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Exploring the robustness of the Synthetic Flood Attenuation Index for large-scale flood hazard assessment

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Abstract: *Dams can modify the propagation of flood hydrographs by naturally dampening flood peaks. However, this effect is often overlooked when assessing flood frequency curves, leading to potential inaccuracies in estimating flood hazard downstream, particularly in areas where a large number of reservoirs exist. This work focuses on a preliminary robustness assessment of the Synthetic Flood Attenuation (SFA) index, which incorporates key factors influencing flood mitigation effectiveness of artificial reservoirs. We update results for a sample of dams in Northwestern Italy from a previous study and compare the SFA index's classification of flood attenuation potentials with a national-scale analysis we recently performed. This comparison aims to understand the suitability of the SFA index across various reservoir-territory combinations, given its assumptions of no spatial rainfall variability and standardized morphology. Our findings suggest the SFA index appears to be a reliable tool for a preliminary assessment of flood attenuation potentials at a national scale in Italy, even if further studies are needed to clarify its range of applicability. This analysis provides a basis for further development and application of the SFA index to support sustainable flood risk management strategies.*

Keywords: *dam, flood, flood attenuation, reservoir, synthetic index.*

1. Introduction

The temporary accumulation of water volumes in an artificial reservoir during a flood event results in a reduction of the peak value of the outflow hydrograph, compared to the inflow hydrograph – a phenomenon commonly referred to as the flood attenuation effect. This makes dams and reservoirs major components of flood protection strategies, especially in flood-vulnerable countries, such as Italy. Despite the importance of artificial reservoirs in flood risk mitigation, a small number of dams were originally designed for flood control. For instance, less than 3% of large Italian dams were built for this purpose. There is now increasing interest in the multipurpose use of existing reservoirs, based on the understanding that these reservoirs may provide sustainable attenuation of flood peaks, which can help to mitigate the impact of severe flooding events.

Flood risk assessment requires a comprehensive understanding of how reservoirs influence the downstream flood regime. While there is significant expertise in understanding the hydraulic aspects of the attenuation process, a major gap exists in methods that can systematically and comprehensively assess the performance and capabilities of dam systems in reducing flood risk and in implementing this effect in large-scale flood frequency analyses. To address this need, researchers often rely on the use of synthetic indices (e.g. Scarrott et al. 1999, Miotto et al. 2007, Batalla et al. 2004, López and Francés 2013, Xiong et al. 2019, Cipollini et al. 2022).

Indices offer simplified yet effective tools for evaluating the flood attenuation potential of reservoirs without requiring extensive hydrodynamic modeling. They are not only easy to use, but can also become compatible with data-based regional statistical methodologies. However, challenges arise when attempting to compare results from different indices, since a standardized reference is needed to determine which is the most accurate one.

The effectiveness of flood attenuation is strongly influenced by hydrological and hydraulic factors. The first category encompasses climatic and morphological features of the upstream basins. From the second category, on the other hand, the lake area and the length of the spillway crest should be certainly mentioned. An early attempt to assess the sensitivity of flood attenuation efficiency, particularly with regard to efficiency ranking, to such factors was carried out by Masoero et al. (2014), with respect to dams in the regions Piedmonte and Valle d'Aosta, in Northwestern Italy. More recently, the sensitivity of dam efficiency throughout Italy has been extensively investigated and proved by Evangelista et al. (2023), which is used here as a term of reference.

In this work, we focus on a preliminary analysis of the robustness of the Synthetic Flood Attenuation (SFA) index by Miotto et al. (2007), which incorporates crucial factors identified by Evangelista et al. (2023) and is directly comparable with the actual attenuation coefficient resulting from the solution of the differential equation of the lakes. Indeed, the SFA index is not purely empirical but derived from a simplified lake equation under the assumption of a rectangular incoming hydrograph, following a dimensional analysis of the attenuation phenomenon.

The contribution of this work is twofold; first, the results obtained by Masoero et al. (2014) are updated. Then, to quantify the suitability of the SFA index, the results of the classification of flood attenuation potentials produced by Evangelista et al. (2023) for 265 Large Dams throughout Italy, selected on the basis of preliminary criteria of relevance, are compared with those obtained using the SFA index. The comparison aims to understand the extent and for which class of reservoirs the use of the SFA index may be recommended. Given the basic logic of the SFA index, which assumes no spatial variability of rainfall and standardized morphology, this comparison is crucial to verify its behavior and identify any potential biases, especially in terms of efficiency ranking.

