

# Mapping flood and flooding potential indices: a methodological approach to identifying areas susceptible to flood and flooding risk. Case study: the Prahova catchment (Romania)

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**Abstract** Given that floods continue to cause yearly significant worldwide human and material damages, flood risk mitigation is a key issue and a permanent challenge in developing policies and strategies at various spatial scales. Therefore, a basic phase is elaborating hazard and flood risk maps, documents which are an essential support for flood risk management. The aim of this paper is to develop an approach that allows for the identification of flash-flood and flood-prone susceptible areas based on computing and mapping of two indices: FFPI (Flash-Flood Potential Index) and FPI (Flooding Potential Index). These indices are obtained by integrating in a GIS environment several geographical variables which control runoff (in the case of the FFPI) and favour flooding (in the case of the FPI). The methodology was applied in the upper (mountainous) and middle (hilly) catchment of the Prahova River, a densely populated and socioeconomically well-developed area which has been affected repeatedly by water-related hazards over the past decades. The resulting maps showing the spatialization of the FFPI and FPI allow for the identification of areas with high susceptibility to flash-floods and flooding. This approach can provide useful mapped information, especially for areas (generally large) where there are no flood/hazard risk maps. Moreover, the FFPI and FPI maps can constitute a preliminary step for flood risk and vulnerability assessment.

**Keywords** flash-flood, flooding, Flash-flood/Flooding Potential Index, Prahova River catchment, Romania

## 1 Introduction

Flash floods and flooding are hazards with large-scale occurrence and high destructive potential. They may generate major societal damage and environmental alteration. Over the past decades, an increase in floods' frequency and magnitude was recorded, related to both climate and land use changes (Marchi et al., 2010; Kourgialas and Karatzas, 2011; Stocker et al., 2013). Thus, on average, flood frequency has increased globally from 123 per year between 1994 and 2003 to 171 per year between 2004 and 2013 (CRED, 2015).

A major role in flood genesis is played by accelerated runoff (Georgakakos, 2006; Norbiato et al., 2008; Braud et al., 2010; Diakakis, 2011), which also accounts for erosional processes (Jain and Kothyari, 2000; Gobin et al., 2004; Pimentel, 2006; Conoscenti et al., 2008). At the European scale, the accelerated runoff is responsible for the delimitation of three representative regions with a very high flood potential: Mediterranean, alpine, and continental areas (Norbiato et al., 2008). Romania is part of the continental region, and is one of the European countries with high flood risk (Roo et al., 2007; Kundzewicz et al., 2013).

Given the continuous increase of damages caused by floods over the past decades, flood risk assessment has become increasingly relevant at different spatial scales. This domain targets both hazard and vulnerability analysis, as both are major components of flood risk (UNISDR, 2009). A first step of such analysis refers to hazard and flood risk maps fulfillment, based on which appropriate flood risk management plans are to be subsequently designed (DEPC, 2007).

In the European Union and Romania, this phase was

enforced by means of various legislative documents, of which the most representative are the *2007/60/EC Directive on the assessment and management of flood risks*, and the *Medium and long term national flood risk management strategy*, adopted in 2010. In Romania, according to the two aforementioned documents, reports and maps on areas with high flood risk potential and also flood risk and hazard maps have already been achieved, for both the whole country and the main hydrographic basins and districts. These maps were made using a unitary methodology (mainly based on analyzing historical flooding events and estimating future flood related potential damages), and they have a spatial resolutions ranging from 1 to 10 m (RWNA, 2014). Such spatial analyses are necessary for the national territory, especially given the fact that certain regions of the country are currently being affected by various forms of climate change (Busuioc et al., 2010; Dumitrescu et al., 2015; Croitoru et al., 2016; Prăvălie et al., 2016a), some of which are directly linked to changes in the hydrologic regime (Bîrsan et al., 2014; Croitoru and Minea, 2015; Prăvălie et al., 2016b), as well as to the increase in intensity and frequency of hydrologic risk phenomena.

In this context, the present paper aims to identify and map areas susceptible to flood and flooding hazards on a spatial scale that corresponds to the Prahova River catchment. It is an area densely populated and well developed economically (especially the upper and middle sectors), which increases its vulnerability to floods and flooding.

The study is based on computing and mapping two indices in a GIS environment: FFPI (Flash-Flood Potential Index) and FPI (Flooding Potential Index). These indices are obtained by integrating several geographical factors that influence runoff (in the case of FFPI) and favour water accumulation and flooding (in the case of FPI).

The methodology used for computing the FFPI and FPI is based on one featured by previous studies: Smith (2003), Teodor and Mătreacă (2011), Zaharia et al. (2012), Fontanine and Costache (2013), Minea (2013), Prăvălie and Costache (2013), Jacinto et al. (2015), Zaharia et al. (2015) for FFPI; and Shaban et al. (2001, 2006), Kourgialas and Karatzas (2011), Costache and Prăvălie (2012), Costache et al. (2015) for FPI. These studies computed the FFPI in a GIS environment based on overlapping several geographical factors (in raster format) that favour surface runoff (e.g., high slopes, profile curvature, land use), while for the FPI the methodologies were based on the analysis of geographical factors that favour water stagnation and accumulation (e.g., low slopes, relief altitude, distance from the river). Our methodology develops the existing ones and aims to improve the results by integrating additional variables in the estimation of the two considered indices.

The mapping of the FFPI and FPI is mainly suitable for large areas (i.e., the river catchment scale), considering, for

instance, the spatial resolution of the Digital Elevation Model (the main source for obtaining the morphometric parameters used for computing the two indices), which however does not allow the detailed (local) identification of areas with a high accelerated runoff/flooding potential. Similarly, the FFPI was applied, from the very beginning, on a large scale in the south-west of the United States, in the Colorado River catchment (Smith, 2003). At a later stage, in areas where high susceptibility to flash-floods and flooding was identified, a more in-depth investigation is recommended, based on hydraulic models that allow flood-prone area delineation (Zaharia et al., 2015). Finally, flood vulnerability and risk maps are obtained, which could help the decision makers to take appropriate measures for flood impact mitigation (Balica et al., 2014; Godfrey et al., 2015; Gonçalves et al., 2015). The methodology based on mapping the two indices can be useful for identifying areas prone to flash-floods and flooding, in catchments in which there are no maps/information on flood and flooding hazard.

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## 2 Study area

The study area overlaps the upper (mountainous) and middle (hilly) sectors of the Prahova River catchment, located in central-eastern Romania (Fig. 1). Its area is 2603 km<sup>2</sup>, which constitutes 70% of the total catchment area. Altitudes decrease from north to south, from over 2500 m a.s.l. to less than 200 m a.s.l.

The upper sector of the study area overlaps the Carpathian Mountains and reaches the maximum altitude of 2505 m in the Bucegi Massif (Omu Peak), located in the north-west (Fig. 1). The lower sector is part of the Subcarpathians, an orogen unit, located at the extremity of the Carpathian chain. It is characterized by highly complex geology, reflected in the variety of landforms.

The study area is crossed by a rich river network, with average densities of 0.6–0.8 km/km<sup>2</sup> in the Carpathian area, and of 0.4–0.6 km/km<sup>2</sup> in the Subcarpathian sector (Zaharia, 2005a). The main rivers are the Prahova and its tributaries, of which the most important are: the Azuga River, the Doftana River, the Teleajen River (with its main tributaries: Crasna, Vărbilău, Cosmina, and Telega rivers), and the Cricovul Sărat River (with tributaries Lopatna, Sărățel, and Matița rivers) (Fig. 1). There is a high frequency of hydrographic convergence areas, especially in depressions, which favours water accumulation and, therefore, land flooding.

