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## Geological – Geomorphological Features of River Catchments in Flood Susceptibility Assessment (on the example of Middle Struma Valley, Bulgaria)

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**Abstract.** The geological-geomorphological features of the river catchments control flood propagation by influencing the surface runoff and its redistribution to surface and underground flow. The paper analyses the geological-geomorphological susceptibility to floods in a part of the river Struma valley – Municipalities Kresna and Strumyani (Bulgaria, EU). The following parameters are considered: lithology (presented by water permeability, capacity and type of rock reservoirs), distance from streams/river, slopes and fluvial landforms. Raster layers for each one of these parameters are created in geographic information system (GIS) environment and susceptibility rates are assigned. The flood susceptibility map is elaborated by spatial weighted sum overlay of the raster layers. The results show that the susceptibility is the highest in the low part of the valley, south of Kresna. The susceptibility of flooding is not equal over the whole area of the floodplain but depends on the retention capacity of the alluvial deposits and the hydro-geomorphological state of the floodplain. The river bank height above the water level and the river bed type are also taken into consideration by application of fuzzy logic. Using the fuzzy logic minimizes some imperfections of the initial data and gives good results in data-scarce areas. The fuzzy logic model is designed as a two-level hierarchical system with three inputs and one output. The output gives the complex assessment for geological-geomorphological flood susceptibility of study area regarding the interaction of the three inputs. The results of the current research aims to direct the attention of planning experts and decision-makers to the importance of geological-geomorphological parameters in flood management and can be considered as a first step of flood hazard assessment.

**Keywords:** Flood susceptibility, Overlay analysis, Fuzzy logic, Floodplain.

### 1 First Section

Floods are ones of the most important natural hazards in Europe in terms of economic loss [1, 2] and when they concern human life this is a risk. According to the Directive 2007/60/EC [3] the flood risk means the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event. In this regard the risk is

considered as a function of hazard (the probability of flood event). The flood hazard is determined by the hydro-climatological features of the area which behavior is controlled by the other environmental conditions (lithological composition, physical-mechanical properties of soils, character of the topography, vegetation) and also on the land use type. The review of the literature and practice in flood management shows different approaches. The traditional strong engineering approach is based on hydrological and hydraulic analyses and modelling [4-6]. This approach is often limited by the availability of the data which requires the fusion of hydrologic observations, historical information about past flood events, estimates of surface roughness, boundary conditions, and topographical features [7]. In this regard many publications consider the importance of sedimentary and geomorphological approaches in providing base-line flood data for validation hydrologic and hydraulic models and emphasize on the maintenance of natural geomorphological functioning of the river channels and floodplains for effective flood management [8-11]. A combined application of geomorphological and hydrological approaches in flood hazard investigation is considered in publications Patton and Baker, Lastra, Dimitriu, etc. [10, 12, 13].

The complex nature of the flood event requires an integrated approach in flood hazard / flood risk assessment and management. An integrated approach employing remote sensing data coupled with digital elevation models (DEM), hydrological study and field observations is recommended to understand the causative factors of flooding [14]. The need of processing a large volume of spatial data motivates the geoinformation approach and use of geographic information systems (GIS), and remote sensing in flood hazard assessment [14-18].

Taking into account the complex nature of flood events, the aim of the current research is to assess flood susceptibility of geological-geomorphological features in the Middle Struma valley by application of GIS technology and fuzzy logic. The susceptibility is considered as a sensitivity degree of the area and determining the flood susceptibility is the first step in flood risk assessment. Although the intensive precipitation have triggering role for flood propagation the differences in the distribution of floods in the river basin show the control of geomorphological and geological factors. The geological-geomorphological features of the area influence the flow of surface runoff and the redistribution of the runoff into the underground and surface component. This influences the water capacity of the area and possible occurrence of floods. The composition of the rocks, their grain size and physical properties determine the water permeability of the rocks as well as their retention capacity. In this relation, in flood susceptibility assessment the water permeability of the rocks should be considered in a complex with other environmental characteristics such as water retention capacity, groundwater level, location of the site relative to the water level / river bed, landforms, etc.

In this research an integrated assessment of these factors is elaborated in GIS environment and by fuzzy logic. The following geological-geomorphological parameters of the investigated area are evaluated: lithological composition, slopes, fluvial landforms and the distance from the rivers. A flood susceptibility map is created in GIS environment by application of weighted sum overlay. A similar approach combined with application of analytic hierarchy process is used many publications about different areas

and shows good result, even for data-scarce areas [17, 19-21]. In difference, the present study focuses the geological and geomorphological conditions of flooding by evaluating the water permeability, retention capacity and type of the rocks reservoirs. For the purpose of modelling a fuzzy logic is applied additionally to the results of the spatial GIS overlay.

## 2 Data and Methods of the Research

The flood susceptibility modelling in the current research is elaborated for a part of the Middle Struma valley (Bulgaria), the areas lower than 600 m. Special attention is given on the fluvial landforms – floodplains and low river terraces, as well as alluvial / proluvial fans. Field investigation and literature review, including analyses of geological (sheets Blagoevgrad, Razlog and Petrich, 1:100 000) and geomorphological maps [22, 23] are done for data collection. The analysis of geological and geomorphological data is proceeded in AcrGIS environment (ESRI Inc.). For this purpose a GIS database was built which includes:

- Municipalities boundaries – polygon layer (source: GIS, Ministry of regional development, Bulgaria, EU);
- Stream / river network – generated on the base of DEM;
- Slopes – generated on the base of DEM;
- Geology data: rock permeability; capacity and type of the reservoir – polygons layers created on the base of the geological map of Bulgaria, 1: 100 000;
- River terraces, alluvial / proluvial fans – polygons determined on the base of publications [23, 24], topographic map of Bulgaria 1: 50 000 and field investigations;
- Settlements – polygons (CORINE Land Cover 2012 project [25]);
- Digital elevation model (DEM), SRTM, 30 m NASA JPL [26].

