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FLOOD HAZARD MAPPING IN CONVEX FLOODPLAIN: MULTIPLE PROBABILITY MODELS FUSION, BANK THRESHOLD AND LEVEES EFFECT SPATIALIZATION

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EXTENDED ABSTRACT

Negli ultimi trent'anni, l'esposizione delle comunità urbane e rurali dell'area Europea ai fenomeni di alluvionamento è aumentata a causa dei cambiamenti climatici. Nel 2007, con l'emanazione della Direttiva Europea 60/EC, tutti gli stati membri sono stati invitati a dotarsi di mappe di pericolosità e di rischio almeno per le aree individuate quali a rischio di alluvionamento.

La valutazione della pericolosità può essere eseguita combinando modelli di alluvionamento, sviluppati sulla base di dati topografici ad alta risoluzione, e modelli di probabilità, sviluppati a partire dall'analisi di serie storiche dei livelli idrometrici, previa la definizione dell'evento di riferimento. A partire dal 1918, i corsi d'acqua italiani sono stati monitorati con un numero sempre crescente di stazioni di misura. Nonostante la limitata continuità e persistenza temporale delle misure, esse rappresentano una risorsa estremamente importante nell'ambito delle valutazioni di pericolosità da alluvionamento. In molti casi, uno stesso corso d'acqua è monitorato attraverso stazioni multiple cosicché la spazializzazione e fusione di modelli di pericolosità derivati dalle singole serie temporali rende le valutazioni meglio rappresentative delle dinamiche fluviali. Un altro fattore significativo da considerare è la presenza, lungo la piana fluviale, di opere di mitigazione. In tale quadro, questo lavoro presenta una procedura di valutazione della pericolosità da alluvionamento di tipo probabilistico che prevede la spazializzazione e la fusione di modelli multipli di pericolosità ottimizzata per l'applicazione in piane fluviali morfologicamente convesse e che tiene in considerazione la presenza di strutture di mitigazione.

Tale procedura è stata applicata al tratto finale del fiume Volturno tra i comuni di Cancello ed Arnone e Castel Volturno. Tale zona si presta particolarmente alla modellazione probabilistica considerata la presenza di due stazioni di monitoraggio, la convessità della piana fluviale e la presenza di opere di mitigazione. La valutazione della pericolosità è stata completata attraverso i) la creazione di un modello di inondazione derivato da dati LiDAR, ii) lo sviluppo di due coppie di modelli di probabilità (due modelli per ogni stazione) attraverso la parametrizzazione della distribuzione generalizzata dei valori estremi (GEV) e della distribuzione Gamma, iii) la spazializzazione dei modelli e iv) la loro fusione attraverso una media pesata considerando la distanza Euclidea tra le stazioni.

A questo punto, v) il modello generale è stato modificato per le condizioni di convessità della piana alluvionale utilizzando un fattore moltiplicativo che rappresenta la probabilità di superamento dell'altezza della soglia morfologica costituita dagli argini naturali. Ottenuto questo modello, vi) è stato considerato l'effetto delle opere di mitigazione utilizzando un ulteriore fattore moltiplicativo applicato alle aree estere agli argini artificiali. Utilizzando le due distribuzioni di probabilità GEV e Gamma, sono stati ottenuti due scenari di pericolosità sulla base dei quali è possibile sviluppare valutazioni di rischio.

Tali scenari presentano delle limitazioni derivanti dalla discontinuità e lunghezza limitata delle serie temporali utilizzate e dal tipo di distribuzione di probabilità implementata. In particolare, è noto che le stime derivanti dalla distribuzione GEV possono essere meno accurate rispetto a quelle derivanti dalla distribuzione Gamma soprattutto per eventi caratterizzati da frequenza di accadimento medio-bassa, soprattutto in presenza di serie particolarmente povere di dati.

