Derivation of Wildfire Ignition Index using GIS-MCDA from High-Resolution UAV Imagery Data and Perception Analysis in Settlement Sali, Dugi Otok Island (Croatia)

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Keywords: Wildfire Risk Ignition Index, GIS-MCDA, High-Resolution UAV Imagery, Perception.

Abstract: In recent years, wildfires have become one of the most hazardous natural disasters because of their overall impact on the natural and urban environment. In this paper, we have generated a wildfire risk ignition index for the Sali settlement (Dugi Otok, Croatia). This model was generated within the INTERREG PEPSEA (*Protecting the Enclosed Parts of the Sea in Adriatic from pollution*) project. Wildfire ignition index is based on the GIS-MCDA (Multi-Criteria Decision Analysis). The process was performed using 13 criteria grouped in five clusters. Criteria were derived from high-resolution multispectral (5 bands) orthomosaic and digital terrain model (DTM) produced from imagery acquired with *Matrice 600 Pro* and *Matrice 210 RTK V2 UAV*. The criteria weights were determined using the AHP (*Analytic Hierarchy Process*). The model of wildfire ignition risk was classified into five classes, from *very low* (1) to *very high* (5). The model indicates that 14.14 % of the study area falls in a very high (5) ignition risk zone. The fire-risk perception was analyzed and the wildfire ignition model was evaluated using a questionnaire. The results indicate that all recent wildfire ignition locations occurred in high (4) and very high (5) risk class. Furthermore, the population recognized wildfires as a moderate threat to the ecosystem of the wider Sali area. A set of specific management measures has been proposed to prevent wildfire ignition. This proposed methodological framework and results can provide valuable information and specific management tools to local government.

1 INTRODUCTION

Wildfire (Pavlek et al., 2017) or wildland fire (Eskandari, 2017) burns uncontrollably in a natural environment in which the primary fuel is vegetation. Wildfire is the one of most hazardous natural disasters (Bonazountas et al., 2005) and important cause of land degradation which lead to desertification, deforestation (Eskandari, 2017), and destabilization of soil-water conservation (Sharma, 2012). They can have profound effects on global gas emissions, biodiversity, land cover change, health, and local economies (Sebastián-López et al., 2008, Somashekar et al., 2009, Thompson and Calkin, 2011, Ajin et al., 2016). One of the most important phases in wildfire management are prevention (Vasilakos et al., 2007, Sebastián-López et al., 2008) and early detection (Doolin and Sitar, 2005, Hefeeda and Bagheri, 2007, Vescoukis et al., 2012). Namely, risk management begins with an assessment of the areas with the highest possibility of fire ignition (Gigović et al., 2018). An important measure in fire prevention is a derivation of the fire ignition risk (Roland et al., 2015) which can indicate the vulnerable areas and can provide specific management tools to authorities (Bonazountas et al., 2005). Fire ignition risk refers to the chance of a fire starting as determined by the presence and activity of any causative agent. It is regarded as an essential element in analyzing and assessing fire danger (Vasilakos et al., 2007, Catry et al., 2010). Identification of factors affecting the ignition of forest fire is one of the basic tools for forest fire control and fighting actions. Zonation of fire risk ignition is one

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of the basic tools for forest fire control and action measures (Mohammadi et al., 2010).

The Mediterranean, one of the most flammable ecosystems in the world (Pausas et al., 2016), is one of the most endangered areas considering the wildfire (Catry et al., 2010, Pavlek et al., 2017). As a Mediterranean country, the Republic of Croatia (HR) (Fig. 1A-B) has a constant increase in the danger of wildfires, averaging over 1000 registered wildfires annually (Pavlek et al., 2017) and it is recognized as a country with high forest fire risk (Stipaničev et al., 2007). The HR especially has a pronounced risk of fire ignition in the coastal zone and on the islands (Pavlek et al., 2017).

