



HAL
open science

Objective Analysis of Envelope Curves for Peak Floods of European and Mediterranean Flash Floods

William Amponsah, Francesco Marra, Lorenzo Marchi, H el ene Roux, Isabelle Braud, Marco Borga

► To cite this version:

William Amponsah, Francesco Marra, Lorenzo Marchi, H el ene Roux, Isabelle Braud, et al.. Objective Analysis of Envelope Curves for Peak Floods of European and Mediterranean Flash Floods. *Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate*, Springer International Publishing, pp.267-276, 2020, Book series: *Climate Change Management (CCM)*, 978-3-030-37424-2. 10.1007/978-3-030-37425-9_14 . hal-04486263

HAL Id: hal-04486263

<https://hal.science/hal-04486263v1>

Submitted on 1 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destin ee au d ep ot et  a la diffusion de documents scientifiques de niveau recherche, publi es ou non,  emanant des  tablissements d'enseignement et de recherche fran ais ou  trangers, des laboratoires publics ou priv es.



Open Archive Toulouse Archive Ouverte


OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible

This is an publisher's version published in: <http://oatao.univ-toulouse.fr/25766>

Official URL:

https://doi.org/10.1007/978-3-030-37425-9_14

To cite this version:

Amponsah, William and Marra, Francesco and Marchi, Lorenzo and Roux, H  l  ne  and Braud, Isabelle and Borga, Marco *Objective analysis of envelope curves for peak floods of European and Mediterranean flash floods.* (2020) In: *Climate change, hazards and adaptation options : handling the impacts of a changing climate.* (Climate Change Management). Springer International Publishing, Cham, 267-276. ISBN 978-3-030-37425-9.

Any correspondence concerning this service should be sent to the repository administrator: tech-oatao@listes-diff.inp-toulouse.fr

Objective Analysis of Envelope Curves for Peak Floods of European and Mediterranean Flash Floods



William Amponsah, Francesco Marra, Lorenzo Marchi, H el ene Roux, Isabelle Braud and Marco Borga

Abstract Flash floods rank highly among natural disasters in terms of number of affected people and number of fatalities. This paper analyzes the scaling of the highest flash flood peaks at multiple spatial scales for different hydro-climatic regions in Europe and in the Mediterranean. The analysis is based on an integrated, high-resolution dataset of discharges concerning a number of high-intensity flash floods that occurred in these regions from 1991 to 2015. Quantile regression has permitted to define regional envelope curves of unit peak discharge versus drainage basin area, which summarize the current bound to extreme flash floods in a given region. Mean and standard error of the envelope curves' parameters are objectively derived, permitting to explore the similarities in the slopes of the regional envelope curves. Results indicate that the exponent of the envelope curves shows almost negligible variations among climatic region whereas the multiplier depends on the climatic regions.

W. Amponsah (✉)

Department of Agricultural and Biosystems Engineering, College of Engineering, KNUST, Kumasi, Ghana

e-mail: wamponsah@knust.edu.gh

F. Marra

Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem, Israel

L. Marchi

CNR IRPI, Padua, Italy

H. Roux

Institut de M ecanique Des Fluides de Toulouse, Universit e de Toulouse, INPT, UPS, IMFT, All ee Camille Soula, Toulouse 31400, France

I. Braud

INRAE, RiverLy, Villeurbanne F-69625, France

M. Borga

Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro, Italy

  Springer Nature Switzerland AG 2020

267

W. Leal Filho et al. (eds.), *Climate Change, Hazards and Adaptation Options*, Climate Change Management, https://doi.org/10.1007/978-3-030-37425-9_14

Introduction

Flash floods are usually the consequence of short, high-intensity rainfalls mainly of spatially confined convective origin and often orographically enhanced (Gaume et al. 2009). Due to the relatively small temporal scales, catchment scales impacted by flash floods are generally less than 2000–3000 km² in size (Marchi et al. 2010; Braud et al. 2016). Given the large rainfall rates and the rapid concentration of streamflow promoted by the topographic relief, flash floods often shape the upper tail of the flood frequency distribution of small- to medium-size catchments.

