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A GIS tool for cost-effective delineation of flood-prone areas

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ABSTRACT

Delineation of flood hazard and flood risk areas is a critical issue, but practical difficulties regularly make complete achievement of the task a challenge. In data-scarce environments (e.g. ungauged basins, large-scale analyses), useful information about flood hazard exposure can be obtained using geomorphic methods. In order to advance this field of research, we implemented in the QGIS environment an automated DEM-based procedure that exhibited high accuracy and reliability in identifying the flood-prone areas in several test sites located in Europe, the United States and Africa. This tool, named Geomorphic Flood Area tool (GFA tool), enables rapid and cost-effective flood mapping by performing a linear binary classification based on the recently proposed Geomorphic Flood Index (GFI). The GFA tool provides a user-friendly strategy to map flood exposure over large areas. A demonstrative application of the GFA tool is presented in which a detailed flood map was derived for Romania.

1. Introduction

Floods are the most frequently occurring and costliest natural hazard throughout the world, and flood damages constitute about a third of the economic losses inflicted by natural hazards (Munich, 2005). In the period 1975–2001, a total of 1816 flood events killed over 175,000 people and affected > 2.2 billion worldwide (Jonkman, 2005). Moreover, the United Nations (UNISDR and CRED, 2015) has estimated that one third of the world's population (around 2.3 billion people) has been effected by flood in the last 20 years.

Flood inundation maps are at the base of flood risk management, informing the public and city planners about flood-prone areas in a region. Most flood inundation maps are developed by computer modelling, involving hydrologic analyses to estimate the peak flow discharge for assigned return periods, hydraulic simulations to estimate water surface elevations, and terrain analysis to estimate the inundation area (Alfieri et al., 2014; Bradley, Cooper, Potter, & Price, 1996; Knebl, Yang, Hutchison, & Maidment, 2005; Sole et al., 2013; Whiteaker, Robayo, Maidment, & Obenour, 2006).

Despite recent advancements in computational techniques and availability of high-resolution topographic data, flood hazard maps are still lacking in many countries. The main difficulty in using a specific method or model is primarily correlated to the significant amount of data and parameters required by these models. Thus, their calibration and validation is a rather challenging task, especially considering that gauging stations are heterogeneously and unevenly distributed (Di Baldassarre, Schumann, & Bates, 2009). This is especially relevant in developing countries, which suffer from weak coping strategies and inefficient mechanisms for disaster management due to limited resources for flood protection. Traditional modelling approaches are costly, making them unaffordable not only for developing countries, but also for more developed ones. For instance, in the U.S., many rural counties and several minor tributaries do not have any associated flood inundation information. FEMA (Federal Emergency Management Agency) (2006) estimated that flood inundation mapping could cost from $3000 to $6000/km of river reach in the U.S. Therefore, there is a need to look for efficient and inexpensive ways to derive flood inundation maps.

In this scenario, several studies have demonstrated that flood-prone areas can be delineated using methods which rely on geomorphologic characterization of a river basin (Clubb et al., 2017; De Risi, Jalayer, & De Paola, 2015; Degiorgis et al., 2012; Dodov & Foufoula-Georgiou, 2006; Gallant & Dowling, 2003; Jafarzadegan & Merwade, 2017; McGlynn & Seibert, 2003; Nardi, Vivoni, & Grimaldi, 2006; Noman, Nelson, & Zundel, 2001; Wolman, 1971). A mutual causal relationship exists between flooding and the shape and extension of floodplains, since fluvial geomorphology is essentially shaped by flood-driven phenomena (Arnaud-Fassetta et al., 2009; Nardi, Biscarini, Di Francesco, Manciola, & Ubertini, 2013).

Given this assumption, we have developed a practical and cost-effective procedure (proposed by Samela, Troy, & Manfreda, 2017) to preliminarily delineate flood-prone areas in poor data environments and for large-scale analyses based on easily available information.

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2. Background of the project

The above-mentioned research stems from an idea proposed by Manfreda, Di Leo, and Sole (2011) of using a topographic descriptor of the surface in order to obtain preliminary indications about the flood exposure of a basin. The authors suggested using a modified version of the Topographic Index (*TI*) developed by Beven and Kirkby (1979) to detect flood hazard exposure. The authors compared the modified *TI* and flood inundation maps obtained from hydraulic simulations and observed that the portion of a basin exposed to flood inundation is generally characterized by a TI_m higher than a given threshold, τ. Therefore, they proposed a GRASS GIS tool (Di Leo, Manfreda, & Fiorentino, 2011) that adopts the TI_m to delineate the flood prone areas using simple regression functions to estimate the parameters τ and n. Interestingly, they observed that both parameters are strongly controlled by the cell size of the Digital Elevation Model (DEM).

Later on, Manfreda, Nardi, et al. (2014) carried out a comparative analysis between three different geomorphic procedures: the modified *TI* by Manfreda et al. (2011), the linear binary classifiers method by Degiorgis et al. (2012, 2013) and a hydrogeomorphic algorithm by Nardi et al. (2013, 2006) over the Upper Tiber River and Chiascio River basin. This study proved that a preliminary delineation of the flood-prone areas can be carried out using procedures that rely on basin geomorphologic features, and provided an initial investigation about the role played by some morphologic features on flood exposure. Analysing performances, flexibility, and structure complexity, the linear binary classification has proven to be the most appealing tool since it showed good detection performance with simple requirements in terms of input data, costs, and computational times. It allows implementation of a binary classification based on any morphologic descriptor or combination of descriptors and derivation of a flood susceptibility map over large areas starting from the study of a small portion of the basin; it also requires the calibration of a single parameter.

