case study (left panel) in Northwestern Italy and location of the 57 dams used in this study (right panel); most of them are in mountainous areas.

A catalog with the most relevant information regarding each reservoir has been compiled before the analysis, including the dam height, reservoir volume, spillway characteristics for both top and bottom ones. Structural and hydraulic characteristics have been obtained from the Direzione Generale Dighe of the Italian Ministry of Infrastructures and Transports which supervises and approves the building of new dams and operations on existing ones. Given the heterogeneity in the size and type of spillways, a detailed analysis of each reservoir was carried out, to summarize the main characteristics and the functioning scheme of the spillways.

The database of dam characteristics has been extended to include also the information necessary to evaluate the peak flow frequency curve (PFFC) related to the basin closed at the dam location. The effect of the dam on peak flow will determine the changes in the PFFC downstream the structure.The PFFC can be computed based on fitting a probabilistic model to observed flood data or by means of a regional statistical analysis, depending on record availability. In this work we apply the regional approach proposed by Claps and Laio (2008) and Laio et al. (2011), designated as Spatially Smooth Estimation Method (SSEM). It has been calibrated on the basis of the recent database of flood records (Barbero et al., 2012), which includes more than 100 records across the region of interest. Details on the methods are reported in the following section. A large number of basin characteristics can be found, for the same area, in a Morphological Atlas (Gallo et al., 2013) that supports the application of the SSEM. Such characteristics, also known as descriptors, are computed through standard GIS procedures by processing a digital elevation model (DEM) and a number of thematic maps (e.g., precipitation extremes, land use, soil type, vegetation, etc.), all available for the region at hand.

3. Peak Flow Frequency Curves

The assessment of the dam attenuation effect on floods depends on the inflow hydrographs, given the flood peak quantile. The peak flow is, in general, easier to evaluate than the hydrograph shape and volumes, thanks to a greater data availability, and has been calculated in this study according to the above-mentioned SSEM procedure; this procedure will be described below. The definition of the synthetic hydrographs will be treated in section 4.

The SSEM is the most up-to-date regional flood frequency model applied in the area under analysis, and provides relationships to estimate the L-moments of the PFFC from a set of basin descriptors. The L-moments are distribution-free statistics which describe the mean, the variability and the skewness of the distribution of peak maxima, and will be referred to, in the following, as Q_{ind}, L_{CV} and L_{CS} respectively. If an observation record is available and adequately long, L-moments can be directly estimated on the sample record. Otherwise, the regional model is preferable as it compensates the lack of local information (in the ungauged site of interest) with spatial information (time series from other gauged basins).

The SSEM is used here to estimate L-moments of the PFFC for each basin closed by the reservoirs; it computes L-moments from descriptors through regression models accurately selected and tested among a large set of possible alternatives (see Laio et al., 2011 for models set up). Besides being based on an up-to-date hydrological database, the SSEM has also some novel methodological characteristics with respect to other regional models. In a first instance, it does not require the definition of homogeneous regions, thus avoiding subjective elements in the choice and delineation of the regions and their homogeneity testing. As a consequence, Q_{ind}, L_{CV} and L_{CS} are allowed to (smoothly) vary at any river section. SSEM can anyway be considered as an extention of the index-flood method (Dalrymple, 1960), as the expected flood peak Q_T for a fixed return period T is

$$\boldsymbol{Q_T = Q_{ind} \cdot K(L_{CV}\,, L_{CS}\,, T)} \qquad [1]$$

where Q_{ind} is the index-flood (the mean of the PFFC) and the growth factor K K_T is a function of the higher-order L-moments, LCV and LCS. K_T is, however, variable from site to site due to the LCV and LCS variability and it is not region-dependent.

The second main feature of the SSEM concerns the analytical definition of K_T, which is a generic dimensionless (i.e. with unitary mean) probability distribution representing the shape of the frequency curve. In SSEM the choice of the distribution is done only after the regionalization of the L-moments, while other regional models require the distribution to be fixed a priori, in order to regionalize its parameters or its quantiles. In this way, the SSEM avoids to introducing uncertainty due to the choice of the distribution, at least within the regionalization process. Of course, a probability distribution must be selected to apply eq. [1] and compute flood quantiles, but this happens only after the computation of L-moments and this make the estimation of the prediction uncertainty more reliable. In this work, the 3-parameters log-Normal distribution (Hosking and Wallis, 1997) is used to represent the PFFC in the area of interest according to Laio et al. (2011). The SSEM also allows the assessment of Q_T uncertainty through Monte Carlo simulations, but this issue is not considered in this study and it is delegated to future works.

