Safety of Italian dams in the face of flood hazard

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1. Introduction

Dams have segmented most rivers with associated environmental impacts, sometimes disruptions. The interspacing of dammed, inundated, preserved and restored reaches has fragmented large watersheds by disconnecting once integrated free-flowing systems (*e.g.* [1]), and river impounding is often blamed for jeopardizing biodiversity downstream [2–4]. However, dams provided support to economic and social development worldwide, and a large number of dams under construction and planned is a matter of significance in the world today. The safe operation of dams has significant social, economic, and environmental relevance, and appropriate management procedures are necessary (*e.g.* [5,6]). Dams will continue to provide valuable services, but rehabilitation is needed because of (1) the new hydrological safety requirements posed by increasingly risk-averse societies, (2) the changes in the downstream river and riparian system after the dam were built, and (3) the modified priorities of watershed management.

A large number of dams was built in Italy during the XX century under different engineering, social, economic, and possibly climate conditions from those nowadays. As a consequence large uncertainties affect the policies for mitigation of flood hazard in regulated rivers. Uncertainties descend from the complexity of both physical and man-controlled processes, including scale problems in observation and modeling, management strategies and operational practice. Additional uncertainty is given by the lack of knowledge of the effects of dams on floods downstream, let alone the unexplored evolution of social perception of flood risk after dams were built and operated for a long time. Lack of knowledge of worldwide dam accidents is a further factor of uncertainty, in spite of the role of incident reporting and data collection in enhancing reservoir safety [7].

Berga [8] reported that dam failures had been significantly reduced in the XX century. The percentage of failures before 1950 was 2.3%, while for dams constructed from 1951 to 1982 it reduced to 0.2%, and since 1982 it was 0.09%. Major advances are associated with ameliorated structural safety, but hydrological safety of dams, and safe design of flood spillways are also major concerns, and hydrologists worldwide continuously investigate new methods to approach spillway design under uncertainty (*e.g.* [9,10]). The Committee on Failures and Accidents to Large Dams [11] of USCOLD estimated that overtopping covered more than 40% of dam failures worldwide. Charles et al. [12] showed that most of the failures of embankment dams causing loss of life can be attributed to the embankment breaching due to either of two

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causes, namely: (1) overtopping during an extreme flood, and (2) internal erosion due to piping or hydraulic fracture. Study of overtopping is largely within the province of hydrology, and so is design flood assessment for the provision of appropriate spillway and freeboard, and guidelines emphasize the importance of design flood as a key factor to dam safety [13,14]. For instance, in the United States, over 2000 dams (3% of the 75,000 US dams) were identified as potential hazards to people living in upstream or downstream areas, due to inadequate spillway capacity [15]. The International Commission on Large Dams [16] suggested that the return period R of the spillway design flood should range from 1000 to 10,000 years, depending upon exposition and vulnerability of downstream riparian areas (*e.g.* [17], for a comparative study of regulatory frameworks for dam safety worldwide). One notes that the length of the available hydrological series (typically $R \leqslant 50$–100 years), is too short for any site specific flood estimation based on local data, if available.

The American Society of Civil Engineers [18] reports that the average age of the 84000 dams in the country is 52 years. Many of these dams were built as low-hazard dams protecting undeveloped agricultural land. However, with an increasing population and greater development downstream, the overall number of high-hazard dams continues to increase, to nearly 14,000 in 2012. The number of deficient dams is estimated at more than 4000, which includes 2000 high-hazard dams. The Association of State Dam Safety Officials estimates that it will require an investment of $21 billion to repair these aging, yet critical, high-hazard dams.

In Italy there are 548 large dams, *i.e.* those displaying dam height higher than 15 m, or impounded storage larger than 10^6 m^3 (*e.g.* [19], and Fig. 1). Design and building records are available for 488 dams only, 83% of which (403 dams) were built before 1970, and roughly 41% (198 dams) before 1950. About 63% (332 dams) are concrete dams (arch, gravity, or both) and 31% (165 dams) are earth dams. Spillway design flood q_S was generally evaluated using empirical formulas based on stream flow records available at the time of dam completion, without any probabilistic argument to support hydrologic hazard and dam safety. Governmental surveillance of dams was enforced after 1925, after a major dam's failure occurred at the Gleno reservoir, on December 1st 1923, causing at least 353 deaths. However, a national authority was established in 1989 only, called SND and further RID. It operated for about 20 years before being discontinued, and its mission included generic infrastructure management, with unclear liabilities by the National and Regional Administrations. RID recommended the rehabilitation of dam spillways in order to accommodate the 1000 years flood, regardless of dam's type.

To assess the capability of the existing dam spillways to accommodate the 1000 years flood one has to face large uncertainties. The assessment of low frequency flood flows is cumbersome in Italy, because the average length of Annual Flood Series (*i.e.* the largest observed annual peak flow, henceforth referred to as AFS) is about 28 years [20]. After 1970, systematic stream flow records decreased countrywide, because of lacking responsiveness by both governmental and local agencies. Also, a few dam sites, if any, are equipped to measure hydrological flows continuously, so site specific data of (long term) dam operation are unavailable in practice. Notwithstanding so, one needs to achieve a first, approximate but comprehensive assessment of flood hazard in Italian large dams, hopefully before some catastrophic event will focus the social perception of risk. The estimation of low frequency flood figures plays an essential role in assessing current and future hazard. This paper provides an answer to this question using the regional approach to low frequency estimation of flood flows.

2. Flood frequency estimation and safety of dams in Italy

2.1. Regional approach

Statistical prediction of floods with low frequency has been a major task of hydrology insofar (*e.g.* [21,22]). Manifold methods are available to predict flood frequency in poorly gauged basins, but large uncertainties still remain for floods with high return periods, *e.g.* larger than 100 years. Application of regional methods provides the state-of-the-art approach, also supported by scaling arguments [23]. Extreme value theories (*e.g.* [24], for a comprehensive review) provide the mathematical core. The index flood method provides the operational framework [25–28]. This is a two-step procedure. The first step is the identification of homogeneous regions, where a common extreme value probability distribution can be adopted to accommodate renormalized flow figures. Homogeneity of a region can be assessed using different criteria [23,29,30,31]. In a homogenous region one can assume that the renormalized variable, say X, has the same frequency distribution, $F_X(x)$, for all river sites in the region, and the R-year flood can be estimated as $q_R = q_i\, x_R$, where x_R denotes the R-years quantile of X, and q_i the renormalization parameter, i.e. the index flood, which is usually taken as the expected value or the median of the probability distribution of maximum annual flood. The regional cumulative distribution function $F_X(x)$ of X, henceforth referred to as *cdf*, is known as the *growth curve*, and it is generally understood to reduce uncertainty for increasing return period as compared with estimates achievable by fitting the *cdf* to single site data [32–34]. If insufficient or no stream flow data are available, the regional flood frequency curve provides more accurate estimates than that achievable by deriving the *cdf* from precipitation and other climate statistics [20].

The estimation of index flood, q_i, is the second step. The approach mainly depends on data availability, and the methods range from statistical regression of flood data versus catchment parameters and/or precipitation and other climate statistics [35], to conceptualization of rainfall runoff processes [36], and high resolution watershed modeling using a spatially distributed framework [37].