In pursuing this approach, we aim to lay some basis for a rapid, yet robust, countrywide assessment of the flood mitigation effect, which would be of significant value for both scientific research and practical applications.

2. Data and Methods

The analysis is carried out on a carefully selected sample of dams, excluding decommissioned dams, those already used for flood control purposes, dams where no flood attenuation volume is available, and those with lake-to-watershed area ratios below 1/150. Structural information on the 265 reservoirs considered and hydrological and morphological features of their upstream basins are sourced from a recent database, produced in collaboration with the General Department of Dams and Hydro-Electrical Infrastructures, as detailed in Evangelista et al. (2023). This database represents a significant improvement over previously available fragmented information. Key advancements are the control of lake area values using a high-resolution digital elevation model, the systematic computation of basin contours and the calculation of basin parameters of critical importance for flood hydrology, especially rainfall-related parameters, updated to 2019.

Figure 1 shows the sample of selected dams, classified according to their storage volume, with a quite uniform distribution across the country.

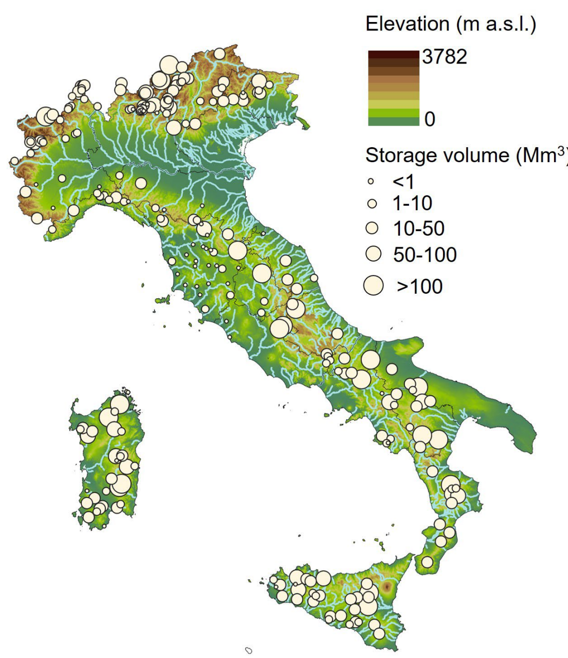


Figure 1. Distribution of storage volumes for 265 selected large dams.

2.1. Synthetic non hydrological method

The SFA index (Miotto et al., 2007) arises from a dimensional analysis of the attenuation phenomenon, by considering a linear reservoir forced by a rectangular incoming hydrograph. The quantitative nature of the SFA index was the main reason we chose to focus on it rather than other indices available in the literature.

The index is defined as:

$$SFA = \frac{1}{R}\left(\frac{R}{R+1}\right)^{R+1} \tag{1}$$

where

$$R = \frac{A_L(1-n)}{2t_L C_d W} \tag{2}$$

In Eq. (2) A_L is the lake area, C_d is a discharge coefficient that depends on the spillway type and W is the length of the spillway crest. t_L is the basin lag time and n is the scaling exponent of the index rainfall curve, according to:

$$h_{mean} = ad^n \tag{3}$$

where h_{mean} is the average rainfall depth, a is the rainfall depth for 1-hour duration and d is the duration. An expeditious SFA can be applied if considering that: i) C_d can be assumed to be constant, given that most of the existing spillways have a standard Creager weir; ii) an average n value can be assumed; iii) the basin lag time can be simplified by the square root of the basin area A_B, as suggested by Rossi and Villani (1994). R will be then defined as:

$$R = \mathrm{c}\frac{A_L}{W\sqrt{A_B}} \tag{4}$$

with c=100 based on the above simplifications. Eq. (4) enables the systematic and parsimonious application of the index at national scale.

