Coupled Use of Hydrologic-Hydraulic Model and Geomorphological Descriptors for Flood-Prone Areas Evaluation: A Case Study of Lama Lamasinata

Beatrice Lioi(✉), Andrea Gioia, Vincenzo Totaro, Gabriella Balacco, Vito Iacobellis, and Giancarlo Chiaia

Politecnico di Bari, via Orabona 4, 70125 Bari, Italy
{beatrice.lioi, andrea.gioia, vincenzo.totaro, gabriella.balacco, vito.iacobellis, giancarlo.chiaia}@poliba.it

Abstract. The delineation of flood risk maps is a fundamental step in planning urban areas management. This evaluation can be carried out by hydraulic/hydrological modelling that allows obtaining water depths and related flooded areas. In this way, it is possible to mitigate and contain the catastrophic effects of floods, which become more frequent in the last decades. These events result in losses of both human lives and assets. In addition, the growing availability of high-resolution topographic data (i.e. Digital Terrain Models - DTM), due to new technologies for measuring surface elevation, gave a strong impulse to the development of new techniques capable of providing rapid and reliable identification of flood susceptibility. In this study, two methodologies for mapping flood-prone areas in karst ephemeral streams in Puglia region (Southern Italy) are compared, highlighting how DTM-based technologies are a precious source of information in data-poor environments. Results are in perfect agreement with previous studies on similar areas, showing the marked influences of topography in defining flood-prone areas. These researches can also be useful in investigating a wider gamma of hydrological-related aspects, in particular with respect to the social behavior of communities.

1 Introduction

In the last decades floods impact increased dramatically in many regions of the world, requiring a proper understanding of interactions between physical and social processes. A future worsening is expected due to the increase in alluvial phenomena and the rise of sea level [1]. Among several situations which have to be tackled in terms of flood risk, in this paper particular attention is dedicated to the ephemeral streams typical of the Apulian territory, defined as *lame* (in Italian). These karst streams convey the rainwater from the Murgia plateau towards the outlet of the watershed to which they belong, and are widespread throughout the Apulian regional territory but mainly in the metropolitan area of Bari. Lame are geomorphological structures with fertile alluvial soils [2–4] and represent a structural typology typical of the Apulian karst

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environments; more generally in this region different types of risk may coexist connected with the presence of waterways, for example in above-mentioned karst [5, 6], with respect to the type of soil [7] and in reservoirs [8]. Different approaches can be used for the management and mitigation of hydraulic risk, for example by making use of theoretical tools in the framework of derived flood frequency distributions [9, 10] or in the context of conceptual models [11]. In addition, useful support for flood management is provided by satellite data, which use is widespread in the environmental field, both for the evaluation of hydrological parameters [12–16] and for flood risk assessment [17–20]. Recent advances in the definition of high-resolution Digital Elevation Models (DEM) were carried out exploiting the use of Unmanned Aerial Vehicle (UAV) (e.g., [21]). Furthermore, an interesting application of these methodologies can be found in the field of landslide detection [22]. Flood management issues can also extend to other areas, such as damage to structures. In particular, different models can be adopted to define the levels of damage connected, among others, both to flood and seismic events [23–25].

The paper is structured as follows. In Sect. 2 details of Lama Lamasinata are illustrated, while in Sect. 3 the main features of bidimensional hydraulic/hydrological models and geomorphic descriptors are described. In Sect. 4, instead, the main results of this analysis will be highlighted. In the conclusive section, instead, some comments and operative proposals are reported.

2 Study Area

This study is focused on lama Lamasinata (Fig. 1), a karst ephemeral stream that flows through the metropolitan area of Bari (Puglia region, Southern Italy). It crosses the municipalities of Toritto, Palo del Colle, Bitonto, Binetto, Bitetto, Modugno and Bari and slopes down, channelled, to the pinewood of San Francesco, in Bari. This stream has a basin area of about 650 km^2.

The main characteristics of the basin are shown in Table 1.