Data availability is the major concern. If local flood data are available, one can either use the observed AFS to get a direct statistical estimate of the mean or the median, or explore the observed Partial Duration (PDS) series, or the Peaks Over a Threshold (POT) series, to improve accuracy of estimation [32,38,39]. PDS approach requires, a preliminary, not trivial, threshold estimation to assess statistical independence of peaks [40]. When few or no stream flow data are available, the index flood may be estimated via rainfall-runoff simulation, using of either observed precipitation data [41–43], or generated data through stochastic simulation methods [44–47]. These methods may provide accurate results, but involve time consuming data handling and processing, and 'business-as-usual' application is not straightforward. Alternatively, index flood value can be estimated by way of derived distribution approach based upon expected storm scaling [48,49], multiple regression and other regional empirical formulas, historical flood marks, paleohydrology or fluvial geomorphology of bank-full discharge figures [50]. However, all these methods require site specific investigations, so application to large scale assessment is cumbersome. A straightforward method to achieve a countrywide assessment is power law scaling of floods against drainage area, based upon the finding that maximum annual flood peaks within homogeneous regions display statistical scale invariance as parameterized by drainage areas, A [51,52].

2.2. Regional flood assessment in Italy

Italy stretches for more than 1000 km from North to South, and displays tremendous relief from the coast to mountainous inland. Climate regimes of Italy range from Mediterranean hot, to continental with cold Winter and hot Summers, to Alpine with seasonal snow cover and permanent glaciers and permafrost (*e.g.* [53]). Hydrologic regime and flood generation processes strongly vary in space and time, so flood prediction must account for these factors. Also, most flood series are relatively short (about 28 years on average), so introducing large uncertainties in floods estimates with low frequency. A countrywide assessment of flood frequency figures was provided starting more than twenty years ago by the National research Council of Italy (henceforth referred to as CNR) after the completion of the National Flood Estimation Project (henceforth referred to as *VAPI*). The final report is a collection of regional reports delivered by major research institutions in this research area (see [54], where one retrieves the list of individual regional reports). *VAPI* project identified 23 homogeneous regions countrywide (see Fig. 2) and two different *cdf*s were adopted to accommodate $F_X(x)$ to regional observations. The General Exteme Value distribution (henceforth referred to as GEV) was selected to accomodate the variability of growth curve in North-Western Italy. Elsewhere, the two component estreme value (TCEV) *cdf* [55–58] was used based on the conjecture that floods are generated from two different mechanisms, or precipitation patterns, *i.e.* frontal and convective [59].

Bocchiola et al. [60] further tested the performance of GEV, TCEV, three parameters Log-Normal (Gibrat-Galton) and Generalized Logistic to accomodate renormalized regional flood data in these 23 regions. Statistical analysis using state-of-the-art hypothesis testing procedures showed that GEV predictions provide the most accurate estimates in most cases, and that these estimates display the lowest variance of estimation for regional samples. Therefore, they provided GEV estimates of renormalized maximum annual flood countrywide, and these estimates were suggested by RID based on parsimoniousness and reliability arguments. The GEV *cdf* is used here to represent renormalized regional flood, X, in Italy in order to estimate regional quantiles, x_R. Regional power law scaling is then used to estimate index flood at each dam site.

The estimated index flood is then combined with the regional growth curve to assess the expected return period of spillway design capacity, q_S. We further investigated the role of drainage area in determining the potential hazard, in order to assess safety of major dams. This helps in assessing the need of rehabilitation, also indicating the route towards ameliorated dam operation and river management.

2.3. Dam safety in Italy

In Italy governmental surveillance of dams was enforced after the Gleno dam failure in 1923. After three major accidents in year 1935 (Molare dam, more than 100 deaths), in year 1963 (Vajont dam, about 2,500 deaths) and in year 1985 (Stava reservoir, 268 deaths) the surveillance procedures by the national authorities were progressively enforced. Several accidents with minor or no losses of human lives occurred after year 1985, the last of which at Montedoglio dam in Central Italy, on December 2010. This dam was initiated in year 1978, and then completed in 1990, so it is a rather recent facility as compared with the average age of Italian dams.

Spillway capacity q_S could be evaluated for 445 dams out of 584, based on the design reports and the periodical surveys made available by former *RID*. One notes that spillway facilities are complex structures in most cases, because they involve both open and submerged weirs, operating in parallel under both automatic and manually operated modes. In most cases, physical scale models were built at the time of dam construction or after its completion, to test the effective capability of the spillway system.

3. Methods

3.1. Regional growth curves GEV

We exploited the available data sets from the CNR *VAPI* reports for the 23 homogenous regions of Italy (Fig. 1(b)) to build normalized flood frequency quantiles using the GEV distribution, as

$$x_R = \varepsilon + \frac{\alpha}{k}(1 - \exp(-k\, y_R)) \tag{1}$$

with ε, α, k, denoting the regional GEV position, scale and shape parameters, respectively, and $y_R = -\ln[\ln(R/(R-1)]$ the Gumbel variate. The data base we used here includes about 7300 AFS sampling values, *i.e.* the maximum annual flood figures observed in 264 gauged rivers, evenly spread countrywide. The period of observation is from 1921 to 1970 countrywide, and from 1921 to 1993 for North Western Italy. The data were collected and controlled by the former SIMN agency (Servizio Idrografico e Mareografico Nazionale) now discontinued.

The definition of homogeneous regions flood wise was carried out in Italy based upon a TCEV distribution, and hierarchical approach [57] except for regions 2(a)–(c) in Fig. 1. Thus, we assumed that statistical homogeneity in a hierarchical TCEV analysis may translate into statistical homogeneity into a non-hierarchical GEV application, which is not proven as yet for Italy. However, hierarchical approach to regional flood assessment can be pursued successfully also when using GEV distribution [58], so there is no *a priori* limitation in this sense. Notice that the focus here is not to either discuss the potential drawbacks and limitation of the present regional framework of *VAPI*, or to develop a new regionalization method, which would require effort way beyond this paper, and building of credible motivation against use to the present one, but to use the presently available method to provide an assessment of dams' safety for Italy. As reported SND and RID enforced retrofitting of flood spillways with $R_S = 1000$ years, based upon the *VAPI* regions, so use of such template seems warranted. According to a recent study from the authors, regionally estimated GEV distribution would provide better estimation of flood quantiles (within the same regions, and based upon the same pooled flood data), while providing a mathematically simpler way for quantile calculation, than the iterative approach required by TCEV. Also, using GEV, one may assess confidence limits for R years quantile [33], not available for TCEV that we know of. Given such purely data driven evidence, GEV distribution is tentatively used here. For each catchment within each homogenous region, we calculated index flood q_i, as the average of the AFS series of maximum yearly flood, q. Then, the yearly maximum floods in each site were made dimensionless with respect to q_i to obtain a growth factor, as $x = q/q_i$.

For each region, all the growth factors x values in the pertaining catchments were pooled into one single sample, so obtaining 23 pooled samples (one for each homogeneous region). This sample, supposedly homogeneous, was used to estimate the regional GEV distribution of the (dimensionless) growth factors x_R, using L-moments approach [61]. To assess distribution fitting of the so obtained GEV distribution a number of statistical tests were then carried out (namely Pearson or χ^2, Anderson–Darling AD, Kolmogorov–Smirnov KS, and confidence limits for GEV quantiles CL [33]).