The flow rates vary from one river to another depending on the catchment's size and flow control factors. The mean annual discharge of the Prahova River is 8 m<sup>3</sup>/s or 17 L/s · km<sup>2</sup> (at Cămpina gauging station), while that of the Teleajen River is 5.5 m<sup>3</sup>/s or 11 L/s · km<sup>2</sup> (at Gura Vitoarei gauging station), and for the Cricovul Sărat River 1.9 m<sup>3</sup>/s or 3.2 L/s · km<sup>2</sup> (at Cioranii de Sus gauging station)

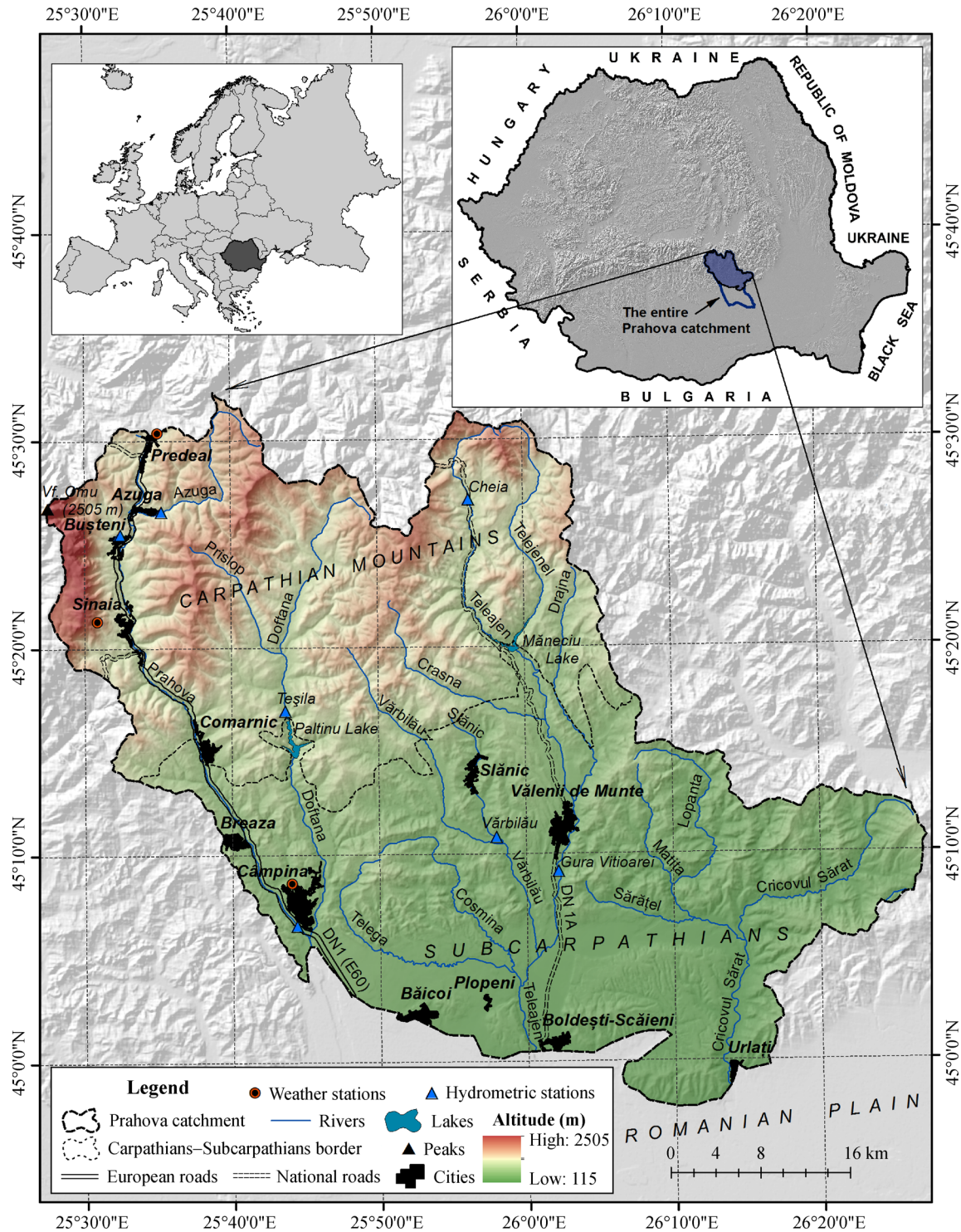


Fig. 1 Study area and its location in the Prahova River's catchment and in Romania.

(Zaharia, 2005a, b). The hydrologic regime of these rivers is characterized by high flow and flash floods in spring (following high rainfall and snowmelt), and low flow in autumn and winter. In April – June, the monthly runoff is about 13%–15% of the mean annual volume, while in September–February, the monthly runoff decreases to 4%–6% (Zaharia, 2005a, b). Flash floods generated by heavy

rains of convective genesis are frequent in summer, while in autumn flash floods can occur as a consequence of frontal rainfalls.

At a regional scale, even though historically there have been certain anthropogenic influences on water flow in this central south-eastern region of the country (Ioana-Toroimac et al., 2010; Ioana-Toroimac, 2016), in the study area

there is currently a relatively small number of hydraulic structures that influence the rivers' natural flow. The most important are 2 reservoirs: the Paltinu Lake on the Doftana River (built in 1971, with an area of 1.975 km<sup>2</sup> and an active volume of 53 mil m<sup>3</sup>), and the Măneciu Lake on the Teleajen River (built in 1994, with an area of 1.92 km<sup>2</sup> and a volume of 50 mil m<sup>3</sup>) (Fig. 1). The 2 reservoirs are mainly used for water supply for downstream settlements. They also contribute to river flow regulation and flood control (Zaharia, 2005b).

The river flow regime is closely related to climate variation. The general climate of the study area is temperate-continental, with average annual temperatures ranging between −2°C and 4°C–6°C in the mountainous region, and between 6°C and 9°C in the hilly sector (Bogdan, 1983; Sandu et al., 2008). Annual precipitation ranges between 800 mm and 1000 mm in the Carpathian region, and between 600 mm and 800 mm in the Subcarpathian sector (Zaharia and Beltrando, 2007). The highest rainfall is recorded in May–July (monthly shares of 12%–15% of annual precipitation, with a peak in June), which explains the flash floods that occur in this period. In winter and autumn, monthly shares are of 5%–8% (Sandu et al., 2008). In summer (June–August), when heavy rains are frequent, maximum precipitations exceeded 100–200 mm in 24 hours (Zaharia et al., 2011). The snow layer, having an important role in the rivers' supply in spring, reaches a mean monthly thicknesses of up to 80–90 cm in the mountainous area (Sandu et al., 2008).

The study region is overall well-inhabited, and various economic activities are being carried out. The mean population density is 94.3 loc/km<sup>2</sup> (227 loc/km<sup>2</sup> in the Subcarpathian area, and 65 loc/km<sup>2</sup> in the Carpathian sector), and the urbanization rate is 62% (urban population), exceeding the national average value of 55%. It comprises 12 cities totaling 152,506 inhabitants (according to the data provided by the “Romanian National Institute of Statistics” in 2015). In the mountainous region, the main economic activities are related to tourism, forestry, and animal husbandry, while in the hilly area the activities tend to be more diverse (industrial, agricultural, tertiary). The area is overall crossed by a rich rail and road transport infrastructure, mainly along the rivers, of which many are of national and European importance. The most important are the European road and railroad along the Prahova River, crossing the Carpathians and representing the main way which connects the capital (Bucharest) to the country's central and western regions, and finally to Western Europe.

The high population density and economic development induce an increased vulnerability of the study area to floods and flooding. This paper, through the proposed methodology, allows for the identification of areas with the highest potential for flash floods and flooding occurrence. Knowing these areas is relevant for enforcing flood risk mitigation measures at regional and local scales.

### 3 Data and methodology

#### 3.1 Data

This paper is mainly based on two types of data: spatial and hydrologic. *The spatial data* consist of geographic features of the study area, which are control factors for flood (tangential curvature, runoff, profile curvature, catchment shape, L-S factor, lithology, convergence index, drainage density) and flooding (slope, wetness index, runoff, lithology, drainage density, convergence index, elevation, altitude above channel) (Figs. 2 and 3). The data were mostly obtained from cartographic documents (topographic, geological, and pedological maps) and digital database sources (SRTM altimetry database, CORINE Land Cover database, 2006 edition). They were processed in GIS environment with several software programs (ArcGIS 10.1, Global Mapper 13, SAGA GIS, and IDRISI Selva).