Understanding the hydro-meteorological processes that control flash flooding is therefore important from both scientific and societal perspectives. On one hand, the analysis of these events often shows unexpected features of flood response or displays expected but previously undocumented behaviour (Delrieu et al. 2005; Archer et al. 2007). On the other hand, flash floods rank highly among natural disasters as well as the most destructive process among weather-related hazards in many parts of the world in terms of the number of people affected and the number of fatalities (Barredo 2007; Borga et al. 2011; Terti et al. 2017). In the typical data-poor conditions which characterize flash flood forecasting and warning, the relationship between catchment size and flood peaks provides a regional context to evaluate the severity of flash flood events. Also, derivation of empirical envelope curves (upper bounds) for these relationships could be used as probabilistic surrogate for design flood estimation at ungauged sites (Castellarin 2007).

Flash floods are very difficult to monitor, predict and simulate, due to the mismatch between the space-time scales of occurrence and the features of the typical hydro-meteorological sampling networks (Borga et al. 2010). This has stimulated the development of an integrated post-event hydrologic observation strategy, which involves post-flood indirect estimation of peak discharges, use of weather radar rainfall estimates, and hydrological modelling for water budget analysis (Gaume and Borga 2008; Borga et al. 2008; Marchi et al. 2010; Amponsah et al. 2016; Borga et al. 2019). The systematic application of this observation strategy in specific regions permitted the development of a freely accessible European and Mediterranean flash flood database including hydrometeorological data and related observations concerning a wide number of flash floods that occurred between 1991 and 2015, referred to as the EuroMedeFF Database (Amponsah et al. 2018). The EuroMedeFF Database was used as the reference for the work proposed in this article.

This paper aims at exploring the extremal characteristics of flash flood regimes for different hydro-climatic regions in Europe in order to develop envelope curves for peak flows. Regional envelope curves are developed which summarize the current bound of extreme flash floods in a given region. In this study, the method of quantile regression is used to derive objective estimators for the regional envelope curves for a number of flash flood events included in the EuroMedeFF database. The method permitted the derivations of the mean and standard deviation for the parameters of the envelope curve, which allowed to explore the similarities in the intercept and slope of the envelope curves for different climatic regions in Europe and the Mediterranean.

Materials and Methods

The EuroMedeFF Database

The EuroMedeFF database consists of an integrated, high-resolution dataset of hydro-meteorological and geographical variables (rainfall, discharge, topography) concerning 49 high-intensity flash flood events that occurred in France (30), Israel (7), Germany (1), Slovenia (1), Romania (3), and Italy (7) between 1991 and 2015. Data comprises digital elevation models (DEM) of the impacted area (resolutions 5–90 m), high space-time resolution radar-rainfall estimates (60 min or less), flood hydrographs and flood peak estimates from post-flood surveys. The EuroMedeFF Database was created in the framework of the HyMeX international programme (Drobinski et al. 2014) and made available to the public (Amponsah et al. 2018).

Figure 1 presents the spatial location of the flash flood events included in the EuroMedeFF database, which covers from Continental Europe through the Mediterranean to Arid climates. A unit peak discharge of $0.5 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ is considered as the lowest value for defining a flash flood event. This means that, for an event to be included in the database, at least one measured flood peak should exceed the above value. The upper limit for a catchment impacted by the flood is 3000 km^2 , whereas the upper limit for the duration of the flood-triggering storm is up to 48 h.

Discharge data in the EuroMedeFF database derive from both streamflow monitoring stations and post-flood indirect estimates of flow peak. Streamflow data permit recording of flood hydrographs, thus enabling assessment of not only discharge, but also time response and flood runoff volume estimation. Flood hydrographs were checked for the uncertainties affecting rating curves at high-flood stages by using

