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Flood-Prone Areas Assessment Using Linear Binary Classifiers based on Flood Maps obtained from 1D and 2D Hydraulic Models

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ABSTRACT

The identification of flood-prone areas is a critical issue becoming everyday more pressing for our society. A preliminary delineation can be carried out by DEM-based procedures that rely on basin geomorphologic features. In the present paper, we investigated the dominant topographic controls for the flood exposure using techniques of pattern classification through linear binary classifiers based on DEM-derived morphologic features. Our findings may help the definition of new strategies for the delineation of flood-prone areas with DEM-based procedures. With this aim, local features - which are generally used to describe the hydrological characteristics of a basin - and composite morphological indices are taken into account in order to identify the most significant one. Analyses are carried out on two different datasets: one based on flood simulations obtained with a 1-D hydraulic model, and the second one obtained with a 2-D hydraulic model. The analyses highlight the potential of each

morphological descriptor for the identification of the extent of flood-prone areas and, in particular, the ability of one geomorphologic index to represent flood inundated areas at different scales of application.

Keywords: flood hazard, DEM, terrain analysis, geomorphic approaches, ungauged basins.

1 1 INTRODUCTION

2 Floods, which are becoming more frequent in urban areas, are one of the natural 3 phenomena more difficult to prevent and to deal with, especially in developing countries (Douglas et al., 2012). The remarkable number of inundations that caused, 4 5 in the last decades, thousands of deaths and huge economic losses, testifies the vulnerability of many Countries to the flood hazard. On one hand, the exposure of 6 7 human activities is increasing with the expansion of cities, leading to the reduction of 8 the natural water retention capacity of the soil (e.g., Cannon, 1994; Ceola et al., 9 2014); on the other hand, there is a motivated suspect that the frequency of great floods is increasing with time (e.g., Milly et al., 2002; Prudhomme, 2002). The 10 11 current situation is pushing the international community to find new strategies to cope 12 with flood hazards.

The European legislation has introduced new policies for the assessment and management of flood risk for territory protection with the Floods Directive 2007/60/EC. This Directive requires Member States to assess the flood risk, mapping the flood extent over their territories, in order to evaluate assets and humans at risk, and to take adequate and coordinated measures to reduce this risk for a sustainable hydraulic protection of the territory. The European case is just an example of context where the flood risk is felt as a critical issue that should be faced, in terms of planning, at a large scale. For this reason, the definition of procedures able to provide extended description of the flood-prone areas is a growing need in Europe and several other countries. Therefore, much effort is going into the identification of flood-prone areas through the use of time-consuming hydrological/hydraulic simulations.

The patterns of flood inundations are also critical for the ecology of floodplains (Townsend et al., 1998). In fact, the temporal and spatial dynamics of floods may alter the distribution of vegetation and biodiversity of wetlands (Sharitz and Mitsch; 1993). Therefore, the accurate representation of inundation extents, as well as of surface water bodies, is crucial for the management and conservation of wetland ecosystems (Nei et al., 2009; Bridgham et al., 2013).

30 In this framework, the research has recently shown that the delineation of flood-prone 31 areas can be carried out using simplified methods that rely on basin geomorphologic 32 features (e.g., Nardi et al., 2006; Manfreda et al., 2011; Degiorgis et al., 2012; 33 Manfreda et al., 2014a; Jalayer et al., 2014; De Risi et al., 2014; Papaioannou et al., 34 2014). Such innovative procedures may provide a preliminary delineation of the flood-prone areas useful for the planning of numerical analyses, and for insurance 35 36 companies that have a growing interest toward the identification of the assets and population at risk. 37

This kind of approach may be extremely beneficial in the definition of new procedures for the identification of flooded areas from remote sensing techniques, where the topographic information may be used as external constraint in the adopted algorithms, that generally rely only on the local slope or the distance to the channel
(e.g., Brivio et al., 2002). For instance, Fluet-Chouinard et al. (2014) used the
topographic information to generate inundation probability maps for downscaling
course-scale remote sensing data.

