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Prediction of Karst susceptibility combining GIS based modelling and remote sensing data analysis

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ABSTRACT: Karst phenomena represent important geohazards and risks to be faced during the railways and motorways design and construction. The prediction of their features, occurrence and impacts on the environment is often difficult because of the complex interaction of geo related factors which control the process. Facing this problem, a karst susceptibility analysis was performed over a more than 650 km^2 wide area within the Russian Nizhegorodskaya region. The applied methodological approach is based on GIS modelling of geospatial data combining different methods such as Frequency Ratio (FR), Fuzzy Logic and Analytic Hierarchy Process (FAHP). The analysis includes 4 main stages: 1) the input data were collected and processed in ArcGIS environment. 2) The principal karst triggering factors were defined and mapped. 3) For each factor, the Frequency Ratio model was used to calculated Fuzzy Membership Values. Using a pairwise comparison matrix based on FAHP criteria, the “importance” (weight) of each factor in karst process was defined and the fuzzy maps multiplied for their relative weights. A final karst Susceptibility Map was finally obtained combining the spatial contribution of each factor map. 4) Eventually, the results were validated by observational field data, remote sensing analsysis and satellite monitoring of ground deformation (SqueeSAR analysis). Both karst prediction and model reliability were considered overall good and consistent with the observed phenomena.

Keywords: Karst hazard assessment, Fuzzy Analytic Hierarchy Process, GIS based Modelling, frequency ratio.

1 Introduction

The prediction of the Karst occurrence is one of the most critical geohazard to be faced during civil infrastructural works design and construction. Karst phenomena are natural processes triggered by the complex interaction of different geological, geomorphological and hydrogeological factors which in many cases cannot be completely predicted. Given this intrinsic uncertainty, different methods and techniques can be applied to the study of karst hazard. The reliability and effectiveness of the methods depend on factors such as quality and quantity of input data, local constraints and final targets to be achieved during the study. The methods of analysis can be deterministic or probabilistic but they basically adopt GIS based spatial modelling to estimate as best as possible the spatial contribution of each triggering element (factor) in karst process. GIS based spatial models, Fuzzy Logic and AHP methods are currently implemented in different geological areas (landslide’s hazard assessment, modelling of groundwater potential zones, etc..) but can also be used to the study of others geohazard as well as in geological and hydrogeological prospection with suitable results (Ebadi et al., 2004). Therefore, a similar approach was applied in this study which is as a part of a motorway design in Russia and was focused on the best and most safe road alignments selection.

2 Geological and geomorphological setting of the study area

The study area is approximately 650km^2 extended within the Russian Nizhegorodskaya region. This area belongs to the central part of the Russian platform, and it is characterized by the alternance of flat areas (alluvial plans) and gentle hills separated by permanent and temporary streams.