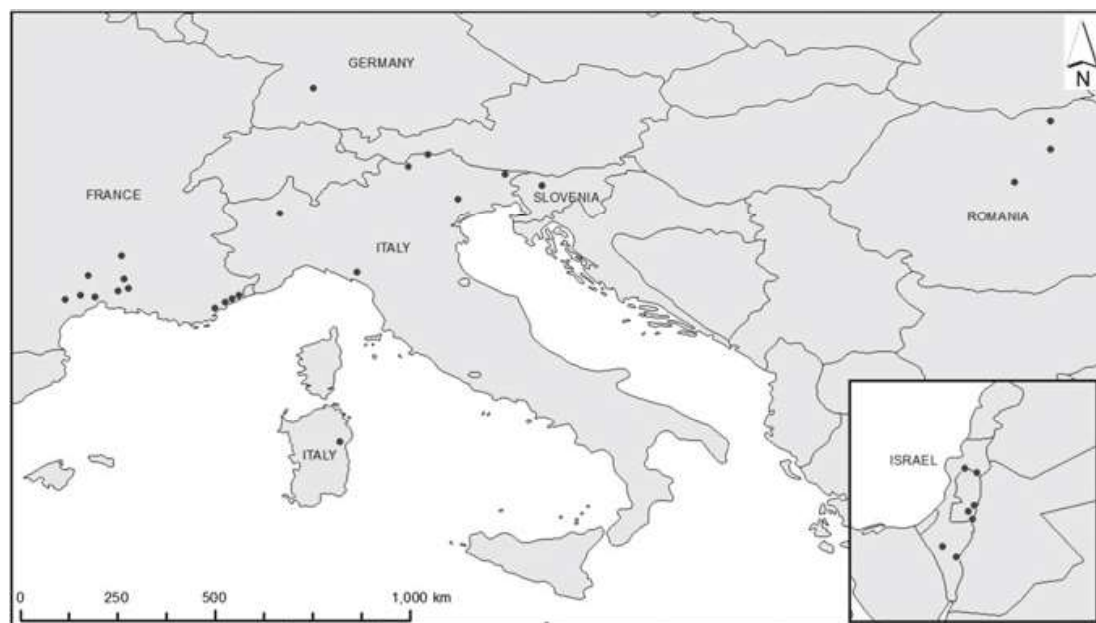


Fig. 1 Location of the flash floods included in the EuroMedeFF database

hydraulic models and topographic data. Discharge data from reservoir operations, water levels and use of the continuity equation, when available, were also included in the database after accurate quality control.

Different methods have been used for the indirect reconstruction of flow velocity and peak discharge from flood marks, such as slope-area, slope-conveyance, flow-through culvert, and lateral super-elevation in bends. Amongst these methods, the most commonly used for the implementation of the dataset presented in this paper is the slope-conveyance, which consists of the application of the Manning–Strickler equation, under assumption of uniform flow, and requires the topographic survey of cross-section geometry and flow energy gradient, computed from the elevation difference between the high water marks along the channel reach surveyed (Gaume and Borga 2008; Lumbroso and Gaume 2012).

Overall, 680 peak discharge data are included in the archive: 32% (219) were recorded by river gauging stations or based on data from reservoir operations, and 68% (461) from post-flood surveys. We followed the geomorphic impact-based linear error analysis of the slope conveyance discharge determination presented in Amponsah et al. (2016) for the uncertainty assessment of the post flood estimates. Almost 90% of the included discharge data are from the Mediterranean region, which is consistent with increasing collation and analysis of flash flood data in this region compared to other climatic regions in Europe (e.g. Gaume et al. 2009; Marchi et al. 2010).

Use of Quantile Regression for Derivation of Flash Flood Envelope Curves

We use here a power law equation for the flash flood envelope curve, in the form of:

$$Q_u = a \cdot A^b \quad (1)$$

where Q_u is the unit peak discharge in $\text{m}^3 \text{s}^{-1} \text{km}^{-2}$, A is the watershed area in km^2 , and a and b are the parameters describing the specific envelope curve. Equation (1) shares the same structure as typical equations relating watershed area and the annual peak discharge with a given return period. Empirical values of the exponent b , often called scaling exponent, have been found to lie in the range $-0.5 < b < 0$ (Benson 1962; Leopold et al. 1964; Alexander 1972). Hereinafter, the parameter ‘ a ’ is termed coefficient.