2.2. Hydrological method

A more quantitative analysis has been conducted in the studies by Masoero et al. (2014), for Northwestern Italy, and Evangelista et al. (2023), at the national level. The flood attenuation potential has been determined by the ratio η between the peak of the outgoing flood to the peak of the incoming flood; the effectiveness of the dam increases as η decreases. The outflow discharge $q_o(h(t))$ required to estimate η has been computed by solving the differential equation of lakes:

$$q_i(t) - q_o(h(t)) = \frac{dV(h(t))}{dt} \tag{5}$$

where $q_i(t)$ is the inflow discharge, V is the lake volume and h is the water level above the spillway crest.

Two different hydrograph shapes, including a rectangular one, are used in Evangelista et al. (2023) and index-flood from the rational method is adopted as the incoming peak value. To manage the uncertainty associated with the input hydrograph estimation, twenty-four different design floods are derived adopting two hydrograph shapes and minimal parameter options, i.e., the basin runoff coefficient, the time of concentration, which controls the hydrograph duration, and the rainfall parameters a and n of Eq. (3).

To ensure consistency across all assessed dams and facilitate a robust comparative analysis, several hypotheses are introduced by both Masoero et al. (2014) and Evangelista et al. (2023). First, only surface spillways are used for flood attenuation, without any active gate management. This simplifies the operational dynamics of the reservoirs, making it easier to apply the analysis uniformly all over Italy. This assumption doesn't seem too restrictive as, in Italy, over

50% of large dams are equipped with only free spillways. Furthermore, the initial water level in the lake is assumed to be equal to the level of the spillway crest, i.e. the reservoir is full when the flood routing starts. This prudential approach also removes the variable nature of the initial reservoir level, which can fluctuate significantly throughout the year. Finally, the analysis permits reservoir levels to exceed their maximum designed value during flood events, implying no constraints due to potential overtopping. In other words, the reservoir is considered to be unlimited in capacity. This assumption is introduced to evaluate the full attenuation potential of the reservoirs, independent of structural safety limits.

Results and Discussion

2.3. Updated assessment of flood attenuation potentials in Northwestern Italy

A first comparison with the work of Masoero et al. (2014) was carried out on a subset of 32 reservoirs of Piemonte and Valle d'Aosta. The scatterplots in Figure 2 show some of the parameters used to perform the analyses described in Section 2.2. The rainfall parameters a and n have undergone substantial updates (Figures 2a and 2b) due to the integration of recent rainfall records. These differences have direct consequences on the estimates of flood peaks entering the dams (consider, for example, the rational formula for peak discharge estimation).

As for the catchments upstream of the dams, their areas appears to be almost unchanged (Figure 2c). Indeed, it is reasonable to assume that there have been no significant changes in the procedure adopted to delineate the basin boundaries.

On the dam side, Figures 2d and 2e show that the lake areas and the lengths of the spillway crest have undergone some variations. While changes in the lake area values are due to the recomputation performed by Evangelista et al. (2023), changes in the lengths of the spillway crests may reflect instances where dam geometry has been modified to accommodate higher flow discharges. Changes in the values of A_L and W directly impact the estimated SFA values, as shown in Figure 2f. Among the dams analyzed, the Lago Eugio (1), Lomellina (2) and Ostola (3) dams exhibit the largest differences in SFA values.