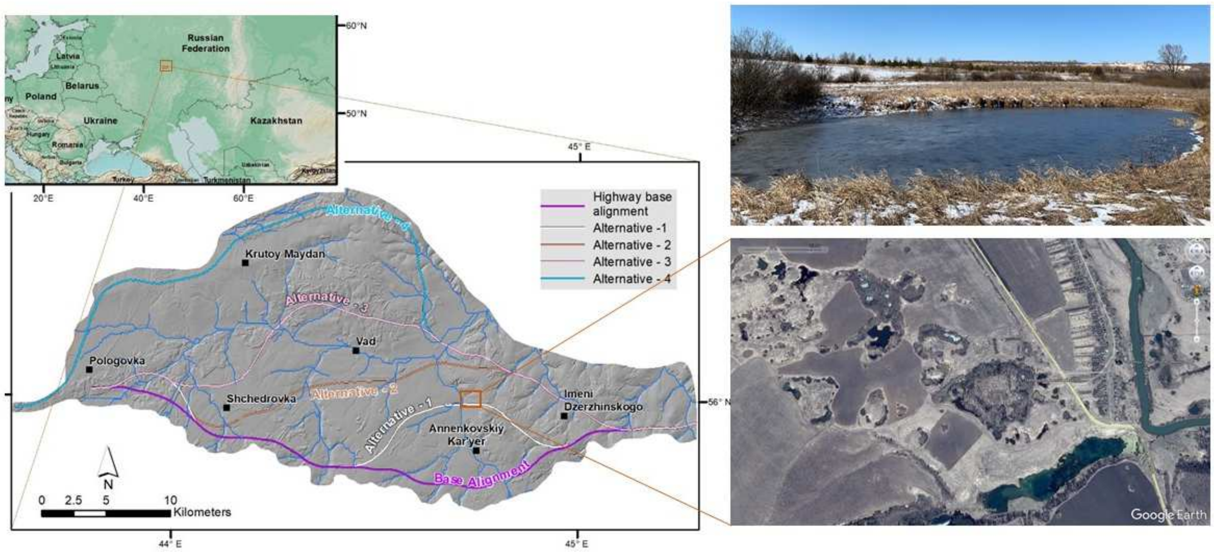

Figure 1. location map of the study area with proposed road alignments.

The geology of the area is characterized by the presence of Palaeozoic to Mesozoic sedimentary geological formations (bedrock), Permian to Cretaceous in age, covered by quaternary glacial, glacio-fluvial and alluvial deposits. The karst affected geological formations are middle to low Permian in age end consist of carbonated-sulphate rock type sequence. From the younger to the older, the Permian bedrock includes the following geological units:

- Urzhumskiy stage (middle Permian in age P_2 ur) consisting of clay, sandstones and marly-carbonate ground types.
- Kazanskiy stage (middle Permian - P_2 kz) including limestone and dolomite rock types with local layer of sandy clayey sediments.
- Sakmarskiy stage (lower Permian – P_1 s+a) consisting of gypsum and anhydrite rock types.

The bedrock depth is not homogeneous and ranges from few meters to more than 70m depending on the local structural and stratigraphic setting as well as the paleo-topography of the area. The Permian karst sensitive formations are locally covered by some tens of meter thick low permeable clay, sandy and marly sediments belong to the Urzhumskiy stage (middle Permian in age P_2 ur); in the eastern part of the region, the Jurassic-cretaceous (J-K) clayey-marly sediments outcrop as well. The presence of these formations mitigates the karst process, reducing the water infiltration rate and the karst evolution up to the ground surface but they are not continuous in the project area.

From the structural point of view, the project area is characterized by the Volgo-Uralskaya Anteclise which form a large and uplifted structure in Russian continental platform. According to some regional geological studies some ductile (bending folds) and brittle structures were identified in the area. Brittle structures include NE-SO oriented and subordinate NW-SE oriented fault systems; most of them were interpretated as upthrows – over-thrust structures with southern-eastward vergence (Kolodyazhnyi, 2015). These regional structures modelled the landscape creating uplifted zones, depressions, structural highs and lows within the bedrock.

Concerning the hydrogeology, two different aquifers can be recognized in the study area: one located within the Quaternary deposits (sandy silty glacial and alluvial sediments); one deeper, within the fractured and permeable carbonate rock formations belonging to the Kazanskij - Sarmanskiy stages. Where Permian bedrock outcrops close to the ground surface, the groundwater table level changes significantly during the seasons due to the direct recharge by the rainfalls from the surface.