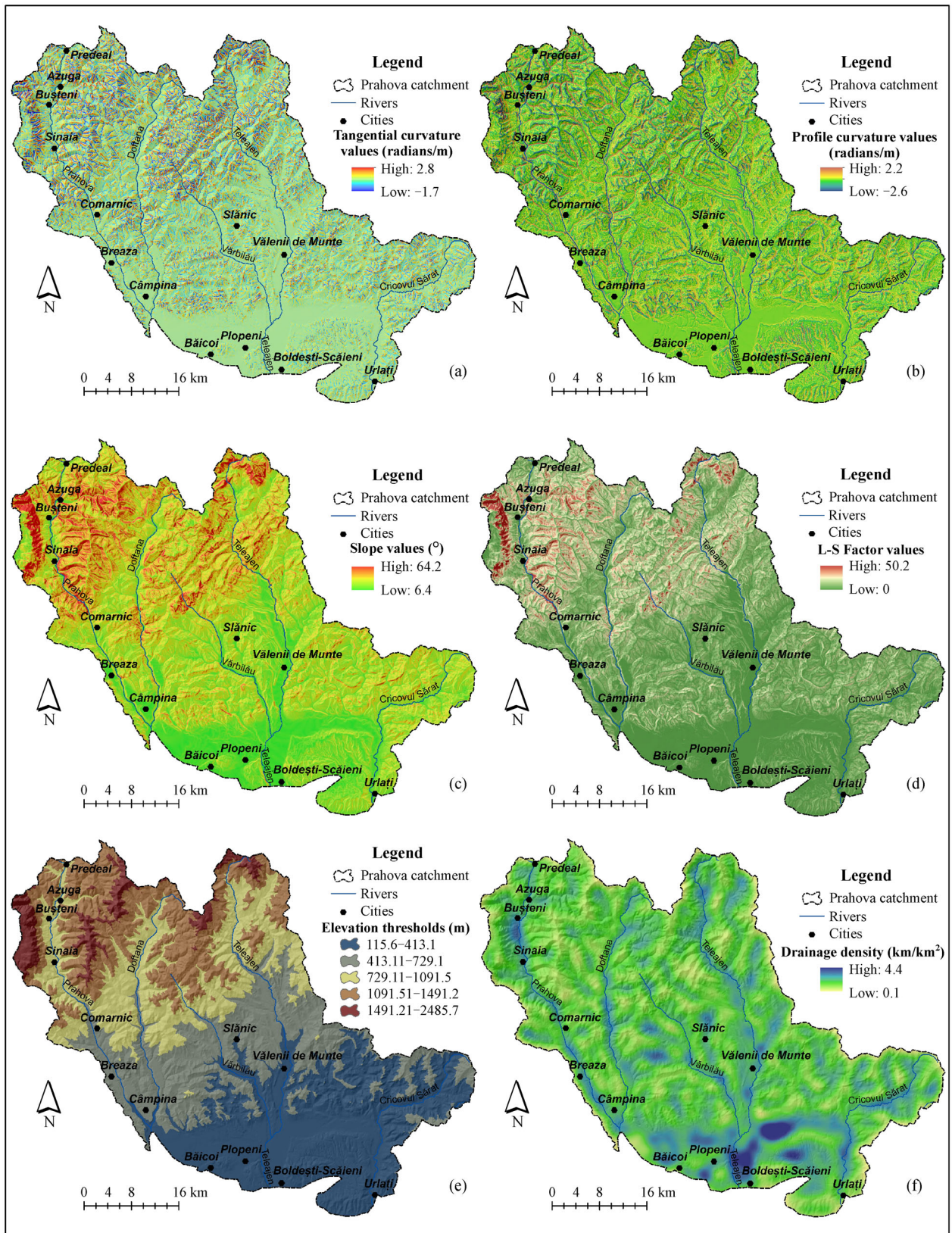
*The hydrological data* mainly include the annual peakflows recorded at some hydrometric stations located on the main rivers in the area (Fig. 1). Table 1 contains morphometric and hydrologic data for the analyzed rivers.

The hydrological data were provided by the National Institute of Hydrology and Water Management and were used for analysing the magnitude and frequency of recorded floods in the study area.

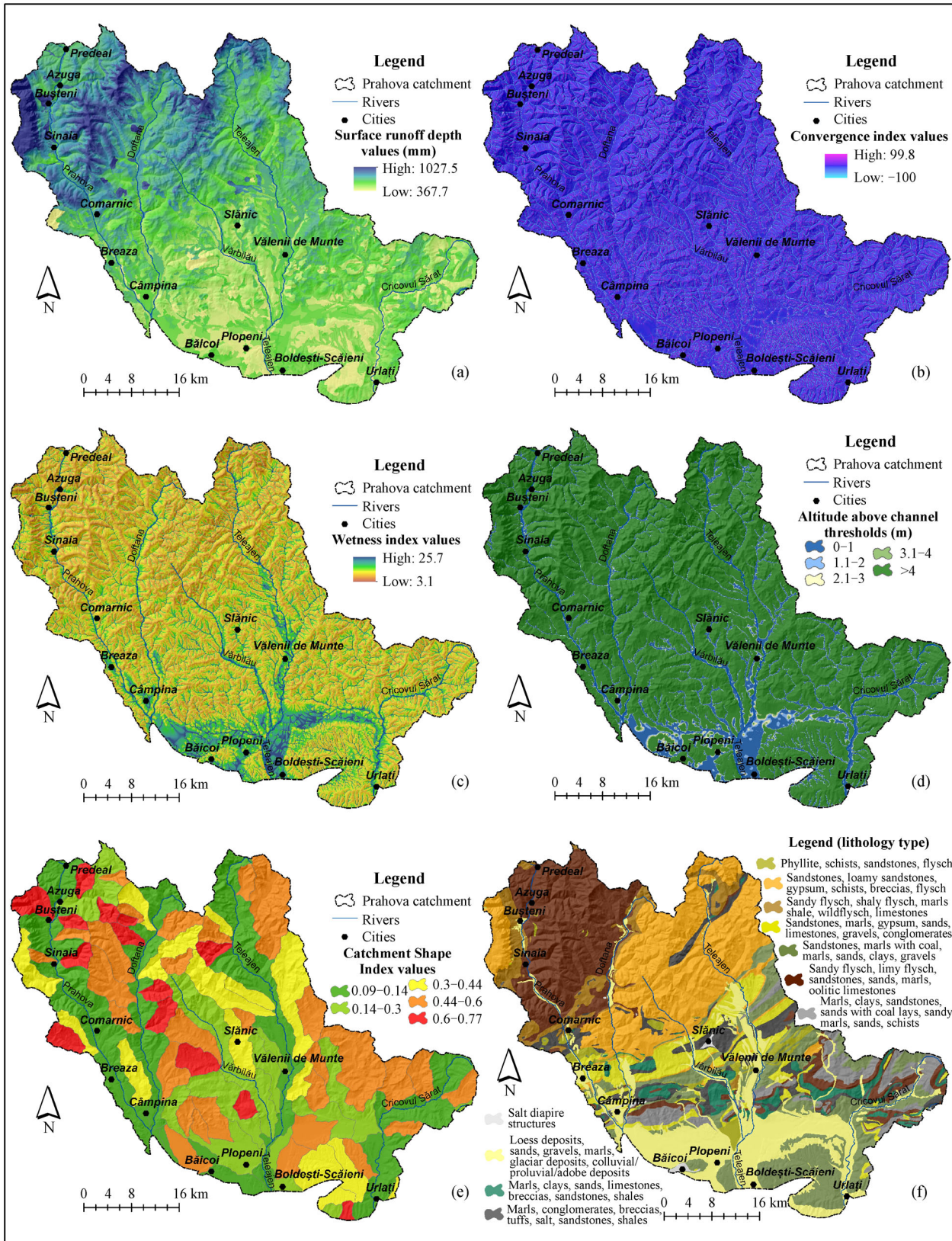
#### 3.2 Methodology

As mentioned in the introduction, the study is based on computing and mapping two indices in GIS environment: 1) FFPI, used to identify areas with accelerated runoff favouring flash-flood occurrence, and 2) FPI, used to identify flooding-prone areas. The indices were estimated and mapped at the studied catchment scale. The main aim of separately computing the two indices was to spatially highlight the complementarity of the two phenomena that are specific to each index. Thus, for the FFPI, the areas with a high accelerated slope runoff potential were highlighted, while for the FPI the emphasis was placed on areas with high water accumulation potential; in most cases, these areas are highlighted at the foot of slopes with high runoff potential, or in the inferior sectors of torrential basins.

The methodology used for computing FFPI and FPI was developed in previous studies: Smith (2003), Teodor and Mătreacă (2011), Zaharia et al. (2012), Fontanine and Costache (2013), Minea (2013), Prăvălie and Costache (2013), for FFPI, and Shaban et al. (2001, 2006), Kourgialas and Karatzas (2011), Costache and Prăvălie (2012), for FPI. Specifically, for the FFPI, the study of susceptibility to flash-floods in the Colorado catchment authored by Smith (2003) was based on the use of cartographic algebra by overlapping certain raster-type



**Fig. 2** Maps of the geographic variables used for estimating the FFPI and FPI: (a) tangential curvature, (b) profile curvature, (c) slope, (d) L-S Factor, (e) absolute elevation, (f) drainage density.



**Fig. 3** Maps of the geographic variables used for estimating the FFPI and FPI: (a) runoff depth, (b) convergence index, (c) wetness index, (d) altitude above channel, (e) catchment shape, (f) lithology.