This article presents a wildfire risk ignition result performed within the INTERREG Italy-Croatia PEPSEA (*Protecting the Enclosed Parts of the Sea in Adriatic from pollution*) project. The wildfire risk ignition index was derived using GIS-MCDA and acquired high-resolution (GSD<5 cm) UAV imagery data (RGB and multispectral). Furthermore, the risk perception about the dangers of wildfires was examined by a questionnaire. The main goal of the research was: (a) generate wildfire risk ignition index, as a part of a quantitative rating system, using the quickly definable parameters and GIS-MCDA; (b) propose fire prevention measures based on available resources of the study area with a basic aim of reduction of fire ignitions; (c) examine residents' awareness of a wildfire hazard. The research was carried out within the drainage basin of the Sali located on the island of Dugi Otok in HR.

2 STUDY AREA

The study area (235 ha) includes drainage basins of the Sali and Saščica bays located in the settlement Sali (Dugi Otok island, Croatia) (Fig. 1C). This landscape is dominated by abandoned agricultural (dominance of olive groves) areas with Aleppo pine forests and predominantly degraded holm oak forests.

3 MATERIALS AND METHODS

3.1 GIS-MCDA

Wildfire ignition index was derived using multicriteria GIS analysis (GIS-MCDA). The GIS-MCDA process was performed in six steps which included: (1) identification of problem and definition of the main goal, (2) determination of criteria and constraints, standardization of criteria (3), determination of weight coefficients (ponders) (4), criteria aggregation (5) and validation of created model (6) (Fig. 2) (Malczewski and Rinner, 2015, Domazetović et al., 2019).

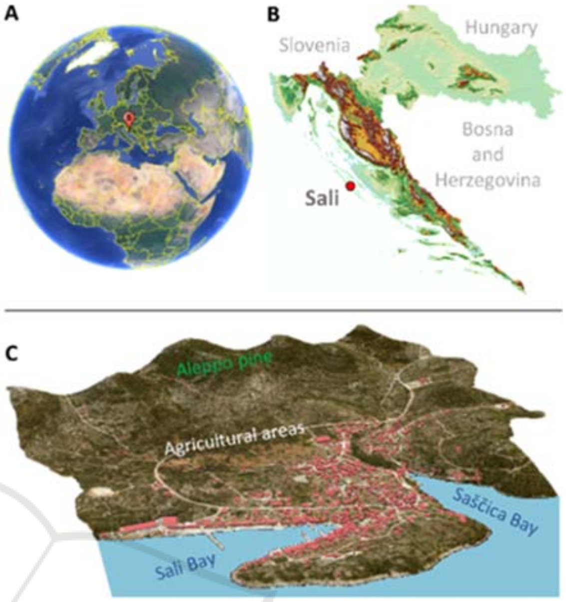

Figure 1: Location of Sali settlement.

3.1.1 Selection of Evaluation Criteria

All predisposing criteria of fire ignition were generated from the digital terrain model (DTM) and multispectral orthomosaic produced from high-resolution UAV imagery (Fig. 2). Four groups of continuous values criteria and two (boolean) criteria were used in the GIS-MCDA. These groups were (1) morphometric (slope, elevation, aspect, terrain ruggedness, topographic wetness index - TWI); (2) vegetation (land cover, normalized difference vegetation index - NDVI); (3) climate (insolation, heat load index - HLI); and (4) anthropogenic (distance from a road, distance from housing units) (Fig. 2).

Aspect affects the amount of sunlight the area receives and temperature. The study area is located in the northern hemisphere therefore southern slopes receive more sunlight. Elevation as an important physiographic variable affects the volume of rainfall, air humidity, vegetation patterns, and exposure to wind (Tiwari et al., 2021). Fire ignitions at higher elevations are generally less frequent due to lower temperatures and higher rainfall. Most wildfires occur on slopes between 0 and 20º. It has been found that the rate of wildfire ignition decreases with a higher slope (Swanson, 2018). Also, fire ignitions are more