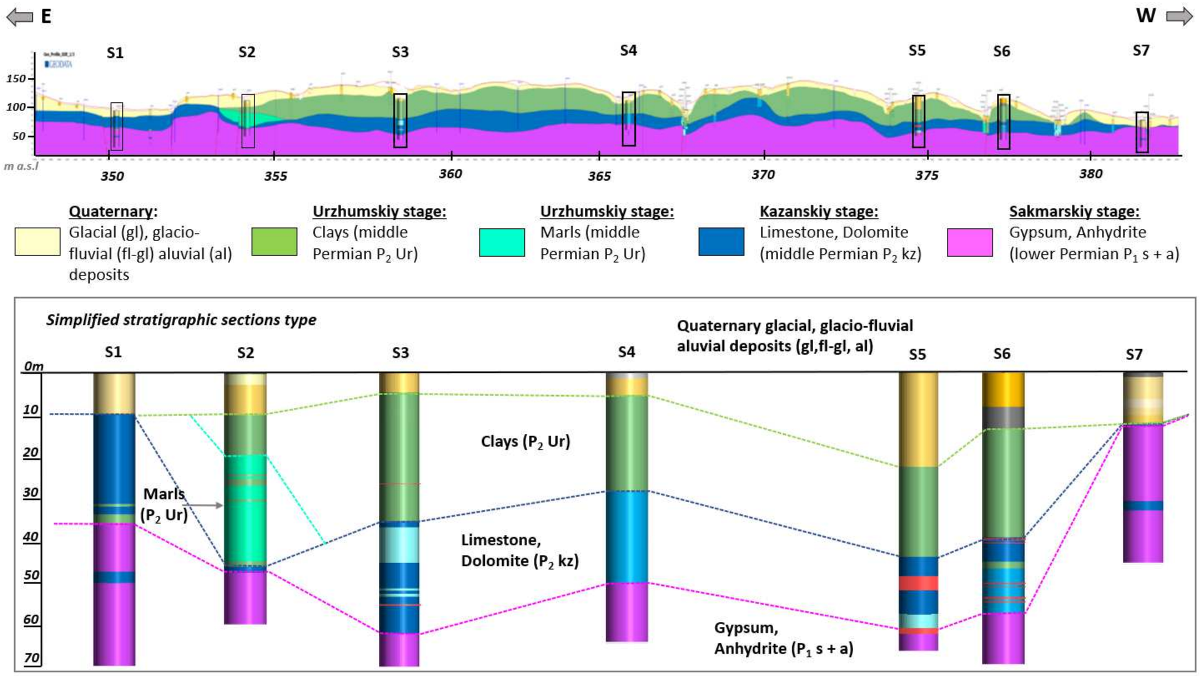

Figure 2. Typical geological and stratigraphic sections od the area.

Karst is active and widespread within the study area and typical forms such as depression, sinkholes, locally vertical shafts can be easily observed. The suffusion is the main geological process that generate subsidence and sinkholes reaching the ground surface. Karst starts from the shallowest and most fractured limestone and gypsum rock mass and migrates upward because of dissolution process, erosion, and progressive roof collapse. Sinkholes are widespread in clayey soil cover while subsidences occur principally in presence of sandy dominant ground.

3 Karst Susceptibility Mapping (KSM)

3.1 Project input data

In this study, different sources of information (reference, spatial, direct field data, ground investigation and monitoring) were used. A spatial database in GIS environment was set out to collect, process and harmonize different geodata layers. Based on the local geological knowledge, six principal Karst related factors were defined as illustrated in Figure 3. They include the following: density of shallow karstic forms, depth to bedrock, morphology and elevation, distance to fault zone, depth to groundwater table and distance to stream.

The karst inventory was carried out based on field observations and remote sensing analysis. Slope, morphology and elevation were obtained from the Digital Elevation Model DEM with 30x30m grid while the high-resolution topographic data were generated using data from NASA's Shuttle Radar Topography Mission (SRTM). The distance to streams was calculated using topographic map generated by DEM, while geological, structural and hydrogeological setting was defined collecting reference information, outcomes of remote sensing analysis, field observations and ground investigation.

3.2 Description of the Karst related factors

The occurrence of karstic forms in the project area can be associated to six principal factors, and their interaction, coded F1 to F6 hereafter.

F1 - Density of shallow karstic forms [n./km^2]

Geological investigation surveyed caves, subsidence and sinkholes related to most critical karst sensitive areas. Existing karst processes still active accelerate the rock dissolution rate. In these areas, the karst occurrence can be related to the presence of carbonate sulphate rocks close to the ground surface and water infiltration at depth. For each karst form an influence radius of 50m was assumed. Four frequency classes (n./km^2) were defined: 0 (1), 1-10 (2), 10-50 (3), >50 (4) (Figure 3a).