In order to assess flood susceptibility a spatial overlay analysis is done on the base of geological and geomorphological features of the area. The complex influence of the lithological composition, slopes, fluvial landforms and the distance from the rivers were evaluated in determining the susceptibility to floods. The evaluation is done using weighted sum overlay in ArcGIS. For this purpose, the geological-geomorphological factors are entered in raster layers, and depending on their characteristics, each one is classified from 1 to 5 (1 - the lowest flood susceptibility, 5 - the highest). In the overlay analysis a weight of 30% is given to each one of the layers of river distance and fluvial relief, 20% - for lithological composition and 20% for slopes. As a result of the overlay analysis a map of geological-geomorphological susceptibility to flooding is created.

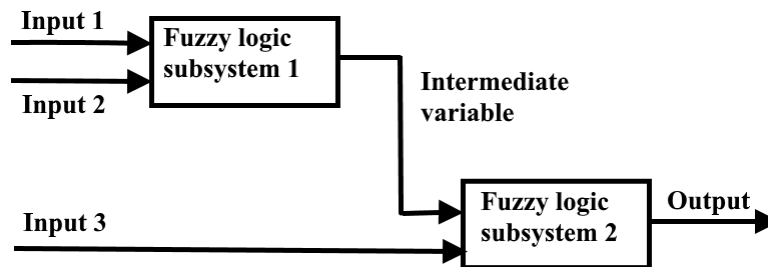
Taking into account the limitation of the data we applied fuzzy logic in order to further develop the assessment. The following additional parameters are considered: river bank height above the water level and the river bed type. The first one is considering the aptitude of river water to flood the adjacent areas. About the river bed we define 3 types: sandy, rocky and mixed. Sandy bed has higher water permeability which is a prerequisite for better infiltration and less surface stream flow, while rocky bed determines less infiltration and higher flood susceptibility. On the other side because of

the high water permeability of sands they are usually related with high level of ground water and this can lead to high flood susceptibility if the river bed is saturated. In this relation all available geological and geomorphological conditions of the area should be considered in interaction in flood susceptibility modelling.

It is necessary to note, that the fuzzy logic approach is an appropriate tool for the risk assessment from natural disasters [27-29]. This approach provides adequate processing the expert knowledge and uncertain quantitative data [30, 31]. In particular, the flood risk assessment is performed under the subjective and uncertain conditions (for example, there are short records or only few measured points) [10, 20, 32]. For these reasons the fuzzy logic are used for the flood risk assessment [21, 33, 34]

In this research, a fuzzy logic model for complex assessment of flood susceptibility based on geological – geomorphological features of river catchments is proposed. The fuzzy logic model is designed as a two-level hierarchical system with three inputs and one output. Each level of the system is consisted of one fuzzy logical subsystem with two inputs.

The fuzzy logic system output gives the complex assessment for geological-geomorphological flood susceptibility of study area regarding the interaction of the three inputs. A scheme of this two level hierarchical fuzzy system is presented on Fig. 1.



**Fig. 1.** Two-level hierarchical fuzzy system with three inputs

The fuzzy system inputs are defined on the basis of expert knowledge and current research of study area, as follow:

- Input 1 “*Flood susceptibility according to the river bank height above the water level*”;
- Input 2 “*Flood susceptibility according to the river bed type*”;
- Input 3 “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*”.

An intermediate variable “*Flood susceptibility according to the river bank height and bed type*” is defined.

Here, the inputs of the first fuzzy logic subsystem are Input 1 “*Flood susceptibility according to the river bank height above the water level*” and Input 2 “*Flood susceptibility according to the river bed type*”, and the output variable is the Intermediate variable “*Flood susceptibility according to the river bank height and bed type*”.

The inputs of the second fuzzy logic subsystem are Intermediate variable “*Flood susceptibility according to the river bank height and bed type*” and Input 3 “*Flood susceptibility rate according to the overlay analysis of geological-geomorphological parameters (map results)*”. The output of second fuzzy logic subsystem is the variable “*Complex geological-geomorphological flood susceptibility*”, which is actually the output of the proposed fuzzy logic system.

The value of the variable “*Complex geological-geomorphological flood susceptibility*” can be considered as a useful assessment in informative decision making about the flood susceptibility regarding geological – geomorphological features of river catchments in the study area. The higher value corresponds to the higher flood susceptibility rate.

In the proposed fuzzy logic model, the linguistic variables, corresponding of the three inputs, intermediate variable and system output are defined by different trapezoid membership functions. The input variables (Input 1, Input 2, Input 3 and Intermediate variable) are assessed in the interval [0, 5] and the system output - in the interval [0, 100].

The membership functions are defined as follows:

- Input 1 “*Flood susceptibility according to the river bank height above the water level*” is described by five fuzzy membership functions: “*Very low (VL)*”, “*Low (L)*”, “*Moderate (M)*”, “*High (H)*”, and “*Very high (VH)*” (Fig. 2);
- Input 2 “*Flood susceptibility according to the river bed type*” is described by three fuzzy membership functions: “*Low (L)*”, “*Moderate (M)*”, “*High (H)*” (Fig. 3);
- Input 3 “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is described by five fuzzy membership functions: “*Very low (VL)*”, “*Low (L)*”, “*Moderate (M)*”, “*High (H)*”, and “*Very high (VH)*” (Fig. 2);
- Intermediate variable “*Flood susceptibility according to the river bank height and bed type*” is described by five fuzzy membership functions: “*Very low (VL)*”, “*Low (L)*”, “*Moderate (M)*”, “*High (H)*”, and “*Very high (VH)*” (Fig. 2);
- Output of the fuzzy logic system “*Complex geological-geomorphological flood susceptibility*” is described by five fuzzy membership functions: “*Very low (VL)*”, “*Low (L)*”, “*Moderate (M)*”, “*High (H)*”, and “*Very high (VH)*” (Fig. 4).