**Table 1** Morphometric and hydrologic data for the analyzed rivers

River	Gauging station	Period (for Qmax)	A/km <sup>2</sup>	Hm/m	Qo/(m <sup>3</sup> ·s <sup>-1</sup> )	Qmax/(m <sup>3</sup> /s) / year
Prahova	Câmpina	1962–2007	476	1106	8.02	399/2005
Azuga	Azuga	1962–2007	87	1364	2.02	94/1975
Valea Cerbului	Bușteni	1962–2007	25	1530	0.468	62.3/2001
Doftana	Teșila	1962–2007	288	1200	4.5	218/1999
Teleajen	Cheia	1962–2007	39	1265	0.777	85/1970
Teleajen	Gura Vitioarei	1962–2007	491	896	5.53	308/2005
Slănic	Vărbilău	1966–2007	412	519	0.268	158/1975

A = Catchment's area corresponding to the gauging station; Hm = Catchment's mean altitude corresponding to the gauging station; Qo = Mean multiannual streamflow (1950–1995 period); Qmax = annual peak flow. Source data: for A, Hm and Qo – Zaharia, 2005b ; for Qmax – National Institute of Hydrology and Water Management.

geographical factors such as slope, vegetation, soil type, and land use. Teodor and Mătreacă (2011) had a similar approach for the Ilișua catchment (Romania), where they took into account the vegetation coverage, slope, and soil type. Also in Romania, the FFPI was computed by Zaharia et al. (2012), who integrated in a GIS environment other factors such as profile curvature and lithology. Other morphometric factors, i.e., L-S Factor, drainage network density and convergence, and slope aspect, were used for computing the FFPI by Prăvălie and Costache (2013). For computing the FPI, while the method is similar to that used for the FFPI, the difference consists in that in the aforementioned studies, the geographical characteristics that influence water stagnation at ground level (e.g., low altitude, low slopes) were also taken into account. Unlike the previous studies, in this approach we introduced new parameters for computing the two indices: the tangential curvature for the FFPI and the runoff depth for the FPI.

**For the computation of the FFPI**, in this paper, eight variables influencing the runoff and its concentration to the channel flow were integrated in the GIS environment, namely: tangential curvature, curvature profile, L-S factor, drainage network convergence index, drainage density, catchment shape, lithology, and mean annual runoff depth. The variables used for computing FFPI (and FPI) are mapped in Figs. 2 and 3. Except for lithology and runoff depth, the other variables were derived from the digital elevation model (DEM) with 20 m-sized cells, which was obtained by interpolating the vectorised level curves at an equal distance of 5 m on Romania's Topographic Map 1:25,000. The 20 m cell size of the DEM is suitable for hydrologic studies (Bilașco, 2008).

*The tangential curvature* is the result of multiplication of two morphometric factors with a major influence on the runoff potential, slope, and plane curvature (Drobot, 2007; Zaharia et al., 2012; Prăvălie and Costache, 2013). Negative values of the tangential curvature designate areas where there is a convergent (accelerated) overland flow, while positive values correspond to divergent areas with decelerated overland flow.

*The profile curvature* marks the difference between

convex and concave surfaces. Accelerated runoff is specific for convex slopes (marked on the map with negative values), and decelerated runoff (positive values) is specific for concave slopes (Constantinescu, 2006).

*The L-S Factor index* is used frequently in studies on accelerated runoff potential (Bilașco et al., 2009; Arghiuș and Arghiuș, 2011). It is defined as the ratio between the slope gradient and the slope's length, and is computed with the formula proposed by Moore et al. (1993), cited by Constantinescu (2006):

$$L-S = \left( (m+1) * (As/22.13)^m \right) * (\sin\beta/0.0896)^n, \quad (1)$$

where:  $As$  = catchment area,  $m = 0.4$ , and  $n = 1.3$ .

*The convergence index* of the drainage network (obtained with the SAGA GIS 2.0.8 software) highlights low convergent areas (channels) through negative values, while positive values are typical for ridges/interfluvies, where the runoff potential is much lower.

*The drainage network density* (in km/km<sup>2</sup>) was determined and mapped by using the line density tool of the ArcGIS 10.1 software. It was computed as the ratio between the river segments' length and the drained area. The high drainage network density determines a high water concentration and accumulation potential (in low areas) (Drobot, 2007).

*Catchment shape* influences flash-flood occurrence potential (Merlă, 2012). For the same rain event (if all other variables are the same), a circular-shaped watershed has a faster concentration time, resulting in a higher peak flow, in comparison to a watershed with a long narrow shape, where a lower peak flow will result at the outlet because more time is required for the water to reach the outlet (Musy and Higy, 2011). The circularity ratio ( $R_c$ ) was used in order to express the catchments' shape, and it was computed by means of the formula below (Zăvoianu, 1978):

$$R_c = 4\pi F/P^2, \quad (2)$$

where  $F$  = the catchment's area (in km<sup>2</sup>) and  $P$  = the catchment's perimeter (in km). The closer to 1 the

circularity ratio value is, the more circular the catchment shape is.

The lithology, due to rock permeability, has a major influence on the runoff and flood/flooding occurrence. Permeability influences the volume and the time to peak of a flood wave, as well as the groundwater flow from aquifers to support low river flows (Musy and Higy, 2011). The lithological map of the study area was obtained by vectorizing rock types, based on Romania’s Geological Map 1:200,000, retrieved from geospatial.org. The map was initially obtained in polygon vector format and was subsequently converted to 20 m cell resolution raster format.

The mean multiannual runoff depth in the study area was estimated by means of the SCS-CN (Soil Conservation Service – Curve Number) method, developed by the US Natural Resources Conservation Service (Costache et al., 2014; Hooshyar and Wang, 2016). This method is widely used internationally (Auerswald and Haider, 1996; Kottegoda et al., 2000; Young and Carleton, 2006; Reistetter and Russell, 2011; Grimaldi et al., 2013). It estimates the runoff depth, the breadth of which varies depending on precipitation amounts, previous soil humidity conditions, hydrological soil group, and land use type in the given area. The runoff depth is estimated by using the following formula (Xiao et al., 2011):

$$Q = \frac{(P - 0.2 * S)^2}{P + 0.8 * S}, \tag{3}$$

where:  $Q$  = runoff depths (mm),  $P$  = rainfall (mm),  $S$  = water retention potential (mm), computed based on the curve number of the area, land use, and hydrological soil class. The value of  $S$  is computed with the formula (Xiao et al., 2011):

$$S = \frac{25400}{CN} - 254, \tag{4}$$

where:  $CN$  = curve number. This is an index with predefined values depending on the area’s land use types

and hydrological soil class. CN values were set by the U.S. and presented in standard tables. They range from 0 to 100. For Romania, CN values were adapted by Chendeş (2007).

The mean annual runoff depth was computed by means of the SCS-CN method in a GIS environment with the ArcCN – Runoff extension (Zhan and Huang, 2004) in the ArcGIS 10.1 software. Thus, three data sets were introduced and intersected in the extension: land use/cover (CLC, 2006); soil types (provided by NIRDSSAEP, 2002), grouped according to hydrological classes (Domnița, 2012), and mean multiannual precipitations on the studied area (Sandu et al., 2008). The distribution of precipitation, necessary for mapping the values of the mean multiannual runoff depth in the study area, was made through regression kriging. This geostatistical method used the mean multiannual precipitation values recorded at 11 weather stations located both inside and outside the study area, as well as their absolute altitude.

In order to compute and map the FFPI in the study area, the features of the eight variables were assigned a weighting factor from 1 to 5, depending on how they influence the runoff (Table 2).

Given that not all factors influence the runoff to the same extent, the weighting was deemed appropriate and was conducted by using the weight module of the Idrisi Selva software (Valle Junior et al., 2014). This module is an automatic instrument for applying the semi-objective weighting method analytic hierarchy process (AHP) (Valle Junior et al., 2014), which was applied in this study because water runoff is influenced by certain geographical factors to different degrees. By means of this method, a matrix was created for comparing the relative importance of a factor to that of other factors (Mahmoud et al., 2015). For the FFPI, the highest relative importance values were given to the tangential curvature and runoff depth, while for the FPI it was the slope and runoff that were given the highest relative importance values when compared to the other factors. Finally, the FFPI values were computed by the weighted sum of the

**Table 2** Weighting and classification of geographical factors for determining the FFPI index in the middle and upper sectors of Prahova catchment

Parameters/Weight (%)	FFPI (classes)				
	17.8 – 25.5	25.5 – 29.2	29.2 – 32.9	32.9 – 36.7	36.7 – 48.1
Tangential curvature – 17%			0.9 – 2.8	0 – 0.9	–1.7 – 0
Runoff (mm) – 21%	367 – 513	513 – 665	665 – 789	789 – 894	894 – 1027
Profile curvature – 13%			0.9 – 2.5	0 – 0.9	–2.5 – 0
Catchment shape – 8.8%	0.09 – 0.14	0.14 – 0.3	0.3 – 0.44	0.44 – 0.6	0.6 – 0.77
L-S Factor – 11%	0 – 1.5	1.5 – 3	3 – 4.5	4.5 – 6	>6
Lithology – 10%	Loess deposits	Gravels, sands	Marls, clays	Conglomerates	Sandstones, Shists
Convergence index – 9.6%	> 0	0 – (–1)	(–1) – (–2)	(–2) – (–3)	< –3
Drainage density (km/km <sup>2</sup> ) – 9.6%	< 1.5	1.5 – 2.25	2.25 – 3	3 – 3.75	> 3.75
Bonitation score	1	2	3	4	5

eight considered variables. This was performed with the raster calculator tool of the ArcGIS 10.1 software by applying the formula:

$$\text{FFPI} = 1.7 * \text{Tc} + 1.3 * \text{Pc} + 2.1 * \text{Q} + 1.1 * (\text{L-S}) \\ + \text{Li} + 0.96 * \text{Dd} + 0.96 * \text{Ci} + 0.88 * \text{Cs}, \quad (5)$$

where: FFPI = Flash-Flood Potential Index; Tc = Tangential curvature; Pc = Profile curvature; Q = Runoff depth; L-S = L-S Factor; Li = Lithology; Dd = Drainage density; Ci = Convergence index; Cs – Catchment shape.

