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Investigation on the use of geomorphic approaches for the delineation of flood prone areas

Salvatore Manfreda [a,*], Fernando Nardi [b], Caterina Samela [a], Salvatore Grimaldi [c], Angela Celeste Taramasso [d], Giorgio Roth [d], Aurelia Sole [a]

[a] University of Basilicata, Potenza, Italy
[b] University for Foreigners of Perugia, Perugia, Italy
[c] Tuscia University, Viterbo, Italy
[d] University of Genova, Genova, Italy

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SUMMARY

Three different geomorphic approaches to the identification of flood prone areas are investigated by means of a comparative analysis of the input parameters, the performances and the range of applicability. The selected algorithms are: the method proposed by Manfreda et al. (2011) based on a modified version of the Topographic Index (TI_m); the linear binary classifier proposed by Degiorgis et al. (2012), which uses different geomorphic features related to the location of the site under exam with respect to the nearest hazard source; the hydro-geomorphic method by Nardi et al. (2006) simulating inundation flow depths along the river valley with the associated extent of surrounding inundated areas. Comparison has been carried out on two sub-catchments of the Tiber River in Central Italy. The simulated flooded areas, obtained using the selected three methods, are evaluated using as a reference the Tiber River Basin Authority standard flood maps. The aim of the research is to deepen our understanding on the potential of geomorphic algorithms and to define new strategies for prompt hydraulic risk mapping and preliminary flood hazard graduation. This is of foremost importance when detailed hydrologic and hydraulic studies are not available, e.g., over large regions and for ungauged basins.

1. Introduction

The identification of flood prone areas is a critical issue that is becoming more challenging and pressing for our society (e.g., Sivapalan et al., 2012; Di Baldassarre et al., 2013a,b). Both public administrators and private companies (e.g., insurance companies) call for the development of new tools and strategies for prompt risk identification and mapping over large regions.

In the last few decades, the scientific community developed significant efforts to improve techniques for the detection of areas exposed to the flood hazard and, nowadays, there are several hydrologic and hydraulic modelling approaches that are regularly used for practical applications (e.g., Merz et al., 2007; Grimaldi et al., 2013). Those standard models are classified according to their geometric and physical representation of the flood domain (e.g., grid cell or triangular irregular networks) and physical dynamics (e.g., 1D and 2D models). Physically based 2D models are able to describe the inundation hydrodynamics, allowing the mapping of flow depth and extent at the scale of the single building and down to the scale of micro-topographic and vegetation features (e.g., Cobby et al., 2003; Kim et al., 2011). Nevertheless, 2D flood models are computationally intense and require a significant amount of data and parameters values to describe the riverbed and floodway morphology as well as the surface roughness. This poses a challenging problem for their calibration and validation (Horritt and Bates, 2002; Di Baldassarre et al., 2009).

Notwithstanding the limitation of these models, there are several attempts to provide a global flood mapping collecting all available information (e.g. Dilley et al., 2005; Moel et al., 2009) or using large scale physically based models of rainfall-runoff and river routing (e.g. Pappenberger et al., 2012; Winsemius et al., 2013). Even if the full mosaic is not available yet, because of the limitations in the resolution of the products and the scale of the river basins considered, it may be extremely useful in reinsurance, large scale flood preparedness and emergency response (e.g. Kappes et al., 2012).

In order to overcome modelling limitations, a significant effort is oriented in the optimization of the existing algorithms for global flood mapping. In this contest, it is interesting to recall the recent

* Corresponding author. Tel.: +39 0971 205140; fax: +39 0971 205160.
E-mail address: salvatore.manfreda@unibas.it (S. Manfreda).

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work by Lamb et al. (2009) that suggested the use of technology from the computer graphics industry to accelerate a 2D diffusion wave flood model that have been used in several countries in Europe. Nevertheless, a comprehensive and detailed flood map at the global scale is still lacking.

On the other end, the river basin morphology intrinsically contains an extraordinary amount of information on flood-driven erosion and depositional phenomena, constituting a useful indicator of the flood exposure of a given area (e.g., Arnaud-Fassetta et al., 2009). These information may be used to enhance our ability to identify the portion of a river basin frequently submerged or extend information extractable from hydraulic simulation. In fact, the terrain morphology plays a central role in flood waves behavior in a fundamental interplay that govern the landscape evolution across multiple spatial and temporal scales (e.g., Tucker et al., 2001; Tucker and Whipple, 2002). Following this theoretical principle, several authors have shown that the delineation of flood prone areas at the large scale can be carried out using simplified methods that rely on basin geomorphologic feature characterization (e.g., Noman et al., 2001; McGlynn and Seibert, 2003; Gallant and Dowling, 2003; Dodov and Foufoula-Georgiou, 2006). This kind of applications were originally hampered by the scarcity of detailed topographic data, but the advent of new technologies to measure topographic surface elevation (e.g., GPS, SAR, SAR interferometry, and laser altimetry), combined with the growing power of computers and the development of Geographic Information Systems (GIS), has given a strong impulse to the development of geomorphic approaches for valley bottoms identification using Digital Elevation Models (DEMs) as main data source.