The numeral values of trapezoidal membership functions and the corresponding linguistic variables of the Input 1, Input 2, Input 3, Intermediate variable and Output are presented in Table 1

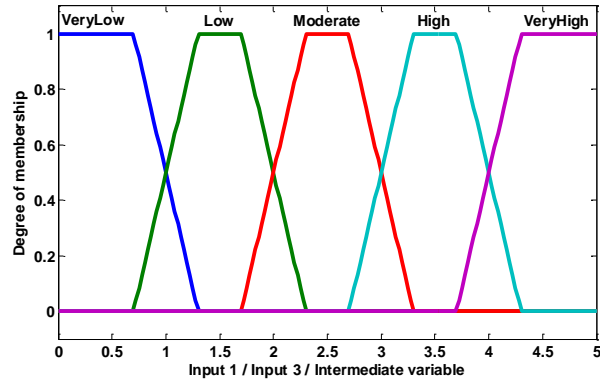


Fig. 2. Membership functions of the Input 1, Input 3 and Intermediate variable

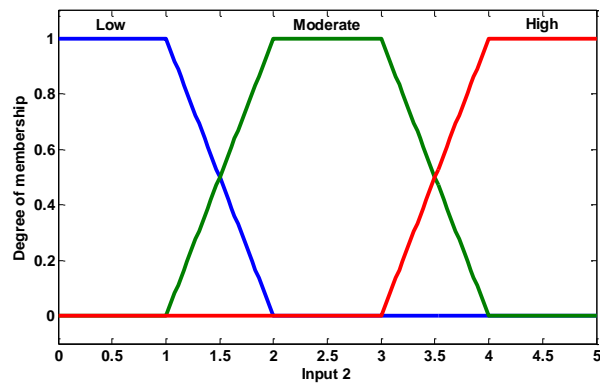


Fig. 3. Membership functions of the Input 2

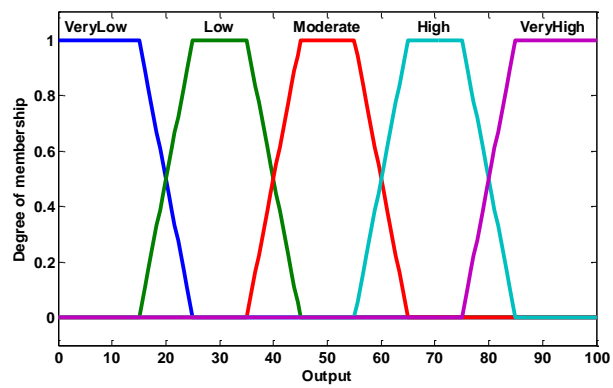


Fig. 4. Membership functions of the Fuzzy logic system output

**Table 1.** The numeral values of trapezoidal membership functions and the corresponding linguistic variables of the Input 1, Input 2, Input 3, Intermediate variable and Output

Input 1, Input 3, Intermediate variable	Input 2	Output	Linguistic variables
[0, 0, 0.7, 1.3]		[0, 0, 15, 25]	Very low (VL)
[0.7, 1.3, 1.7, 2.3]	[0, 0, 1, 2]	[15, 25, 35, 45]	Low (L)
[1.7, 2.3, 2.7 3.3]	[1, 2, 3, 4]	[35, 45, 55, 65]	Moderate (M)
[2.7 3.3, 3.7, 4.3 ]	[3, 4, 5, 5]	[55, 65, 75, 85]	High (H)
[3.7, 4.3, 5, 5]		[75, 85, 100, 100]	Very high (VH)

The inference rules in the fuzzy logic subsystem are defined through “IF - THEN”-clause. The number of rules in the knowledge base (logic matrix) of the two fuzzy logic subsystems (FLS) is the following: FLS 1 - 15 and FLS 2 – 25. Some of the inference rules are defined as follow:

IF “*Flood susceptibility according to the river bank height above the water level*” is “Very low” and “*Flood susceptibility rate according to the river bed type*” is “High” THEN “*Flood susceptibility according to the river bank height and bed type*” is “Low”;

IF “*Flood susceptibility according to the river bank height above the water level*” is “Moderate” and “*Flood susceptibility according to the river bed type*” is “High” THEN “*Flood susceptibility according to the river bank height and bed type*” is “Moderate”;

IF “*Flood susceptibility according to the river bank height above the water level*” is “High” and “*Flood susceptibility rate according to the river bed type*” is “Moderate” THEN “*Flood susceptibility according to the river bank height and bed type*” is “High”;

IF “*Flood susceptibility according to the river bank height and bed type*” is “Very low” and “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is “Moderate” THEN “*Complex geological-geomorphological flood susceptibility*” is “Low”;

IF “*Flood susceptibility according to the river bank height and bed type*” is “Low” and “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is “High” THEN “*Complex geological-geomorphological flood susceptibility*” is “Moderate”;

.....

IF “*Flood susceptibility according to the river bank height and bed type*” is “Moderate” and “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is “Very high” THEN “*Complex geological-geomorphological flood susceptibility*” is “High”;

IF “*Flood susceptibility according to the river bank height and bed type*” is “High” and “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is “Very low” THEN “*Complex geological-geomorphological flood susceptibility*” is “Moderate”;



IF “*Flood susceptibility according to the river bank height and bed type*” is “High” and “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is “Very high” THEN “*Complex geological-geomorphological flood susceptibility*” is “High”

IF “*Flood susceptibility according to the river bank height and bed type*” is “Very high” and “*Flood susceptibility according to the overlay analysis of geological-geomorphological parameters (map results)*” is “High” THEN “*Complex geological-geomorphological flood susceptibility*” is “Very high”.

The logic matrix with inference rules of one fuzzy logic system with two linguistic input variable can be expressed also in the form of table. The logic matrices corresponding to the proposed two fuzzy logic subsystem are represented in Tables 2 and 3.

**Table 2.** The logic matrix of the first fuzzy logic subsystem

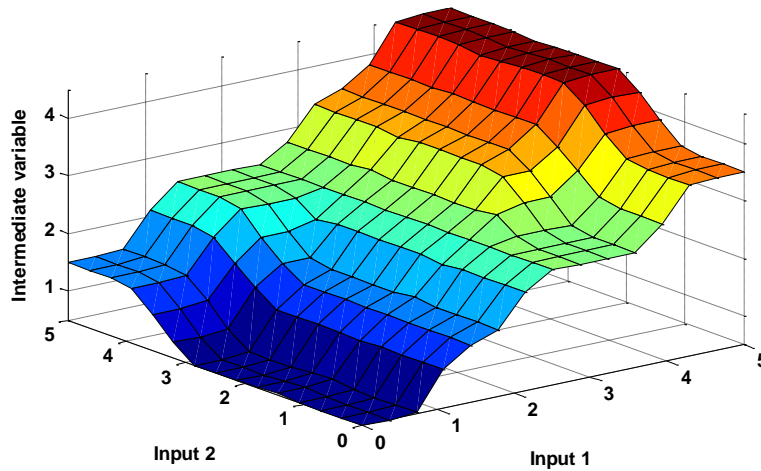
Input 1	Input 2	Intermediate variable
VL	L	VL
VL	H	L
L	M	L
L	H	M
M	L	M
M	H	M
H	L	M
H	M	H
VH	L	H
VH	H	VH