In particular, Degiorgis et al. (2012) introduced the use of linear binary classifiers to investigate the relationships between several morphological features and the flooding hazard at the catchment scale. In the present work, we extend the number of morphological features investigated, using single local features as well as composite indices (built with the specific aim to represent a metric of flood hazard) derived from Digital Elevation Models (DEMs).

51 The performances of the selected morphological features on the Bradano River 52 (Southern Italy) are evaluated at different scales of application, using two reference 53 flood inundation maps: one obtained applying a mono-dimensional approach over the 54 entire basin (basin scale) and one obtained using a two-dimensional approach at the 55 basin outlet (local scale). This last represents an extremely interesting study case that 56 has never been considered for geomorphic applications. In fact, most of the 57 applications made since now have only compared morphological features with monodimensional simulations over mountainous areas, but it is well known that the most 58 59 challenging problem for hydraulic studies is represented by flat areas. Hence, the 60 main motivation for this study is the identification of a metric suitable for both 61 mountainous and flat areas.

In recent studies, the best-performing local features, among those adopted, were the difference in elevation between the considered point and the source of risk (H), and the distance from the nearest stream (D). These features have been also applied in the 65 present study case with a number of additional morphological indices. Results 66 highlighted remarkable differences in the performances of indices and features 67 applied in different contexts. The study allowed to better address the sensitivity of 68 each index with the change of scale, spatial resolution, etc.

69

70 2 STUDYAREA

The Bradano River is one of the major rivers of the Basilicata Region (southern 71 Italy), with a drainage area of about 2,765km². The climate is characterized by a dry-72 73 sub humid regime with scarce rains and zero base flow during the summer period (see Fiorentino et al., 2007). More than the 77% of the total surface is covered by 74 75 agricultural areas, and only the 23% by woodlands and semi-natural areas (this 76 information is provided by the CORINE-Land Cover map of the European 77 Environmental Agency). The upper basin is characterized by a marked topography; 78 by contrast, the terminal portion of the basin, close to the outlet, is extremely flat.

79 This river basin is one of the most critical in terms of flooding for both the Basilicata 80 and the contiguous Puglia Region. It produced several floods, causing significant 81 damages especially in the portion of the basin close to the river outlet to the Ionian 82 Sea. The first documented flood of the Bradano River refers to the 1827, when two 83 bridges were destroyed interrupting the connection from the South to the City of 84 Matera (this historical event is documented in the archives of the Kingdom of the 85 Two Sicilies under Ferdinando II). Later on, a dramatic event occurred in 1959 when 86 the cities near the coast were significantly damaged and several buildings were 87 destroyed. More recently, flooding also occurred in 1972, 2004 and 2011 (see Figure 1), producing inundations in the outlet portion of the river basin, which is 88

89 characterised by gentle slopes and flat surfaces. Some additional information on the

- 90 damages produced by most of these events can be found on http://www.evalmet.it/.
- 91

92 3 METHODS AND DATASETS

93 **3.1 Flood Maps**

94 The extent of the inundated areas was studied by the River Basin Authority of 95 Basilicata (RBAB), that mapped all the rivers of this region. The complex 96 morphological characteristics of the basin forced the RBAB to use both one-97 dimensional (1D) and two-dimensional (2D) hydraulic models for flood mapping. 98 The first was used for flood propagation along the main river, while the 2D model 99 application was limited to a smaller portion of the river basin nearby the outlet (about 100 80km²) characterised by extremely flat surfaces, in order to reduce the computational 101 efforts.

102 Two-dimensional models allow studying flood propagation in the areas where it is not 103 possible to recognize a prevailing direction of the water flow. Nevertheless, these 104 models are computationally intensive and for this reason their application is generally 105 limited to a portion of a river basin, while 1D models allow providing a more 106 extensive description of the flood extent at the basin scale. In fact, in the present case 107 the evaluation of the flood-prone areas for a given return period for the main river 108 was carried out by the use of the HEC-RAS model (HEC-RAS, 2010), which is less 109 reliable when dealing with the flat portion of the river basin. Therefore, the basin 110 outlet was investigated by using a 2D approach. Both maps were obtained using a 111 synthetic hydrograph derived from regional analyses assuming a return period of 30 years. The flood peak was calculated using the VAPI methodology (Claps et al., 112

113 1999), while the synthetic hydrograph was obtained exploiting the synthetic flow
114 hydrograph proposed by NERC (1975) and modified by Fiorentino & Margiotta
115 (1999).