Linear regression represents the dependent variable, as a linear function of one or more independent variables, subject to an ‘error’ term. It estimates the expected value of the dependent variable for given levels of the independent variables. For this type of regression, where the central tendency in a dataset is the aim of the analysis, ordinary least squares (OLS) is an effective parameters estimation method. OLS loses its effectiveness when the analysis aims to examine the extremes of a

data set. Koenker and Bassett (1978) introduced Quantile Regression (QR) as an extension of OLS for the estimation of models for conditional quantile functions of a data distribution. The central special case is the median regression estimator that minimizes a sum of absolute errors. The remaining conditional quantile functions are predicted by minimizing an asymmetrically weighted sum of absolute errors, weights being the function of quantile of interest. This makes QR a robust technique even in presence of outliers.

We propose a methodology based on QR to objectively estimate the parameters of the envelope curves. By definition envelope curves are mathematical relations that represent the upper limit (envelope) of a given dataset, therefore, if a sufficiently high quantile q is sought by the QR, the estimated curve will represent an envelope curve. We propose to define q as a quantile which is exceeded by less than 1 data point:

$$q = (N - 0.5)/N \quad (2)$$

where N is the number of data points in the dataset of interest. This permits objective identification of the parameters in presence of different sample sizes limiting the numbers of data points exceeding the threshold in the case of large data samples.

Uncertainty in the estimated parameters depends on the available sample from the population; a proper quantification should thus account for the characteristics of the dataset. Bootstrap methods (Efron and Tibshirani 1993) allow for a consistent quantification of such uncertainties and are used in different fields of climatology and hydrology in which data sample issues are dominant factors, such as frequency analyses (Overeem et al. 2008) and thermodynamic scaling of extreme precipitation with temperature (Peleg et al. 2018).

In this study, the QR was computed using the *quantreg* matlab function (*Math-Works*) and the uncertainty in the parameters was quantified as the standard error of 200 bootstrap iterations (with replacement) for each dataset.

Results and Discussion

The aim of the analysis is to assess the similarities between the slopes of the envelope curves estimated from a linear quantile regression model for the four categories of climatic regions in Europe (Mediterranean, Alpine-Mediterranean/Alpine, Inland Continental, and Arid-Mediterranean/Arid) as delineated by Amponsah et al. (2018). Figures 2, 3 and 4 show the envelope curves and their relative 95% confidence intervals for the full EuroMedeFF dataset (Fig. 2), for the four climatic regions (Fig. 3) and for the two discharge estimation methods (Fig. 4). Table 1 summarizes the envelope curve parameters and their relative standard error.

The adopted quantiles range between 99.93 (full dataset, 680 data points) and 95.0 (Arid-Mediterranean/Arid region, 10 data points). The envelope curve characterizing the full dataset (Fig. 2) is parametrized as $Q_u = 96.8 \cdot A^{-0.37}$ and is fully overlapping with the envelope curve characterizing Mediterranean climates (Fig. 3a). This clearly

Fig. 2 Unit peak discharge versus watershed area for the EuroMedeFF database showing the envelope curve at 95% confidence interval