**For determining and mapping the FPI**, a similar method was used, which considers eight variables influencing water accumulation and stagnation, as follows: convergence index, drainage network density, lithology, mean multiannual runoff depth, land slope (in this case, low slope values favour the flooding process), elevation (absolute), altitude above channel, and wetness index.

The *elevation* is an important factor in identifying areas that are highly prone to flooding, as such areas are generally located at low altitudes.

The *altitude above channel* is a useful parameter for identifying flooding-prone areas; it indicates a surface's relative altitude in relation to an adjacent river channel (the highest flooding risk corresponds to relatively low areas).

The *wetness index* was derived from the DTM with the SAGA GIS software. High values of this index correspond to areas favouring water accumulation.

As previously done for the FFPI, in order to compute and map FPI values, the variables were reclassified by assigning them weighting factors depending on the extent to which they influence water accumulation (Table 3).

In the end, the weighted sum of the considered parameters was carried out according to the equation:

$$\text{FPI} = 2.1 * \text{S} + \text{E} + 1.2 * \text{Ac} + 0.96 * \text{Dd} + 0.96 \\ * \text{Ci} + 1.9 * \text{Q} + 0.88 * \text{Wi} + \text{Li}, \quad (6)$$

where: FPI – Flooding Potential Index; S – Slope; E –

Elevation; Ac – Altitude above channel; Dd – Drainage density; Ci – Convergence index; Q – Runoff depth; Wi – wetness index, Li – Lithology.

In order to validate the results concerning the estimated FPI and its spatial distribution, we compared our generated map with the one showing the significant historical flood-affected areas extracted from the official “Report on a preliminary flood risk assessment”, designed for the Buzău-Ialomița Water Branch (which includes the study area) by experts from the Romanian Ministry of Environment and Forests, the “Romanian Waters” National Administration and the National Institute of Hydrology and Water Management. This document was drawn up in accordance with the standards imposed by Directive 2007/60/EC that refers to flood risk management in the European Union. Only the events with flows with exceedance probabilities higher than 10% that caused serious damages (at least 10 casualties/missing persons, a minimum of 2 affected social objectives and 10 economic objectives, at least 100 affected houses per event) were considered for mapping the areas in which historical floods were recorded (RWNA, 2013).

For a better validation of the map with the spatial distribution of the FPI, the number of damaging flood events that affected localities in the study area was counted based on communication bulletins of the Inspectorate for Emergency Situations of Prahova County (IESP), available for 2009–2016 period (IESP, 2016). The field investigations also helped to partially validate the results.

## 4 Results and discussion

Results firstly highlight flood hazard characteristics (magnitude, frequency, duration) and consequences, as well as the main factors influencing its occurrence. The results of the computation and mapping of the FFPI and FPI indices are thereafter presented and analyzed.

**Table 3** Weighting and classification of geographical factors for determining the FPI index in the middle and upper sectors of Prahova catchment

Parameters/Weight (%)	FPI (classes)				
	13.3 – 22.3	22.3 – 25.6	25.6 – 29.5	29.5 – 34.4	34.4 – 46
Slope (°) – 21%	>30	20 – 30	10 – 20	5 – 10	0 – 5
Wetness index – 8.8%	3.1 – 6.4	6.4 – 8.3	8.3 – 10.8	10.8 – 15.1	15.1 – 25.7
Runoff (mm) – 19%	367 – 513	513 – 665	665 – 789	789 – 894	894 – 1027
Lithology – 10%	Loess deposits	Gravels, sands	Marls, clays	Conglomerates	Sandstones, Shists
Drainage density (km/km <sup>2</sup> ) – 9.6%	< 1.5	1.5 – 2.25	2.25 – 3	3 – 3.75	>3.75
Convergence index – 9.6%	>0	0 – (-1)	(-1) – (-2)	(-2) – (-3)	< -3
Elevation (m) – 10%	1491 – 2485	1091 – 1491	729 – 1091	413 – 729	115 – 413
Altitude above channel (m) – 12%	>4	3.1 – 4	2.1 – 3	1.1 – 2	0 – 1
Bonitation score	1	2	3	4	5

#### 4.1 Flash-flood hazard and its main controlling factors

##### 4.1.1 The highest flash-floods in the study area and their consequences

The analysis was based on processing the annual flood peaks recorded at the region's gauging stations, whose features and analyse periods are mentioned in Table 1.

The highest flash-floods recorded on the main monitored rivers occurred in 1970, 1975, 1988, 1999, 2001, 2002, 2005, 2006, and 2007 (Table 4). Most frequently, the highest flash-floods occurred in summer (June–August), as a result of the season's typical heavy rains. Considering the annual flash-floods occurring on the analyzed rivers, the highest frequency was recorded in the May–August period (a monthly average of 14%–20% of the total annual flash-floods), which indicates their predominantly pluvial origin. The few having occurred in winter and the beginning of spring have nival or mixed origin.

The analysis of annual peak flow indicated a relatively high frequency of high-magnitude flash-floods: at most of the stations, over a third (up to 40%) of annual flash-floods in the analyzed periods had discharges exceeding the mean of the annual peak flow. After 2000 an increased frequency of high-intensity flash-floods can be noticed.

The magnitude of floods was highlighted using the ratio between the annual peak flow and the mean multiannual discharge. The highest ratios were identified in the case of the Slănic River (395–653). High ratios (over 100) were recorded also during the greatest floods occurring on the rivers Valea Cerbului and Teleajen (Table 4). A flash-

flood's duration varies depending on the features of the rainfall that generated it and those of the catchment. In mountainous regions with steep slopes, flash floods can be extremely short-lived, lasting for few hours. As an example, the flash flood of July 2004 that occurred on the Valea Cerbului River had a total duration of only 2.5 hours (Perju, 2012). On the Prahova River, at Câmpina gauging station, the flash flood of July 2005 (with the highest magnitude of the period 1962–2007) had a total duration of approximately 12 hours (Ioana-Toroimac, 2009).

The flash-floods and the related phenomena (flooding, riverbank erosion) have generated significant socio-economic damages in the region (Fig. 4). For instance, in 2005 (a year during which flash-floods and flooding have affected the whole country with catastrophic damages), in Prahova County, which the study area overlaps, 29 settlements were affected by flooding, most of which were located in the mountainous and hilly sectors of the Prahova River's catchment. The most affected were the houses, roads, bridges, and agricultural fields in the area: more than 3000 houses and household annexes, 59 socio-economic units, 490 bridges and culverts, over 5000 km of roads, approximately 1500 ha of agricultural land, and 25 engineering works. The total estimated cost of the damages was of 120,688.1 thousands RON, i.e., almost 27 million euros (MEWM, 2006).