3.2. Regional index flood estimation

Flood flow records are not available at dam sites, usable to estimate the index flood based on site specific observations. A

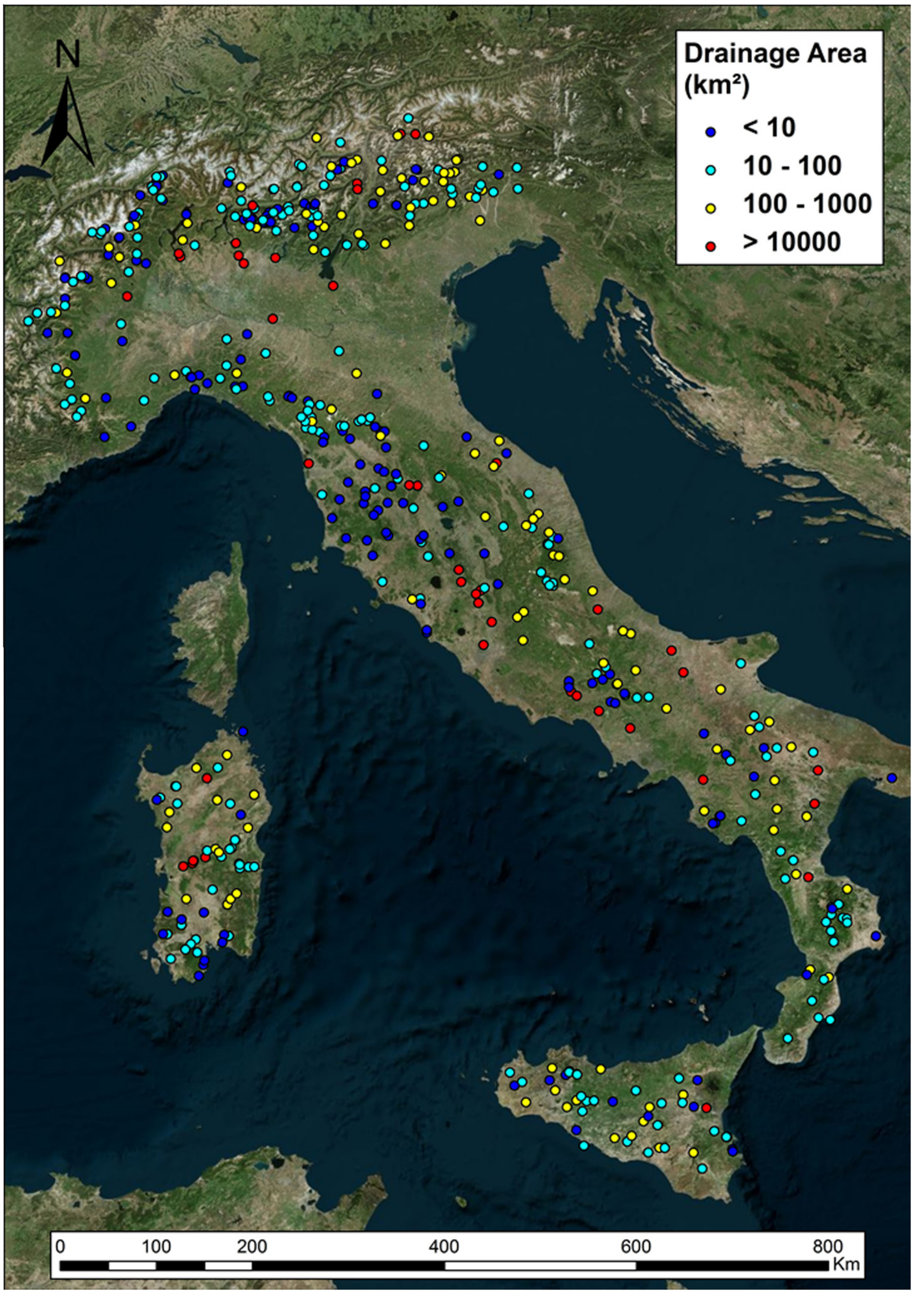


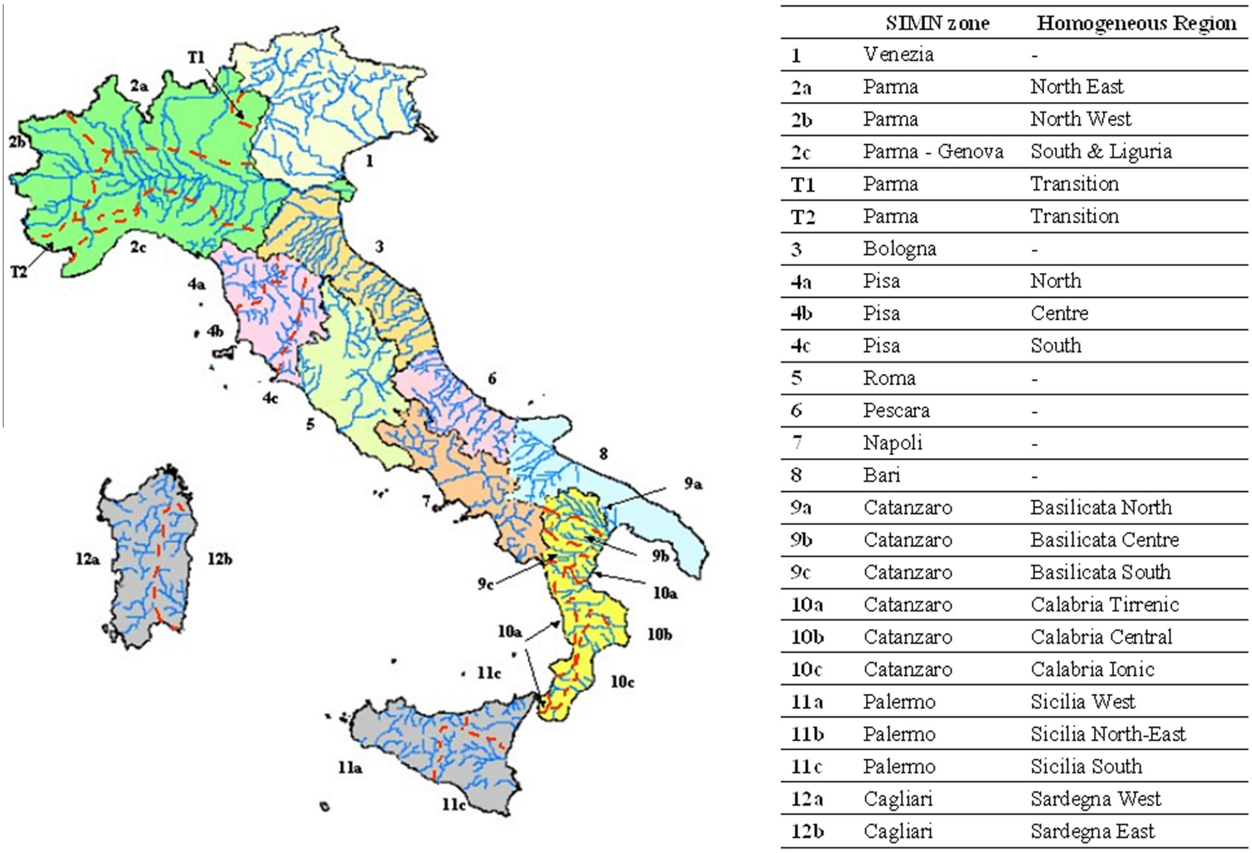
Fig. 1. Investigated large dams of Italy. Color scale of dams sites displays the contributing area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