Table 1. Hydro-geomorphological characteristics

Hydro-geomorphological characteristics of the Lama Lamasinata			
Average slope of the basin i_m (%)	Maximum basin height Q_{max} (m a.s.l.)	Medium basin height Q_m (m a.s.l.)	Length of the main stream network L_{max} (km)
0.9	513.46	276.19	54.14

The importance of Lama Lamasinata is mainly due to the marked interaction with the urban environments of Palo del Colle, Binetto and Bitetto.

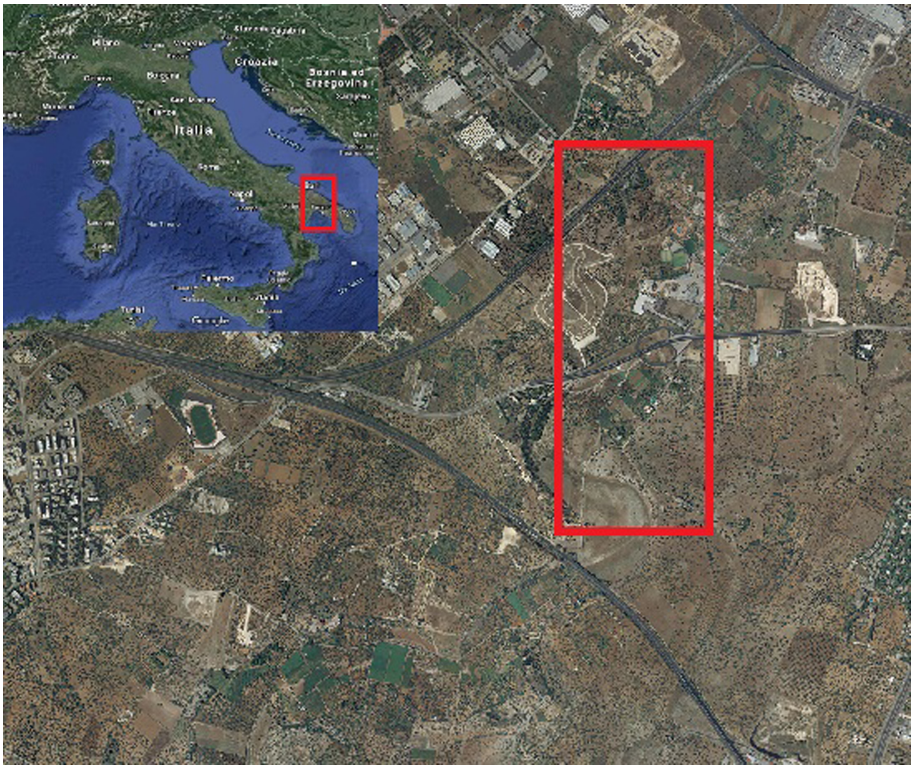

Fig. 1. Study area (Lama Lamasinata, Bari)

3 Materials and Methods

This section illustrates the two methodologies implemented in the present study:

- the evaluation of flooded areas through a coupled hydrological-hydraulic model;
- the assessment of flood-prone areas by means of geomorphological descriptors.

The river channel as well as the digital elevation model of the area of interest, were reconstructed in a GIS environment starting from georeferenced vector cartography. This study aims to evaluate floodable areas in terms of water depth.

The Southern Apennines Hydrographic District identifies the areas with hydraulic hazard as portions of territory characterized by the same flood probability, which corresponds to the return periods of the reference flood equal to 30, 200 and 500 years, in accordance with current national legislation.

3.1 Hydrologic-Hydraulic Model

The management of hydraulic risk is carried out through the definition of maps able to highlight the areas of the territory subjected by assigned risk levels. Through the use of

numerical modeling it is therefore possible to predict the areas affected by flooding after assuming all the input elements, such as morphology, land use and flood event. Currently, the determination of floodable areas can be performed through the use of coupled hydrological and hydraulic models. In the proposed work the hydraulic simulation was carried out using a two-dimensional (2D) FLO-2D software, which provide flood-prone areas delineation, starting from flood hydrographs obtained for fixed return periods.