It is necessary to remark that the RBAB's studies are limited to a portion of the basin that includes the main River, but several tributaries are not analyzed. Therefore, it is highly desirable to have a tool able to provide an extensive characterization of the flood hazard over the entire river network. With this aim, we explored the use of binary classifiers exploiting the two flood maps that refer to the same basin, but differ for reference scale, DEM resolution and methodology adopted for flood mapping.

In order to clarify the procedure used by the RBAB to delineate flood maps, it is useful to provide some additional information about the models adopted. One model is HEC-RAS that probably does not require further descriptions, being a widely used software well documented on the web page of US army Corps of Engineers (http://www.hec.usace.army.mil). On the contrary, it seems appropriate to provide additional information about the 2D hydraulic model named FLORA-2D (FLOod and Roughness Analysis) recently introduced by Cantisani et al. (2012, 2014).

129

130 **3.2 FLORA-2D**

FLORA-2D was developed recently within a collaboration between the University of Basilicata and the company "Research on Energy System" (RSE spa). It has been developed with the aim to simulate flood propagation in flat areas taking into consideration the dynamic effect of vegetation. In fact, flow resistance due to vegetation can be a dominant factor in the inundation process for relatively shallow inundation (<1 m). 137 FLORA-2D has the capability to simulate the inundations considering the spatial and 138 temporal variation of the resistance due to vegetation. Each node of the 139 computational matrix has a roughness coefficient depending on the type of vegetation, flow depth and velocity. In particular, the Manning coefficient n is 140 141 calculated according to Petryk and Bosmajian (1975) when the vegetation is rigid, 142 and Freeman et al. (2000) in the case of flexible vegetation. The general algorithm 143 governing the flood propagation is based on the "shallow water equations" simplified 144 by neglecting the convective terms.

145 The model has been validated over the Bradano river using flood maps obtained from 146 satellite data. This kind of procedure is becoming more common with the increased 147 potentials of remote sensing products (see e.g., Frappartet al., 2005; Iacobellis et al., 148 2013, Domeneghetti et al., 2014). An example of a remote sensed image for the flood 149 event of March 2011 is given in Figure 1.A, which has been used by Cantisani et al. 150 (2014). Model reliability has been further investigated using for comparison the 151 model Mike21 HD by the Danish Hydraulic Institute, FLO-2D by O'Brien (2007), 152 FLATModel by Medina et al. (2007). In all cases, the results were comparable in 153 terms of flood extent, but with the great advantage of a significant reduction of the 154 computational costs.

In the present application, the computational domain was defined by a square grid with resolution of 10m, while the time step was set to 2sec. This resolution provides a good compromise between simulation time and data accuracy for a correct representation of the process (Sole et al., 2011). It was also observed that the time step of 2s ensures the model stability.

160 The above-mentioned hydrograph was assigned as upstream boundary condition,

while a constant water level equal to 0.5 m a.s.l. was considered as downstream
boundary condition (the sea level is assumed slightly above the ordinary conditions).
Finally, the spatial distribution of the flow resistance was derived from LiDAR data,
used to generate maps of vegetation height (Cobby et al., 2001).

165 **3.3 Digital Elevation Models**

Digital Elevation Models (DEMs) contain a significant amount of information that
may be helpful for the delineation of flood-prone areas (see e.g., Manfreda et al.,
2014).

In the present case, we used, for the entire river basin, the USGS HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales-hydrosheds.cr.usgs.gov/index.php) elevation data, available for the entire globe at a fairly good resolution; instead for the portion of the basin outlet we adopted a high resolution LIDAR-derived DEM.

Figure 2 provides a graphical description of the investigated area; in particular, Figure 2.A describes the digital elevation model of the Bradano river basin (called SRTM DEM), extracted from HydroSHEDS (hydrosheds.cr.usgs.gov/index.php) and Figure 2B shows the digital elevation model at the outlet (called LiDAR DEM) of the same basin, extracted from a LiDAR high-resolution DEM and resampled to a 10m x 10m grid.