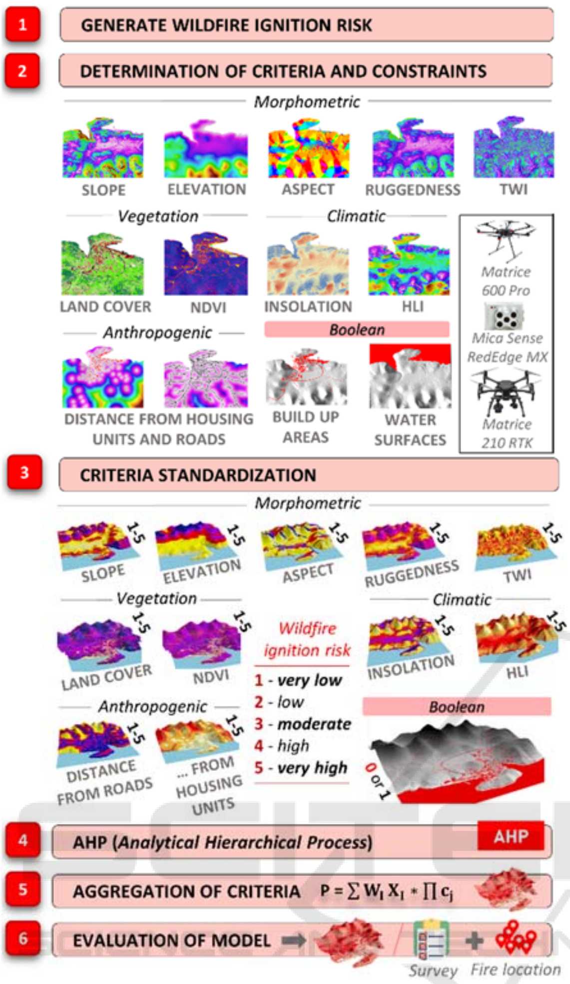

Figure 2: Methodological framework of wildfire ignition index generation using MCDA-GIS.

frequent at less complex (ruggedness) terrain. The topographic wetness index (TWI) is a measure of long-term moisture that uses the upslope contributing areas and slope to determine an index of moisture (Iverson et al., 2004). Higher values mean more tendency of an area to accumulate water (Mattivi et al., 2019) therefore these areas have a lower risk of wildfire ignition. Land cover is the key factor in the ignition of wildfire (Carmo et al., 2011). In a Mediterranean wildfire, risk should be higher for shrublands, pine stands and, grasslands than croplands and broadleaf forests. Normalized difference vegetation index (NDVI) can indicate higher vegetation dryness due to water stress which is a predisposing factor for fire occurrence (Maselli et al., 2003). Decreased values of NDVI in the Mediterranean can be linked to a higher probability of fire ignition during summer (Zipoli et al., 2000). Most fires are caused by human-related causes. Therefore, a closer distance from roads and housing units is linked to higher a probability of fire ignition (Gigović et al., 2018). The heat load index (HLI) is a parameter that takes into account the steepness of the slope when calculating the amount of solar radiation received by the slope. Area solar radiation tool was used to calculate the insolation across a study area. In both parameters, higher values indicate a higher risk of fire ignition. Using the geographic object-based image analysis (GEOBIA), built-up areas (I) and water surfaces (II) were extracted and used as (5) boolean criteria. These criteria represent the areas where wildfire can't occur.

3.1.2 Production of Digital High-Resolution Terrain Model (DTM) and Multispectral Orthomosaic Model

First, the high-resolution digital surface model was derived from aerial images collected with the unmanned aerial vehicle (UAV) (Matrice 210 RTK + Zenmuse X7-16mm) (Fig. $3_{1.1}$). The flight was performed in the DJI GSPro application. Aerial imagery was acquired using the double grid mission with front and side overlap of 80% (Fig. $3_{1.2}$). The flying height was around 200 m. Camera self-calibration was done in Agisoft Metashape 1.5.1. The image workflow process was done in five steps: (1) orientation of aerial imagery; (2) addition of ground control points (GCP); (3) creation of a dense cloud; (4) creation of a digital surface model (DSM); and (5) creation of a digital orthophoto (DOP). A total of 10 GCP were collected with the GNSS device Stonex S10 (Fig. $3_{1.3}$). Total RMSE of GCP was 4.3 cm. Since the terrain characteristics are important for deriving the criteria the final step involved generating a digital terrain model (DTM) through correction and filtering of the DSM. A correction was performed using the DSM2DTM algorithm (Chirico et al., 2020) which gradually removes anthropogenic and natural elements elevated above the bare ground and smoothes the final model by removing surface irregularities (Fig. 4).