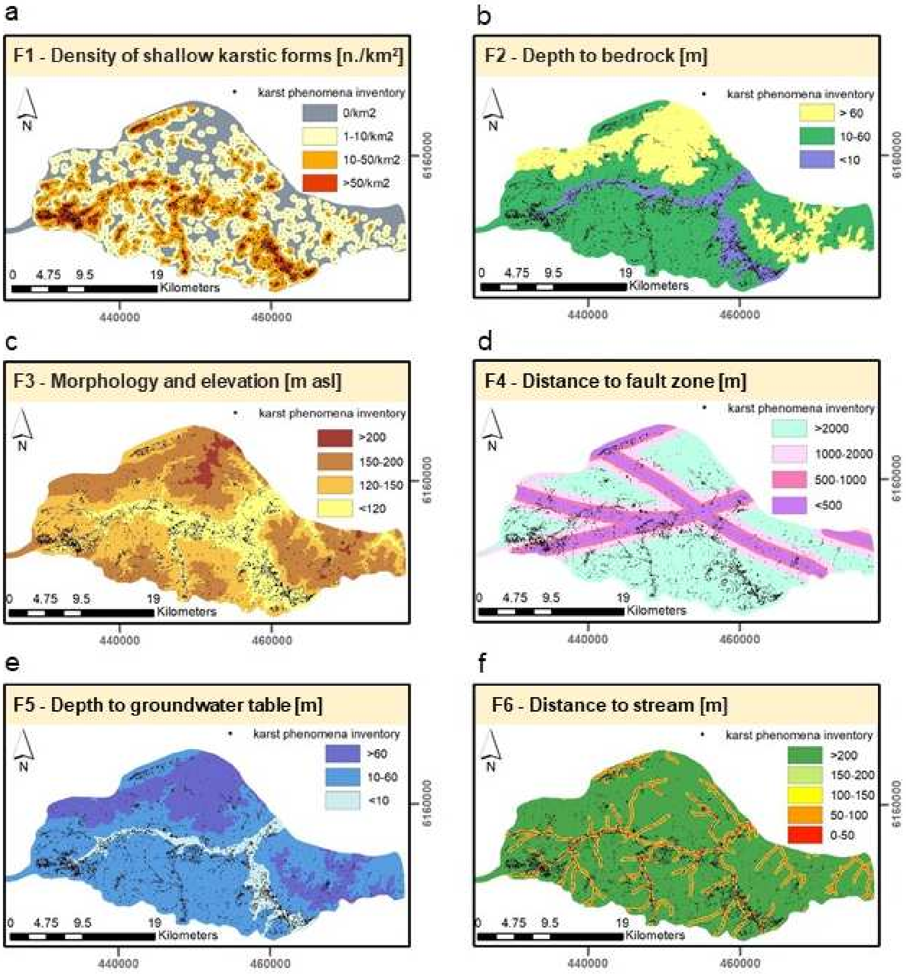

Figure 3. Karst related factor maps.

F2 - Depth to bedrock [m]

Geological structures such as bending folds, faults and thrust produce structural highs and lows within the Permian sequence. This complex scenario determines the irregular trend of the contact between the quaternary soil cover and the Permian bedrock. Within the study area, the depth to bedrock increases moving northward and eastward ranging from some meters to more than 70m. For this factor, three different classes of depth (m from the ground surface) were defined: <10m (1), 10-60m (2); 60m (3) (Figure 3b).

F3 - Morphology and elevation [m asl]

As already mentioned, the Volzhsko-Okskaya platform consist relative flat areas where an articulate drainage pattern took place forming an irregular alternance of gentle hills and river valleys with absolute ground level from 70m and 250m asl. The “morphology factor “was considered because it influences the spatial distribution of groundwater recharge zones and drainage areas. Four classes of ground elevation were identified (m asl): <120m (1), 120-150m (2), 150-200m (3), >250m (4) (Figure 3c).

F4 - Distance to fault zone [m]

Fault zones are structural weakness zones characterized by highly fractured and weathered rock masses. The movement acting along a fault zone can deeply influence karst processes, producing uplift of the carbonate sulphate bedrock up to the ground surface, permeable horizons and preferred paths for groundwater circulation. Filed observations show that the probability of karst occurrence decreases as the distance to fault increases. Distance to fault zone was divided into 4 buffer zones: <500m (1), 500-1000m (2), 1000-2000m (3), >2000m (4) (Figure 3d).