Motivated by these observations, several studies have been dedicated to understanding which geomorphic attributes are the most predictive with regard to the flood inundation process, and how to use these descriptors to map the flood exposure over large spatial scales. To this purpose, eleven morphological descriptors presumed to be good candidates as indicators of flood hazard exposure were tested to identify the performances in different hydrologic, climatic and topographic contexts: in several Italian gauged basins; an ungauged basin in Africa (Bulbula River, Ethiopia) (Manfreda, Nardi, et al., 2014; Manfreda et al., 2015; Manfreda, Samela, et al., 2014; Samela et al., 2016); and over the entire continental U.S., moving from basin-scale analyses to a continental-scale application (Samela, Manfreda, & Troy, 2017; Samela, Troy, et al., 2017).

In light of this extensive investigation, the classifier based on the Geomorphic Flood Index (GFI) consistently exhibited higher classification accuracies compared to the others in each test. Moreover, it presented a low sensitivity to changes in the input data in terms of dominant topography of the training area, size of the training area, DEM resolution, standard flood maps adopted (1-D or 2-D hydraulic model), return time, and scale of the analysis (Samela, Troy, et al., 2017). Therefore, GFI has been acknowledged as the most suitable morphologic classifier among those examined for preliminary mapping over large unstudied areas and in data-sparse environments.

With the specific aim of transferring the knowledge acquired from these years of research to the scientific and technical community, the full procedure has been implemented in a new plugin named Geomorphic Flood Area tool (GFA tool), working in the open-source Geographic Information System Quantum GIS (QGIS). In fact, the transfer of scientific findings from the research to a wider range of users is an important component of progress for the society that may benefit from an advance in flood mapping techniques. The tool has a user-friendly interface and enables rapid detection of flood-prone areas starting from readily available data. It also allows generation of complementary information like the GFI, which may be used as river basin descriptor in other applications such as detection of inundated areas by remote sensing techniques (e.g. D'Addabbo et al., 2016) and delineation of floodplains.

The GFA tool source code is published under free and open-source software licenses with end-user rights to analyse, modify and redistribute it for any purpose. Anyone can contribute to the methodologies/algorithms adopted and further develop and exploit the technology into new products, processes, applications, materials, or services generating new data through a community-based development process.

3. The Geomorphic Flood Area tool

3.1. Method description

The Geomorphic Flood Area tool makes it possible to derive a flood susceptibility map of a basin by combining geomorphological information extracted by DEMs along with flood hazard information from existing inundation maps which are usually available for limited portions of a basin. This is achieved by classifying the points within a basin into two groups – flood-prone areas and areas not prone to floods – by using a linear binary classifier based on the Geomorphic Flood Index (GFI) (Samela, Troy, et al., 2017). The index has been defined as:

$$\ln\left(\frac{\mathrm{h_r}}{\mathrm{H}}\right) \tag{1}$$

It compares in each point of the basin the water level h_r in the nearest element of the river network identified following the hydrological paths ('r' stands for 'river'), with the elevation difference (H) between these two points. h_r is estimated as a function of the contributing area using the hydraulic scaling function proposed by Leopold and Maddock (1953) and more recently investigated by Nardi et al. (2006) (see Eq. (2)):

$$\mathrm{h_r} \approx \mathrm{A_r^n} \tag{2}$$

where h_r is the water depth [m], A_r [km^2] is the contributing area calculated in the nearest point of the river network hydrologically connected to the point under examination, and n is the exponent (dimensionless).

The relationship between the GFI and the standard flood map, and therefore the linear boundary of decision between the two classes, is first calibrated within a training area, and then applied to map the flood susceptible areas at the basin scale. This boundary is expressed by a value of a threshold and, according to the analyses of Samela, Troy, et al. (2017), a calibration area equal or larger than 2% of the basin of interest is required in order to calibrate the optimal threshold.

This method can be useful when there is an absence of detailed data for flood simulations and provides preliminary indications about locations geomorphologically prone to floods. The analysis can be performed using data freely available online (nowadays several free DEM sources exist, especially for research purposes), and is therefore economic and fast. The method works consistently over a range of dominant topographies, available calibration areas (minimum required is 2% of the basin of interest), spatial scales, and DEM resolutions (Samela, Troy, et al., 2017).

However, this kind of analysis does not consider the physical processes of runoff generation, and cannot describe flood propagation in space and its interaction with infrastructures (e.g. bridges or artificial obstacles). Nevertheless, this preliminary information may be useful to identify the most critical locations and to define the computational domain of a hydraulic model for more detailed studies when needed, as suggested for other DEM-based methods (e.g. Nardi et al., 2006).

We underline that in areas were hydrologic, hydraulic and topographic information can be obtained to perform a proper hydraulic study, that study must be undertaken.