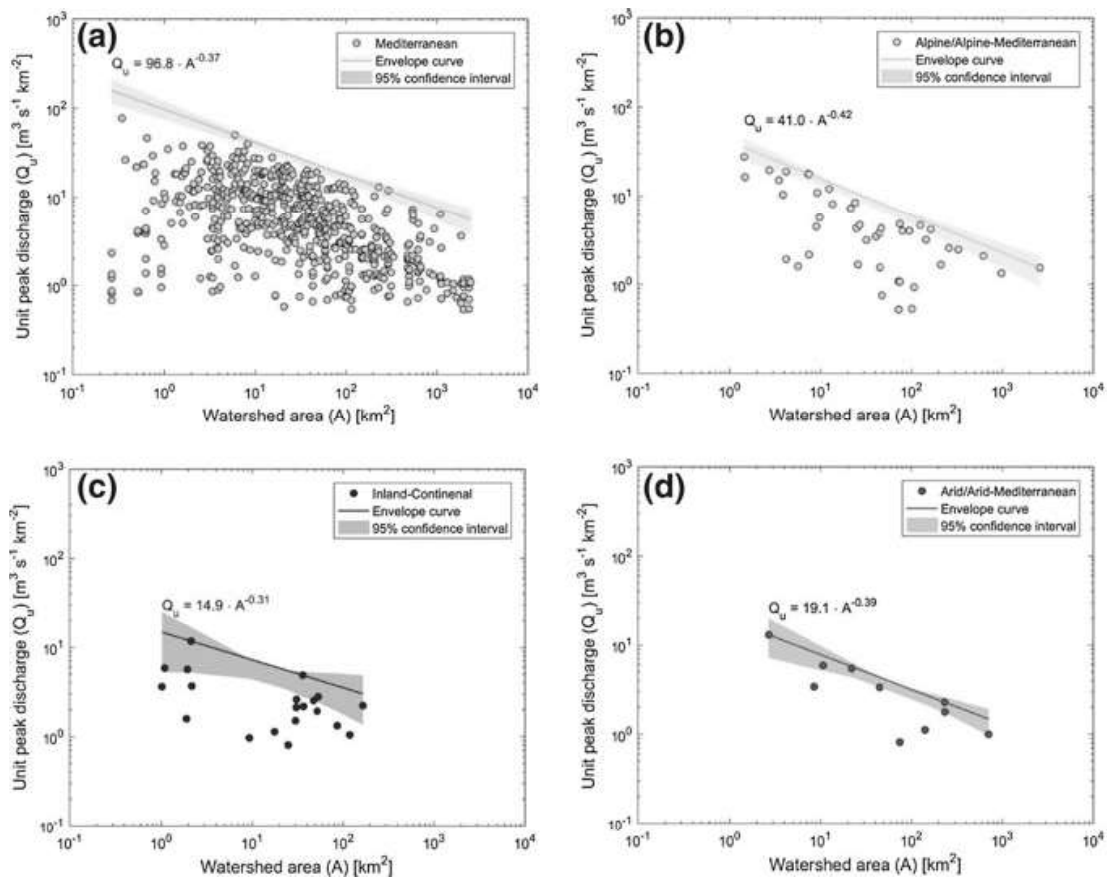
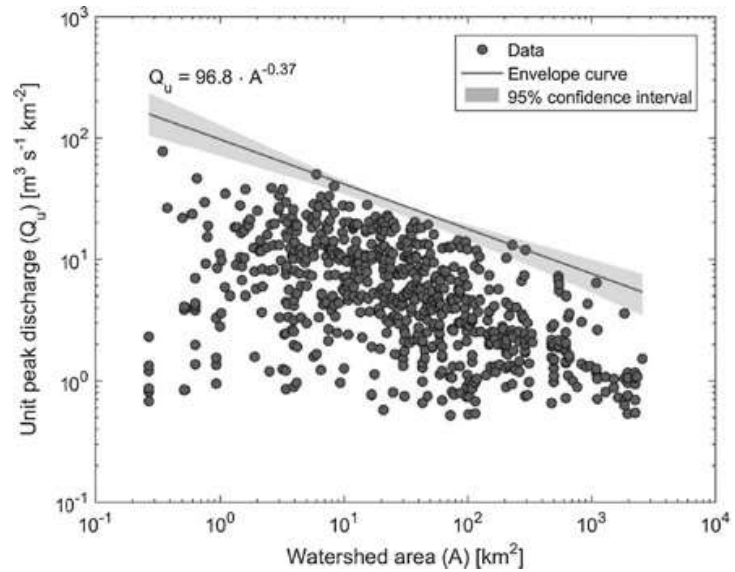


Fig. 3 Unit peak discharge versus watershed area based on climatic regions: **a** Mediterranean catchments, **b** Alpine-Mediterranean and Alpine catchments, **c** inland continental, and **d** Arid and Arid-Mediterranean catchments. The envelope curves at 95% confidence interval are reported