##### 4.1.2 The main factors favouring flash floods occurrence

The occurrence and features of flash floods and flooding

**Table 4** Flash-floods with the highest magnitudes (top five in terms of flood peak value) in the upper and middle Prahova River's catchment

River	Gauging station	Q <sub>max</sub> / (m <sup>3</sup> ·s <sup>-1</sup> )	Date month/year	Q <sub>max</sub> /Q <sub>0</sub>	River	Gauging station	Q <sub>max</sub> / (m <sup>3</sup> ·s <sup>-1</sup> )	Date month/year	Q <sub>max</sub> /Q <sub>0</sub>
Prahova	Câmpina	399	VII/2005	49.8	Teleajen	Cheia	85	VIII/1970	109.4
		369	VII/1988	46			66.2	VII/1975	85.2
		340	VII/1975	42.4			57.8	VII/1969	74.4
		292	VIII/1997	36.4			51.7	V/1984	66.5
		265	VIII/1982	33.0			46.4	VI/1985	59.7
Azuga	Azuga	94	VII/1975	46.5	Teleajen	Gura Vitioarei	308	IX/2005	55.7
		92.4	IX/2001	45.7			286	III/2007	51.7
		81.5	III/2007	40.3			234	VI/1991	42.3
		74.6	VII/1988	36.9			226	VIII/2006	40.9
		53.8	V/1984	26.6			216	V/1980	39.1
Valea Cerbului	Bușteni	62.3	VI/2001	133.1	Slănic	Vărbilău	175	VII/2002	653.0
		54.2	VII/1988	115.8			158	VII/1975	586.6
		24.7	VIII/1999	52.8			130	VI/1998	485.1
		22.2	VII/1969	47.4			127	VIII/2005	473.9
		22.2	VI/1981	47.4			106	VII/1979	395.5
Doftana	Teșila	249	III/2007	55.3					
		218	VIII/1999	48.4					
		181	V/2005	40.2					
		173	VI/2001	38.4					
		131	VIII/1970	29.1					

Q<sub>max</sub> = annual peak flow; Q<sub>0</sub> = mean multiannual discharge. The periods correspond to the ones mentioned in Table 1. Data source: National Institute of Hydrology and Water Management.



**Fig. 4** Left: Buildings on the Prahova River at Comarnic, damaged by riverbank erosion as a result of the flash-flood of July 2005 (photo: Gabriela Ioana-Toroimac). Right: Bridge destroyed by the flash-flood which occurred on the Prahova River in July 2005, at Nedelea (photo: Liliana Zaharia).

are controlled by many factors (Patra, 2008; Musy and Higy, 2011), such as those related to: the climatic and meteorological conditions (mainly rainfall features: intensity, duration, spatial, and temporal distribution), the morphology and morphometry of the catchment (size, altimetry, shape, slope orientation), the characteristics of the drainage network (structure, dimension, drainage density, channel slope, hydraulic properties, channel form, and geometry), and the nature of the surface of the catchment and of its cover (nature of the lithology, soils and their antecedent moisture content, vegetation, land use, other covers). Alongside these natural factors, a significant influence on flash flood occurrence and features can be attributed to river engineering work, especially to reservoirs, which are created for flood control. In extreme cases, the dams' breaking might cause catastrophic flash floods and flooding.

As previously mentioned, most flash floods in the study area are of pluvial origin, as they are generated by heavy rains in the summer months. In July 1975, the rainfall that caused the flash-flood on the rivers in the study area cumulated in 2 days (1–2 July) 179 mm at Predeal, 157 mm at Sinaia and 144 mm at Câmpina weather stations. On July 1st there were 94 mm at Predeal, 106 mm at Sinaia and 112 mm at Câmpina, which are among the highest rainfall amounts recorded in 24 hours since 1961 (Mustătea, 2005; Ioana-Toroimac, 2009). On September 11th 2001, in the upper catchment of the Prahova River, rainfall quantities reached 71 mm at Predeal and 67 mm at Sinaia, which caused fast flash-floods on small rivers, the most representative on the Valea Cerbului River (with 62.3 m<sup>3</sup>/s), and on the Azuga River (with 94.4 m<sup>3</sup>/s, the second highest value of the study period 1962–2007) (Ioana-Toroimac, 2009). In 2005, Romania was affected by several flooding episodes (Zaharia et al., 2006). On May 7th, rain gauges recorded 51 mm at Predeal, 64 mm at Sinaia and 16 mm at Câmpina. On July 12th, rainfall amounts reached 52 mm at Predeal, 53 mm at Sinaia and

82 mm at Câmpina. On August 14th, at Câmpina, 108 mm were recorded. On 19–20 September, in the upper and middle Prahova River's catchment, exceptional rainfall amounts were recorded, totaling 157 mm at Predeal, 194 mm at Sinaia, and 226 mm at Câmpina (Ioana-Toroimac, 2009). The 2005 rainfalls caused high-magnitude flash-floods, which were among the highest recorded at the gauging stations during the measurement periods (Table 4). As already mentioned, they generated significant economic damage. In 2007, high-magnitude flash-floods occurred in late March. They were generated by the rainfall recorded between 21–25 March, which exceeded 150 mm in the Carpathian sector of the Prahova River's catchment, while the Subcarpathian sector cumulated 100–150 mm (Ioana-Toroimac, 2009).

An important role in the occurrence and features of flash-floods (magnitude, duration) is played by the morphologic and morphometric features of the catchments. The most important such features were identified, mapped, and integrated in the computation of the two aforementioned indices. In the study area, hillslope runoff and water concentration in river channels are favoured by high altitudes and steep slopes (Fig. 2). Thus, almost 1/3 of the total area has elevations exceeding 1000 m a.s.l.: 1% at over 2000 m a.s.l., 4% between 1500 and 2000 m a.s.l., 24% between 1000 and 1500 m a.s.l., and the average altitude of the entire study area is of 720 m a.s.l..

In terms of slopes, 15% of the study area ranges between 0 and 3°. Approximately 40% belong to the average slope class, with values ranging from 7° to 15°, while slopes exceeding 15° cover around 30% of the study area. Steep slopes favour accelerated runoff and water concentration to river channels, while low slopes favour water accumulation and stagnation during flooding generated by torrential runoff or river overflow.

The lithology favours runoff especially in the Carpathian sector, which mainly consists of highly impermeable Cretaceous and Paleocene flysch (including sandstone,

marl, marly limestone, micro-conglomerates, black shale, clay and marl shale with sandstone and limestone elements). In the Subcarpathian sector, the hillslope runoff is diminished due to water loss, as it infiltrates sedimentary molasse deposits typical for this area, which includes marl, clay, sandstone, sand, shale, salt (diapire), but also Carpathian Paleocene flysch formations (Mutihac et al., 2007).

In terms of land use, the largest regions in the study area are covered by deciduous forests, which amount to 1/3 of the total area. While in the mountainous sector the percentage of forested areas reaches 70%, in the hilly sector it drops to 33%, thus favouring hillslope runoff and soil erosion.

#### 4.2 Flash flood potential assessment

Once the methodology described in section 3.2 was applied, FFPI values were computed and mapped for the upper and middle catchment of the Prahova River. FFPI values range between 17.8 and 48.1. They were grouped in five classes through the Natural Breaks classification method of the ArcGIS 10.3 software.

The first class, ranging from 17.8 to 25.5 (very low potential for accelerated runoff), covers approximately 16% of the study area (Fig. 5(a)). This mainly corresponds to the hilly area of the Prahova River's catchment. Very low FFPI values are generally found in forest areas, with slopes under 3° and sandy soils.

The second class of FFPI values, ranging from 25.5 to 29.2 (low runoff potential), covers approximately a quarter of the study area (Fig. 5(a)). Similarly to the first class, the low FFPI values generally correspond to the hilly sector of the study area, mainly along the valleys of rivers Cricovul Sărat, Doftana, and Teleajen.

The third class (29.2–32.9) holds 27.2% of the study area and indicates a medium potential for accelerated runoff. Such values are evenly distributed throughout the study area, except for the north-western area, where only isolated instances were identified (Fig. 5(a)). Average FFPI values generally correspond to agricultural lands, slopes of up to 15° and predominantly clayey soil texture.

High and very high potentials for accelerated runoff correspond to FFPI classes 4 and 5, ranging between 32.9 and 48.1 (Figs. 5(a) and 5(b)). These areas are mostly located in the mountainous sector of the Prahova River catchment, which covers 32% of the total area. They are situated especially in the north-western part of the study region, in the interfluvium which separates Doftana and Prahova valleys, but also on the eastern side of the Bucegi Massif. Such areas were also identified in the upper sector of the Teleajen River's catchment. Slopes exceeding 15°, deforested areas covered with grasslands, and impermeable soils with predominantly clayey texture favour overland runoff and the occurrence of flash-floods in torrential streams.

#### 4.3 Flooding potential assessment

The flooding potential index (FPI) values range between 13.3 and 46. Similarly to the FFPI, FPI values were grouped into five classes, through the natural breaks classification method of the ArcGIS 10.3 software. The first classes, with low and very low FPI values, range between 13.3 and 25.6 (Fig. 6(a)). They are located on approximately 60% of the study area, especially in the mountainous sector, with slopes exceeding 15° that don't favour water accumulation and stagnation, and where the extensive forest cover and sandy soils favour rainwater retention and infiltration.