Multispectral orthomosaic was derived from aerial images collected with UAV DJI Matrice 600Pro on which a Red Edge-Mica SenseMX camera was mounted (Fig. 4). Radiometric calibration of the multispectral camera using a calibrated reflectance panel (CRP) was done before and after each mission.

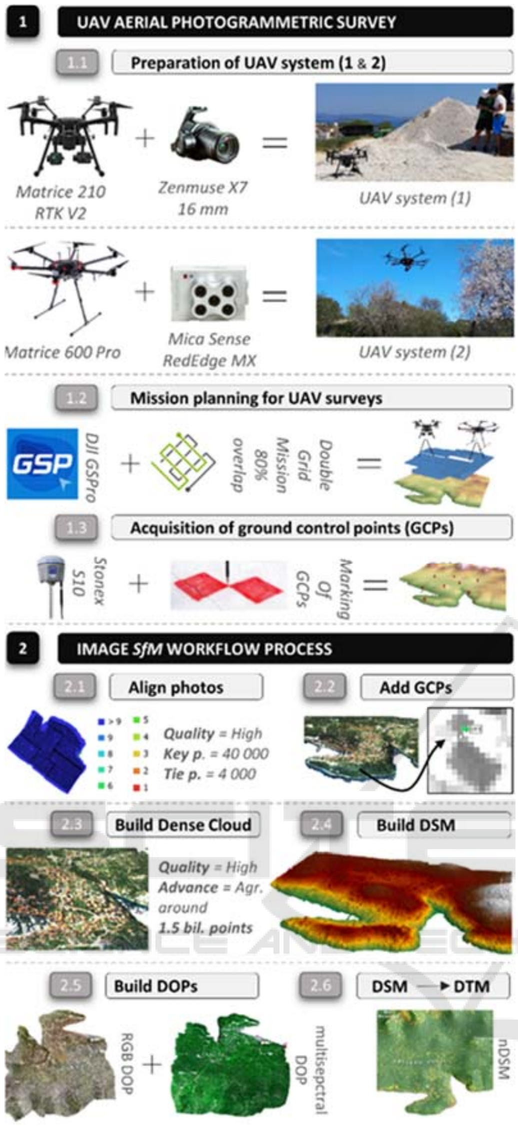

Figure 3: Derivation of DSM and multispectral orthomosaic model.

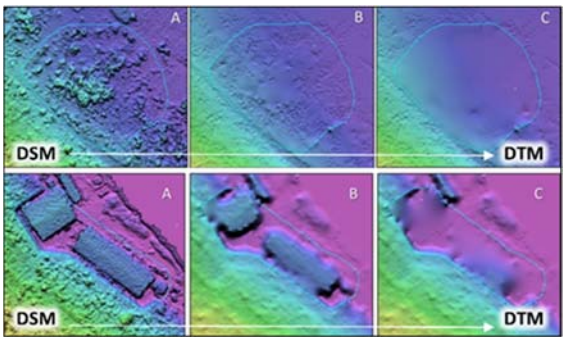

Figure 4: Conversion of DSM in DTM.

3.1.3 Standardization of Criteria

Standardization of criteria was conducted so their mutual comparison on the same numerical scale would be possible (Malczewski and Rinner, 2015). Standardization was performed with a numerical interval from 1 to 5 where class (1) referred to very low ignition risk, (2) low, (3) moderate, (4) high, and (5) very high. The criteria were standardized by combining two methods. The decision-maker standardization method (Domazetović et al., 2019) was used for criteria that were used in similar case studies. Jenks (natural breaks) classification method was used to optimize the arrangement of a set of values into "natural" classes for criteria where it is difficult to accurately determine class boundaries to the risk of a wildfire ignition risk.

3.1.4 Analytical Hierarchy Process (AHP)

Determination of weighting coefficients (Table 1) was performed using the AHP, which ranks the selected criteria according to their importance, i.e. the level of influence on the decision or model. The criteria were compared based on a scale of absolute values that represent the extent to which one criterion dominates over the other (Saaty, 2001). Furthermore, a wildfire risk model has been created where all criteria have the same weighting factor.

Table 1: Weighting coefficients (Woc) for wildfire ignition predisposing criteria.