ABSTRACT

This paper presents a first attempt to model flood hazard in convex upward floodplains through the combination of multiple probability models fusion and topographic-based flood inundation models. Our procedure is optimized for convex floodplains through the adoption of a multiplicative probability threshold that simulates the effect of natural banks bounding the river course and is able to account for the presence of artificial levees. We have applied this procedure to a segment of the lower course of the Volturno river in the Caserta Province. This area has been historically affected by flood events and since 1927 has been monitored with several hydrometric stations. We have used data from two of these stations and a LiDAR derived high-resolution topography to develop two flood hazard scenarios. The first is derived using a Generalized Extreme Value distribution, while the second is derived using a Gamma distribution function of available data. As boundary condition, we have considered a reference scenario corresponding to an estimated 500-year flood. The hazard maps provide an overview of the flood hazard in the lower sector of the Volturno river.

Keywords: *flood, hazard, probability model, convex floodplain, LiDAR, Volturno river, data fusion*

INTRODUCTION

In the last decades, the exposure to floods of European urban and rural communities has increased as a consequence of the ongoing climate change (e.g. Knox, 1993). In 2007, the European Parliament enacted the Floods Directive 60/EC on the Assessment and Management of Flood Risks with the aim of providing a new approach to manage flood risk and protecting communities from the impact of flooding. The article 6 of this Directive underlines the need of preparing, for each Member State, flood hazard and flood risk maps for identified flood risk areas.

Flood hazard evaluation requires the development of flood inundation models that, showing the water depth during flood events of specific magnitudes, predicts the extent of the potential flooded areas and the identification of a design event (i.e. reference extreme flood scenario, e.g. Woo & Waylen, 1986; Guerriero *et alii*, 2018) that represents the boundary condition of the analysis. For segments where fluvial stage data are available, flood hazard can be estimated from topography-based flood inundation models and probability analysis of monitoring time series (e.g. Woo & Waylen, 1986). In this way, flood hazard maps can be obtained through flood probability spatialization. The resolution and spatial accuracy of the hazard map depend on the characteristics of the topographic base map used for the development of the inundation model. To make them as accurate as expected to guide land planning in urban and suburban areas, the flood inundation model should be produced using numerical flood plain models developed on the basis of very high resolution topography (e.g. LiDAR data, Montané *et alii*, 2017). The design event can be estimated on the basis of historical data (e.g. Sutcliffe, 1987). However, depending on the availability, the duration, the reliability and the continuity of the records (e.g. Hosking & Wallis, 1986) it can be a very challenging task. If no monitoring or historical data are available, the magnitude can be estimated on the basis of geomorphological observations (e.g. Magliulo & Cusano; 2016; Montané *et alii*, 2017). In Italy, the guidelines of the Ministry of Environment and Land Protection indicate that the design event, or in other words the lower boundary of the hazard zonation (boundary of the low hazard zone), should be an event of magnitude corresponding to that of a 300 to 500 years flood.

The Italian fluvial network has been monitored by an increasing number of hydrometric stations since 1918. Monitoring data were first published in the form of monitoring bulletins (*"Bollettini Idrografici" in Italian*) and from 1927 assumed their present-day form of *"Annali Idrologici"* (*in Italian*). Although hydrometric time series are often discontinuous and in a number of cases cover only a limited time period, this dataset is a resource of dramatic importance for flood hazard evaluation across the national territory. The monitoring network of main river courses, in fact, is formed by multiple stations, which makes the hazard evaluation more reliable for long river segments if all of the available stations (i.e. probability models) are considered and merged. A further aspect that needs to be taken into account in flood hazard mapping is that most of the major Italian rivers, being historically affected by floods, have been already bounded by artificial levees for risk mitigation purposes.

On October 15th, 2015, a destructive flood hit the lower course of the Calore river in the Benevento Province and the middle and the lower course of the Volturno river in the Caserta Province of southern Italy. This event induced diffuse damages to buildings and local agriculture and has a number of historical precedents in this area. An important example is the flood of October 1949, remembered for its magnitude and impact on the society and territory. On this basis, and following the work by Guerriero *et alii* (2018) that used hydrometric data and a LiDAR-derived high resolution topography to develop a flood hazard map of two segments of the lower course of the Calore river, we have used data from multiple monitoring stations and a high resolution topography to derive two flood hazard scenarios (i.e., maps) of a segment of the lower course of the Volturno river, and its convex floodplain, optimized through multiple probability models fusion, convexity threshold estimation and levees mitigation effect spatialization. Our analysis can be considered a step toward the development of a simplified procedure of flood hazard mapping in concave and convex floodplains controlled by artificial levees, where multiple probability models can be developed on the basis of hydrometric time series.