straightforward method is to apply the concept of scale invariance with basin area within a homogenous region, as introduced, among others by Gupta et al. [51], Robinson and Sivapalan [52] and Bocchiola et al. [28]. Power laws of flood quantiles against drainage area stem from the (self-similar) structure of channel networks, climate and soil properties, and scaling theory gives reason of the physical implications of floods formation in streams [62,63]. Scale invariance against area A in each homogeneous region was estimated here using q_i at each dam site within the region as

$$\hat{q}_i = q_i(1)\,A^m \tag{2}$$

where m is a scaling exponent and $q_i(1)$ is the index flood associated to the unit area, both calculated by a multiple regression of the logarithmic transformed sample mean, $\mathrm{Log}(q_i)$, versus the logarithmic transformed values of drainage area Log (A), within a homogeneous region. Here, we assessed $q_i(1)$ and m by way of jack-knife linear regression. Although scale invariance usually holds over a limited range of scales (or areas), to be determined from observed data [23], scaling with catchment area is sometimes assumed as a reasonable working assumption over a wide range of scales for rule-of-thumb estimation [64]. The estimation variance of q_i depends upon the properties of the homogeneous region and can be assessed by the determination coefficient D of the regression. One has $\sigma^2_{\hat{q}i} = \sigma^2_{qi,s}(1-D^2)$, where $\sigma^2_{qi,s}$ denotes the variance of the observed sample of q_i in the homogeneous region, estimated from the observed data.

Eventually, to evaluate the return period associated with the spillways design discharge q_S of a specific dam site j with known drainage area A_j we carried out a three steps procedure, namely (i) estimate local index flood according to Eq. (2), (ii) associate an



	SIMN zone	Homogeneous Region
1	Venezia	-
2a	Parma	North East
2b	Parma	North West
2c	Parma - Genova	South & Liguria
T1	Parma	Transition
T2	Parma	Transition
3	Bologna	-
4a	Pisa	North
4b	Pisa	Centre
4c	Pisa	South
5	Roma	-
6	Pescara	-
7	Napoli	-
8	Bari	-
9a	Catanzaro	Basilicata North
9b	Catanzaro	Basilicata Centre
9c	Catanzaro	Basilicata South
10a	Catanzaro	Calabria Tirrenic
10b	Catanzaro	Calabria Central
10c	Catanzaro	Calabria Ionic
11a	Palermo	Sicilia West
11b	Palermo	Sicilia North-East
11c	Palermo	Sicilia South
12a	Cagliari	Sardegna West
12b	Cagliari	Sardegna East

Fig. 2. Homogeneos regions of Italy for flood hazard assessment in Italy.

estimated growth factor corresponding to local spillways design discharge q_{Sj}, and (iii) invert Eq. (1) as a function of that growth factor, to assess the frequency of exceedance of q_{Sj}, as

$$\begin{aligned} F_S(q_{Sj}) &= \exp\left\{-\left[1-\frac{k}{\alpha}(x_{RSj}-\varepsilon)\right]^{\frac{1}{k}}\right\} \\ &= \exp\left\{-\left[1-\frac{k}{\alpha}\left(\frac{q_{Sj}}{\hat{q}_i}-\varepsilon\right)\right]^{\frac{1}{k}}\right\} \\ &= \exp\left\{-\left[1-\frac{k}{\alpha}\left(\frac{q_{Sj}}{q_i(1)A_j^m}-\varepsilon\right)\right]^{\frac{1}{k}}\right\} \qquad (3) \end{aligned}$$

We then estimated the return period R_S of the saturated capacity of the spillway as

$$R_S = \frac{1}{1-F_S} \qquad (4)$$

4. Results

Tables 1 and 2 report the parameter estimates for flood evaluation. Table 2 also contains information on AFS data availability (N_s number of gauged sites, N_e number of equivalent years) for the 23 Italian homogeneous regions of the *VAPI* procedure. Also, Table 1 reports estimated scaling of index floods according to Eq. (2). In Basilicata and Calabria regions (see Fig. 2) a few gauged rivers were available, so homogeneity of index floods when scaled against area was obtained by grouping some sub regions. In Pescara region, flood scaling was observed to differ in gauged sites of the Pescara river from that observed elewhere in the region, so two different power laws were adopted. The scaling exponent m ranges from $m = 0.24$ for Palermo region (however based upon five sites only) to $m = 1.04$ for Calabria (a,b) region, but it is mostly clustered within a quite narrow range of variability, namely with $E[m] = 0.75$, and $CV[m] = 0.18$. Visual inspection did not display noticeable changes of scaling exponent with area, or scale breaks in either region. However, accurate investigation of scale breaks is beyond our current purpose, and it should be targeted by a specific analysis.

Fig. 3 shows the countrywide growth curves x_R against y_R for Italy, the corresponding parameters are reported in Table 1, where a summary of statistical tests are also reported (χ^2, AD, KS, and CL), with significance level 5%. The chosen statistics for AD and KS tests are valid for an *a priori* known distribution (*i.e.* with parameters assumed *a priori*, and not estimated from data). Notice that *a posteriori* reference statistics for AD and KS tests, albeit possibly found for some distributions (e.g. GEV, Generalized Logistic, for AD test in [65]), are not available for both tests, and for all distributions (*e.g.* TCEV, Lognormal, etc.), that we know of.

Pearson χ^2, accounting for parameter estimation, also indicates good fitting using GEV. CL test indicates that mostly GEV distribution fits well the observed data.

Fig. 4 reports the share of dams displaying a given range of return period of spillway saturation, as per four area bins from 0.1 to 10,000 km^2. Globally, 55% (245) of the dams display $R_S > 10{,}000$, and $R_S > 1000$ for 71% (315) of the investigated dams. There are 130 dams (29%) with spillway saturation occurring with a return period $R_S < 1000$ years, this indicating a not negligible potential risk of failure. One also finds 62 dams (14% of the countrywide sample) with a spillway displaying a value of $R_S < 100$ years, *i.e.* there might be a noteworthy potential risk of dam overtopping. The distribution of R_S is independent of basin area, except for catchments with area $A > 1000$ km^2. Focusing on

Table 1

Estimated parameters, and goodness of fit test of GEV distribution for the 23 hydrologically homogeneous regions of Italy according to *VAPI* procedure. Shape parameter $k = 0$ (–) implies use of Gumbel distribution. Goodnes of fit assessed using three different tests, Pearson or χ^2, Anderson–Darling AD, and Kolmogorov–Smirnov KS. Ref. is reference statistics (AD, KS, *a priori* distribution fitting, $\alpha = 5\%$). CL is test for confidence limits ($\alpha = 5\%$), passed (Y), or not passed (N). In *italic* we report cases when goodness of fit test is not passed.