	1	2	3	4	5	6	7	8	9	10	11	Woc
1	1	2	3	3	4	4	5	5	6	7	1	0.26
2	0.50	1	2	2	3	3	4	4	5	6	0.50	0.18
3	0.33	0.50	1	1	2	2	3	3	4	5	0.33	0.12
4	0.33	0.50	1	1	2	2	3	3	4	5	0.33	0.12
5	0.25	0.33	0.50	0.50	1	1	2	2	3	4	0.25	0.08
6	0.25	0.33	0.50	0.50	1	1	2	2	3	4	0.25	0.08
7	0.20	0.25	0.33	0.33	0.50	0.5	1	1	2	3	0.20	0.05
8	0.20	0.25	0.33	0.33	0.50	0.5	1	1	2	3	0.20	0.05
9	0.17	0.20	0.25	0.25	0.33	0.33	0.50	0.50	1	2	0.17	0.03
10	0.14	0.17	0.20	0.20	0.25	0.25	0.33	0.33	0.50	1.00	0.14	0.02
11	0.11	0.13	0.14	0.14	0.17	0.17	0.25	0.25	0.33	0.50	0.11	0.02

1 - land cover, 2 - distance from roads, 3 - aspect, 4 - area solar insolation, 5 - distance from housing unit. 6 - NDVI, 7 - HLI, 8 - slope, 9 - elevation, 10 - TWI, 11 – ruggedness

3.2 Collection of Vegetation Data

After multispectral orthomosaic production, the field (in-situ) vegetation samples were collected. Samples were acquired to make easier identification of vegetation species and to facilitate the process of deriving the land cover (LC) model. Samples were collected with a process divided into four steps (Fig. 5). A total of 390 samples were collected.

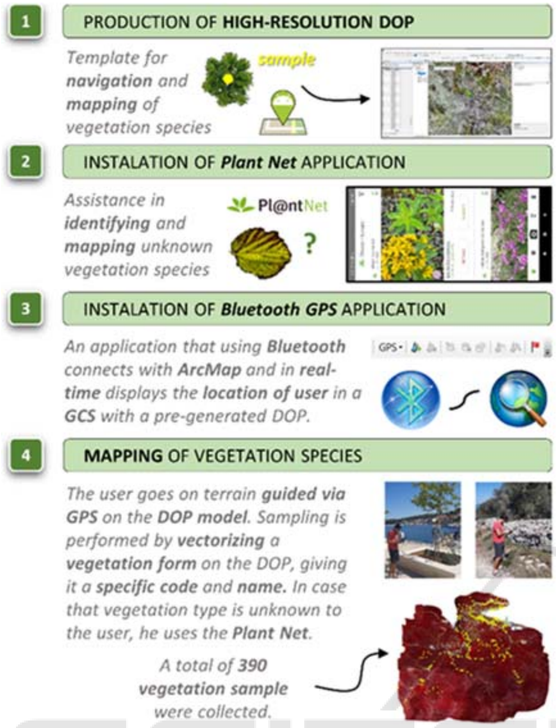

Figure 5: Methodological framework for collection of vegetation type data.

3.3 Wildfire Perception Analysis

The questionnaire was conducted in the period from 25 to 30 June 2020. It involved 38 respondents, which is 5% of the Sali population. In the project, the degree of potential 33 threats (including wildfire) to the natural environment was examined. Each questionnaire was conducted at a different address (Fig. 6). The type of sample was stratified, and the selection was random. Only adult citizens were selected.

Figure 6: Surveying respondents in Sali.

4 RESULTS AND DISCUSSION

4.1 Wildfire Ignition Index Models

Two models of ignition index have been derived (Fig. 7). In the first model weight coefficients were determined by the AHP method (Table 1). In the second model, all defined predisposing criteria had equal weighting coefficients (0.091).