F5 - Depth to groundwater table [m]

The most unfavourable hydrogeological scenario for karst triggering is the presence of the groundwater table close to the ground surface with direct recharge by rainfalls. The main aquifer of the area is located within the carbonate – sulphate bedrock (Kazanskiy aquifer) which depth ranges from some meters, nearby the main river valleys, to more than 70m moving northern and eastern ward within the study area. Being strictly bound to the bedrock depth, three classes were identified for this factor:<10m (1), 10-60m (2), >60m (3) (Figure 3e).

F6 - Distance to stream [m]

The distance from the river valleys is an important parameter related to the karst occurrence. In fact, along the river valleys the erosional processes can remove partially or totally the quaternary grounds overlaying the Permian bedrock. Moreover, the erosional process takes place over zones of weakness and high fractured rock masses where water infiltrations phenomena are also frequent. Observational data show that the probability of karst occurrence decreases moving away from the stream axis. The parameter "distance to stream" was divided into five buffer zones with intervals of 50m (Figure 3f).

3.3 Methodological approach and stages of the analysis

As general criterium, the Karst Susceptibility Mapping is performed assessing how factors contribute to the karst occurrence. Karst occurrence is used to determine the factor importance considering that the geological and morphological conditions at the base of the present karst can be responsible for similar and future deformation. The karst inventory is used to drive the analysis of factors importance in the karst process. The methodological approach adopted in this study consists of a combination of spatial information and statistic/fuzzy models with the aim to discretize the karst susceptibility of a certain area. In this study, the following workflow was applied as illustrated in Figure 4.