**Table 3.** The logic matrix of the second fuzzy logic subsystem

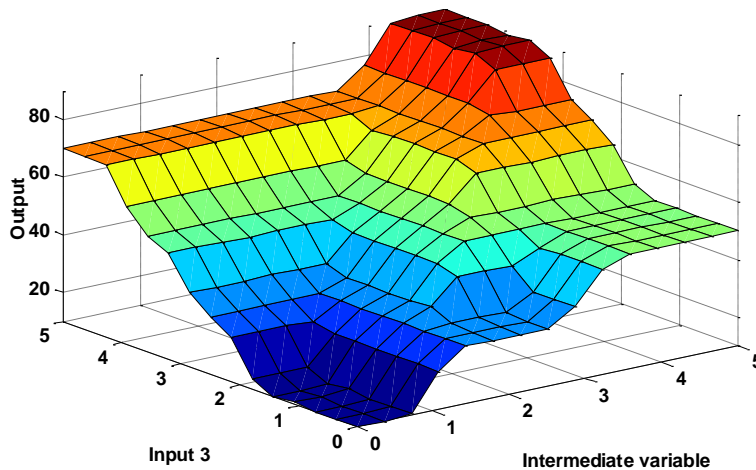
Intermediate variable	Input 3	System output
VL	VL	VL
VL	L	VL
VL	VH	H
L	VL	L
L	H	M
L	VH	H
M	VL	L
M	L	M
M	VH	H
H	VL	M
H	M	H
H	VH	H
VH	M	H
VH	H	VH
VH	VH	VH

Here, the fuzzy logic hierarchical system is designed in MATLAB computer environment using Fuzzy Logic Toolbox [35]. The two fuzzy logic subsystem are based on Mamdani's inference machines, max/min operations and center of gravity defuzzification [36].

The inference surfaces in 3D for the two fuzzy logic subsystems are shown on Figures 5 and 6, respectively as follow: (Input 1, Input 2, Intermediate variable) and (Intermediate variable, Input 3, Fuzzy logic system output).



**Fig. 5.** Inference surfaces of the first fuzzy logic subsystem in 3D



**Fig. 6.** Inference surfaces of the second fuzzy logic subsystem in 3D

### 3 Study area of the Current Research

The research is done on the example of 2 Municipalities located in South-western Bulgaria – Kresna and Strumyani (Fig. 7.). The main river in this area is the river Struma. This is one of the biggest rivers in Bulgaria. It springs from Vitosha Mountain, near to Sofia and flows to South crossing the Bulgarian – Greece boundary. The river collects many tributaries from high mountains located to the East and West.

Considering the prevailing mountainous relief and the gorge nature of the river Struma valley, the assessment of the geological-geomorphological conditions for floods is made for the low parts of the river valley, and the territories with an altitude above 600 m are excluded of the assessment.

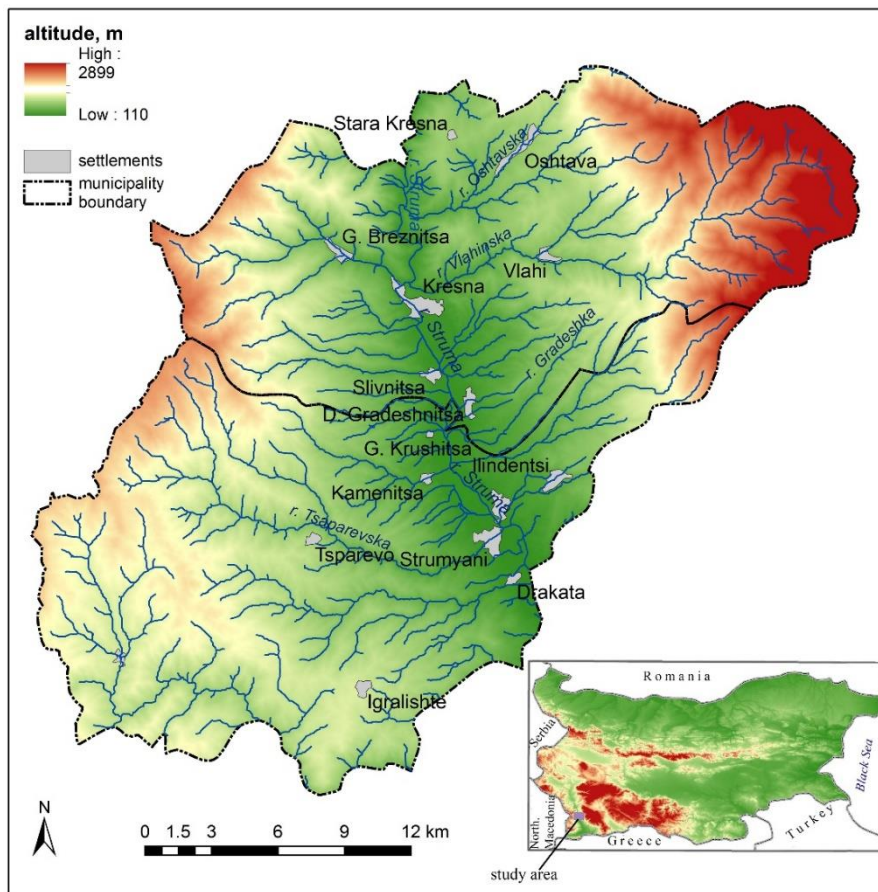


Fig. 7. Study area

The rock varieties in the study area can be divided according to their water retention properties, the water permeability and the distribution of surface and underground runoff. Porous, cracked, cavernous and mixed type (porous and cracked) reservoirs are distinguished in the area. Porous reservoir properties have quaternary alluvial and deluvial deposits, and Neogene and Paleogene clastic sediments. The weathering crust, which is a few meters thick on the granite and the metamorphic rocks can be presented as a porous reservoir, as well as the deluvial deposits. Granite and the metamorphic rocks have a cracked reservoir. Cavernous reservoirs are found only in highly soluble rocks and most often they are carbonates - limestone, dolomite or marble.