A medium flooding potential (FPI values ranging between 25.6 and 29.5) was found for approximately 24% of the upper and middle parts of the Prahova River catchment (Fig. 6(a)). This class is mostly located at the contact area of the Carpathians and Subcarpathians. It is characterized by slopes ranging between 7° and 15°, mainly agricultural land use, and clayey textured soils.

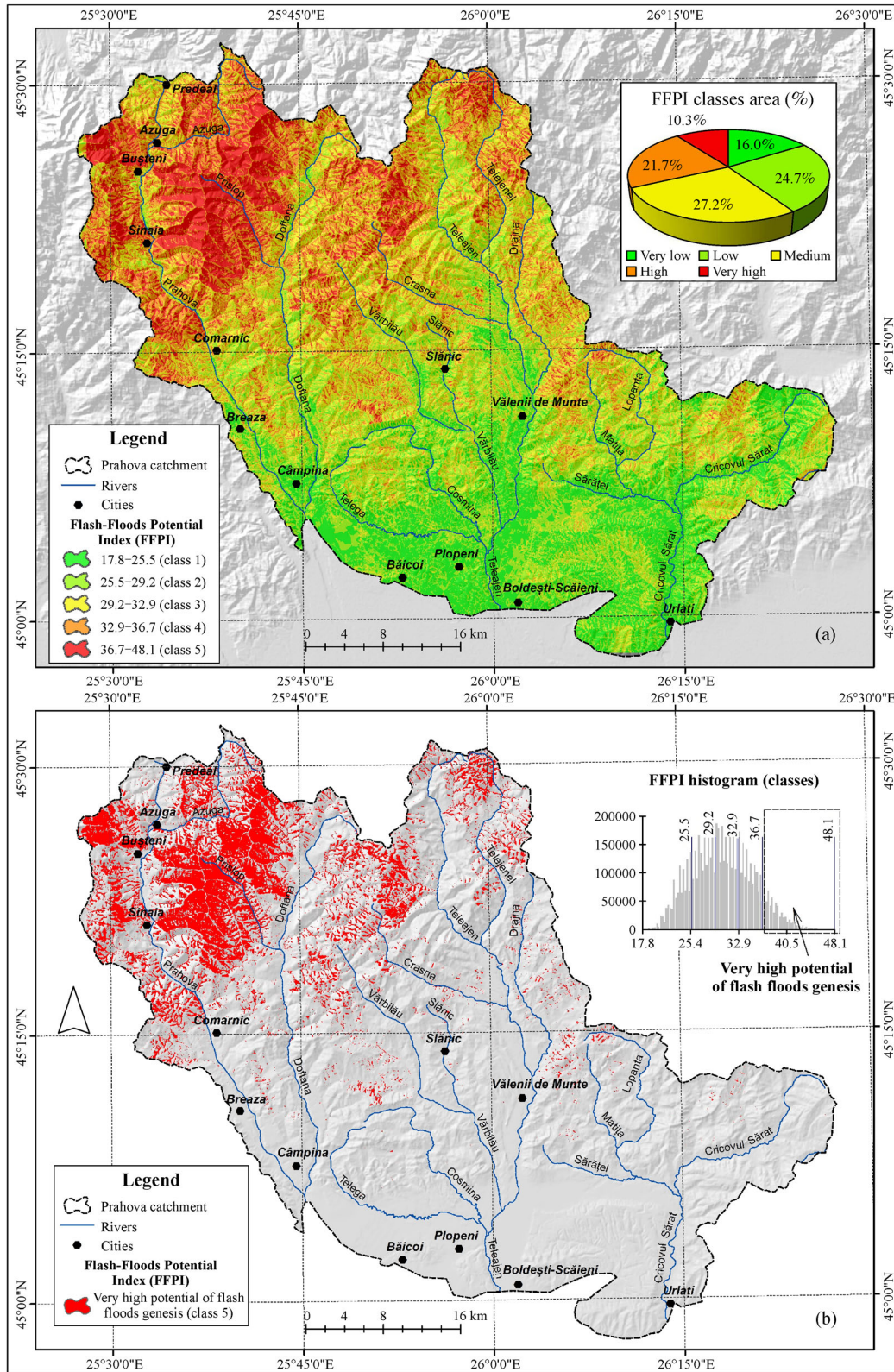
High and very high flooding potential, i.e., FPI values ranging between 29.5 and 46, are found, as expected, along the main rivers (Figs. 6(a) and 6(b)). Such areas cover 17% of the study area. They are mainly located on slopes under 3°, which favour water accumulation and stagnation, with predominantly argillaceous soils and built areas that prevent water infiltration. A high concentration of such values can be noticed at the convergence of Teleajen River's tributaries in the southern part of the study area, in the vicinity of Boldești-Scăieni city (Figs. 6(a) and 6(b)).

#### 4.4 Results validation and discussion

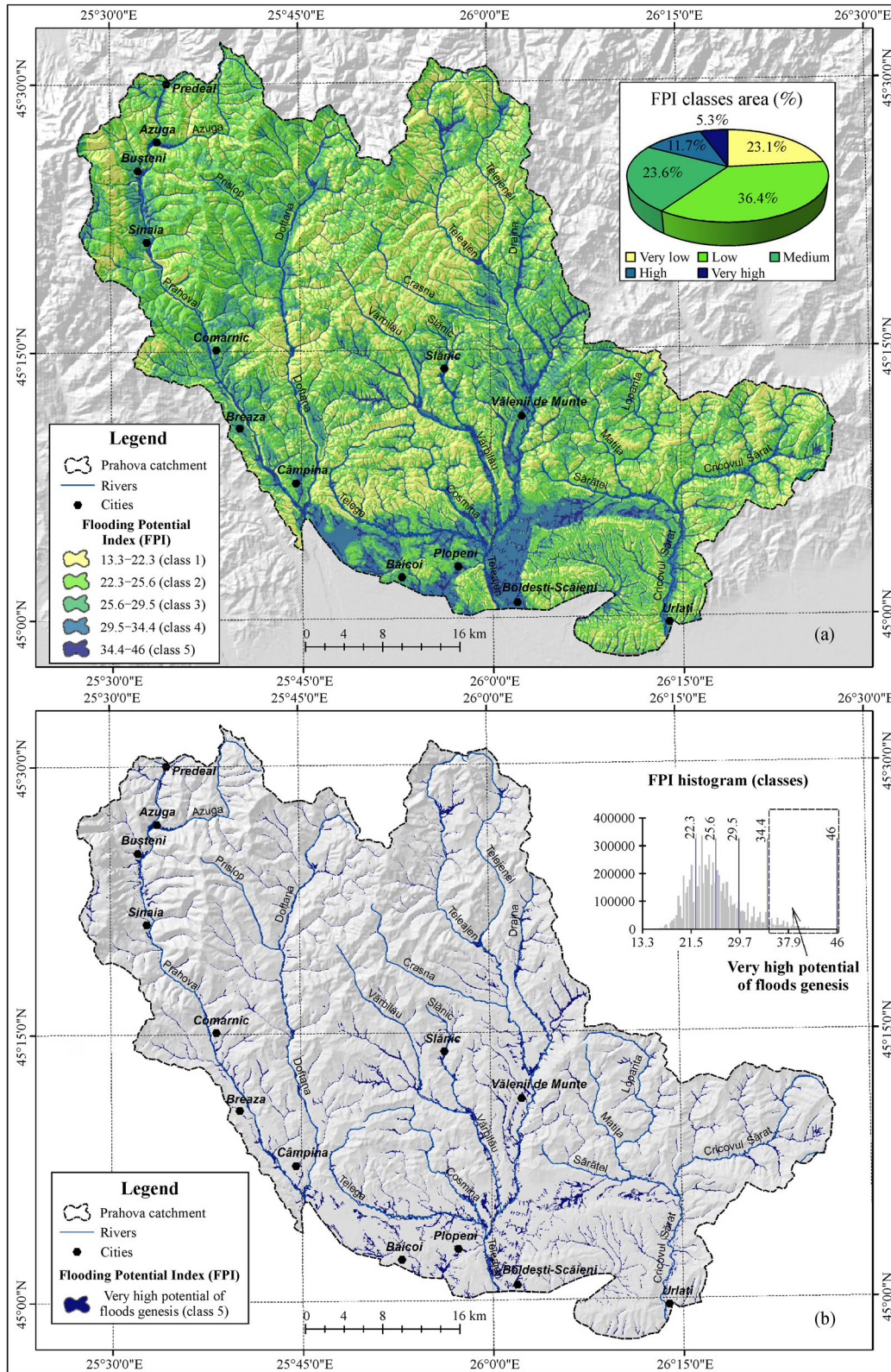
As mentioned in chapter 3.2 (on methodology), in order to validate the results, we compared our generated map showing the spatial distribution of FPI values with the one indicating the significant historical flood-affected areas, published in "Report on a preliminary flood risk assessment" (RWNA, 2013), devised for the Buzău-Ialomița Water Branch. The areas that were affected by the most massive floods (totaling ~ 3000 hectares) overlap, for the most part, areas with FPI values exceeding 34.4, which are typical areas with very high flood potential (5th class, Fig. 7). At the same time, areas that are exposed to flood events entirely overlap FPI values above 29.5, representative of high flood occurrence susceptibility (4th class, Fig. 7).