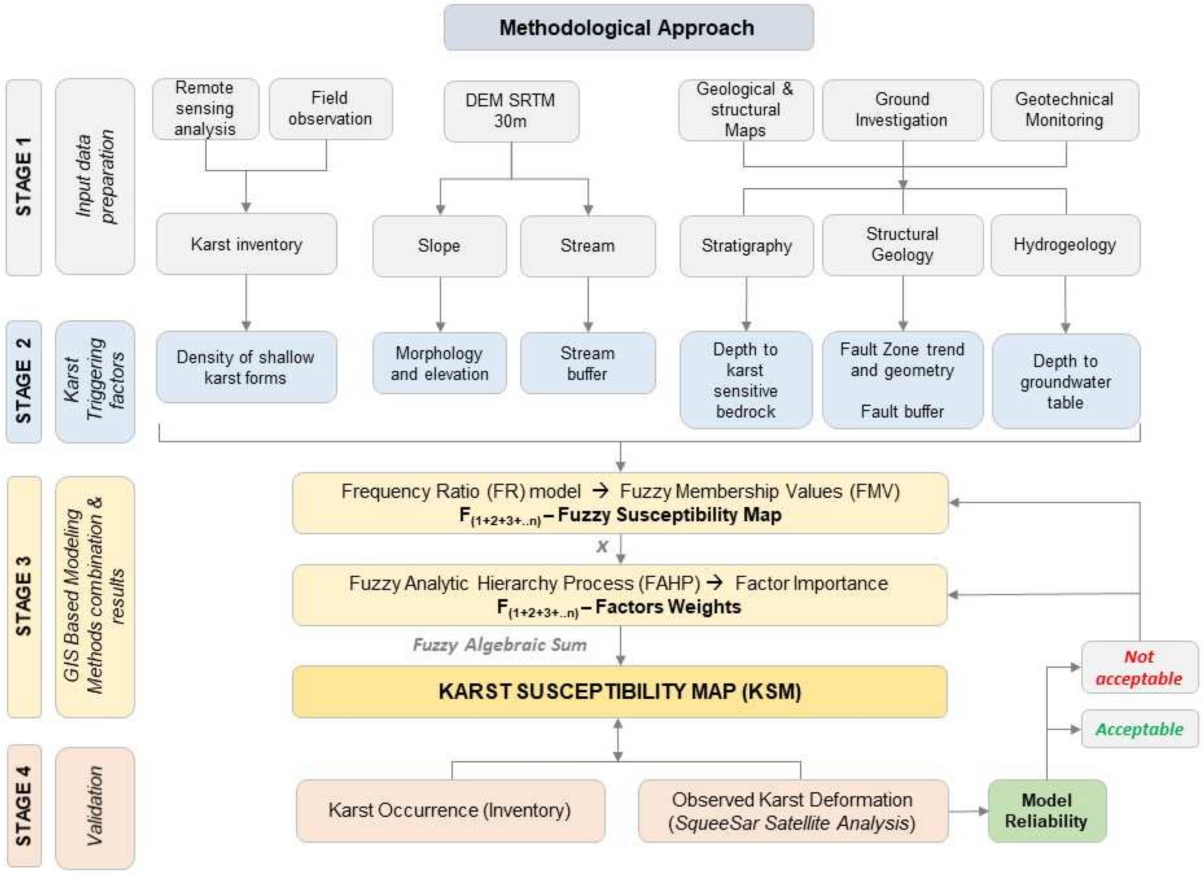

Figure 4. Methodological approach applied to the study.

Stage 1 – Input data preparation

The first stage of the analysis is the input data preparation related to the six main karst related factors in GIS environment. For the resulting factor maps, input data with similar level of detail and spatial distribution were used.

Stage 2 – Karst triggering factor maps

Once input data were structured, the karst triggering factor map were produced. For each factor map, different classes were defined according to the criteria described in section 3.2.

Stage 3 - methods combination and results

The fuzzy approach, which enable handling of vague information, is considered by expert as the most realistic description (Rather et al., 2020). For each factor it is possible to link a s fuzzy sets defined as a classes of objects with continuous grades of membership. Such a set is characterized by a membership function which assign to each object a grade of membership ranking from 0 to 1 (Shadman Roodposhti et al., 2013; Tazik et al., 2014). To create Factor Fuzzy Susceptibility Maps, the Frequency Ratio (FR) model was adopted for calculate Fuzzy Membership Values (FMV). The FR It is a ratio of landslides occurred area with respect to the total study area and is also the proportion of the landslide occurrence probabilities to a non-occurrence for a given attribute (Bonham-Carter, 1994; Lee & Talib, 2005). In FR model, a statistical value for each class of a factor map using the following equation:

$$FR = \frac{Npix(Si)/Npix(Ni)}{\sum Npix(Si)/\sum Npix\ (Ni)}$$

Where, $Npix(Si)$ is the number of karst pixels containing class i, $Npix(Ni)$ is the total number of pixels of class i, $\sum Npix(Si)$ is total number of karst pixels in the entire study area, whereas $\sum Npix(Ni)$ is the total number of pixels of the entire study area.

Table 1. Frequency Ration and Fuzzy Membership Values obtained for each factor and related classes

Code	Factor	Class	Npix(Si)	Npix(Ni)	Frequency Ratio (FR)	Fuzzy Membership values (FMV)
F1	Density of shallow karstic forms [n./km^2]	>50/km2	119752	349925	5,98	1,00
		10-50/km2	205463	1769531	2,03	0,34
		1-10/km2	64809	3072607	0,37	0,06
		0/km2	0	1618742	0,00	0,00
F2	Depth to bedrock [m]	<10m	93850	604288	2,71	1,00
		10-60m	268052	4422921	1,06	0,39
		>60m	28122	1783596	0,28	0,10
F3	Morphology and elevation [m asl]	<120	185082	1480672	2,18	1,00
		120-150	154429	2674052	1,01	0,46
		150-200	49723	2492731	0,35	0,16
		>200	790	163312	0,08	0,04
F4	Distance to fault zone [m]	<500	56676	941809	1,05	1,00
		500-1000	49799	832947	1,04	0,99
		1000-2000	88362	1545325	1,00	0,95
		>2000	195187	3490724	0,98	0,93
F5	Depth to groundwater table [m]	<10m	93850	604288	2,71	1,00
		10-60m	268052	4422921	1,06	0,39
		>60m	28122	1783596	0,28	0,10
F6	Distance to stream [m]	>200	266816	5625314	0,83	0,35
		150-200	21315	277784	1,34	0,57
		100-150	24005	287550	1,46	0,62
		50-100	31981	300600	1,86	0,79
		0-50	45907	319557	2,36	1,00
Σ Npix(Si) = 390024; Σ Npix(Ni)= 6813482						

Once defined the FR and FMV, the FAHP methodology was implemented to determine the importance of the Karst related factors. In FAHP approach, a pairwise comparisons run in the Fuzzy evaluation matrix are numbers that are modified by the designer emphasis and judgements (Kahraman et al. 2003).