The landforms, which are most vulnerable to floods, and on the other hand, impact on the floods propagation are floodplain. Two floodplains (low and high) are developed in the river Struma valley, south of the Kresna gorge. There are also dynamic river deposits - islands that are 1 to 2 m above the average water level. Due to the active hydrodynamics of the river, the height of the floodplains is not constant. Often the connectivity of the low floodplain is cut and this increase the flood susceptibility and hazard.

## **4 Flood Susceptibility Assessment**

### **4.1 Flood Susceptibility According to the Lithology**

The lithological composition is assessed as a complex indicator, calculated as a weighted sum of the susceptibility rates of water permeability, capacity and type of rock reservoirs. In this sum 40% weight is given to the indicator type of the reservoir, 35% - to the water permeability and 25% - to the reservoir capacity. For this purpose a GIS polygon layer is created on the base of geological map [22] and field investigations. The different rocks are rated from 1 (very low) to 5 (very high) according to their importance for surface runoff retention and the probability for high water (Table 4).

The flood susceptibility rates are determined by expert assessment and taking into account the specific geological-geomorphological conditions of the environment. For example, sands and gravels have the highest water permeability, they can collect a significant part of slope runoff, convert it into an underground flow, and thus minimize the risk of flooding, but already saturated, these can help to form larger surface runoff. Regarding that sands and gravels are usually related to high level of ground water they have to be rated with higher flood susceptibility in the complex assessment. About the reservoir type, the karst and pore reservoirs are rated with lower flood susceptibility considering their surface water-retaining properties relative to surface runoff, and cracked reservoirs have a higher coefficient because they determine a greater surface runoff.

Based on the susceptibility rates for the above indicators the resultant indicator of flood susceptibility is determined by weighted sum overlay in ArcGIS environment (Fig. 8).

**Table 4.** Flood susceptibility according to the lithology

Rocks	Flood susceptibility rates		
	Water permeability	Capacity of the reservoir	Type of the reservoir
amphibolites and amphibole gneiss	4	3	4
layered ortho-amphibolites	3	3	4
biotite and two-mica gneisses, migmatites, amphibolites	4	3	4
gneiss, gneiss-shale, schist, marbles, amphibolites	3	3	4
garnet-biotite-muscovite gneisses	4	4	4
metamorphosed gabroids and ortho-amphibolites	3	4	4
marbles, slates	2	3	2
normal and subalkaline dacites, trachidacites, andesite and trachyandesites	4	3	4
biotite granite and quartz monzonite	5	3	4
porphyroid granites and granodiorites	4	3	4
sandstones, alevrolites, clays	3	2	2
equally-grained biotite granite to granodiorite	5	3	4
boulders, pebbles, sands	2	3	1
sands and pebbles	3	3	1
pebbles, sandstones and clays	4	4	1
sandy clays, pebbles	4	4	1
pebbles, sandstones, conglomerates	2	3	1
conglomerates, sandstones	2	3	1
marble breccias	1	2	3
breccias-conglomerates, conglomerates, sandstones	2	3	1

#### 4.2 Flood susceptibility according to the slopes

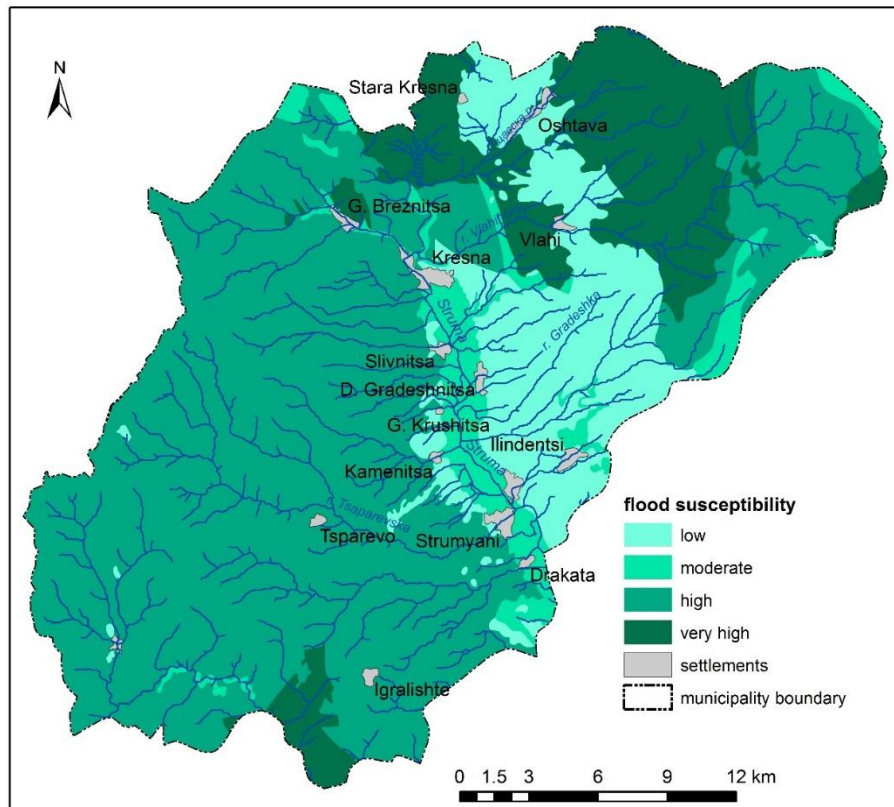
The slopes of the topographic surface affect the flow rate of slope runoff and the water retention, and in this relation the possibility of flooding. The slopes are calculated by ArcGIS (Spatial Analyst Tools > Surface) based on the digital elevation model (SRTM) [26] and are rated to susceptibility as follow (5 – very high, 1 – very low), (Table 5).