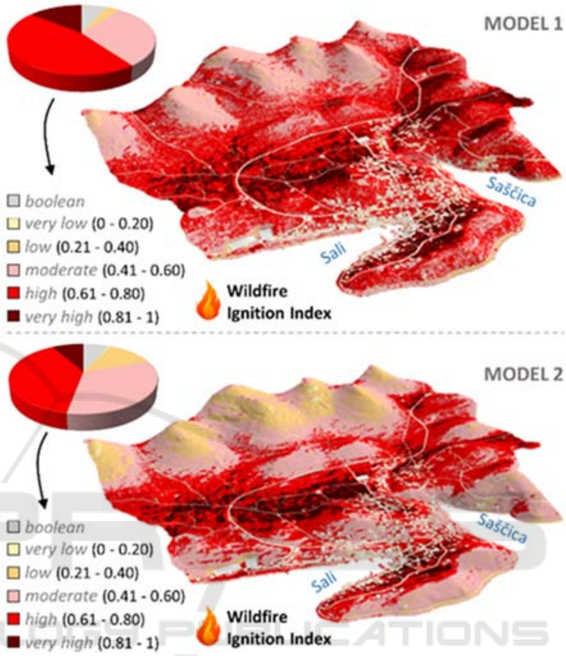

Figure 7: Derived models of wildfire ignition index.

In both cases, the models were classified using the equal interval method. The share of risk classes in the total studied area was calculated. In model 1, very high (5) and high (4) classes occupy almost 60% of the total area. The most risk area includes the neglected agricultural area and evergreen vegetation near the roads. In model 2, very high (5) and high (4) classes include 47% of the total area. However, the areas of the highest risk of fire ignition generally coincide with the first model.

Vegetation cover, dominated by Aleppo pine, maquis, other shrublands, and neglected agricultural areas, combined with other predisposing factors make the wider area of Sali very risky from fire ignition. This is not surprising given that the Dalmatian coast and islands are classified as the most endangered areas of wildfire ignition in HR. Therefore, we believe that the proposed framework, with minor modifications, can be applied in other Mediterranean countries that have a high risk of wildfires.

4.2 Proposed Measures for Wildfire Prevention

A system of surveillance cameras has been proposed with the aim of preventing and timely detection of wildfires. Within the study area, a binary visibility analysis was performed at two proposed locations where cameras could monitor very high risk (class 5) areas of wildfire ignition. In total, (model 1 + model 2) 39.21 ha of the study area has a very high risk of wildfire ignition (Fig. 8A).

The camera at a height of 10 m and the range of surveillance with a radius of 2 km was assumed. The installed cameras could monitor an area of 114.58 ha, of which 38.21 ha falls into the category of the very high risk (Fig. 8B), which means that 97.45% of this surface could be monitored from proposed locations.

Other measures are also proposed: raising the level of awareness about the dangers of wildfire; revitalization of abandoned and neglected agricultural plots; thinning and cleaning of forests and construction of narrow, cleared paths to achieve easier movement in the terrain in the event of a wildfire spreading.

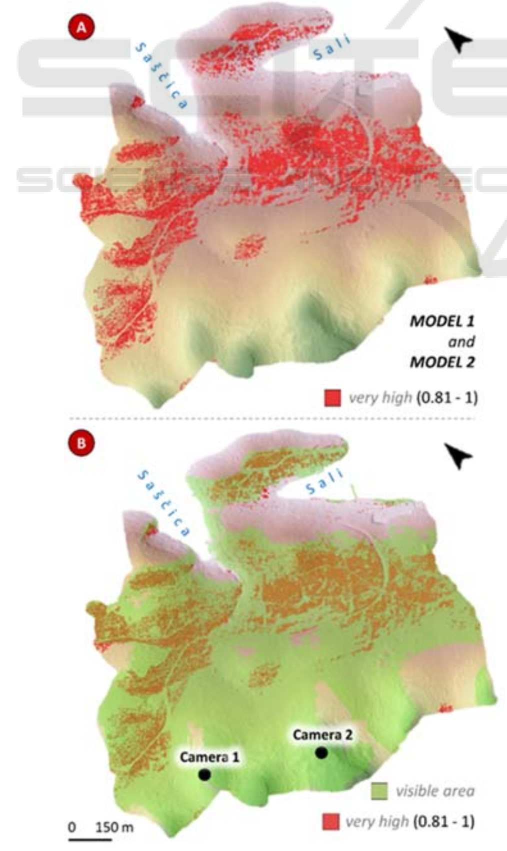

Figure 8: Coverage of very high (5) wildfire ignition risk area with surveillance camera.