The first step of the procedure was implemented by importing the Digital Terrain Model (DTM) in ASCII format on which the calculation grid will be subsequently built. For this purpose, it was necessary to specify the grid pixel, i.e. the size of the cell that represents the elementary unit of the model. Subsequently, the altimetric value is assigned to each cell. The creation of the grid represents a central element of the simulation as it defines the resolution with which the model will perform the simulation. Obviously, the higher the resolution, the greater the accuracy with which the flooded areas are evaluated. It is straightforward that higher resolutions (small cell size) correspond to long processing times. Therefore, the choice of the grid must be based on an adequate compromise between an accurate representation of the morphology of the soil and a maximum acceptable number of cells. Indicatively the maximum value of the ratio between the peak value of the flow rate and the area of the cell should not exceed the value of 0.3 m^3s^{-1}/m^2; beyond this value the calculation may become unstable, although the simulation may take place. For the purposes of the present study, a cell with a resolution of 10 m $\times$ 10 m was selected. The grid cell to which associate the inflow condition is identified through the use of a design hydrograph. Then, a triangular hydrograph with a flow peak rate of Q_P = 606.64 m^3/s, corresponding to a return period of 200 years, was selected.

The flood hydrograph is characterized by a concentration period that extends for a duration equal to the corrivation time (t_c = 10.34 h) and ends with the reaching of the flow peak, followed by a recession curve that has a double duration respect to the corrivation time. In this way, the hydrograph extends for a total of 31.02 h. Another parameter that influences the results of the hydraulic simulation is given by the roughness of the surfaces. The two-dimensional hydraulic model FLO 2D takes into account the roughness coefficients that must be known for each cell of the calculation domain. A Manning coefficient of 0.04 $m^{-1/3}s$ is then considered.

Similarly, the hydrological model with a return period of 30 years corresponding to the high hydraulic hazard, with a flow rate of 224.74 m^3/s, is applied.

3.2 Geomorphological Descriptors

Geomorphological descriptors represent promising tools for a rapid assessment of flood-prone areas [26, 27]. They exploit morphological features of floodplains, providing a quantitative measure for a preliminary detection of areas exposed to flood hazards. In fact, the morphology of a river basin is the basic element that allows the identification of the effects of the outflow distribution, resulting from the occurrence of meteoric events that characterize the input of the basin itself. Geomorphic descriptors analyzed in this document were obtained from a DTM compatible with the version of the basic FLO-2D open-source software, having 10 * 10 m spatial resolution. It should

be remarked that the characteristics of the DTM could significantly affect descriptors performances.

3.2.1 Synthetic and Composite Descriptors

Consistently with their nature, geomorphological descriptors can be subdivided into two main categories:

Synthetic Descriptors

- upslope contributing area, A_s [m^2];
- elevation to the nearest stream, H [m];
- distance from the nearest stream, D [m];
- surface curvature, $\nabla^2 H$ [-];
- local slope, S [-].

Composite Descriptors

- modified topographic index, TI_m:

$$TI_m = \ln\left[\frac{A_d^n}{\tan(\beta)}\right] \tag{1}$$

  A_d is the drainage area per unit of length, tan (β) is the local gradient and n is a dimensionless parameter with a value less than 1.
- downslope index, DW_i:

$$DW_i = \tan(\alpha_d) = \frac{d}{L_d} \tag{2}$$

  the index aims to describe the length (L [m]) of the flow path which deprives the particle of water a given amount of potential energy d [m]. We imposed d = 5 m.
- $\ln\left[\frac{h_l}{H}\right]$: this index relates, in each point, the water depth h with the synthetic descriptor H, where h can be defined for each basin location with the following relationship:

$$h_l \cong bA_l^n \tag{3}$$

  with A_l [m^2] upslope contributing area at the point of interest, b a scale factor usually set equal to 10^{-2} and n a dimensionless exponent set equal to 0.3.
- Geomorphic Flood Index (GFI) $\ln\left[\frac{h_r}{H}\right]$: this index is different from the previous, because the upslope contributing area A_r is computed on the cell belonging to the hydrographic network hydraulically nearest to the considered one.
- $\frac{[h_r - H]}{D}$: an evolution of the last index, with the introducing D into the denominator.