HydroSHEDS DEMs are derived from remote sensed elevation data of the NASA Shuttle Radar Topography Mission (SRTM). The original SRTM data have been conditioned using a sequence of automated procedures: a DEM–VOID has been released, where the no-data voids have been filled and the main elevation inconsistencies removed. Furthermore, a DEM–CON is also available for hydrological applications; it has been further conditioned in order to accurately reproduce the actual river network. The conditioning process alters the original elevation data and this limits the use of the DEM–CON to drainage network identification procedures. Both the mentioned DEMs have been used for the Bradano River, with a resolution of 3 arc-second that corresponds, for the current study area, to a square grid size of about 90m.

191 The LiDAR high-resolution DEM, instead, was obtained combining airborne LiDAR 192 survey and field measurements that were carried out specifically for the RBAB, 193 paying particular attention to position and elevation of levees. The laser scanning 194 survey was carried out with a density of point equal to 0.7 points/m².

Figure 3 provides a representation of the standard flood maps used as reference for the application of the linear binary classification. In particular, Figure 3.A shows a flood map derived using a one-dimensional approach over the entire Bradano River, instead Figure 3.B provides a representation of the flooded areas identified by the application of the FLORA-2D model at the outlet of the Bradano basin.

200 **3.4 LINEAR BINARY CLASSIFIERS AND ROC ANALYSIS**

201 Techniques of pattern classification are used to compare DEM-derived quantitative 202 morphologic features and existing flood hazard maps. The linear binary classifiers 203 represent a useful tool for the scope, allowing a quantitative comparison between two 204 binary maps (see Degiorgis et al., 2012). In particular, the flooded areas are easily 205 converted into a binary map assigning a code 1 for flooded areas and a code 0 for 206 marginal hazard areas. The marginal hazard areas are introduced in order to identify 207 the portion of the river basin where a clear distinction between flooded and nonflooded areas is possible. The comparison with morphological features is possible 208

imposing a threshold value to distinguish between the two possible values of the map.In this scheme, the threshold value becomes a parameter that may be changed inorder to optimize the performance of each feature.

Binary classifiers need to be trained. For this reason, areas predicted as flooded by the use of hydraulic models (one-dimensional over the entire Bradano basin and twodimensional at the outlet) are used to calibrate the optimal threshold that allows to distinguish flood-prone areas for each selected feature.

216 Single and composite morphologic features are scaled in normalized features lying 217 between -1 and 1. Different normalized thresholds are applied to each normalized 218 features obtaining a binary map of 0 and 1. Comparing this map with the flood map 219 obtained by the hydraulic model, there are four possible conditions in each point of 220 the map: if the threshold detects a flooded area when this condition is present, the 221 point is counted as a true positive; otherwise, if it classifies a point as non-flooded 222 (negative), it is counted as a false negative. If the site is defined non-flooded by the 223 inundation map and it is classified as negative, it is counted as a true negative; 224 otherwise, if it is classified as positive, it is counted as a false positive.

The quality of each binary classifier is evaluated using the Receiver Operating Characteristic (ROC) curves that represent a good measure of performance. The ROC graphs are obtained by varying the threshold of the classifier and are defined as the set of pairs of true positive rate (plotted on the Y axis) and false positive rate (plotted on the X axis). ROC curves are also used to select a suitable threshold value (see Fawcett, 2006).

231 We recall that the true positive rate (also called hit rate) is estimated as:

232

233
$$r_{tp} \approx \frac{Positives \ correctly \ classified}{Total \ positives}$$
 [1]

235 The false positive rate (also called false alarm rate) of the classifier is:

236

237
$$r_{fp} \approx \frac{Negatives incorrectly classified}{Total negatives}$$
 [2]

238

The diagonal line y = x represents the strategy of randomly guessing a class. Any classifier that appears in the higher left triangle performs better than random selection. The best value of the normalized threshold is obtained by minimizing the sum of the false positive rate and the false negative rate $r_{fp} + (1 - r_{tp})$ assigning equal weights to the two rates.