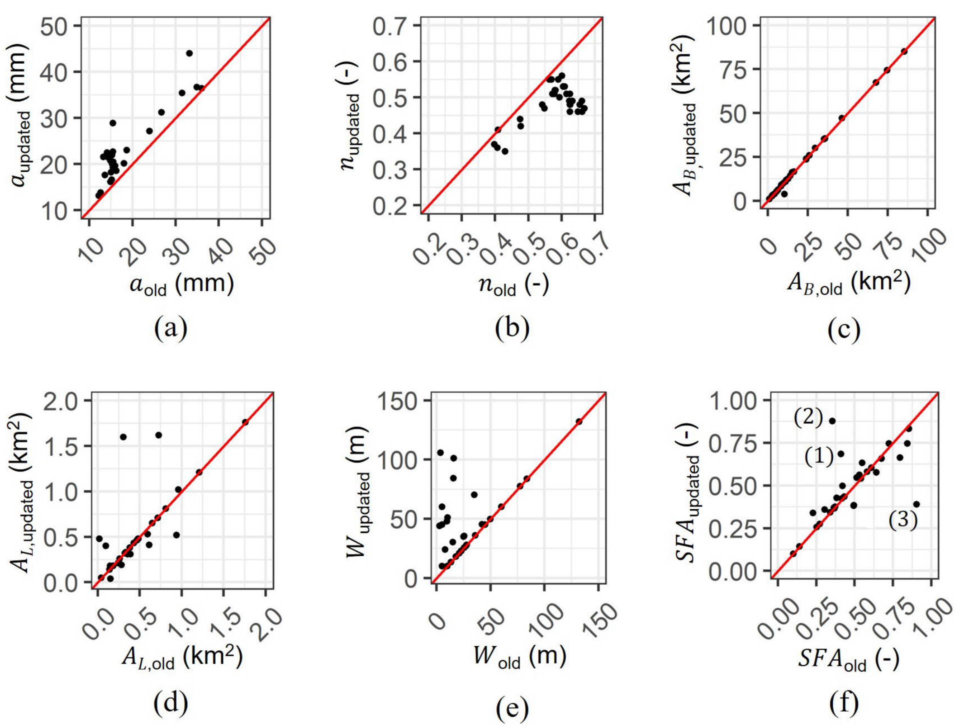


Figure 2. Update, for a sample of dams in the regions of Piemonte and Valle d'Aosta, of the rainfall curve parameters a (a) and n (b), upstream catchment areas (c), lake areas (d), spillway crest lengths (e) and values of the SFA index (f). The x-axes display the parameters used by Masoero et al. (2014), while the y-axes show those updated by Evangelista et al. (2023). In (f) the Lago Eugio (1), Lomellina (2) and Ostola (3) dams are highlighted.

A direct comparison in terms of the attenuation coefficient η, derived from the solution of Eq. (5), has not been possible due to differences in the methodologies employed by the two studies: Masoero et al. (2014) considered a 100-year flood quantile, whereas in Evangelista et al. (2023) an average flood has been used.

2.4. Towards the integration of dam effects in flood frequency analyses

In Masoero et al. (2014) an initial attempt to compare η and SFA values has been made. Here a more systematic comparison is carried out at the national scale. The empirical cumulative distributions of SFA values and actual reservoir efficiencies (η) obtained using three synthetic hydrographs with non-rectangular shapes are presented in Figure 3. Although the shape of the input hydrograph was found to not be a crucial factor for flood mitigation assessment (see Evangelista et al. (2023)), η values derived from non-rectangular hydrographs have been selected for the comparison to further evaluate the robustness of the index.

Hydrographs are built by considering site-specific rainfall and geomorphological characteristics of the upstream basins, employing varying levels of simplification. As a result, these hydrographs differ in both peak value and duration. While the specific characteristics of the three hydrographs are not of primary importance now, the key observation from Figure 3 is that the empirical cumulative distribution function (hereinafter ECDF) of the synthetic index is congruent with the others. In general, we can observe an overestimation of efficiency for low values of the attenuation potential (distribution of SFA below the others) and an underestimation for high values of the attenuation potential (distribution of SFA above the others). It is important to note that overestimating attenuation capacity for low values of η may represent an issue, as such a result is not safety-oriented. However, this is less concerning for dams that already perform well in flood attenuation. It should also be pointed out that this overlapping does not imply that a single dam may not have significantly different SFA and η values when moving from one ECDF to another.