4.3 Results of Risk Perception Analysis

The average age of 38 respondents was 41.36 years. In comparison to all analyzed threats to the natural environment of the settlement Sali, respondents (n=38) have evaluated the risk of wildfire ignition in 17th place out of 33 analyzed threats (Fig. 9). Respondents have rated the risk of wildfire ignition as moderate (3.00), while the standard deviation in responses was 1.16.

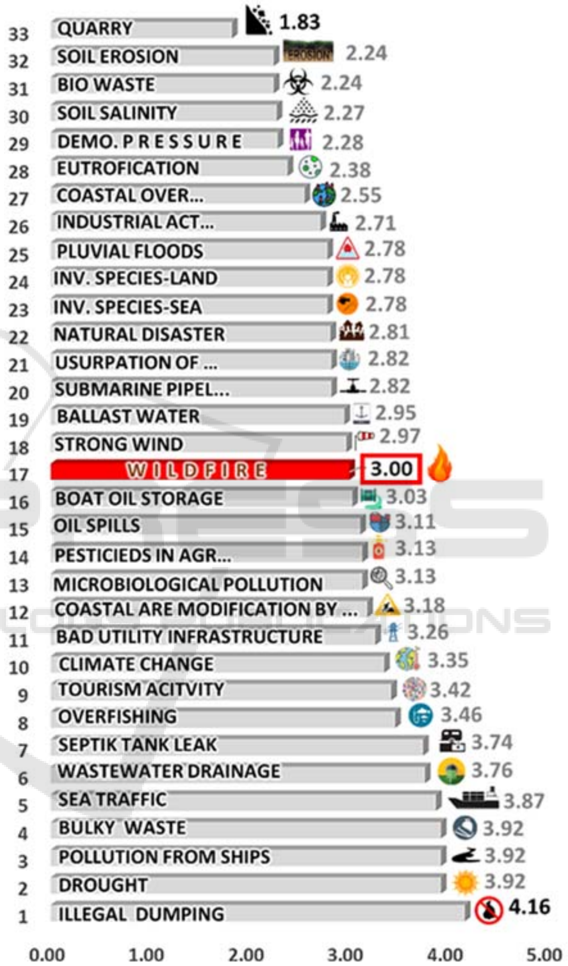

Figure 9: Perceptions of the threats to the natural environment of the Sali wider area.

Since official data about the historical location of wildfires in Sali settlement do not exist, respondents have detected recent locations of wildfires on the generated high-resolution DOP. It is necessary to point out that this is the main drawback of the research. Namely, there is a lack of wildfire occurrence data to accurately validate the model. Respondents were able to detect only a few recent wildfires. The difference between the models is difficult to determine since in both models all wildfire ignition locations are located within (4) high or very (5) high-risk classes. (Fig. 10).

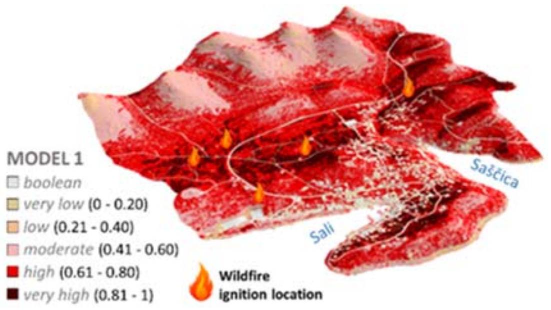

Figure 10: Detected locations of wildfire ignition.

5 CONCLUSION

High-resolution UAV imagery (RGB and multispectral) and GIS-MCDA were used to derive a wildfire ignition index. The wider area of Sali settlement can be considered as a high-risk area for wildfire ignition. Risk perception analysis showed that the respondents perceived wildfires as a moderate ($\bar{x}$=3.00) threat to their natural environment. A set of specific measures (surveillance cameras, forest thinning, etc.) has been proposed to prevent wildfire ignition. In future research, the presented methodology framework will be applied to a larger study area. The GIS-MCDA will be expanded with additional criteria (e.g. power lines, landfill sites) depending on the characteristics of the study area. Also, more wildfire occurrence data will be collected for model validation.

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