For a detailed overview of these indices, see [28].

3.2.2 Calibration Procedure

Calibration procedure is an important part in the implementation of geomorphic descriptors for flood-prone areas detection. In this process, each of the investigated indexes was scaled in the range [−1; 1]; then a moving threshold was applied into this interval, generating binary maps to be compared with the flooded reference map. In this respect, each cell of the descriptor matrix can be classified as True Positive (TP), False Positive (FP), True Negative (TN) and False Negative (FN). For each threshold, the following measures are computed:

True Positive Rate

$$r_{tp} = \frac{TP}{TP + FN} \tag{4}$$

False Positive Rate

$$r_{fp} = \frac{FP}{FP + TN} \tag{5}$$

All of these computed values allow to build a function able to provide a measure of error, the *objective function*:

$$OB = r_{fp} + \left(1 - r_{tp}\right) \tag{6}$$

Threshold corresponding to the minimum value of this function provides the best performing map for the analyzed descriptor.

True positive and false positive rates can be exploited for implementing another performances indicator based on the Receiver Operating Curves (ROC) [29]. In this approach, false positive rate is plotted against the true positive rate, and Area Under Curves (AUC) can be computed from this line and used as metric (closer to 1 is AUC, better is the index fit).

4 Results and Discussion

The application of the hydrologic-hydraulic model and geomorphological descriptors led to comparable results. In this paragraph a more specific discussion about the two implemented methodologies is reported.

4.1 Hydrologic-Hydraulic Model Results

In the FLO-2D two-dimensional model, the MAPPER module was used to extract the model outcomes regarding the flooded areas in terms of maximum flow depth.

In Figs. 2a and b the flooded areas corresponding to return periods of 200 (medium hazard) and 30 (high hazard) years are respectively shown:

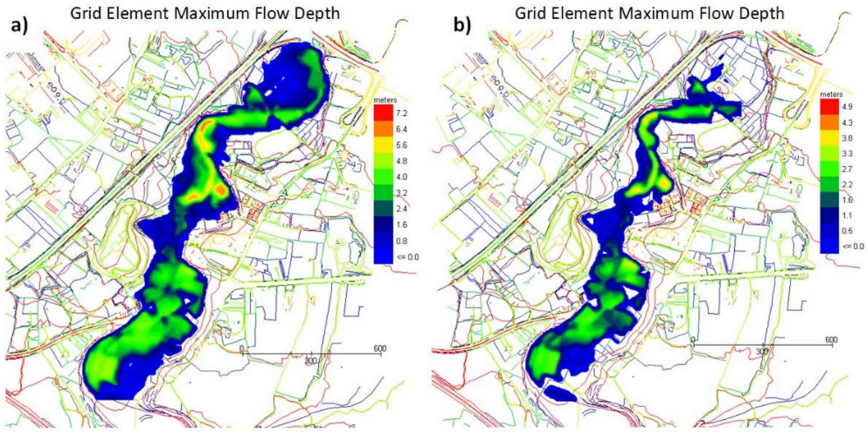

Fig. 2. Flooded areas obtained from FLO-2D simulation. Return periods are 200 (a) and 30 (b) years

It can be seen that the flooding obtained by propagation, affects the channel near the existing structures, probably due to the narrowing of the section, which determines a backwater condition, with the consequent raising of the free surface.

4.2 Results of Geomorphological Descriptors

Results obtained by applying the above-mentioned geomorphological descriptors are showed in terms of flood-prone areas and indices performances. For the sake of clarity, only floodable areas with a return period of 30 years are showed in Fig. 3, while ROC curves and calibration outputs are reported for the two investigated flood events. As it emerges from the comparison between the results of the two applied methodologies, effects of the urbanization in the investigated area with respect to flood extension led us to consider appropriate to redefine the study area. For the same reason, an excess of flooded area using the FLO-2D model was depicted (Fig. 3b).