4. Evaluation of the effect of floods on reservoirs

The ability of a reservoir to attenuate a flood peak is estimated over the entire set of 57 dams, using the respective PFFC estimated as described above. As anticipated, the first method used a simplified approach based on the Synthetic Flood Attenuation index (SFA), as it will be briefly discussed in the following.

4.1 SFA index of Flood attenuation

The SFA index (Miotto et al., 2007) is obtained by setting up a simplified framework which considers a linear reservoir forced by rectangular inflow hydrographs. This index is defined as

$$SFA = \frac{1}{R} \cdot \left(\frac{R}{R+1}\right)^{R+1} \qquad [2]$$

where R is:

$$R = 100 \cdot \frac{A_L}{L \cdot \sqrt{A_B}} \qquad [3]$$

R depends, analogously to the FARL index (Scarrott et al., 1999), on the basin area (A_B) and on the lake area (A_L) but also contains the length of the crest spillway (L), one of the most relevant dam characteristics for this analysis. The SFA index results then variable between 0 and 1.

Although the SFA index is only a synthetic indicator, as it does not depend on the inflow discharge, it provides an useful overview on the attenuation performances of the reservoirs. SFA Indices were computed for all of the considered dams and their values will be considered as analogous to the attenuation coefficient η :

$$\eta = \frac{\max[Q_o(t)]}{\max[Q_i(t)]} \qquad [4]$$

that are computed in the second instance of the application. η is the ratio between the outflow peak and the inflow peak. Consequently, the attenuation effect on PFFC curves would result in a translation of the curves, according to the value of the SFA obtained.

4.2 Application of the continuity equation

A more realistic analysis of the flood attenuation is performed through the use of the continuity equation in the form:

$$q_i(t) - q_o(H(t)) = \frac{dV(H(t))}{dt} \qquad [5]$$

where $q_i(t)$ is the inflow hydrograph, $q_o(t)$ is the outflow hydrograph, V and H are respectively the flood control volume and the water level above the spillway crest. The outflow discharge represented by the term $q_o(t)$ is a dam-related equation as it depends on the particular geometrical features of the spillway. Although the solution of equation [5], coupled with a proper spillway equation $q_o(H(t))$, is not particularly complex, a notable problem remains the choice of a reliable inflow hydrograph. In fact, while the peak flow can be reasonably assessed by the regional model, the choice of one (or more) appropriate flood hydrographs is highly subjective, in particular where few or no data is available.

In this study we are mainly interested in the behavior of the reservoir for peak flow at different return periods, which is equivalent to study the change of the PFFC from upstream to downstream the dam. This is important because highlight the “global” behavior of the reservoir, allowing one to identify possible safety limits. At this stage a detailed analysis of the reservoir behavior is not needed because it should be very site-specific. In this context, we prefer to focus on the reliability of the inflow hydrograph peaks, while volume and shapes of the hydrographs are determined with approximated methods.

The peak flow values are computed using eq. [1] for a fixed set of return periods, ranging from 50 to 1000 years, equally spaced in the log(T) space. For each basin, the attenuation coefficient η is obtained for each return period considered.

The duration (D) of the flood event has been taken equal to the double of the concentration time t_c of each basin. There are different empirical equations to compute the concentration time, depending on a number of basin characteristics. Here we consider t_c equal to the ratio between the longest river path and a comprehensive flow velocity of 2 m/s. This approximated method yields values similar to those obtained from the Giandotti equation (Giandotti, 1934), widely used in the Italian context.

The inflow hydrograph is determined according to the peak flow reduction factor introduced by NERC (1975), which is defined as

$$\varepsilon_D = (1 + b \cdot D)^{-c} \qquad [6]$$

where ε is the peak flow reduction for a moving-window of duration D, b and c are two parameters to be determined. Fiorentino et al. (1997) showed that, under some hypotheses, the parameters can be estimated as a function of t_c and the exponent n of the Intensity-Duration-Frequency curve of precipitation extremes. If The average IDF is expressed in the form $h=a\ d^n$, parameters of the [6] can be estimated as $b = 1/t_c$ and $c = 1-n$. For a given event duration D, the flood volume can thus be obtained as $V_D = Q_T \cdot \varepsilon_D \cdot D$, where the dependence on the return periods is included only in the peak flow Q_T. The complete hydrograph is obtained as:

$$q_{in}(t) = Q_T \cdot \varepsilon_D + t \cdot Q_T \cdot \varepsilon'_D \qquad [7]$$

where the apex indicates the first derivative of the function with respect to the duration D. The final hydrograph is obtained after deciding the position of the peak with respect to the beginning of the hydrograph (which fixes the relationship between the chronological time t and the moving-window of duration D): for a central peak and symmetric hydrograph, we have

$$q_{in}(t) = Q_T \cdot [(1 + 2b \cdot\ |t - t_P|)^{-c} - 2b \cdot c \cdot |t - t_P| \cdot (1 + 2b \cdot\ |t - t_P|)^{-c-1}] \qquad [8]$$

The next step toward the solution of the continuity equation is the definition of the relationship between the flood control volume V and the water level H. Similarly to the SFA method, we work with the hypothesis that the initial water elevation in the reservoir is equal to the spillway crest elevation. This is a safety condition because, in case of a lower water level, flood attenuation would be more efficient. Moreover, the V-H law depends on the topography of the area, but can be well represent it in a simplified way. We adopt a reverse pyramidal frustum to describe the flood control volume, which resembles the real shape of most of the Alpine reservoirs.