In order to compare different kinds of binary classifiers, a common method to reduce
ROC performance to a single scalar value is to calculate the Area Under the ROC
Curve, abbreviated AUC. The value of the AUC ranges from 0.5 (completely random
classifier) to 1.0 (perfectly discriminating classifier).

248

249 3.4.1 SINGLE FEATURES

In the present section, we provide a synthetic description of the DEM-derived morphologic features adopted in the present study. Among all possible features, we considered the same list adopted by Degiorgis et al. (2012):

253 1. the upslope contributing area, A_s [m²];

254 2. the surface curvature, $\nabla^2 H$ [-], defined as the Laplacian of the elevation;

3. the local slope, S [-], estimated as the maximum slope among the eight possible
flow directions that connect the cell under exam to the adjacent cells;

4. the distance from the nearest stream, D [m], defined as the length of the path that hydrologically connects the location under exam to the nearest element of the reference drainage network;

5. the elevation to the nearest stream, H [m], computed as the difference between the elevation of the cell under exam and the elevation of the final point of the aboveidentified path.

A description of these features computed for the Bradano River Basin is given in Figure 4, where one can observe the plots obtained using the DEM at 90m of resolution in Figure 4.A (for the entire basin), while the features obtained for the basin outlet with a DEM at 10m of resolution are given in Figure 4.B. It is necessary to specify that in this last case features like the contributing area have been corrected in order to avoid border effects assigning to the channel cells on the border values derived from the larger DEM.

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271 **3.4.2 COMPOSITE INDICES**

In addition to the mentioned features, a number of composite indices have been also used. Some of these indices are taken from the literature and others have been defined with the aim to describe the relative distance between the water surface during a flood and the local elevation (see Manfreda et al., 2014b). In particular, we adopted the following indices:

The modified topographic index, TI_m , first introduced by Kirkby (1975), has proven to be a good indicator for the delineation of areas exposed to flood inundation (Manfreda et al., 2011). This index takes the form:

281

$$TI_m = \ln\left(\frac{A_d^n}{\tan(\beta)}\right),$$
[3]

282 where A_d [m]is the drained area per unit contour length, $tan(\beta)$ is the local gradient, 283 *n* is an exponent <1.

284

The downslope index, DW_i , proposed by Hjerdt et al. (2004) represents a new way of estimating the hydraulic gradient. The method does not use the exit point at the stream as reference; instead, it calculates how far (L_d [m]) a parcel of water has to travel along its flow path to lose a certain amount of potential energy (d [m]). This index is defined as:

290
$$\tan(\alpha_d) = \frac{d}{L_d},$$
 [4]

where *d* was set equal 5m in the present case.

292

H/*D*: it is obtained by calculating the ratio between the flow distance *D* and
elevation difference *H*.

295

296 $\ln[h(A_s)/H]$: this index aims to compare in each point a variable water depth h with297the elevation difference H, where h is calculated for each basin cell assuming a298scaling relationship with the contributing area (A_s) by using an hydraulic scaling299relation:

$$h(A_s) \approx A_s^n, \tag{5}$$

301 where *h* is the water depth [m], A_s is the upslope contributing area at the point of 302 interest [m²], *n* is the exponent (dimensionless) set equal to 0.3 (see e.g. Nardi et 303 al., 2006).

304

 $\ln[h(A_r)/H]$: this index is similar to the previous one, but in this case *h* is computed as a function of the contributing area A_r in the section of the drainage network hydrologically connected to the point under exam (see figure 4).

- 308
- 309

In [h(A_r) - H]/tan(α_d): this index aims to describe, in each point of the investigated basin, the change between water depth h(A_r) and the elevation difference H divided by a surrogate of the hydraulic gradient represented by the downslope index.

314

Image: [h(A_r) - H]/D: this index aims to describe, in each point of the investigated basin,
the change between water depth h(A_r) and the elevation difference H divided by
the distance D.

All the indices and features are standardized in order to assume a value included inthe range -1 and 1.