Making comparisons and calculating relative ratings, a scale of number ranging from 1 to 9 was used to indicate how many times more important one element is over another element with respect to the criterion or properties with respect to which they are compared (Saaty, 2008). According to Goepel (2013), questionnaire amongst experts (participants) was designed and a comparison matrix of consolidated scores was created to calculate factor weights based on the expert responses to the questionnaire (Table 2).

Table 2. pairwise comparison matrix of scores used to calculate weights.

Weight - decision matrix	F1	F2	F3	F4	F5	F6
F1 - Density of shallow karstic forms	1	1 1/4	4 1/3	4 1/3	1 1/4	1 4/5
F2 - Depth to bedrock	4/5	1	4	3 5/8	5/9	1 3/5
F3 - Morphology and elevation	1/4	1/4	1	1 3/5	1/4	1/3
F4 - Distance to fault zone	1/4	2/7	5/8	1	5/9	3/7
F5 - Depth to groundwater table	4/5	1 4/5	4	1 4/5	1	1 3/5
F6 - Distance to stream	5/9	5/8	3	2 2/7	5/8	1
Weight (w)	*0,271*	*0,210*	*0,064*	*0,069*	*0,235*	*0,150*
Consistency Ratio CR=0,03						

The Consistency Ratio CR is defined by the ration between the value of matrix Consistency index (CI) and the random index RI which is the average value of CI. Matrix's result is acceptable if CR value is lover than 0.1 (Alonso et al., 2006):

$$CR = \frac{CI}{RI} < 0.1$$

According to the Alonso et al. (2006), the CR calculation was carried out using the following formula:

$$CR = \frac{\lambda \max - N}{2.7699N - 4.3513 - N}$$

Where:

$\lambda_{\max}$ is the maximum eigenvalue of comparison matrix and N is the number of factors.

The calculated weight of each factor was multiplied for the related Fuzzy Membership Values of the identified classes to get the Fuzzy membership function or weight (μ_i) for ith map. Eventually, the final Karst Susceptibility Map is obtained applying the Fuzzy Algebraic Sum Operator as indicated below (Ebadi et al., 2004):

$$\mu_{Combination} = 1 - \left(\prod_{i=1}^{n} (1 - \mu_i)\right)$$

Where:

$\mu_{icombination}$ =each unit value in output map, μ_i = the weight of ith map, and i=1,2,3….n = maps to be combined.

Stage 4 – Validation

The model was validated to see how reliable the susceptibility classes are. Two sources of data were adopted to validate the model: the karst distribution and the outcomes of SqueeSAR Interferometry analysis. The Squee SAR analysis was carried out using data of European SNT satellite with resolution 30m over a span of 5 years data recording, from 2015 to 2020. Displacements of Permanent (PS) and Distributed Scatterers (DS) were measured and mapped trying to find a link with the most critical karst deformation zones (mm/year). The scatterers distribution fit almost well with the most karst susceptive zones (medium to very high susceptibility classes) and they can be, in many cases, related to active karst ground deformation. This evidence is also consistent with the existing karst distribution observed on field.