The performances of geomorphic descriptors considering return periods of 30 and 200 years are showed below in Tables 2 and 3 respectively. The respective ROC curves are instead plotted in figures from Figs. 4, 5, 6 and 7.

Results show that better performances were obtained with the indices *H,* $\ln(h_r/H)$ and $\ln(h_l/H)$, highlighting the key role of the *H* index. This is perfectly coherent with the particular nature of lame, generally characterized by a regular rectangular section.

Furthermore, *H* provided the best results both in terms of true positive and false positive rate, detecting excellent abilities in interpreting flood phenomenology in this type of karst ephemeral streams. Outputs of this analysis are in accordance with the findings of other studies on similar areas [2, 4], confirming the goodness of fit of the index *H* when applicated to lame.

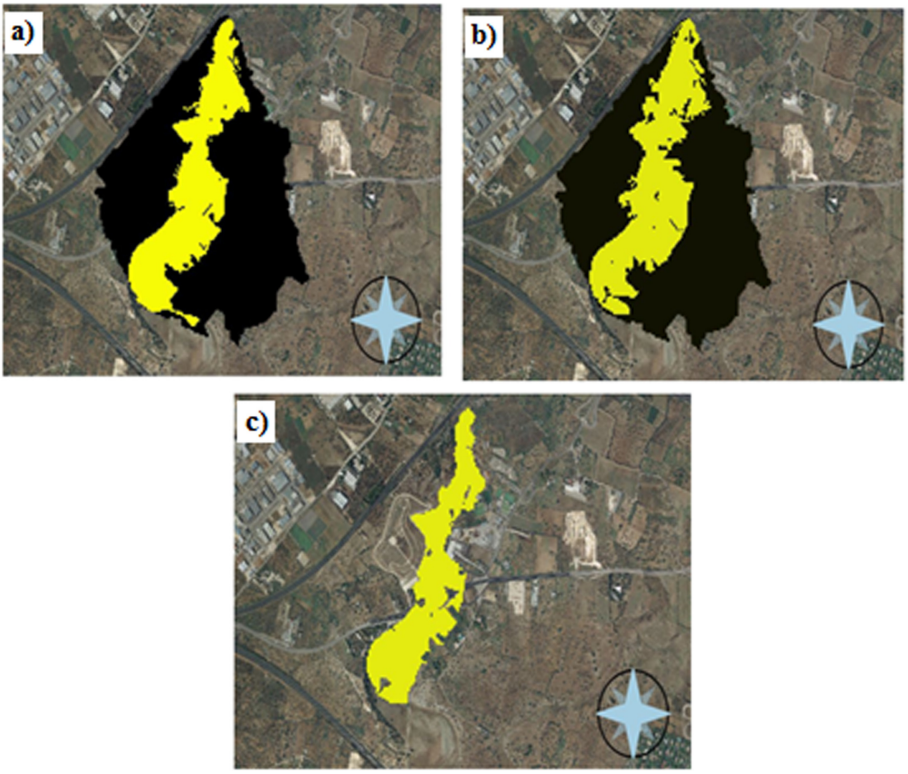

Fig. 3. **a)** Flood inundation identified by the descriptor H; **b)** Flood inundation identified by the descriptor $\ln(\frac{h_R}{H})$; **c)** Flooded area obtained by hydraulic-hydrologic simulation (30 years).