Figure 6 provides a visual description of the introduced indices computed for the entire Bradano River basin (A) and the Bradano outlet (B). It is necessary to state that the present list of indices was developed by the authors with the specific aim of identifying an hydraulic metric able to account for the main features affecting flood diffusion on the landscape. These indices have been tested also on the Tiber River inManfreda et al. (2014b).

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327

4 RESULTS AND DISCUSSION

All suggested features and composite indices have been used to explore their individual ability to describe flood hazard in the Bradano River basin. Given the strong morphological differences existing between the main river and its terminal part, it is extremely interesting to compare the performances of indices applied over the two areas.

333 Figures 7 and 8 show respectively the ROC curves obtained by separately 334 thresholding each feature on the proposed study area for the two datasets previously 335 introduced. In Figures 7, ROC curves are obtained by comparing the proposed 336 features with the flood map of the Bradano basin obtained by using a 1-D hydraulic 337 model, while in Figure 8 by comparing the proposed features with the flood map of 338 the outlet of Bradano basin evaluated using a 2-D hydraulic model. Generally, the 339 best performing parameters are those that minimize the area above the curve or 340 maximize the area under the curve.

The visual comparison of all ROCs highlights the potential of each feature or index in
delineating the flood-prone areas in different contexts. The inter-comparison of the
four panels presented in Figure 7 and 8 allow stating that:

i. Among all single features considered the difference in elevation between the
considered point and the source of risk (*H*), and the distance from the nearest
stream (*D*) generally perform better. In fact, the ROC curve of such features
has a very large AUC in the first area (Figure 7A).

348 ii. The behaviour of single features is different in the two considered study cases.
349 In particular, they lower significantly their performances when applied to the
350 flat area of the basin outlet (see Figure 8A).

- 351 iii. Among the composite indices, the best performing ones are the $\ln(h(A_s)/H)$ 352 and the $\ln[h(A_r)/H]$ indices for the main river (application of 1-D hydraulic 353 model over the entire Bradano river) and $\ln[h(A_r)/H]$ and $[h(A_r) - H]/D$ 354 indices for the basin outlet (see Figure 7B and 8B).
- iv. The composite index, $\ln[h(A_r)/H]$, provides similar performances in the two study areas considered herein, and therefore seems the most promising metric among those considered since now.

It is interesting to underline that the single features become less sensitive when dealing with a flat landscape and even features like *H* and *D*, that generally are well suited for flood mapping in several context, here seem to fail. The reason is certainly due to the specific morphological complexity of the area that probably cannot be characterized by this simple metric. On the other hand, the composite index, $\ln[h(A_r)/H]$, is able to reproduce closely the flood map derived both in the flat area and also over the entire river basin.

In order to provide a quantitative description of the quality of each classifier, we summarize in Tables 1 and 2 the performance of each feature computed for an optimal threshold value, considering the basin scale and the local scale of application, respectively investigated through the one-dimensional and two-dimensional approach. The optimal threshold values were identified by minimizing the sum of the false positive rate and the false negative rate $r_{fp} + (1 - r_{tp})$. In particular, Tables (1 and 2) provide the following information: the relative values of the optimal normalized threshold τ , the false positive rate r_{fp} , the true positive rate r_{tp} , the sum $r_{fp} + (1-r_{tp})$ and the area under the curve AUC for each of the presented features for the Bradano River basin.

375 Results show that the index $\ln[h(A_r)/H]$ is consistently one of the best performing 376 indices in both cases. Furthermore, it is really remarkable that the thresholds 377 identified for this index are similar in the two cases considered herein, while other 378 features or indices show a larger variability of the performances and of the threshold 379 values calibrated in the two considered cases. This result is particularly significant 380 considering the change of scale of the two DEMs and also the reference hydraulic 381 models adopted. This result may be somehow due to the fact that this index try to 382 resample a physical property of flooding that is independent from the scale and the 383 morphological characteristics of the study area. All this should be explored in 384 additional study cases, but it is extremely stimulating if confirmed, because it would 385 demonstrate the great advantage of this methodology, that could allow to extend the 386 flood mapping over large areas starting from the study of a small portion of the basin 387 and using any kind of hydraulic model for the calibration of the method.