Region		*GEV* Parameter			Ref.			GEV			
		ε	α	k	χ^2	AD	KS	χ^2	AD	KS	CL
1	Venezia	0.77	0.32	−0.13	14.1	2.49	0.05	13.7	0.62	0.03	Y
2a	Parma A	0.74	0.36	−0.11	11.1	2.49	0.08	1.5	0.16	0.03	Y
2b	Parma B	0.63	0.35	−0.32	11.1	2.49	0.08	4	0.56	0.06	Y
2c	Genova C	0.64	0.38	−0.28	14.1	2.49	0.05	3.9	0.28	0.01	Y
3	Bologna	0.77	0.36	−0.08	12.6	2.49	0.05	2.5	0.31	0.02	Y
4a	Pisa A	0.68	0.39	−0.20	12.6	2.49	0.06	9.7	0.67	0.03	Y
4b	Pisa B	0.69	0.41	−0.15	12.6	2.49	0.05	15	0.94	0.03	N
4c	Pisa C	0.73	0.37	−0.13	11.1	2.49	0.09	6.9	0.39	0.05	Y
5	Roma	0.78	0.30	−0.13	12.6	2.49	0.07	8.5	0.38	0.03	Y
6	Pescara	0.73	0.36	−0.15	12.6	2.49	0.06	17.1	2.01	0.05	Y
	Napoli	0.78	0.36	−0.05	11.1	2.49	0.08	3.2	0.22	0.02	Y
7	Bari	0.69	0.47	−0.08	11.1	2.49	0.09	3.21	0.20	0.03	Y
8	Basilicata A	0.57	0.50	−0.23	7.8	2.49	0.17	1.63	0.32	0.06	Y
9a	Basilicata B	0.66	0.35	−0.29	7.8	2.49	0.17	2.7	0.28	0.06	Y
9b	Basilicata C	0.77	0.31	−0.16	7.8	2.49	0.13	7.9	0.25	0.04	Y
9c	Calabria A	0.79	0.36	–	7.8	2.49	0.17	6.2	0.60	0.10	Y
10a	Calabria B	0.63	0.40	−0.27	11.1	2.49	0.08	6.5	0.41	0.30	Y
10b	Calabria C	0.60	0.47	−0.24	9.5	2.49	0.13	7.74	0.56	0.06	Y
10c	Palermo A	0.70	0.44	−0.10	12.6	2.49	0.09	16.7	1.99	0.07	Y
11a	Palermo B	0.66	0.48	−0.12	9.5	2.49	0.14	7.1	0.85	0.08	Y
11b	Palermo C	0.61	0.53	−0.14	7.8	2.49	0.17	4.8	0.46	0.07	Y
11c	Cagliari A	0.62	0.47	−0.19	11.07	2.49	0.09	18	2.57	0.09	N
12a	Cagliari B	0.55	0.46	−0.29	9.5	2.49	0.11	3.2	2.29	0.04	Y

Table 2

Data base of flood peaks for the 23 homogeneous hydrological regions of Italy, and estimated parameters of observed flood scaling. $q_i(1)$ is the index flood associated to an unit area, m scaling exponent, and D determination coefficient of the regression.

Region				Flood scaling		
		N_s	N_e	$q_i(1)$ ($m^3\ s^{-1}$)	m (·)	D (·)
1	Venezia	23	857	0.54	0.83	0.50
2a	Parma A	14	316	2.10	0.80	0.65
2b	Parma B	14	347	0.50	0.90	0.65
2c	Genova C	15	753	5.90	0.73	0.78
3	Bologna	30	708	1.99	0.76	0.49
4a	Pisa A	24	493	1.15	0.92	0.91
4b	Pisa B	21	594	2.58	0.76	0.94
4c	Pisa C	7	227	3.58	0.69	0.48
5	Roma	12	383	0.99	0.77	0.88
6	Pescara river	19	550	0.15	0.84	0.75
6	Pescara			0.74	0.89	0.89
7	Napoli	8	259	1.75	0.79	0.81
8	Bari	14	344	1.61	0.737	0.81
9a	Basilicata A	3	66	16.16	0.44	0.54
9b	Basilicata B	2	63			
9c	Basilicata C	5	137			
10a	Calabria A	3	64	0.37	1.04	0.66
10b	Calabria B	11	255			
10c	Calabria C	5	116	3.16	0.66	0.72
11a	Palermo A	12	227	1.98	0.79	0.84
11b	Palermo B	4	97	1.58	0.85	0.84
11c	Palermo C	5	62	66.07	0.24	0.86
12a	Cagliari A	8	234	1.15	0.84	0.79
12b	Cagliari B	5	149	28.54	0.44	0.98

the 37 dams (8.3% of the sample) within the largest contributing area, one finds that 27 display $R_S < 1000$ years (and 23 have $R_S < 100$).

5. Discussion

Our results provide some room for discussion. A number of simplifying hypothesis were made in our dams safety assessment, that may result in some over-simplifications of the application of state-of-the-art methods, to evaluate the multifaceted potential risk associated with old and often un-maintained Italian dams.

Flood routing was neglected in all cases. This has likely a negligible effect on safety assessment of dams impounding small mountain streams, but it can provide an essential contribution to safety of dams impounding large rivers. Therefore, the actual value of R_S may increase for large catchments, and our approach may be distorted therein. This might be reflected in the anomalous number of potentially dangerous dams impounding large rivers as reported. However, one notes that the largest majority of Italian dams was built in rivers with small contributing areas (see Fig. 4).

Notice that the estimated return period R_S refers to the event “Exceeding of spillways design flood”. The latter does not mean *per se* overtopping of the dam for a number of reasons, including flood routing, pool level management, safety margins, semi-height of wind waves, length of fetch, wind direction, etc. A record of overtopping events for Italy is not available that we know of, so no comparison could be made in this sense. Also, overtopping does not imply *per se* the occurrence of any particular event, say if the dam’s body is not breached, and if river conveyance downstream is large enough, so overtopping events may have occurred without any large consequences, and without having been recorded officially.

Clustering of hydrologically similar drainage basins, and extrapolation of regional growth curves relied upon the *VAPI* template of flood wise homogeneous regions. This approach was assumed to better fit the requirement of estimating flood figures with very low frequency, but the database available in Italy is still poor and there is no real hope of improving it in the next future. Pooled rescaled flood data from each homogeneous regions were used to estimate the growth curve, which was accommodated using the GEV model. Fig. 3 and Table 1 show that there is a large variability in Italy, as indicate by shape parameter k ranging from $k = 0$, *i.e.* Gumbel distribution for Calabria B region, to $k = -0.32$ for the Parma B region in Northern Italy.

Index flood estimates using simple scaling with basin area is widely accepted in diagnostic analysis of flood patterns, but using it to back estimate the index flood in ungauged rivers may entail

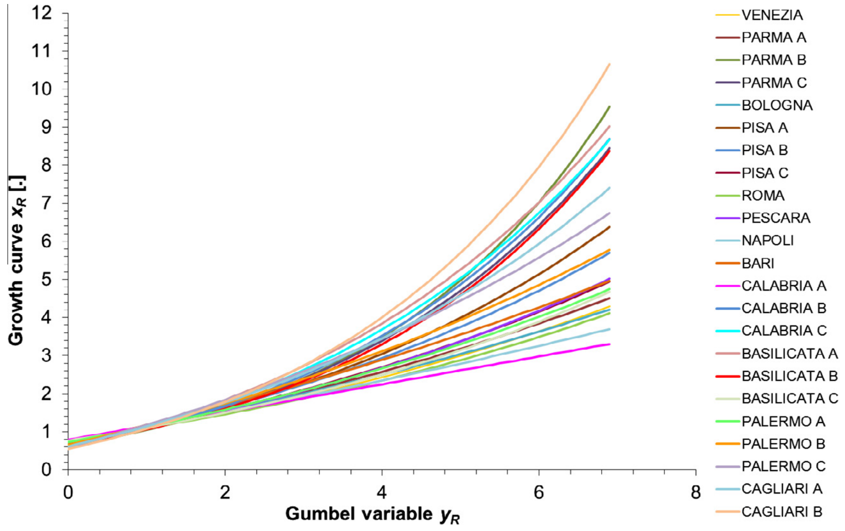


Fig. 3. Growth curves for the 23 homogeneous hydrological regions of *VAPI* project.