The suggested rates concern river floods and are not applicable for torrential floods or debris floods. In interpreting and assessing the slopes, ridges and watersheds lines

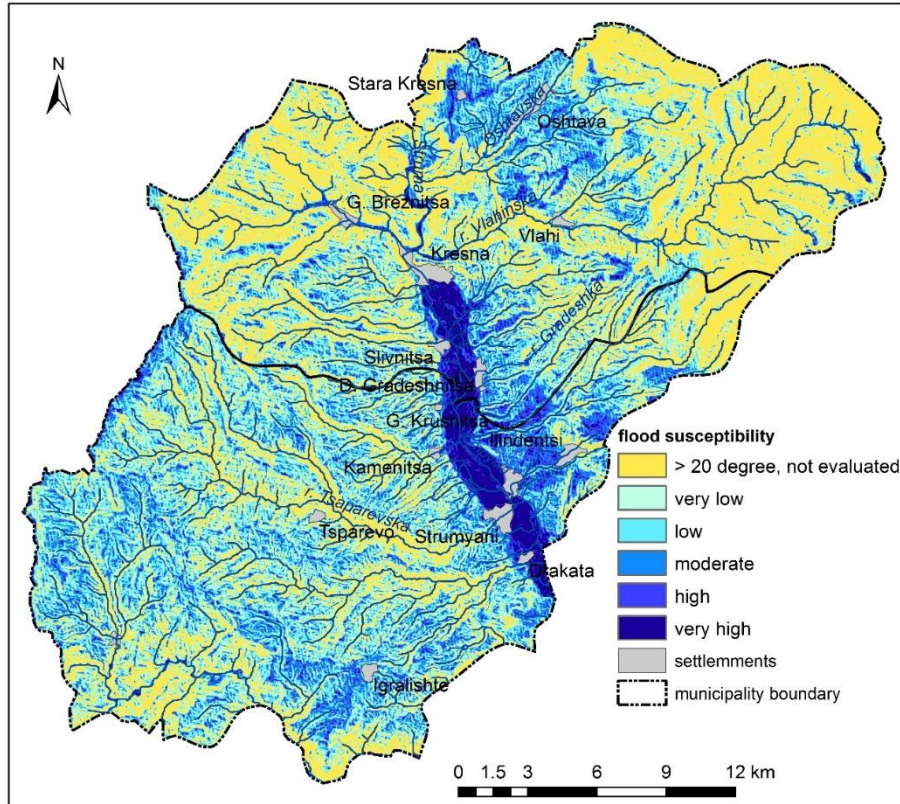
are excluded. The spatial distribution of the slope flood susceptibility is presented on Figure 9. The areas steeper than  $20^{\circ}$  are also excluded from the assessment.

**Table 5.** Flood susceptibility according the slope of the topographic surface

Slope, degree	Flood susceptibility rates
0 - 3	5
3 - 6	4
6 - 10	3
10 - 15	2
15 - 20	1
> 20	Not applicable



**Fig. 8.** Flood susceptibility according to the lithology



**Fig. 9.** Flood susceptibility according to the slopes

Very high and high flood susceptibility is observed south of the town Kresna in the low parts of the river Struma valley. This is determined by small slopes of the topographic surface which is a condition for retention of the surface runoff and also higher level of ground water contribute to high flood susceptibility.

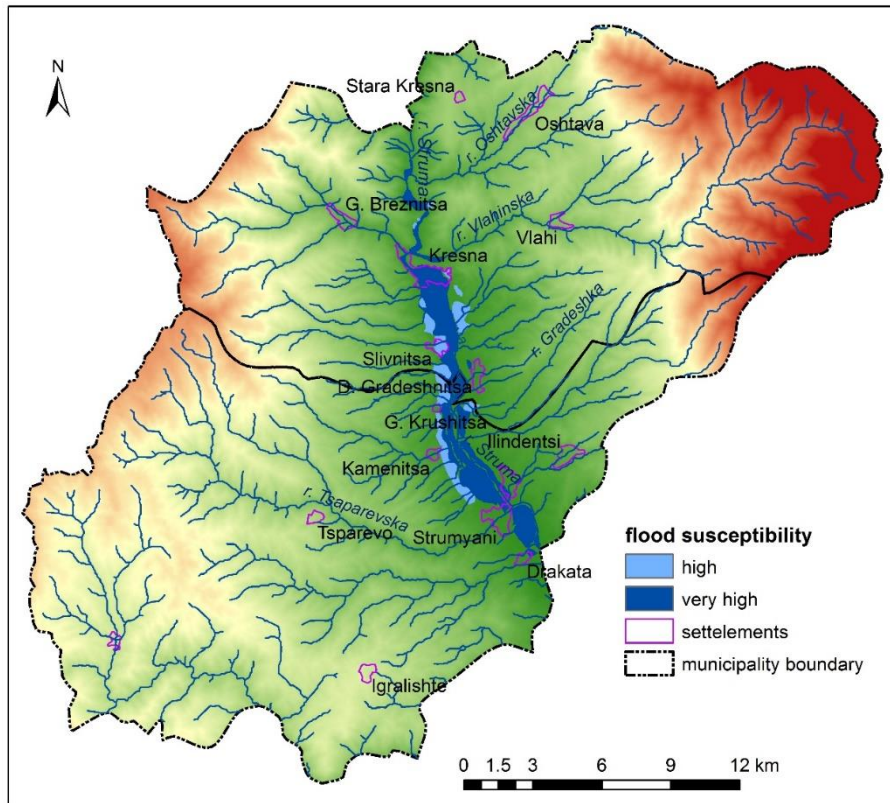
#### 4.3 Flood Susceptibility According to the Fluvial Relief

Floodplains and fluvial fans (alluvial and proluvial) are evaluated for flood susceptibility of fluvial relief. Having regards the closest relation of floodplains and fans to hydrological processes, floodplains are rated as most susceptible to floods (5) and fluvial fans - as highly susceptible (4) (Figure 10).

#### 4.4 Flood Susceptibility According to the Distance from Streams

The distance from rivers and streams is assessed in relation to the possibility of high water to flood adjacent areas. Five distance zones are generated by ArcGIS Analysis Tools - Proximity - Multiple Ring Buffer. They are rated according to the possibility to be flooded from 1 (very low) to 5 (very high). For the aim of spatial overlay analysis

the polygon layer is converted in raster format. The result of the assessment of flood susceptibility by distance from streams is presented on Figure 11. Areas higher than 600 m are excluded of the assessment.