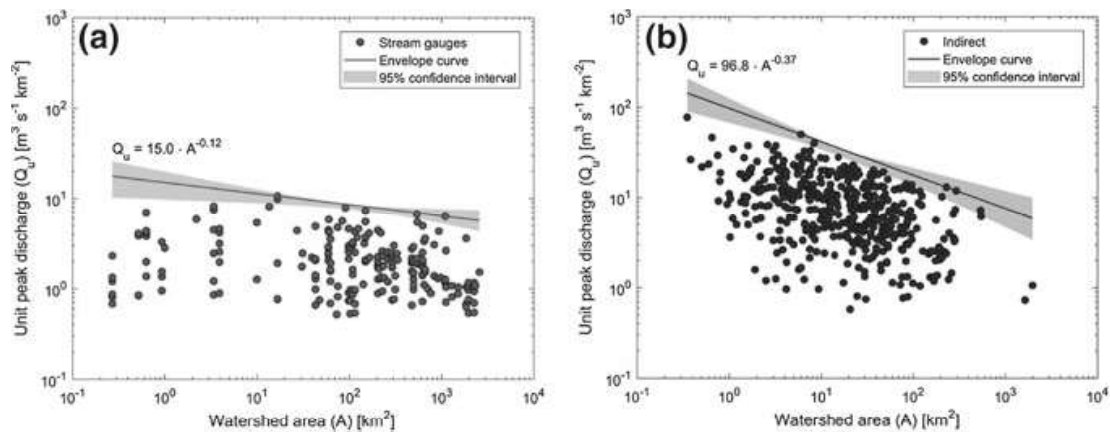


Fig. 4 Unit peak discharge versus watershed area based on discharge assessment methods: **a** stream gauges and **b** indirect methods. The envelope curves at 95% confidence interval are reported

Table 1 Estimated parameters of the envelope curves for the EuroMedeFF database and relative standard error. The used quantiles (q) are defined as in Eq. (2)

	Data sample (N)	Quantile used (q)	Parameters		Standard error	
			Coefficient	Exponent	Coefficient	Exponent
Data (EuroMedeFF database)	680	99.93	96.8	-0.37	0.12	0.030
<i>Climatic regions</i>						
Mediterranean	606	99.92	96.8	-0.37	0.12	0.032
Alpine-Mediterranean/Alpine	44	98.86	41.0	-0.42	0.15	0.042
Continental	20	97.50	14.9	-0.31	0.34	0.117
Arid-Mediterranean/Arid	10	95.00	19.1	-0.39	0.26	0.062
<i>Discharge assessment method</i>						
Stream gauges	219	99.77	15.0	-0.12	0.19	0.038
Indirect method	461	99.89	96.8	-0.37	0.15	0.052

comes from the fact that a large portion of the heaviest events belong to the Mediterranean region, but also indicates that other regions, despite all having comparable exponents within the data sample uncertainties, are characterized by smaller coefficients. This indicates that the scaling of the unit peak discharge with area is rather independent on the climate within the EuroMedeFF dataset. The Mediterranean climates are able to provide the largest unit peak discharges for a given catchment area. This can be associated both to meteorological conditions typical of the region, as well as to specific characteristics of the catchments. It should be however pointed out that limited samples size in the other regions is likely to cause underestimation of the envelope curves due to the insufficient sampling of extreme floods.

Coefficient values (parameter ' a ' equal to 97) reported by Gaume et al. (2009) and Marchi et al. (2010) is consistent with the parameter range reported for the whole dataset (Fig. 2) and the Mediterranean climatic region (Fig. 3a). Coefficient value of 120 reported by Amponsah et al. (2018) falls within the uncertainty range

of the 200 bootstrap iterations for the whole dataset and the Mediterranean climatic region. These authors also reported an exponent of -0.4 , which is comparable to the -0.37 reported for these datasets and also fall within the uncertainty range of the 200 bootstrap iterations. The coefficients and exponents reported by Amponsah et al. (2018) for the other climatic regions (Alpine-Mediterranean/Alpine, Inland Continental, and Arid-Mediterranean/Arid) also fall within the uncertainty range of the 200 bootstrap iterations from the quantile regression method.

Figure 4 shows how the envelope curve characterizing the full dataset is mostly shaped by indirect discharge estimates. The exponent is slightly lower for the stream gauge data compared to the indirect methods. This may be ascribed to the fact that highest values of the peak discharge are often missed by the gauging stations because of insufficient density of streamgauge networks and/or damage to the stations during floods. Furthermore, since the envelope curve of the EuroMedeFF database (as well as the Mediterranean region) fully overlaps with that of the indirect discharge estimation method, it is worth noting that the chosen discharge estimation methods may have an impact on the shape of the envelope curve.