THE STUDY AREA

The study area comprises a segment of the lower course of the Volturno river and part of its convex floodplain (Fig. 1) bounded by artificial channels. This segment stretches between the villages of Cancello and Arnone and Castel Volturno. In this area two hydrometric stations indicated with purple symbols in the map of figure 1 were installed in 1921. The river segment is approximately 18 km long and displays a meandering pattern. Two major cutoff meanders are identifiable west of Cancello and Arnone. Artificial levees bound the river course on its both sides, delimiting a 150 to 1500 m wide band (i.e. the Central sector of the floodplain indicated in the map of figure 1).

This band reaches approximately 2000 m in width at the mouth of the river. The northern and southern sectors of the study area forming the central part of the Volturno floodplain can be considered part of backswamps. The inclination of these zones is very low (~2°) and their aspect indicate a typical divergence from the river course (i.e. convex shape).

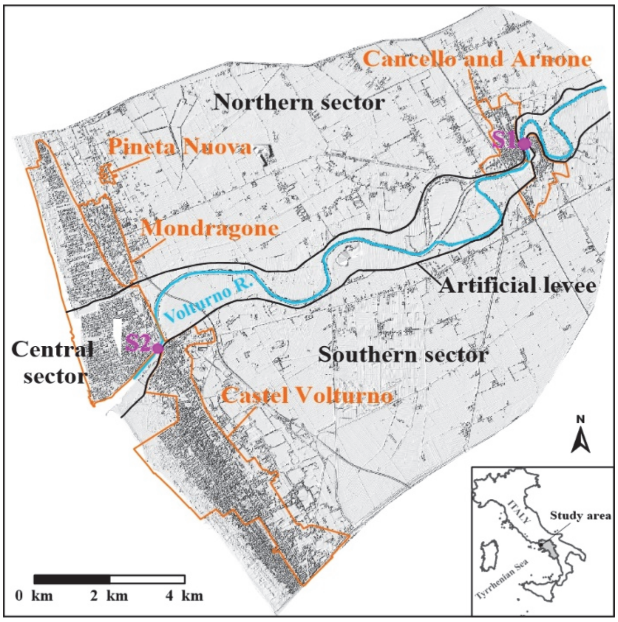

Fig. 1 – Map showing the segment of the Volturno river and the sectors of its floodplain. Major towns are reported using orange polygons, artificial levees are reported using black lines and monitoring station position is reported using purple dots

METHODS

To derive flood hazard maps, we have at first computed a flood inundation model from a LiDAR-derived high resolution topography. The inundation model (i.e. relative elevation above the river) has been computed as a difference between a Digital Surface Model (4 m single sided pixel) and a digital elevation model of the minimum water level (wDEM). The wDEM has been derived by the interpolation of a triangulated irregular network of the water elevation data estimated along cross-sections constructed along the river segment object of our analysis. Cross-section have been selected considering river geometry and surrounding slopes (e.g. Cook & Merwade, 2009).

Once a general inundation model was obtained, we have used multiple probability distribution functions to derive flood probability models from available time series (Fig. 2). Probability models have been obtained using a type III Generalized Extreme Value distribution function (GEV, ξ<0, e.g. Hosking & Wallis, 1986), and a Gamma distribution function (e.g. Yue, 2001).

These functions have been used to fit the annual maxima time series (i.e. discontinuous complementary cumulative distribution function, CCDF) registered at the Cancello and Arnone (upper, S1 in figure 1) and Castel Volturno (lower, S2 in figure 1) hydrometric stations (from 1935 to 2018 and 1935 to 1994, respectively) and estimate the annual probability of exceedance (p) of each specific fluvial stage (x) in the range of interest and the related return periods. The GEV function has the following form:

$$F(x) = exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \quad for\ \xi \neq 0 \qquad (1)$$

where ξ is the shape parameter, σ is the scale parameter and μ is the location parameter. The Gamma distribution function, having the potential to better estimate the intensity of very high return period events, has the following form:

$$F(x) = \frac{\beta^{\alpha}\, x^{\alpha-1} e^{-\beta x}}{\Gamma(\alpha)} \qquad (2)$$

where α is the shape parameter and β is the scale parameter and Γ(α) is the gamma function that is calculated as follows:

$$\Gamma(\alpha) = \int_0^x x^{\alpha-1} e^{-x}\, dx \qquad (3)$$

The distribution function parameterization has been automatically completed using the distribution fitter tool implemented in MATLAB (GEV Cancello and Arnone: ξ = -0.618235, σ = 1.41243, μ = 5.14886; GEV Castel Volturno: ξ = -0.39067, σ = 0.686422, μ = 1.96884; Gamma Cancello and Arnone α =11.9538, β = 0.450535; Gamma Castel Volturno: α = 8.87134, β = 0.243368). Overall, the residual analysis has indicated a high goodness of fit for both distributions computed on the basis of data acquired at both stations (GEV Cancello and Arnone R^2 = 0.99; Gamma Cancello and Arnone R^2 = 0.92; GEV Castel Volturno R^2 = 0.95; Gamma Castel Volturno R^2 = 0.96; Fig. 2).

The derived probability models (i.e. GEV and Gamma distributions) have been used to compute flood hazard maps from the general flood inundation model. In particular, we have at first derived two hazard maps using the two GEV probability models representing the two considered stations and have subsequently derived two hazard maps using the Gamma probability models derived from the same data. These two couples of models have been used as basis for flood hazard model fusion. Model fusion was completed using a Euclidean-distance weighted average operator for the region between the considered stations and assigning the probability values of the Cancello and Arnone and the Castelvolturno stations to the remaining eastern and western sectors of the study area, respectively. The Euclidean distance has been computed on the basis of an arbitrary generated radial distance auxiliary raster and the total elevation difference between the stations. The centre of the auxiliary raster has been arbitrary picked along the line passing for both stations, 87 km far from the nearest station that in this case is the Cancello and Arnone station. This distance has been estimated considering 10 times the distance between the stations.

The obtained combined probability model has then been used as a basis for both convexity threshold application and levee probability coefficient correction that represents the optimization step for topographically convex conditions and presence of artificial levees. This is a way to attempt to model flood hazard through a simple probabilistic approach in an area where topographic convex condition of the floodplain makes the relation between water height and probability of exceedance not fully representative of spatial flood distribution. From a methodological point of view, the “convexity threshold” is a raster derived by interpolation of a triangulated irregular network of the minimum probability value picked next to the river course. These points consistently correspond to the maximum height of the natural banks bounding the river course. In this way, the flood hazard in the central sector of the study area, bounded by artificial levees, is calculated as the product of the probability of exceedance estimated by our models times the probability of exceedance of the height above the river of the banks. Similarly, to account for the mitigation effect of the artificial levees located next to the river course, the flood hazard within the northern and southern sectors of the study area, located outside the area bounded by artificial levees, was computed as the product of the probability of exceedance estimated by our models times the probability of exceedance of the fluvial stage corresponding to the height above the river of