**Fig. 10.** Flood susceptibility of fluvial landforms

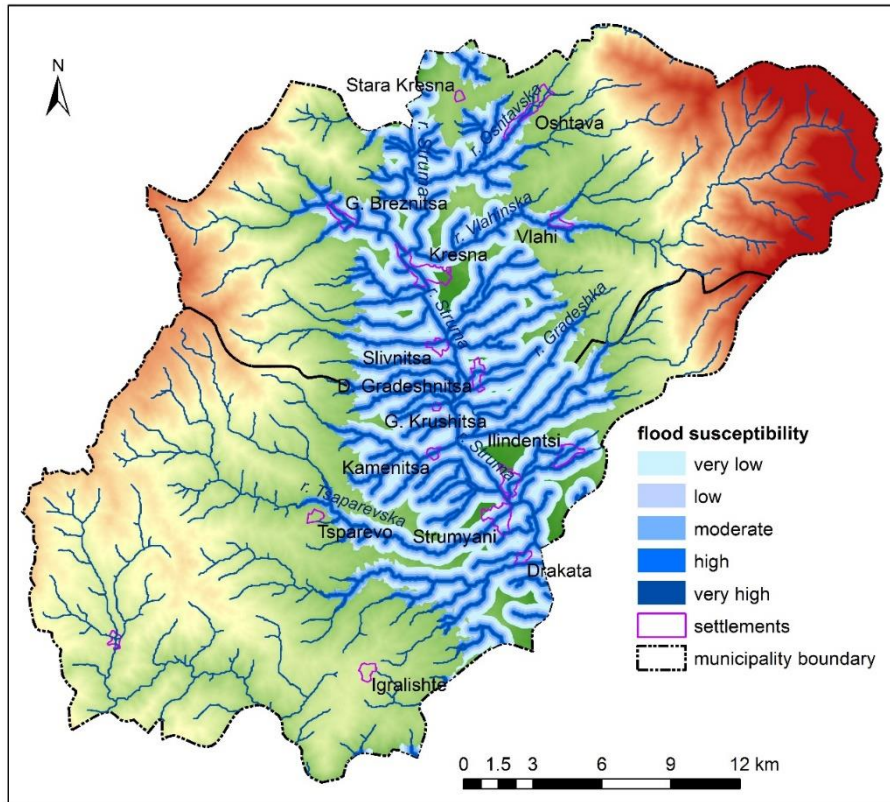
#### 4.5 Geological-geomorphological Flood Susceptibility

The assessment of the geological-geomorphological flood susceptibility is done by the weighted sum overlay in ArcGIS environment of the 4 generated raster layers, presenting the flood susceptibility rates for lithology, slopes, fluvial relief and distance from the streams. In order to determine the weighting rates of these factors, an analytical hierarchy process is used. As a result of the analysis, the following weight coefficients were applied:

- distance from streams - 45%;
- fluvial relief - 35%;
- lithology - 13% and
- slopes - 7%.



The output raster of the weighted sum overlay is shown in Figure 12. Taking into account the environmental characteristics of the investigated area, the analysis excludes areas with mountainous relief, higher than 600 m above sea level.

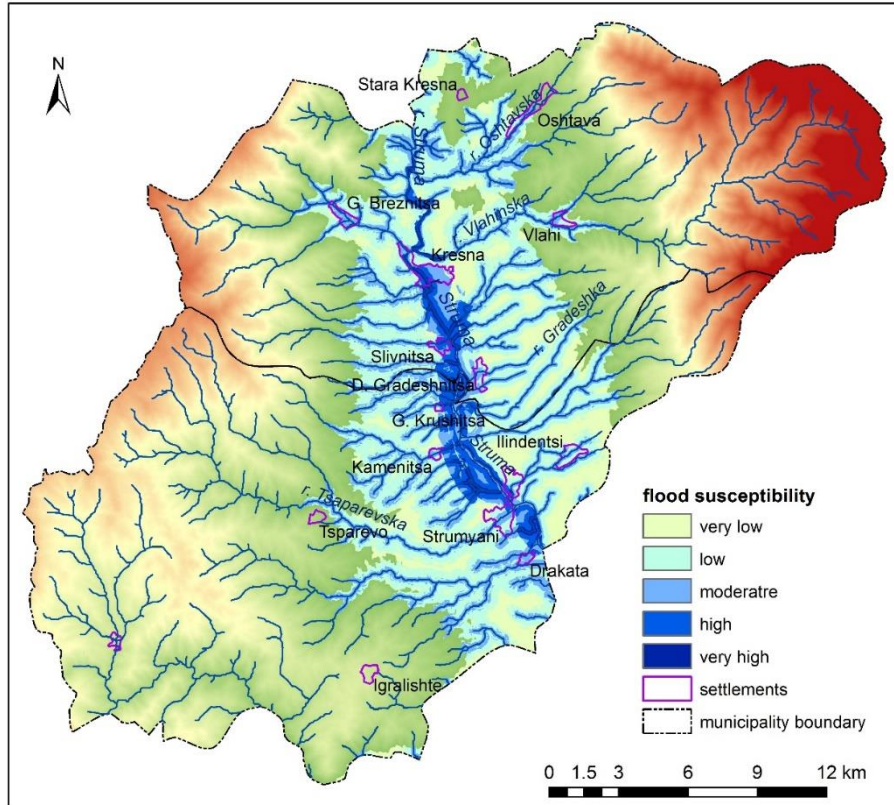


**Fig. 11.** Flood susceptibility of fluvial landforms

If it considers the floodplain as a most susceptible to flooding, the results of the overlay analysis show that not always the whole floodplain is very high susceptible. The susceptibility rates depends on the other environmental parameters, for instance distance from river and retention capacity of the alluvial layer.

#### 4.6 Simulation results from fuzzy logic model

Regarding to the above results, additional 2 parameters are considered for more detailed assessment of geological-geomorphological flood susceptibility. These are “River bank height above the water level, [m]” and “River bed type”. Each one of them is rated according the possibility for flood propagation on the base of literature review and expert assessment (Table 1 and Table 6).