Table 2. Performances of geomorphic descriptors for a return period of 30 years

	τ	r_{fp}	r_{tp}	min(ob)	AUC
As	−0.999	0.247	0.401	0.846	0.583
C	0.231	0.587	0.739	0.848	0.574
S	−0.771	0.721	0.902	0.819	0.614
D	−0.588	0.198	0.929	0.269	0.939
H	−0.801	0.076	0.968	0.108	0.986
TI_m	−0.576	0.671	0.864	0.807	0.635
DW_i	−0.917	0.083	0.708	0.375	0.849
H/D	−0.932	0.045	0.634	0.410	0.821
$\ln(h_r/H)$	−0.551	0.117	0.914	0.203	0.950
$\ln(h_l/H)$	−0.591	0.122	0.924	0.198	0.972
$(h_r - H)/D$	0.681	0.050	0.723	0.327	0.865
$(h_r - H)/DW_i$	−0.975	0.224	0.960	0.264	0.957

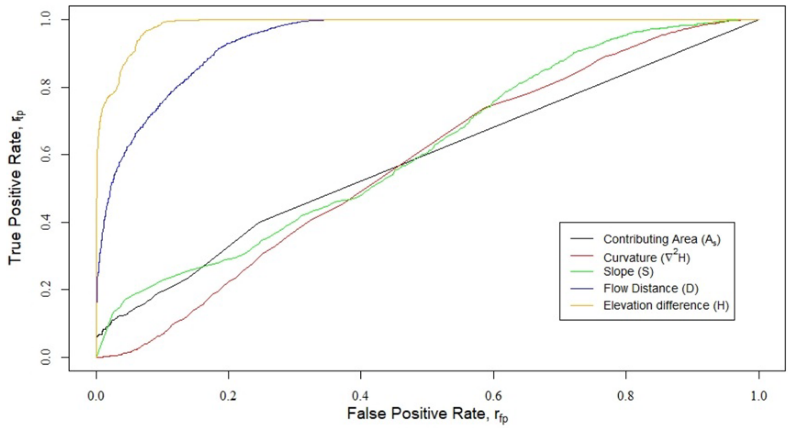

Fig. 4. ROC curves- single features (T = 30 years)

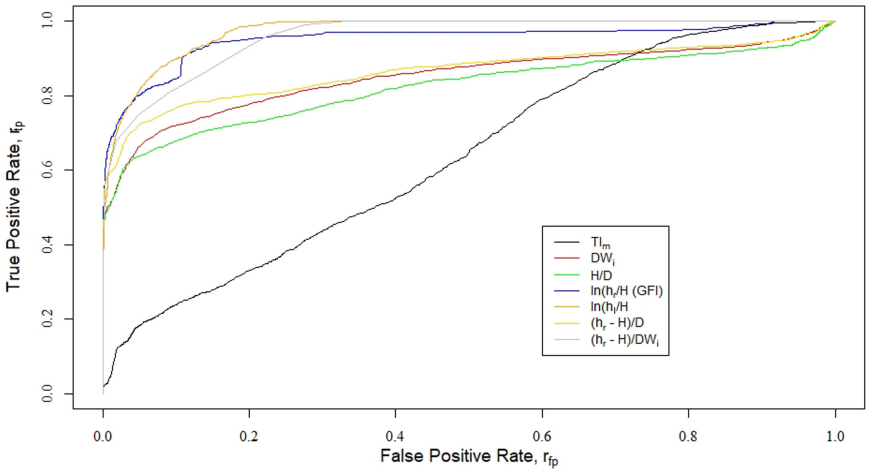

Fig. 5. ROC curves –composite indices (T = 30 years)

Table 3. Performances of geomorphic descriptors for a return period of 200 years

	τ	r_{fp}	r_{tp}	min(ob)	AUC
A_s	−0.999	0.249	0.365	0.885	0.564
C	0.231	0.592	0.698	0.893	0.565
S	−0.715	0.778	0.908	0.871	0.556
D	−0.588	0.148	0.919	0.229	0.952
H	−0.752	0.054	0.986	0.069	0.992
TI_m	−0.648	0.778	0.921	0.857	0.574
DW_i	−0.917	0.074	0.616	0.458	0.807
H/D	−0.932	0.038	0.540	0.498	0.774
$\ln(h_r/H)$	−0.579	0.099	0.912	0.187	0.951
$\ln(h_l/H)$	−0.639	0.141	0.961	0.180	0.970
$(h_r - H)/D$	0.681	0.039	0.626	0.413	0.821
$(h_r - H)/DW_i$	−0.975	0.173	0.952	0.222	0.963