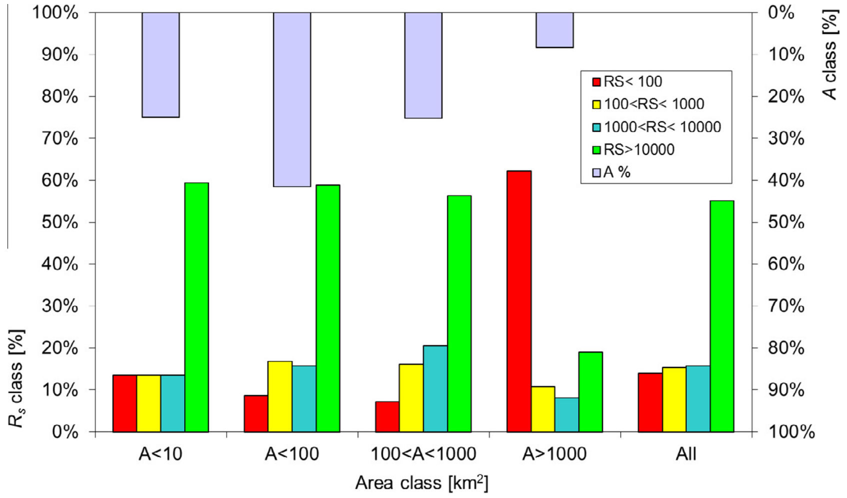


Fig. 4. Class of return period RS os spillway saturation per class of contributing area A.

considerable uncertainty, and local conditions may provide different behavior with respect to the generally valid regional one. We could not collect systematically flow data from all the dams' sites, given that these are not publicly available. The estimated scale invariance parameters (Table 2) pertain to SIMN monitored stream sections, concerning relatively large rivers (*i.e.* $A > 100$ km^2 or so), while several of our dam sites drain relatively small catchments ($A < 10$ km^2, see Fig. 1), and the issue arise whether scale invariance holds for these latter. Recently, we were able to collect AFS data from dam sites with small area ($A \approx 1$–600 km^2) in Region 2a (19 sites), and Region 2b (6 sites), covering 1932–2002 (on average 38 years of data for each basin). We found that for small catchments (down to 1 km^2) scale invariance as reported in Table 2 well fits the observed index floods (not shown for shortness). However, such assessment could not be done systematically country wise given the lack of data as reported.

Our analysis here displayed scaling exponents m generally coherent with those reported in scientific literature, where m values are found to depend upon physical properties of the catchment, including soil thickness, and texture, and hydrological network structure and response [62].

Eventually, the scaling approach seems a powerful method when no information is available locally, and a large scale assessment is needed, like here, to define sites at risk, where more refined studies need be carried out.

We found that almost one third of the investigated dam sites display $R_S < 1000$ years. This apparently indicates that detailed analysis is needed to improve current safety of a large number of Italian dams, so dam rehabilitation should ameliorate spillway capacity when required. The dams in small rivers with spillway saturation for short return period (i.e. $R_S < 100$ years) are the first candidates to re-analysis of dam safety.

In Fig. 4 we report the percentage distribution within the 23 homogeneous regions of those dam sites where $R_S < 1000$ years. One third or so of these dams are located within regions Parma A and Parma C, *i.e.* central Italian Alps (21%), and Thyrrenian Liguria (12%). Also, Palermo C region (South Sicily, 9%), and Cagliari B (East Sardinia, 13%) have some hot spots for dam safety (see Fig. 5).

The estimation of R_S by way of Eq. (3) and Eq. (4) may entail some inaccuracies, as given by uncertainty in flood quantile estimation, *e.g.* expressed using confidence limits [33]. However, one may assume that estimation of low return periods is relatively accurate. In turn, sites with low return periods design flood q_S are more likely to be at risk of exceedance, and accurate assessment is more important therein. We evaluated the confidence limits of R_S, which we back calculated from the confidence limits of x_{RS}

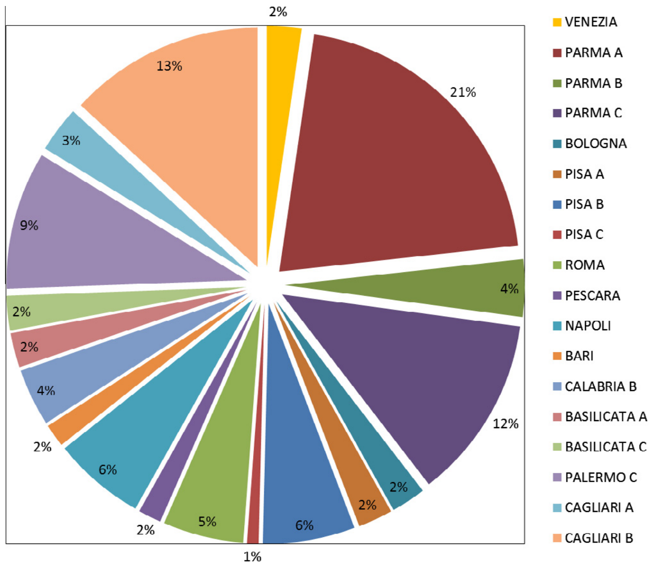


Fig. 5. Percentage distribution of dams with $R_S < 1000$ years within the 23 homogeneous regions of *VAPI* procedure. Regions missing, no dam sites presenting $R_S < 1000$ years.

($\alpha = 5\%$) for regional GEV estimation, as set out by De Michele and Rosso [33], for each of our homogeneous regions (not shown for shortness). The width of the confidence limits (upper value R_S+ minus lower value R_S-) clearly increases with R_S. For sites displaying $R_S \leqslant 10$ years, we found on average confidence limits (variation with respect to the estimated value) within the range ±0.5 years, with a largest value of ±2 years. For sites displaying $10 \leqslant R_S \leqslant 100$ years, we found on average ±6 years, with max ±22 years. For $100 \leqslant R_S \leqslant 1000$ years, we found on average ±57 years, with max ±245 years. For $1000 \leqslant R_S \leqslant 10000$ years, we found on average ±385 years, with max ±2200 years. Of the 130 sites with $R_S \leqslant 1000$ years, only 7 had an upper boundary $R_S+ > 1000$ years (but not larger than 1200 years), and of the 315 sites with $R_S > 1000$ years, only 1 had $R_S- < 1000$ (*i.e.* 990 years). Therefore, the R_S estimates we provided here seem to deliver an acceptably accurate indication as to whether a local assessment needs to be done, and the priority therein, independently of potential uncertainty.