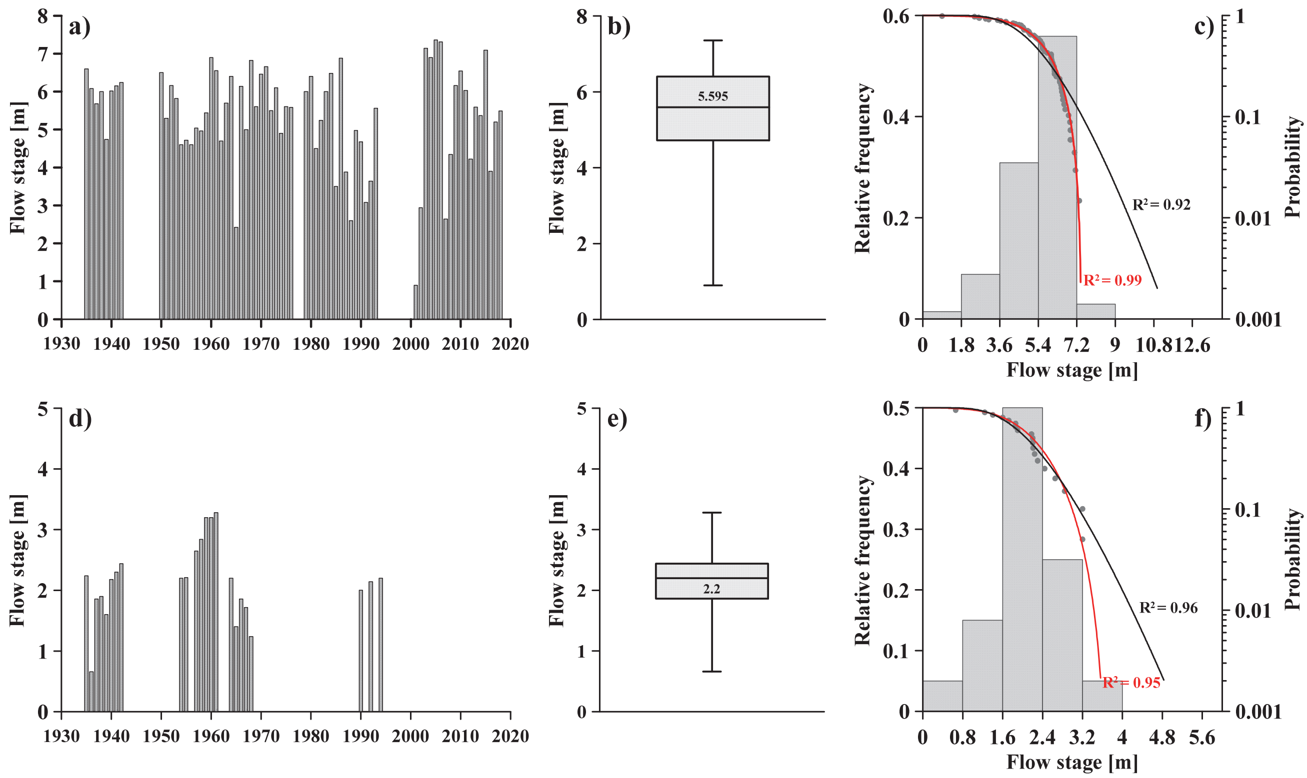

Fig. 2 – Graphs showing hydrometric time series of a) Cancello and Arnone, its b) univariate statistics and c) probability analysis using the GEV (red curve) and Gamma (black curve) distribution functions, and hydrometric time series of d) Castel Volturno, its e) univariate statistics and f) probability analysis using the GEV (red curve) and Gamma (black curve) distribution functions

the levees. For calculation purpose, this probability has been considered as the mode of the distribution of the probability values representing the top of the artificial levees.

RESULTS AND DISCUSSION

Figure 3 reports the hazard maps derived from GIS processing and probability analysis optimized for convex floodplain conditions and presence of artificial levees. In particular, figures 3 a), b), e) and f) represent the results of hazard modelling considering single datasets available for the Cancello and Arnone and for the Castel Volturno stations completed using the GEV and Gamma distribution functions. Figures 3 c) and g) show the result of single station models fusion through the Euclidean distance weighted average operator. Figure 3 d) and h) show the final product of the analysis represented by the combined hazard model optimized for convex topographic conditions through the adoption of a probability threshold representing the bounding action of the natural banks and of a further multiplicative term for the estimation of flood probability within the protected area of the floodplain. These hazard maps show the annual probability of exceedance for the lower segment of the Volturno river in the Caserta Province and represent an interpretation of the flood hazard level between the villages of Cancello and Arnone and Castel Volturno already hit by historical damaging floods. Although these maps are developed on the basis of discontinuous dataset, they should be