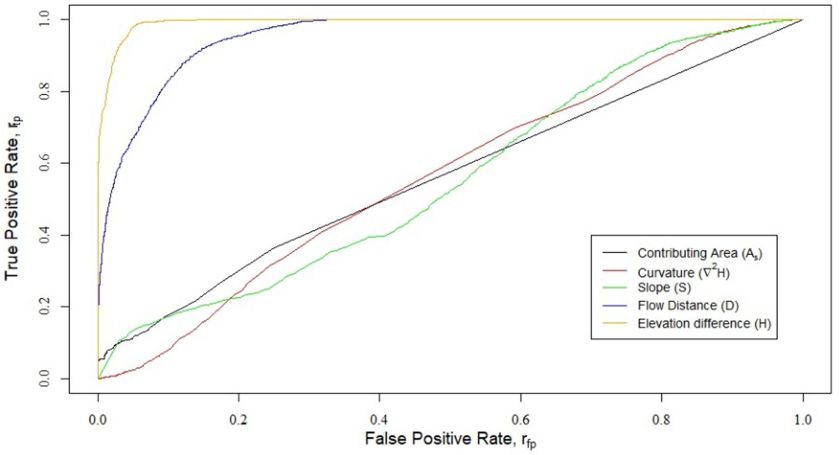

Fig. 6. ROC curves – single features (T = 200 years)

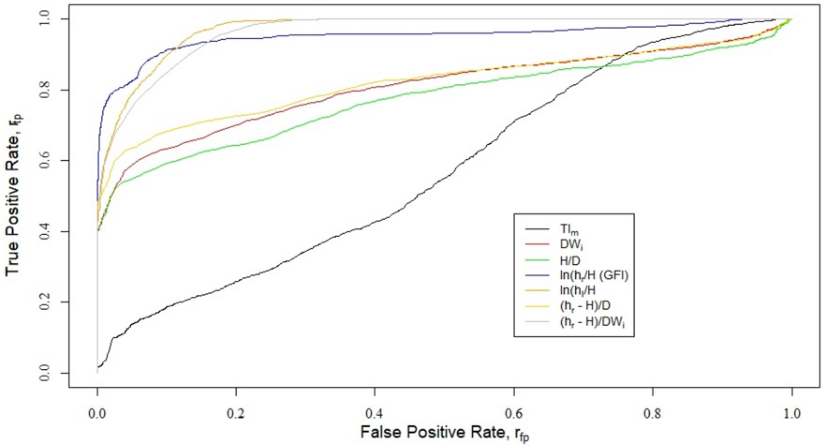

Fig. 7. ROC curves – composite indices (T = 200 years)

5 Conclusions

In this paper, two methodologies were compared for the identification of flooded areas, each one characterized by a different level of complexity and amount of *a priori* information. In the first case, a hydrological-hydraulic model was implemented using the FLO-2D software, while the second methodology is based on the use of geomorphological descriptors and requires, for calibration, a binary flooded area, obtained with numerical simulation. At the base of both approaches the DTM is required as the fundamental element, the dimension of which strongly influences the accuracy of results. For this reason, the correspondence in terms of resolution (i.e. cell size) in both models was necessary. Even if the two compared are conceptually different, they give us comparable outputs. Moreover, the obtained floodable areas are consistent with those proposed by the Southern Apennines Hydrographic District, demonstrating that, although in one case a fast method was used, the results are compatible with each other.

The outcomes of this paper provide a contribution in the field of flood-prone area delineation, highlighting that the use of geomorphic methods, at the expense of their conceptual simplicity, could give relevant information about the susceptibility of areas to flooding.

In this way, the implementation of this kind of methodologies could lead to an improvement in the updating of flood risk maps, in order to give new tools to practitioners and public authorities for a more aware management of risk.

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