The last step is the choice of the spillway functioning scheme. Since the aim of the work is to study the unsupervised attenuation effect of the dam, we consider only the free outflow from the spillway, without resorting to operations on mobile gates.

Under the above hypotheses, equation [5] is numerically integrated by an implicit method to obtain the outflow hydrograph. An example of the inflow and outflow hydrographs for the Ceresole Reale reservoir is shown in the left panel of Figure 2, while the right panel reports the effects on the PFFC with attenuation coefficient η variable with the return periods.

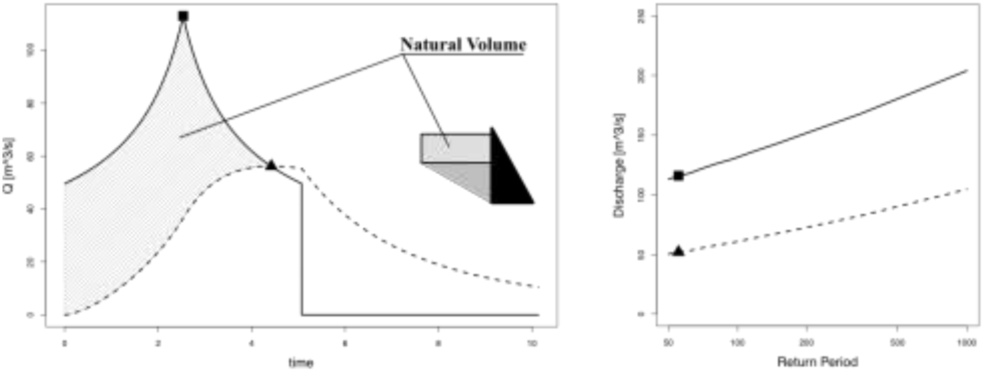

Figure 2: Natural and Attenuated inflow hydrographs and Flood Frequency Curves for the Ceresole Reale Reservoirs. The black square represents the inflow flood peak while the triangle is the outflow peak.

5. Discussion

The attenuation coefficient values η obtained solving numerically equation [5] and the synthetic SFA values have been first compared. Since η values are function of the return period T of the inflow peak discharge is not possible to compare directly the values of η and SFA, but a comparison between the reservoir ranking (i.e. the order of efficiency) is possible.

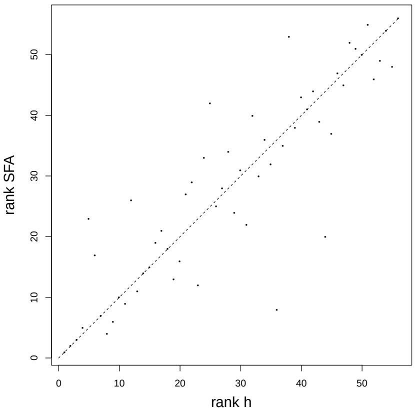

Figure 3: comparison between computed η and synthetic index SFA

As shown in Figure 3, SFA and η have, in most of the cases, similar ranks. SFA index can therefore be considered a reliable method to give a first assessment of the attenuation potential of the Piemonte Region reservoirs that have been studied. On the other hand, SFA index provides only a single level of reservoir efficiency, while η can be function both of hydrograph shape and of peak discharge return period. Solving numerically the continuity equation we obtained a different attenuation coefficients η_T, for each return period T of the incoming flood (Q_T). As can be seen in Figure 4a and 4b, the value of η increases with the return period T, with a greater variability (i.e. the standard deviation σ) for η values close to 0.5. The slope of the η-T line (i.e. the value of σ) is significant for central values of η, while for low ($\eta \approx 0$) or high ($\eta \approx 1$) values the behaviour is still monotonically increasing but with not relevant increments.