**Fig. 12.** Geological-geomorphological flood susceptibility

**Table 6.** River bank and bed flood susceptibility

Parameters	Flood susceptibility rates
<i>River bank height above the water level (m)</i>	
> 3.5	VL
3.5 – 2.5	L
2.5 – 1.5	M
1.5 – 0.5	H
< 0.5	VH
<i>River bed type</i>	
Sandy	L
Mixed (partly sandy and partly rocky)	M
Rocky, bedrock	H

Taking into account the discontinuous nature of available data about river bank height and river bed type, a fuzzy logic model is suggested for determining the complex geological-geomorphological flood susceptibility.

Here, several simulations with proposed fuzzy logic model were done using particular input values in order to calculate the rate of the “*Complex geological-geomorphological flood susceptibility*” (Fuzzy logic system output) of the study area. Some simulation results are shown in Table 7.

The obtained output values (crisp values, established numerical value) from the fuzzy logic model after the defuzzification belong to one of the five sub-intervals of the interval [0, 100].

These five sub-intervals are used to determine the rate of the “*Complex geological-geomorphological flood susceptibility*” of study the region as shown in Table 7. The sub-intervals are defined as follows:

IF the value of “*Complex geological-geomorphological flood susceptibility*”  $\in$  [0, 20)  
THEN the “*Flood susceptibility rate*” is *Very low*;

IF the value of “*Complex geological-geomorphological flood susceptibility*”  $\in$  [20, 40)  
THEN the “*Flood susceptibility rate*” is *Low*;

IF the value of “*Complex geological-geomorphological flood susceptibility*”  $\in$  [40, 60)  
THEN the “*Flood susceptibility rate*” is *Moderate*;

IF the value of “*Complex geological-geomorphological flood susceptibility*”  $\in$  [60, 80)  
THEN the “*Flood susceptibility rate*” is *High*;

IF the value of “*Complex geological-geomorphological flood susceptibility*”  $\in$  [80, 100]  
THEN the “*Flood susceptibility rate*” is *Very high*.

**Table 7.** Simulation results for the rate of the Complex geological-geomorphological flood susceptibility from the fuzzy logic model

Flood susceptibility rates				
Input 1	Input 2	Input 3	Output	
1.5	2.5	0.8	30	L
0.5	2.5	1.8	14.1	VL
0.8	2.0	1.2	11	VL
2.2	3.5	3.5	50	M
3.5	0.8	2.8	50	M
2.8	3.2	4.0	60	H
4.5	3.0	3.8	89.7	VH
4.0	2.3	4.2	77.1	H
3.5	2.3	4.5	70	H
3.3	3.7	2.8	70	H
4.2	3.7	2.8	72.9	H
4.3	3.7	3.3	90	VH
4.3	3.0	3.0	79.1	H
0.6	4.3	3.0	39	L

The simulation results show the importance of the river bank height in flood susceptibility, following the observed cases where floodplains are not equally inundated during flood events (Table 7).

For example if the geological-geomorphological flood susceptibility is *Very low* to *Low* (Input 3 = 0.8), the river bed is partly sandy and partly rocky (*Moderate* flood susceptibility, Input 2 = 2.5) and the height of the river bank is 3 m (Input 1 = 1.5, *Low* flood susceptibility), then the *Complex geological-geomorphological flood susceptibility* is *Low* (Output = 30).

If the initial assessment of flood susceptibility of the overlay analysis of geological-geomorphological indicators is moderate to *High* (Input 3 = 2.8) and the height of the river bank above the water level is 0.5 - 1m (*Moderate* to *High* flood susceptibility, Input 1 = 3.3), and the flood susceptibility according to the river bed type is *High* to *Moderate* (Input 2 = 3.7), then the *Complex geological-geomorphological flood susceptibility* is *High* (Output = 70).

On the other side if the river bank is higher than 3.5 m (Input 1 = 0.6, *Very low* flood susceptibility) and the flood susceptibility resulted by the overlay analysis of geological-geomorphological indicators is *Moderate* to *High* (Input 3 = 3), although the high value of Input 2 = 4.3, then the *Complex geological-geomorphological flood susceptibility* is *Low* (Output = 39).

The observed changes in the flood susceptibility rates after applying suggested logic frame show increasing of the of the susceptibility rates and in some cases could lead to overestimating the susceptibility but following the precautionary principle in disaster risk reduction we consider that the simulation results can be used at the first stage of flood management process and are helpful for informative decision making.

## 5 Conclusions

The applied weighted sum overlay analysis of flood susceptibility rates according to the lithology, slope, fluvial relief and distance from streams for the investigated areas of the river Struma valley (municipalities Kresna and Strumyani) shows high and very high flood susceptibility in the lowest parts of the river Struma valley, south of the town Kresna to the Bulgaria – Greece border. The geological-geomorphological features of the area influence the redistribution of the runoff of the surface and the underground component as well as the time for which the slope flow reaches the riverbed. Regarding the assessment of geological prerequisites for floods special attention have to be given on the indicators related to rock resistance of weathering and erosion, porosity and cracks that influence the water permeability and flood retention capacity. About the geomorphological prerequisites the most sensitive are floodplains, alluvial and proluvial fans.

The result of the analysis provides information about flood sensitive areas and can be used as the basis for organizing monitoring to minimize the risk of flooding. The data obtained should be interpreted in relation to the hydro-climatic conditions and, particularly, taking into account the quantity and duration of precipitation. Having regard the limit of the available data application of fuzzy logic gives good result. The

suggested flood susceptibility model can be used as a basis for further development of a complex flood susceptibility assessment by adding other indicators as precipitation, stream flow, soils, vegetation etc. and can be considered as a first step of flood hazard assessment.

The fuzzy logic model is designed as a two-level hierarchical system with three inputs and one output. Each level of the system is consisted of one fuzzy logical subsystem with two inputs. The fuzzy logic system output gives the complex assessment for geological-geomorphological flood susceptibility of study area regarding the interaction of the three inputs.

The fuzzy logic model for flood susceptibility rate can be used as a basis for further development of a complex flood susceptibility assessment by adding other indicators as precipitation, stream flow, soils, vegetation etc. and can be considered as a first step of flood hazard assessment.

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