For basin areas less than 10 km^2 , the distribution for the stream gauges (Fig. 4a) shows a largely smaller amount of extreme floods with respect to the large areas. On the contrary, smaller amount of extreme floods are observed at the large-area end of the distribution for the indirect methods (Fig. 4b). These points out the major role post-flood surveys play in the documentation and analysis of extreme floods in small- to medium-sized catchments due to the small space–time scales of flash flood occurrence compared to the typical hydrometeorological monitoring networks (Marchi et al. 2010; Amponsah et al. 2016; Borga et al. 2019).

Conclusions

The dependence of peak discharge on drainage area has been investigated for a wide number of floods in different climatic regions. Herschy and Fairbridge (1998) analysed the relationship between the drainage area and the unit peak discharge for 41 maximum floods impacting catchments greater than 100 km^2 from the world whereas Herschy (2002) investigated for the maximum floods in Europe. Gaume et al. (2009) and Marchi et al. (2010) also characterized for different climatic regions in Europe between 1994 and 2008 whereas Amponsah et al. (2018) compiled data for European and Mediterranean flash floods between 1991 and 2015. Whereas the envelope curves developed by these authors may be subjective, the quantile regression approach establishes a more objective way to estimate parameters of the envelope curves and supports their use for the estimation of maximum flood discharge in a given region.

From the quantile regression analysis presented in this work, the exponents of the envelope curves have been found to be quite stable for the different climatic regions, provided the data samples include indirect peak discharge estimates. On the other hand, the coefficients have been found to depend on the climatic regions. Although

we have identified the small sample sizes in some of the climatic region as a major limitation of this work, our choice of quantile (Eq. 2) represents an objective upper bound for variable sample sizes. Overall, we can conclude that the proposed approach is a promising method for the objective estimation and comparison of the parameters of regional envelope curves of flash floods.

Acknowledgements This paper contributes to the HyMeX programme (www.hymex.org). Flash flood data were obtained from the EuroMedeFF database (<https://doi.org/10.6096/mistrals-hymex.1493>) Francesco Marra was funded by the Israel Science Foundation [grant no. 1069/18], by NSF-BSF grant [BSF 2016953], and by a Google gift grant.