To evaluate the return period of design flood q_S bypassing the issue of choosing a parent (*i.e.* GEV here) distribution and of the uncertainty therein, we could have adopted *e.g.* a model-average approach, by simultaneously considering several different distributions, mirroring what done in some cases when dealing with design flood quantile assessment [66]. Indeed, whenever a given distribution would provide a scarce performance in representing flood quantiles x_{RS} (and assessment of the return period R_S of a given quantile in backward estimation as we did here), clearly this would need be discarded, so less performing distribution would not be used anyway. On the other hand, if more than one distribution would provide a similar performance (*i.e.* a similar value of X_{RS}, or return period R_S), the final estimated value will not be so much different, albeit the results may be significantly improved statistically. Notice further that return period here needs basically be assessed on a logarithmic scale, so averaging of different (acceptably performing) distributions would likely change our results marginally. Given the focus here is delivering a first order of magnitude of the frequency (or return period) of exceedance of q_S for a large number of dams, while accurate assessment needs to be carried out locally with more complex studies, this seemed unnecessary here. GEV distribution is easily usable, depicts acceptably flood risk within our target regions, and it is capable of capturing rapidly (hyperbolically) increasing extreme floods, so its use here seemed appropriate.

Operation of Italian reservoirs dates back 60 years and more, sometimes to the end of the XIX century. Ever since then, changes of hydrological behavior of our streams may have occurred due to climate change, and modified hydrological response as per land use changes. Our analysis of flood hazard here implicitly rely upon an assumption of stationarity during the period of measurements (1921–1970), and further assumes that distribution fitting upon that period is representative now, which is debatable indeed. However, we have little way to investigate this facet with no recent data available. Even in the future flood safety of dams may be influenced by climate change, that is expected to enhance flood occurrence and severity in both Alpine and Mediterranean areas [67,68], and large impoundments may even feedback into modified climate conditions locally [69]. However, our method can provide a statistical tool for hazard screening, and duly address investigation of critical cases, also including potential effect of recent, and prospective climate change.

6. Conclusions

We attempted here to perform a countrywide assessment of dam safety for Italy, where flood assessment dates back 60 years and more in some cases, and both hydrologic data and dam operation figures became quite unavailable in last 40 years. This required comprehensive flood evaluation for the peninsula, and neat, locally based assessment of flood quantiles at each and every one of our 450 dam sites. To tackle such large scale effort, we exploited the available state of the art regional approach as provided by *VAPI* of Italy and investigated i) site specific index flood assessment using scale invariance against area, and ii) assessment of the return period of spillway design flood at each dam site using a regionally valid extreme value distribution.

Our results showed that 55% (245) of the 448 examined dams are equipped by spillway with $R_S > 10000$; and 71% (315) of the dams have $R_S > 1000$. Conversely, 29% (130) of the dams display $R_S < 1000$ years, lower than required. The spillway of 14% (62) of the dams has $R_S < 100$ years, indicating unacceptably low frequency of exceedance, and potential overtopping, and witnessing that accurate local re-assessment is utmost needed therein. Uncertain as our results might be given the over simplified approach we adopted, the present work deliver evidences that Italian dams display non negligible hazard hydrologically, and intervention is needed to cope with the most critical cases, and in general to provide an updated assessment of flood risk.

Our results are therefore methodologically interesting for scientist in the field of hydro-geological hazard, and stake holders in the area of reservoirs management, and provide a quantitative, albeit preliminary highlighting of critical cases for hydropower companies in charge of dams' safety maintenance, as well as a potential, priority driven road map for dams' rehabilitation in Italy.

References

[1] Graf WL. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resour Res 1999;35(4):1305–11.

[2] Dugan P, Allison EH. Water: act now to restore river health. Nat Correspondence 2010;468:173.

[3] Palmer MA. Beyond infrastructure. Nat News Views 2010;467:534–5.

[4] Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, et al. Global threats to human water security and river biodiversity. Nature 2010;467:555–61.

[5] Pisaniello JD. A comparative review of environmental policies and laws involving hazardous private dams: 'appropriate' practice models for safe catchments. William Mary Environ Law Policy Rev 2011;35(2) [Article 4].

[6] Pisaniello JD, Tingey-Holyoak J, Burritt RL. Appropriate small dam management for minimizing catchment-wide safety threats: International

benchmarked guidelines and demonstrative cases studies. Water Resour Res 2012;48:W01546.

[7] Charles JA. Use of incident reporting and data collection in enhancing reservoir safety. Dams Reservoirs 2005;15(3):29–35.

[8] Berga L. New trends in hydrological safety. In: Berga L, editor. Dam safety. Rotterdam, The Netherlands: Balkema; 1998. p. 1099–110.

[9] Bowles D, Swain R, Ostenaa D. A framework for characterization of extreme floods for dam safety risk assessments. In: The national dam safety program, research needs workshop: hydrologic issue for dams, 538. Federal Emergency Management Agency, Publication; 2005. p. 125–38.

[10] De Michele C, Salvadori G, Canossi M, Petaccia A, Rosso R. Bivariate statistical approach to check adequacy of dam spillway. J Hydrol Eng 2005;10(1):50–7.

[11] Committee on failures and accidents to large dams of the United States committee on large dams. Lessons from dam incidents, ASCE/USCOLD, New York, USA; 1975.

[12] Charles JA, Tedd P, Halcrow AW. Delivering benefits through evidence. Lessons from historical dam incidents. Bristol, UK: Environment Agency Publication; 2011.

[13] Dubler JR, Grigg NS. Dam safety policy for spillway design floods. J Prof Issues Eng Edu Pract 1996;122(4):163–9.

[14] De Almeida AB, Viseu T. Dams and valley: a present and future challenge. In: De Almeida AB, Viseu T, editors. Proc., int. NATO workshop on dams and safety management at downstream valleys, Lisbon, Portugal. Rotterdam, The Netherlands: Balkema; 1997. p. 3–25.

[15] American Society of Civil Engineers. Dam safety. Policy Statement 280, ASCE Publication, New York; 2000.

[16] International Commission on Large Dams. Dam design criteria. The philosophy of their selection, ICOLD Bullettin 61, 83pp., Paris; 1988.

[17] Bradlow DD, Palmieri A, Salman SMA. Regulatory frameworks for dam safety: a comparative study. Washington, DC: World Bank. License: CC BY 3.0 Unported; 2002. https://openknowledge.worldbank.org/handle/10986/13826.

[18] American Society of Civil Engineers. Report Card for America Infrastructures. Dams. ASCE Online Publication, New York; 2013. http://www.infrastructurereportcard.org/dams/.

[19] Maugliani V. La manutenzione delle dighe e la vigilanza governativa in Italia [Dam maintenance and government surveillance in Italy]. L'Acqua 2010;3: 39–52 [Italian with abstract in English].

[20] Bocchiola D, Rosso R. Use of a derived distribution approach for extreme floods design: a case study in Italy. Adv Water Res 2009;32(8):1284–96.

[21] Fuller WE. Flood flows. Trans ASCE 1914;77:564–617.

[22] Hazen A. Discussion on "Flood flows" by W.E. Fuller. Trans ASCE 1914;77:526–63.

[23] De Michele C, Rosso R. A multi-level approach to flood frequency regionalization. Hydrol Earth Syst Sci 2002;6(2):185–94.

[24] Kottegoda NT, Rosso R. Applied statistics for civil and environmental engineers. Oxford: Blackwell; 2008. 736p.

[25] Benson MA. Factors influencing the occurrence of floods in a humid region of diverse terrain. US Geological Survey Water Supply Paper, 1580B; 1962.

[26] Hosking JRM, Wallis JR. Some statistics useful in regional frequency analysis. Water Resour Res 1993;29(2):271–81.