We should be aware that while the first class of approaches (hydrologic and hydraulic) are able to appropriately identify and delimitate flood hazard areas, the second class (geomorphologic) are useful in ungauged condition to preliminary identify flooded areas.

In this work, we selected three different approaches for DEM-based flood prone areas identification that are hereafter briefly introduced: the modified Topmodel index approach by Manfreda et al. (2011), a linear binary classifier by Degiorgis et al. (2012, 2013) and an inundation hydro-geomorphic characterization algorithm by Nardi et al. (2006, 2013). For simplicity, they will be named Geomorphic Method 1 (GM1), GM2 and GM3, respectively.

GM1 is based on the topographic index by Kirkby (1975), defined as $\ln(A_d/\tan\beta)$, as a function of the local upslope contributing area (A_d) and the local slope ($\tan\beta$). This index, as representative of the runoff production and storage mechanism, is a good indicator of frequently saturated areas as well as flood-prone areas, as recently investigated by Manfreda et al. (2011) that propose an improved index by changing the relative weight of the drained area with respect to the local slope introducing an exponent n ($n < 1$) for the term A_d. This exponent was introduced in order to provide a measure of the relative value assumed by the hydraulic radius ($\sim A_d^n$) in a given point that represents a better descriptor of flood exposure. This index was used to develop a simplified procedure for the identification of flood-exposed areas.

Expanding the idea of using morphological indices for the description of flood prone areas, Degiorgis et al. (2012) investigated the relationship between several morphological features and flood hazard at the catchment scale using linear binary classifiers. Such procedure, here named GM2, is based on five selected morphologic features derived from DEMs. According to this work application, the best-performing feature is the difference in elevation between the location under exam and the downstream river node to which the site is hydrologically connected.

The GM3 estimates the variable water level along the river network and, by evaluating the elevation difference with surrounding areas, identifies the flooded area. This hydro-geomorphic algorithm, representing an extension of the geomorphic constant water level method by Williams et al. (2000), is based on the principle that flood-related erosional and depositional processes shaped the floodplain itself. As a result, the energy associated to these physical river flow phenomena is expressed in elevation terms to identify flood prone areas along fluvial valleys.

The three above-mentioned studies laid the groundwork for the present research that tackles the problem of the identification of the dominant topographic controls on the extend of flood prone-areas, where inundation is most likely to happen. This research question motivates this work that, by investigating the outcomes of the three selected techniques on two sub-catchments of the Tiber River in Central Italy, provides a useful discussion for understanding the simulated flooded areas behavior as a function of the morphological indices. The aim is to better comprehend the potential and limitations of each algorithm to identify the most suitable geomorphic parameters and modelling approaches for the delineation of flood prone areas over large regions.

2. The study area and dataset: the Tiber River in Central Italy

The Tiber River originates from the Apennine Mountains in Emilia-Romagna (Fumaiolo mountain, 1407 m a.s.l.) and flows for 405 km in a generally southerly direction through Umbria and Lazio towards the Tyrrhenian Sea. It is the largest river basin in central Italy with a drainage area of 17.375 km^2 (Fig. 1).

The Tiber River Basin Authority (TRBA) plan reports that the dominant land use for the basin is agriculture that covers about 53% of the surface, while approximately 39% is forested and 5% is urbanized. Its mean discharge at the outlet is approximately 230 m^3/s, while the highest historical flood discharge was recorded in 1598 with a peak flow of about 4000 m^3/s at the outlet (e.g., Calenda et al., 2005). This extraordinary value, corresponding to an estimated return period of 500 year, have been reconstructed starting from the ten surviving flood markers that commemorate the 1598 flood.

For the purpose of this work, the study area is represented by the upper Tiber River basin, which is characterized by a complex topography that is mainly hilly with elevation ranging from 100 to 1500 m a.s.l.. The selected sub-catchments are: the upper Tiber River, with an area of about 5000 km^2, and the Chiascio River (one of the main left tributaries of Tiber River), with a drainage area of approximately 727 Km^2. See Fig. 1 for the geographic and topographic setting of the two selected study basins.

Finally, it is extremely instructive to provide a preliminary description of the alluvial plain based on the geological information available over the area. This area may be considered as the maximum extend for any study related to flooding process. In fact the three formations that may be considered part of the river system from the geological point of view identify a significant portion of the river basin (see Fig. 2) that do not necessarily correspond with the exposed to flood inundation under the scenario considered in the present work.

2.1. Standard flood maps

Several hydrologic and hydraulic studies, with different levels of detail, are available for this river basin. In particular, the "Piano di Assetto Idrogeologico" or PAI (Law Decree 183/1998 and 49/2010 implementing of the European Flood Directive 2007/60/EC) developed by TRBA contains flood hazard and risk maps based on detailed standard hydrologic and hydraulic models as well as guidelines and procedures for mitigation measures to be adopted for an integrated sustainable and safe urban development at the basin scale (TRBA PAI, 2010).