388 An example of application of the procedure over the Bradano River basin is given in 389 Figure 9A and B, where we identified the portion of the basin that have a value of the 390 $\ln[h(A_r)/H]$ index above the calibrated threshold. The maps obtained using the 391 $\ln[h(A_r)/H]$ index provided good performance in both the analysed contexts. After the 392 calibration of the optimal thresholds of this index, the flood hazard has been extended 393 over all tributaries, obtaining a realistic description of the flood prone areas that may 394 be extremely useful for the local River Basin Authority to extend their knowledge 395 about flood hazard.

397 5 CONCLUSION

398 The present study investigates the role of different morphological descriptors in the 399 identification of flood-prone areas over the Bradano River basin. In particular, the 400 performances of the proposed features are evaluated using a linear binary classifier 401 and ROC analysis at two different scales of application: at the entire basin scale, 402 using for comparison a flood map derived by a one-dimensional simulation, and in a 403 flat zone of the river basin, exploiting a flood map derived by a two-dimensional 404 model (FLORA-2D). Among the local features, the best performing ones are the 405 difference in elevation between the considered point and the source of risk (H), and 406 the distance from the nearest stream, D; instead, among the composite indices the 407 ones performing better are the $\ln[h(A_s)/H]$ and $\ln[h(A_r)/H]$. In particular, this last 408 seems to be more consistent and less sensitive to the change of resolution in the 409 adopted DEM, the reference hydraulic map used for calibration, and the different 410 topography of the training area. It also provides a reliable representation of the floodprone areas even in the case of flat areas, where other indices or features become less 411 412 and less sensitive. The outcomes of the present study are particularly promising, 413 especially considering the number of artificial modifications that characterize the 414 Bradano River.

415

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| EntireBradanoBasin - 1D Hydraulic Model | | | | | |
|---|---------------------------|--------------------------------|--------------------------------|-------------------------|-------------------------|
| Single features | τ | r _{fp} | \mathbf{r}_{tp} | $r_{fp}+(1-r_{tp})$ | AUC |
| $\mathbf{A}_{\mathbf{s}}$ | -0.999 | 0.021 | 0.186 | 0.834 | 0.584 |
| D | -0.928 | 0.178 | 0.784 | 0.395 | 0.882 |
| ΔΗ | 0.051 | 0.627 | 0.897 | 0.730 | 0.578 |
| Н | -0.960 | 0.113 | 0.963 | 0.150 | 0.964 |
| S | -0.956 | 0.286 | 0.898 | 0.388 | 0.870 |
| ΔH H S | 0.051 -0.960 -0.956 | 0.627 0.113 0.286 | 0.897 0.963 0.898 | 0.730 0.150 0.388 | 0.578 0.964 0.870 |

| Indices | τ | $\mathbf{r}_{\mathbf{fp}}$ | \mathbf{r}_{tp} | r_{fp} +(1- r_{tp}) | AUC |
|----------------------------|--------|----------------------------|----------------------------|--------------------------|-------|
| Tim | -0.235 | 0.286 | 0.899 | 0.387 | 0.869 |
| $\mathbf{DW}_{\mathbf{i}}$ | -0.980 | 0.142 | 0.883 | 0.259 | 0.919 |
| H/D | -0.974 | 0.272 | 0.812 | 0.460 | 0.841 |
| ln[h(A _r)/H] | -0.422 | 0.143 | 0.939 | 0.204 | 0.950 |
| ln[h(A _s)/H] | -0.612 | 0.134 | 0.953 | 0.182 | 0.953 |
| $[h(A_r)-H]/DW_i$ | -0.991 | 0.790 | 0.992 | 0.799 | 0.654 |
| [h(A _r)-H]/D | 0.818 | 0.133 | 0.874 | 0.259 | 0.933 |

535 Table 1. Results of the linear binary classifiers for the Bradano River basin: the optimal 536 normalized threshold, τ , the false positive rate, r_{fp} , the true positive rate, r_{tp} , the sum r_{fp} +

530 normalized threshold, i, the false positive rate, r_{fp} , the true positive rate, r_{tp} , the sum r_{fp} + 537 $(1 - r_{tp})$, and the area under the curve (AUC) for each descriptor. The best performing features

538 are highlighted using bold characters.