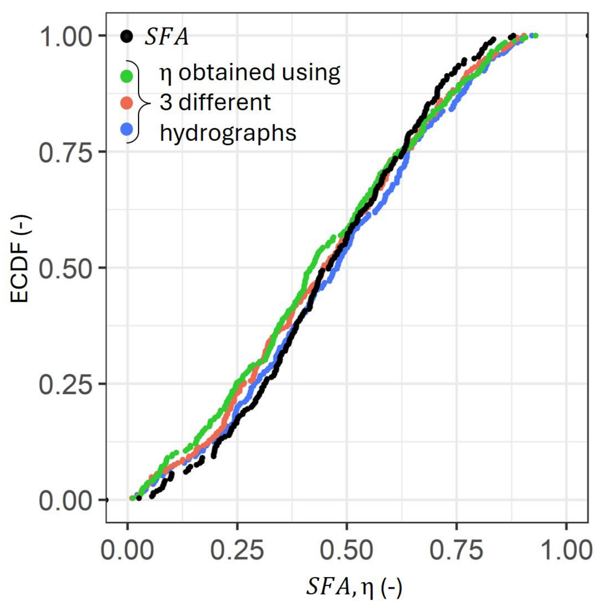
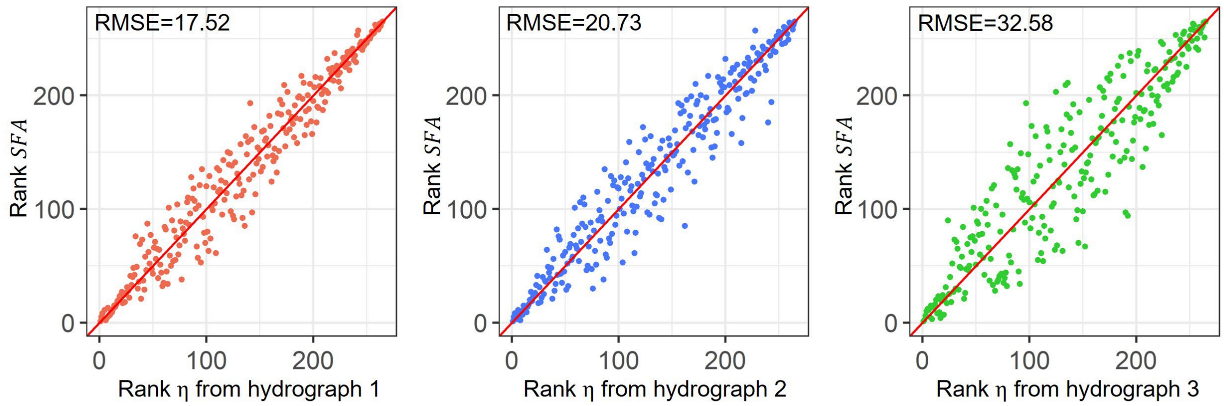


Figure 3. Comparison of empirical distribution of SFA values with η attenuation coefficient values derived from the solution of Eq. (5), considering hydrographs of varying peak and duration.

A comparison in terms of reservoir ranking (i.e. the order of efficiency) is also needed. This allows us to be independent from the specific value of η (or of the SFA index), which strictly depends on the assumptions adopted. 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). Scatterplots in Figure 4 show the variability of the order position of each dam, obtained with the index or attenuation coefficients, along with the Root Mean Square Error (RMSE) values. The RMSE values vary as a function of the type of hydrograph used for comparison. However, it is noteworthy that no significant bias emerges and the index seems to perform well in estimating ranks, despite the simplifications adopted in Eq. (4). This lack of bias reflects the general nature of the index and its independence from the specific attributes of any particular set of dams (see Miotto et al. (2007) for technical details).

These initial findings suggest that the SFA index may be a suitable tool for studies of wide-area flood frequency analyses. Further investigation into hydrograph characteristics that mostly affect the consistency of the rankings will be required for a thorough assessment of robustness. This aspect of the analysis is planned for future research efforts.



(a) (b) (c)

Figure 4. Comparison of efficiency rankings built using the SFA index and attenuation coefficients derived from three different incoming hydrographs. Root mean square error (RMSE) values are given.

3. Conclusions

In this study, a sample of 265 reservoirs is considered to assess unsupervised flood attenuation indices using two categories of methods: a synthetic, non hydrological one (Miotto, 2007) and a complete, hydrological one (Evangelista et al., 2023). While this second approach contributed to clarify the influence of local hydrological and climatic factors on flood attenuation potentials, the synthetic approach is particularly suited for frequency analysis and is compatible with automated statistical methods. The analysis has been performed using a recent database that includes geometric characteristics of dams and morphological and rainfall features of their upstream catchments.

Comparing the results from these two approaches has allowed us to examine the behavior and assess the potential biases of the synthetic method, particularly in terms of efficiency ranking. The indicators identified by Miotto et al. (2007), including the lake area, the length of the spillway crest and the basin area, have been confirmed to be suitable for a rapid assessment of the unsupervised attenuation potential. While the influence of these parameters on mitigation efficiency is well-documented, we have shown that this set of indicators is reliable not only at local scales, but also at the national level. Additional research is needed to more clearly determine the applicability limits of this synthetic approach, with respect to dam-catchment configurations, for large-scale flood frequency assessment.

4. ACKNOWLEDGMENTS

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