References

- Alexander GN (1972) Effect of catchment area on flood magnitude. *J Hydrol* 16:225–240
- Amponsah W, Ayrat PA, Boudevillain B, Bouvier C, Braud I, Brunet P, Delrieu G, Didon-Lescot JF, Gaume E, Lebouc L, Marchi L, Marra F, Morin E, Nord G, Payrastre O, Zoccatelli D, Borga M (2018) Integrated high-resolution dataset of high-intensity European and Mediterranean flash floods. *Earth Syst Sci Data* 10:1783–1794
- Amponsah W, Marchi L, Zoccatelli D, Boni G, Cavalli M, Comiti F, Crema S, Lucía A, Marra F, Borga M (2016) Hydrometeorological characterisation of a flash flood associated with major geomorphic effects: assessment of peak discharge uncertainties and analysis of the runoff response. *J Hydrometeor* 17(12):3063–3077
- Archer DR, Leesch F, Harwood K (2007) Learning from the extreme river Tyne flood in January 2005. *Water Environ J* 21(2):133–141
- Barredo JI (2007) Major flood disasters in Europe: 1950–2005. *Nat Hazards* 42(1):125–148
- Benson MA (1962) Factors influencing the occurrence of floods in a humid region of diverse terrain. U.S. Geol Surv Water Supply Pap 1580-B, p 64
- Borga M, Comiti F, Ruin I, Marra F (2019) Forensic analysis of flash flood response. *Wiley interdisciplinary reviews: water* 6(2). <https://doi.org/10.1002/wat2.1338>
- Borga M, Gaume E, Creutin JD, Marchi L (2008) Surveying flash flood response: gauging the ungauged extremes. *Hydrol Processes* 22:3883–3885
- Borga M, Anagnostou E, Blöschl G, Creutin JD (2011) Flash flood forecasting, warning and risk management: the hydrate project. *Environ Sci Policy* 14:834–844
- Borga M, Anagnostou EN, Blöschl G, Creutin JD (2010) Flash floods: observations and analysis of hydrometeorological controls. *J Hydrol* 394(1–2):1–3
- Braud I, Borga M, Gourley J, Hürlimann M, Zappa M, Gallart F (2016) Flash floods, hydrogeomorphic response and risk management. *J Hydrol* 541:1–5
- Castellarin A (2007) Probabilistic envelope curves for design flood estimation at ungauged sites. *Water Resour Res* 43:W04406
- Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastre O, Yates E, Kirstetter PE, Andrieu H, Ayrat PA, Bouvier C, Creutin JD, Livet M, Anquetin A, Lang M, Neppel L, Obled C, Parent-du-Chatelet J, Saulnier GM, Walpersdorf A, Wobrock W (2005) The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: a first case study for the Cévennes-Vivarais Mediterranean hydro-meteorological observatory. *J Hydrometeor* 6:34–52
- Drobinski P, Ducrocq V, Alpert P, Anagnostou E, Béranger K, Borga M, Braud I, Chanzy A, Davolio S, Delrieu G, Estournel C, Filali Boubrahmi N, Font J, Grubisic V, Gualdi S, Homar V, Ivancan-Picek B, Kottmeier C, Kotroni V, Lagouvardos K, Lionello P, Llasat MC, Ludwig W, Lutoff C, Mariotti A, Richard E, Romero R, Rotunno R, Roussot O, Ruin I, Somot S, Taupier-Letage I,

- Tintore J, Uijlenhoet R, Wernli H (2014) HyMeX, a 10-year multidisciplinary program on the Mediterranean water cycle. *Bull Am Meteor Soc* 95(7):1063–1082
- Efron B, Tibshirani RJ (1993) *An introduction to the bootstrap*. Chapman and Hall, New York
- Gaume E, Borga M (2008) Post-flood field investigations in upland catchments after major flash floods: proposal of a methodology and illustrations. *J Flood Risk Manag* 1(4):175–189
- Gaume E, Bain V, Bernardara P, Newinger O, Barbuc M, Bateman A, Blaškovicová L, Blöschl G, Borga M, Dumitrescu A, Daliakopoulos I, Garcia J, Irimescu A, Kohnová S, Koutroulis A, Marchi L, Matreata S, Medina V, Preciso E, Sempere-Torres D, Stancalie G, Szolgay J, Tsanis I, Velasco D, Viglione A (2009) A collation of data on European flash floods. *J Hydrol* 367:70–78
- Herschey RW, Fairbridge RW (1998) *Encyclopedia of hydrology and water resources*. Kluwer, Dordrecht, The Netherlands
- Herschey RW (2002) The world's maximum observed floods. *Flow Meas Instrum* 13(5–6):231–235
- Koenker R, Bassett G (1978) Regression quantiles. *Econometrica* 46(1):33–50
- Leopold LB, Wolman MG, Miller JP (1964) *Fluvial processes in geomorphology*. W. H. Freeman, New York
- Lumbroso D, Gaume E (2012) Reducing the uncertainty in indirect estimates of extreme flash flood discharges. *J Hydrol* 414–415:16–30
- Marchi L, Borga M, Preciso E, Gaume E (2010) Characterisation of selected extreme flash floods in Europe and implications for flood risk management. *J Hydrol* 394:118–133
- Overeem A, Buishand TA, Holleman I (2008) Rainfall depth–duration–frequency curves and their uncertainties. *J Hydrol* 348:124–134
- Peleg N, Marra F, Fatichi S, Molnar P, Morin E, Sharma A, Burlando P (2018) Intensification of convective rain cells at warmer temperatures observed from high-resolution weather radar data. *J Hydrometeor* 19:715–726
- Terti G, Ruin I, Anquetin S, Gourley JJ (2017) A situation-based analysis of flash flood fatalities in the United States. *Bull Am Meteorol Soc* 98:333–345