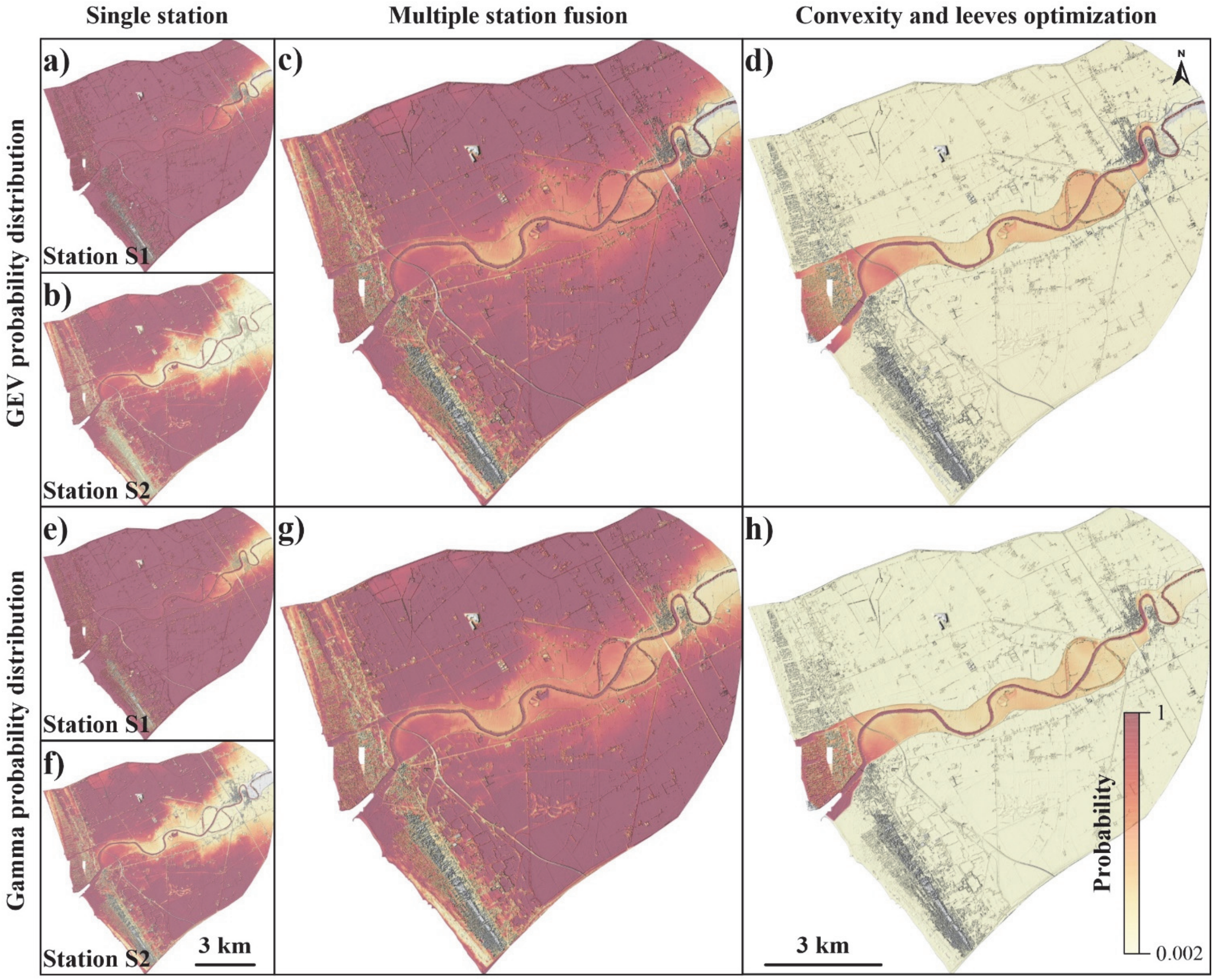

Fig. 3 – Results from the modeling of flood hazard across the near side of the Volturno floodplain using GEV and Gamma probability distributions. a) and b) are flood hazard maps derived by single station modeling (S1 is Cancello and Arnone and S2 is Castel Volturno), c) is the combined hazard model and d) is the optimized hazard model developed using the GEV probability distribution. e) and f) are flood hazard maps derived by single station modeling, g) is the combined hazard model and h) is the optimized hazard model developed using the Gamma probability distribution.

considered as simple tools suitable for identifying the hazard level of each anthropic structure located within the floodplains on an annual basis. In addition, the flood scenarios represented by our probability models can be considered as the first step towards the evaluation of the flood risk in this area.