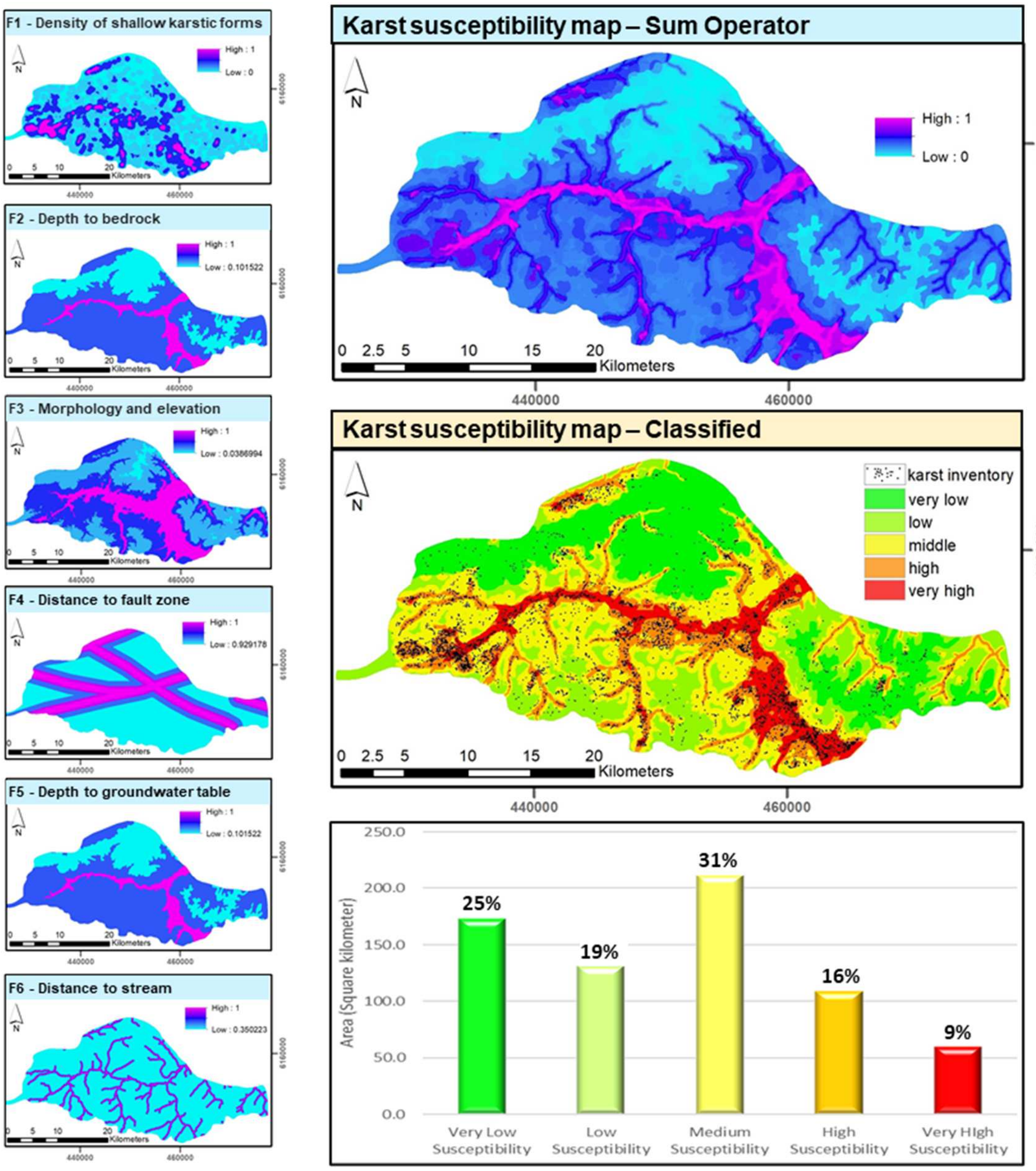

Figure 5. Methods combination and results: Karst Susceptibility Maps (Sum Operator and Classified). Histogram of calculated Karst susceptible areas showing the % included in each susceptibility class.

4 Conclusions

Karst processes are widespread in the Russian Nizhegorodskaya region and represent one of the most Geohazard for natural environment, urban areas, and infrastructural civil works. GIS based spatial models, Fuzzy Logic and AHP are methods currently implemented in geohazard assessment; in this study, a similar approach was adopted for Karst Susceptibility Mapping with suitable results. According to the local geological framework, the most karst susceptible areas are linked to specific sectors such as river valleys or structural highs (horst) where the combined effects of the principal karst-related factors trigger the process. These sectors are classified as medium to very high susceptible areas. They represent the 56% of the whole study area and include the 92% of the total Karst occurrence. The accuracy of the adopted models is overall good, and the obtained results are consistent with field data and observations. Different sources of data were used to validate results: field surveys, satellite imagery, aerial photos and SqueeSAR interferometry analysis. The latter provided interesting results despite some limitations in data recording due to the satellite resolution and local environment conditions (vegetation, presence of ponding areas, distribution of permanent scatterers, etc..).

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