534

| Bradano Outlet - 2D Hydraulic Model | | | | | |
|-------------------------------------|--------|----------------------------|-----------------|--------------------------|-------|
| Single features | τ | \mathbf{r}_{fp} | r _{tp} | r_{fp} +(1- r_{tp}) | AUC |
| As | -0.991 | 0.000 | 0.015 | 0.985 | 0.507 |
| D | -0.842 | 0.247 | 0.458 | 0.789 | 0.625 |
| ΔH | 0.330 | 0.421 | 0.458 | 0.963 | 0.527 |
| Н | -0.574 | 0.768 | 0.990 | 0.778 | 0.609 |
| S | -0.986 | 0.644 | 0.719 | 0.926 | 0.548 |

| Indices | τ | \mathbf{r}_{fp} | r _{tp} | r_{fp} +(1- r_{tp}) | AUC |
|--|--------|----------------------------|-----------------|--------------------------|-------|
| TIm | -0.139 | 0.453 | 0.531 | 0.922 | 0.555 |
| DWi | 0.000 | 0.142 | 0.441 | 0.701 | 0.609 |
| H/D | -0.755 | 0.911 | 0.992 | 0.919 | 0.505 |
| ln[h(A _r)/H] | -0.423 | 0.267 | 0.811 | 0.456 | 0.791 |
| ln[h(A _s)/H] | -0.809 | 0.759 | 0.956 | 0.803 | 0.623 |
| [h(A _r)-H]/DW _i | -0.068 | 0.558 | 0.886 | 0.672 | 0.659 |
| [h(A _r)-H]/D | 0.471 | 0.221 | 0.734 | 0.487 | 0.798 |

Table 2. Results of the linear binary classifier for the outlet of Bradano River basin: the optimal

normalized threshold value τ , the false positive rate r_{fp} , the true positive rate r_{tp} , the sum of r_{fp} +(1- r_{tp}) and the area under the curve (AUC) for each descriptor. The best performing features are highlighted using bold characters.



Figure 10. A) Inundated areas during the flood event of March 2011 obtained by processing
remote sensed images. B) The Ancient Temple of "Tavole Palatine" flooded by the event of
March 2011.





Figure 1. SRTM DEM of the entire Bradano River basin (A). LiDAR DEM of the basin outlet of







Figure 2. Flood map derived by using a one-dimensional approach over the entire basin of

557 Bradano (A). Flood map derived by using a two-dimensional approach at the outlet of Bradano

River basin (B).



561 Figure 3A. Local morphological features estimated for the entire Bradano river basin using the

562 SRTM DEM with 90 m of resolution.



564 Figure 3B. Local morphological features calculated at the outlet of the Bradano basin estimated 565 using the LiDAR DEM with 10 m of resolution.

-2



570 Figure 4. Example of a hydraulic cross-section with the description of the parameters *H* and *h*.



Figure 5A. Composite morphological indices estimated for the entire Bradano river basin using the SRTM DEM with 90 m of resolution.



Downslope Index



In[h(A_r)/H]



 $[h(A_r)-H]/tan(\alpha_d)$





577 Figure 5B. Composite morphological indices computed at the outlet of the Bradano river basin 578 estimated using the LIDAR DEM with 10 m of resolution.



582 Figure 6. ROC curves obtained for local features (A) and composite indices (B) obtained by 583 comparing the proposed features with the flood map of the Bradano basin obtained using the 1-584 D hydraulic model.





589 Figure 7. ROC curves obtained for local features (A) and composite indices (B) obtained by 590 comparing the proposed features with the flood map of the outlet of Bradano basin evaluated 591 using the 2-D hydraulic model.



594 Figure 8. Flood maps of the Bradano River basin obtained using the linear binary classifier 595 based on the index $ln(h(A_i)/H)$ applied on the entire basin (A) and the basin outlet (B).



Figure 9. Inundated areas during the flood event of January 1972 edited by the Province of Matera.