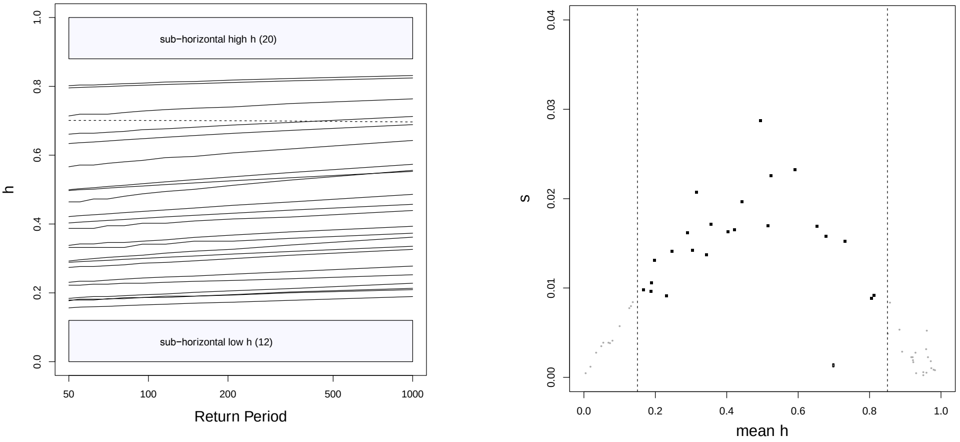

Figure 4: a) η in relation with the return period T. The dashed line is "Brusson" dam, the only one without an increasing trend. b) Relation between mean and standard deviation of η_T, the central values are reported in black.

As the different return periods are equally-spaced in the requency domain (F), a consistent value for the mean attenuation coefficient ($\bar{\eta}$) can be provided for each reservoir. It is then possible to link these mean values of η with a number of physical descriptors, through a multi-regressive analysis. The aim is to provide a way to asses average values of $\bar{\eta}$ for other dams on the basis of its structural features and of morphologic and hydrologic parameters of the related basin. We performed all the possible regressions combining from 1 to 4 of the descriptors used in the SSEM analysis. Regressions coefficients were tested in their significance with the t-Student test, and for multicollinearity with the VIF test. The models presenting all-significant coefficients were sorted according to the related adjusted coefficient of determination (R^2_{adj}).

The final regression model obtained is:

$$\bar{\eta} = -0.44057 - 0.17072 \cdot \mathrm{LOG}(A_{LAKE}) + 0.12583 \cdot \mathrm{LOG}(A_{BASIN}) + 0.01373 \cdot IDF_a \qquad [9]$$

where A_{LAKE} is the lake area, A_{BASIN} is the basin area and IDF_a is the coefficient of the intensity-duration curve. The comparison between computed ($\bar{\eta}$) and estimated coefficients is reported in Figure 5. The multi-regressive analysis provides a good and reliable quantitative assessment of the attenuation coefficient, even if these results are at the moment limited to reservoirs similar to the alpine ones considered in the present study.

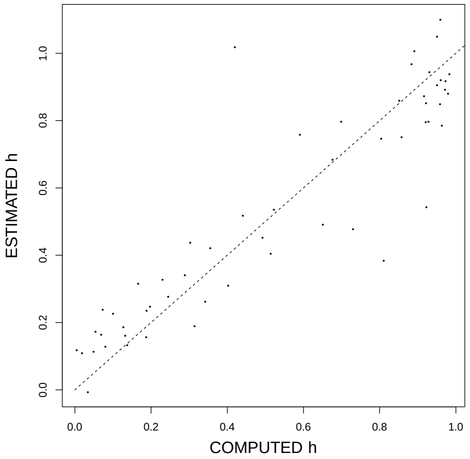

Figure 5: Comparison between computed and estimated coefficient of attenuation η

6. Conclusions

Attenuated Flood Frequency Curves (AFFC) can be derived solving numerically equation [5] for different flood peak discharge, one for each return period T taken into consideration. These curves are derived from a point to point reconstruction of the whole regional FFC and not only from a simple quantiles reduction. AFFC can be a useful tool to define more properly flood hazard in areas downstream the reservoirs. The present study has shown how the attenuation coefficient value η is not constant, but increases with the return period T of the incoming flood peak discharge. In the case study considered the standard deviation of the attenuation coefficient (i.e. the slope) is significantly high for central values of ($\bar{\eta}$). A parametric relation between the mean attenuation value and a series of significant physical descriptor has also been obtained, through multi-regressive analysis. A link between lake and basin characteristics, rain intensity and the reservoir efficiency has been found.

Relation [9] connecting the average attenuation to physical parameters gives a first and reliable indication about the attenuation efficiency of alpine reservoirs. This indication could be used as a method to recognize in advance reservoirs with a good natural attenuation potential from the ones that might need preemptive drawdown operations to properly attenuate the inflow peak discharges.

Further studies are needed to assess until which distance downstream the positive effects of reservoirs in flood peak reduction can still be observed, and to better generalize the results according to different hypotheses on the flood hydrograph shape.

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