Being estimated on the basis of time limited and discontinuous records, our hazard models need to be interpreted in the context of the existing historical knowledge (e.g. HOSKING & WALLIS, 1986) of the area and considering the limitation that typically affects probability models. In particular, it is important to notice that the GEV distribution has a major limitation in underestimating the magnitude of low frequency events. Moreover, if limited input dataset are available, some estimation biases could affect also medium frequency events. For instance, in our case, the GEV model considers the northern and southern sectors of the study area, outside from the area bounded by artificial levees, floodable by a 20 years flood event. In our opinion this is an example of wrong estimation of event magnitude/frequency relation. Conversely, the Gamma model is suitable for flood hazard modelling also in presence of limited dataset. Using this model, the same area is considered floodable by 100 years flood events. This seems to be more reasonable also in consideration of our knowledge of historic flood events.

Moreover, the flood inundation maps, on which the hazard computation is based, are not fully comparable (from the spatial viewpoint and considering their total extent) with any event-map but are able to simulate or be-reliable for different flooding scenarios of same magnitude but generated by different rainfall spatial distribution (e.g. GUERRIERO *et alii*, 2018). This because the presented method is simpler than hydrodynamic models and only based on the relation between floodplain topography and fluvial stage. However, this make the method more flexible and able to work at both local and regional scale. A further simplification is that in the probability analysis we do not consider the effect of climate change and channel adjustment that might influence the reliability of the analysis on the long-term (SCORPIO & ROSSKOPF, 2016).

CONCLUDING REMARKS

The hazard maps provide an overview of the flood hazard in the lower course of the Volturno river in the Caserta Province. The maps represent a step towards the development of a simplified procedure of flood hazard mapping in concave and convex floodplains controlled by artificial levees, where multiple probability models can be developed on the basis of hydrometric time series. The specific hazard level for each structure located across the near side of the river floodplain can be evaluated. Differently from products that are based on hydrodynamic models of flood, these maps are derived from the statistical analysis of measured fluvial stages and LiDAR derived high-resolution topography which make them suitable to guide future land planning in an urban area like that of Castel Volturno. In this way, the presented method has the potential to be applied in many fluvial contexts for which fluvial stages and topographic data are available and it can be used at different scales, from local to regional. A major limitation is that the GEV-derived hazard model tends to underestimate the magnitude of low-frequency events; moreover, if the dataset is limited (e.g., Castel Volturno time series) the probability of exceedance might be locally overestimated. The Gamma derived hazard model seems to be more consistent with our knowledge of historical flood events.

REFERENCES

COOK A. & MERWADE V. (2009) - *Effect of topographic data, geometric configuration and modelling approach on flood inundation mapping*. Journal of Hydrology, **377**: 131–142.

GUERRIERO L., FOCARETA M., FUSCO G., RABUANO R., GUADAGNO F.M. & REVELLINO P. (2018) – *Flood hazard of major river segments, Benevento Province, southern Italy.* Journal of Maps, 14, 597-606.

HOSKING J.R.M. & WALLIS J.R. (1986) - *The value of historical data in flood frequency analysis*. Water Resources Research, **22**: 1606-1612.

KNOX J.C. (1993) - *Large increase in flood magnitude in response to modest changes in climate*. Nature, **361**: 430-432.

MAGLIULO P. & CUSANO A. (2016) - *Geomorphology of the Calore river alluvial plain.* Journal of Maps, **12**: 1119–1127.

MONTANÉ A., BUFFIN-BÉLANGER T., VINET F. & VENTO O. (2017) - *Mapping extreme floods with numerical floodplain models (NFM) in France.* Applied Geogrphy, **80**: 15-22.

SCORPIO V. & ROSSKOPF C.M. (2016) - *Channel adjustments in a Mediterranean river over the last 150 years in the context of anthropic and natural controls*. Geomorphology, **275**: 90-104.

SUTCLIFFE J.V. (1987) - *The use of historical records in flood frequency analysis*. Journal of Hydrology, **96**: 159–171.

WOO M. & WAYLEN P.R. (1986) - *Probability studies of floods.* Applied Geography, **6**: 185-195.

YUE S. (2001) - *A bivariate gamma distribution for use in multivariate flood frequency analysis*. Hydrological processes, **15**: 1033-1045.