[27] Sveinsson O, Boes DC, Salas JD. Population index flood method for regional frequency analysis. Water Resour Res 2001;37(11):2733–48.

[28] Bocchiola D, De Michele C, Rosso R. Review of recent advances in index flood estimation. Hydrol Earth Syst Sci 2003;7(3):283–96.

[29] Burn DH. Catchment similarity for regional flood frequency analysis using seasonality measures. J Hydrol 1997;202:212–30.

[30] Castellarin A, Burn DH, Brath A. Assessing the effectiveness of hydrological similarity measures for flood frequency analysis. J Hydrol 2001;241:270–85.

[31] Di Prinzio M, Castellarin A, Toth E. Data-driven catchment classification: application to the PUB problem. Hydrol Earth Syst Sci 2011;15:1921–35.

[32] Madsen H, Pearson CP, Rosbjerg D. Comparison of annual maximum series and partial duration series methods for modelling extreme hydrologic events. 2: Regional modelling. Water Resour Res 1997;33(4):759–69.

[33] De Michele C, Rosso R. Uncertainty assessment of regionalized flood frequency estimates. J Hydrol Eng ASCE 2001;6(6):453–9.

[34] Katz RW, Parlange MB, Naveau P. Statistics of extremes in hydrology. Adv Water Resour 2002;25:1287–304.

[35] Robson A, Reed D. Flood estimation handbook (FEH), vol. 3. Wallingford, UK: Institute of Hydrology; 1999.

[36] Burlando P, Rosso R. Effects of transient climate scenarios on basin hydrology. 2: Impacts on runoff variability in the Arno river, Central Italy. Hydrol Process 2002;16:1151–75.

[37] Rosso R, Rulli MC. An integrated simulation approach for flash-flood risk assessment. 2: Effects of changes in land use under a historical perspective. Hydrol Earth Syst Sci 2002;6(2):285–94.

[38] Adamowski K. Regional analysis of annual maximum and partial duration flood data by nonparametric and L-moment methods. J Hydrol 2000;229:219–31.

[39] Önöz B, Bayazit M. Effect of the occurrence process of the peaks over threshold on the flood estimates. J Hydrol 2001;244:86–96.

[40] Lang M, Ouarda TBMJ, Bobee B. Towards operational guidelines for over-threshold modelling. J Hydrol 1999;225:103–17.

[41] Cameron DS, Beven KJ, Tawn J, Blazkova S, Naden P. Flood frequency estimation by continuous simulation for a gauged upland catchment (with uncertainty). J Hydrol 1999;219:169–87.

[42] Blazkova S, Beven K. Flood frequency estimation by continuous simulation for a catchment treated as ungauged (with uncertainty). Water Resour Res 2002;38(8):1139.

[43] Boughton W, Droop B. Continuous simulation for design flood estimation-a review. Environ Model Software 2003;18:309–18.

[44] Cowpertwait PSP. A generalized spatial-temporal model of rainfall based on a cluster point process. Proc R Soc London 1995;A450:163–75.

[45] Rahman A, Weinmann PE, Hoang TMT, Laurenson EM. Monte Carlo simulation of flood frequency curves from rainfall. J Hydrol 2002;256:196–210.

[46] Arnaud P, Lavabre J. Coupled rainfall model and discharge model for flood frequency estimation. Water Resour Res 2002;38(6):1075.

[47] Montaldo N, Mancini M, Rosso R. Flood hydrograph attenuation induced by a reservoir system: analysis with a distributed rainfall-runoff model. Hydrol Process 2004;8(3):545–63.

[48] Guo Y. Hydrologic design of urban flood - control detention ponds. J Hydrol Eng ASCE 2001;6(6):472–9.

[49] Vaes G, Willems P, Berlamont J. Rainfall input requirements for hydrological calculations. Urban Water 2001;3:107–12.

[50] Savenije HHG. The width of a bankfull channel; Lacey's formula explained. J Hydrol 2003;276(1–4):176–83.

[51] Gupta VK, Mesa OJ, Dawdy DR. Multiscaling theory of flood peaks: regional quantile analysis. Water Resour Res 1994;30:3405–21.

[52] Robinson JS, Sivapalan M. An investigation into the physical causes of scaling and heterogeneity of regional flood frequency. Water Resour Res 1997;33:1045–59.

[53] Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen–Geiger climate classification. Hydrol Earth Syst Sci 2007;11:1633–44.

[54] CNR. Operational guide for application of regional reports for flood frequency estimation in Italy (*VAPI* Projetct). Gruppo Nazionale Difesa dalle Catastrofi Idrogeologiche, Rome; 1999 [in Italian].

[55] Rossi F, Fiorentino M, Versace P. Two components extreme value distribution for flood frequency analysis. Water Resour Res 1984;22(2):847–56.

[56] Fiorentino M, Versace P, Rossi F. Regional flood frequency estimation using the two-component extreme value distribution. Hydrol Sci J 1985;30(1):51–64.

[57] Arnell NW, Gabriele S. The performance of the two-component extreme value distribution in regional flood frequency analysis. Water Resour Res 1988;24(6):879–87.

[58] Gabriele S, Arnell NW. A hierarchical approach to regional frequency analysis. Water Resour Res 1991;27(6):1281–9.

[59] Francés F. Using the TCEV distribution function with systematic and non-systematic data in a regional flood frequency analysis. Stochastic Hydrol Hydraul 1998;12(4):267–83.

[60] Bocchiola D, De Michele C, Rosso R. L'applicazione della legge generalizzata del valore estremo GEV per l'analisi regionale delle piene in Italia. [Application of the generalized extreme values distribution GEV to regional analysis of floods in Italy]. L'Acqua 2004;1:43–62 [Italian with abstract in English].

[61] Hosking JRM, Wallis JR. Regional frequency analysis: an approach based on L-moments. Cambridge, UK: Cambridge University Press; 1997.

[62] Jothityangkoon C, Sivapalan M. Temporal scales of rainfall–runoff processes and spatial scaling of flood peaks: space–time connection through catchment water balance. Adv Water Resour 2001;24(9–10):1015–36.

[63] Furey PR, Gupta VK. Diagnosing peak-discharge power laws observed in rainfall-runoff events in Goodwin Creek experimental watershed. Adv Water Resour 2007;30(11):2387–99.

[64] Yue S, Gan TY. Simple scaling properties of Canadian annual average stream flow. Adv Water Resour 2004;27:481–95.

[65] Heo JH, Shin H, Nama W, Oma J, Jeong C. Approximation of modified Anderson–Darling test statistics for extreme value distributions with unknown shape parameter. J Hydrol 2013;499:41–9.

[66] Laio F, Ganora D, Claps P, Galeati G. Spatially smooth regional estimation of the flood frequency curve (with uncertainty). J Hydrol 2011;408:67–77.

[67] Groppelli B, Bocchiola D, Rosso R. Spatial downscaling of precipitation from GCMs for climate change projections using random cascades: a case study in Italy. Water Resour Res 2011;47:W03519.

[68] Groppelli B, Soncini A, Bocchiola D, Rosso R. Evaluation of future hydrological cycle under climate change scenarios in a mesoscale Alpine watershed of Italy. Nat Haz Earth Syst Sci 2011;11:1769–85.

[69] Hossain F, Jeyachandran I, Pielke Sr R. Dam safety effects due to human alteration of extreme precipitation. Water Resour Res 2012;46(3):W03301.