The second method used for validating the results (based on the quantification of damaging floods in 2009–2016 period) highlights that 36 localities affected repeatedly by flood events are located in areas with high and very high FPI values. The settlements affected by the most frequent floods (6–9 flood events between 2009 and 2016) were: Boldești-Scăieni, Sinaia, Breaza, Băicoi, Vălenii de Munte and Câmpina (Fig. 7).

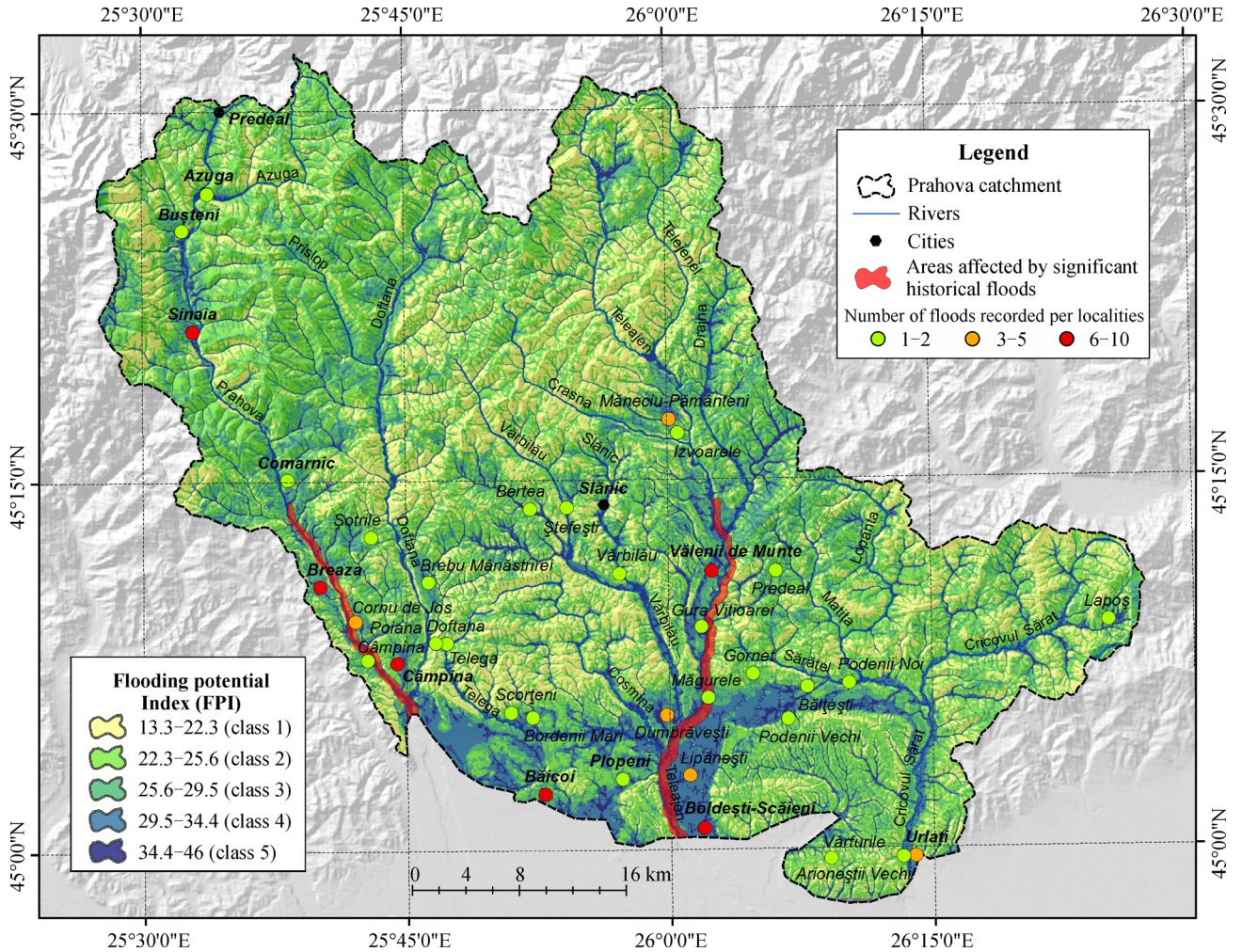
This study enabled the identification of the most susceptible areas to flash-floods and flooding in the



**Fig. 5** Spatial distribution of FFPI values in the upper and middle catchment of the Prahova River: (a) all five classes; (b) only class 5, with the highest accelerated runoff potential. Note: classes 1, 2, 3, 4 and 5 (in (a)) correspond respectively to very low, low, moderate, high, and very high potential of flash-floods genesis.



**Fig. 6** Spatial distribution of FPI values in the upper and middle catchment of the Prahova River: (a) all five classes; (b) only the class 5, with the highest flooding potential. Note: classes 1, 2, 3, 4 and 5 (in (a)) correspond respectively to very low, low, moderate, high, and very high potential of flooding genesis.



**Fig. 7** Spatial distribution of FPI values, areas affected by significant historical floods and number of flood events recorded in the period 2009–2016, in the upper and middle catchment of the Prahova River.

upper and middle catchment of the Prahova River. These areas correspond mainly to the low-lying valley sectors located at the bottom of slopes with high accelerated runoff potential. Given that these areas are densely populated, including important socio-economic units and major transport infrastructures, there is a high risk induced by flash-flood/flooding and associated processes. In the study area, a high and very high risk is associated particularly to the settlements located in the upper and middle sectors of the Prahova Valley (e.g., cities of Azuga, Bușteni, Sinaia, Comarnic, Breaza, Câmpina), as well as to transport infrastructure along the Prahova River, which may be affected by rapid hillslope runoff, as well as by the river's overflow. One such sector has been identified by field investigations in the mountainous Prahova Valley, in Sinaia city, where the road and railroad of national and international importance, as well as buildings situated close to the Prahova River have a high exposure to flood/flooding risk (Fig. 8).

For the areas in which FFPI and FPI maps indicate high and very high susceptibility to flash-floods/flooding, finer-scale studies could be carried out (based on hydraulic modeling) in order to perform more detailed analysis on flood vulnerability and risk. Whereas the calculation and mapping of the FFPI and FPI may be affected by certain errors or inconsistencies (associated with data quality, considered variables, spatial resolutions, etc.), it is necessary to validate the results by different methods and also by field investigations.

## 5 Conclusions

Given that flood risk mitigation is a major issue for water management policies and strategies, from global to regional and local scales, the development of methodologies that would enable the estimation and analysis of flood risk is a continuous challenge.



**Fig. 8** Transport infrastructure (the national/European road DN1/E60 and railroad) and buildings exposed to flood and flooding risk in the upper Prahova Valley, in city of Sinaia (pictures taken by Gabriela Ioana-Toroimac during the flood of March 2007).

This paper aimed to identify and map areas with high potential for flash-floods and flooding occurrence. It is based on computing and mapping two indices in a GIS environment: FFPI, and FPI. These indices were determined by integrating several variables that influence, on one hand, accelerated hillslope runoff, thus controlling flash floods (FFPI) and, on the other hand, water accumulation and stagnation, thus controlling flooding (FPI).

The analysis was focused on the upper and middle Prahova River catchment sectors. The high levels of urbanization in this area increases its vulnerability to flash-floods and flooding. The resulting maps allowed for the identification of flash-flood-prone (based on FFPI) and flooding-prone (based on FPI) areas. In such areas, the analyses can be subsequently developed in order to estimate flood/flooding vulnerability and risk. There is a high risk face to the two hazards in the mountainous sector of the Prahova Valley, along which there are several cities and an important road and railroad. Low and hydrographic convergence areas are the most exposed to flooding due to river overflow and water stagnation processes (e.g. Boldești-Scăieni city area).

The method based on FFPI and FPI mapping can be useful for analyzing flash-flood and flooding susceptibility, especially for large areas (river catchment scale), or for areas in which there are no flood/flooding hazard maps. Their accuracy greatly relies on the spatial resolution of the used variables. In Romania, the FFPI and FPI maps can complete the information supplied by the national flood hazard maps or the ones referring to the country's main basins/catchments. Together they can be important support documents for flood risk mitigation measures.

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