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High-Resolution Fire Risk Assessment and Management Planning in Peri-urban Areas via Coupling Geoinformatics, Machine-learning and Field Observations. Pilot Application in Attica Region, Greece.

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Abstract

Forest fires are among the most catastrophic natural hazards threatening human lives, properties and infrastructure. In recent years, these events keep rising both in frequency and severity mainly due to climate change, constituting fire risk assessment a critical priority. Scientific and technological bloom, during the last decades, offers the required contemporary tools and data for innovative frameworks on risk assessment leading to operational action-plans for prevention, during-the-event management and post-event mitigation actions. This study illustrates an integrated approach, for high-detail fire risk assessment (at building-block level) and management planning in peri-urban areas that are prone to forest fires, through coupling of geoinformatics, machine learning techniques and field observations. The methodology combines fire hazard modelling, vulnerability and exposure assessment. The fire hazard scenarios refer to spatiotemporal simulations of fire spread (generated by applying the adapted FlamMap model), based on the most probable ignition points for possible fire outbreaks (derived by the BEYOND's daily fire risk forecasting machine learning model modified for seasonal forecasts) and on the analysis of the meteorological regime (wind intensity, directions, frequency) of the area of interest. The vulnerability layer was produced by coupling population (density and age) and building characteristics, based on 2011 census data. The exposure layer refers to land value (€/m2) and works as an indicator for the qualitative estimation of possible economic effects in the study area, in case of a fire event. The high-risk areas resulting from the fire risk map, were visited in-situ for validation and update if/where needed. Throughout the field campaign, important areas and critical points (high-risk buildings, traffic congestion areas, population gathering areas etc.) were recorded and included in the mitigation suggestions and management planning. This integrated and iterative process (office-to-field and field-to-office) forms the basis for the synthesis and recommendation of effective and operational mitigation actions, protective measures and coping/management strategies. The methodological framework is developed by BEYOND Centre of EO Research & Satellite Remote Sensing (National Observatory of Athens) and applied in Vravrona, Chamolia and Porto Rafti settlements (pilots) of the Attica Region in Greece, under the project "Seismic, Fire & Flood Risk Assessment in Attica Region, Greece" funded by Attica Region.

1. Introduction

Climate change has led to increases in the vulnerability of forest ecosystems, as it is a major contributor to the rise of forest fires and tree species' inability to adapt to the intensity and frequency of summer droughts (Prodromou et al., 2020). Peri-urban zones, mainly due to uncontrolled urban-sprawl and lack of proper planning, are more vulnerable to wildfires leaving people's lives and properties, as well as the surrounding natural environment and ecosystem, exposed to increased disaster risk. Attica region, Greece, where the country's capital is located and almost half of the country's population along with critical infrastructure, is characterized by a plethora of peri-urban settlements surrounded by intense morphological relief with steep slopes, and with pine forests being the dominant land cover type. Moreover, the region's rich natural landscape results in the intrusion of dense forest parts inside a significant number of settlements. Fire risk assessments are necessary to reduce the impact of natural disasters and support decision making (protective measures, mitigation actions, emergency evacuation procedures, etc.). A cornucopia of fire risk assessment methodologies can be found in scientific literature. The Analytic Hierarchy Process (AHP) is highlighted among them and is usually combined with Geographic Information Systems (GIS) (Gheshlaghi et al., 2019). Several studies also used satellite imagery and GIS (Kanga et al., 2014), fuzzy approaches (Erdin and Çağlar., 2014), artificial neural networks (Goldarag et al., 2016) and LIDAR data (González-Olabarria et al., 2012). The methodology presented in this work, is an integrated approach for fire risk assessment and management planning in peri-urban areas that are prone to forest fires, through machine learning techniques, geoinformatics and field observations. It was developed under the umbrella of the national research project "Seismic, Fire & Flood Risk Assessment in Attica Region, Greece", led and coordinated by the National Observatory of Athens (NOA) and specifically the Centre of EO Research & Satellite Remote Sensing – BEYOND, of the Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing (IAASARS).

2. Material and Methods

2.1. Study Area

The study area (Figure 1), concerning the fire risk assessment, includes the settlements of Vravrona, Chamolia and Porto Rafti of the Municipality of Markopoulo Mesogaia. It has an average altitude of 140 m and borders the Athens International Airport, the settlements of Markopoulo Mesogaia, Artemida and Kouvaras in the wider area of Mount Merenda (614 m), while it is limited from the east by the Southern Gulf of Evia. The area is mainly covered by hardwood vegetation and coniferous forest (~ 50% of the total surface), fruit trees, meadows, vineyards and natural pastures (~ 32.5% of the area) and urban fabric, non-irrigated arable land, bare rocks, etc. concerning the 17.5%. It is worth mentioning the cultural and environmental importance of Vravrona as it brings together an archaeological monument and a NATURA region.

Figure 1- Study Area.

2.2. Methodological framework

The approach (Figure 2) is a fusion of the research team's expertise (EMSN041, 2017[20]; EMSN059, 2019[21]; FireHub[22]; (Apostolakis et al. 2021; Girtsou et al. 2021) and of extensive literature review (Darvishi et al. 2020; Gheshlaghi et al. 2019). To assess the fire risk, were taken into account: i. Selected fire hazard scenarios, ii. The composite spatial layer of fire vulnerability and iii. The spatial layer of land values. According to the fire risk assessment map that has been produced, targeted high risk areas were visited for validation/modification purposes and further important observations were recorded for the development of management plans.

Figure 2- Flowchart of the methodology.

3. Fire Hazard

3.1. Analysis of wind characteristics

For the analysis of wind characteristics of the study area, wind velocity and direction data were derived by the ERA-5[23] mission (from 1990 to 2020) as well as by the METEO[24] platform (from 2013 to 2020). The two aforementioned data sources were combined through the "Q-Q plot mapping" methodology so that the gridded ERA-5 data follow the same distribution as the point observations from the meteorological station of Porto Rafti (Figure 3).

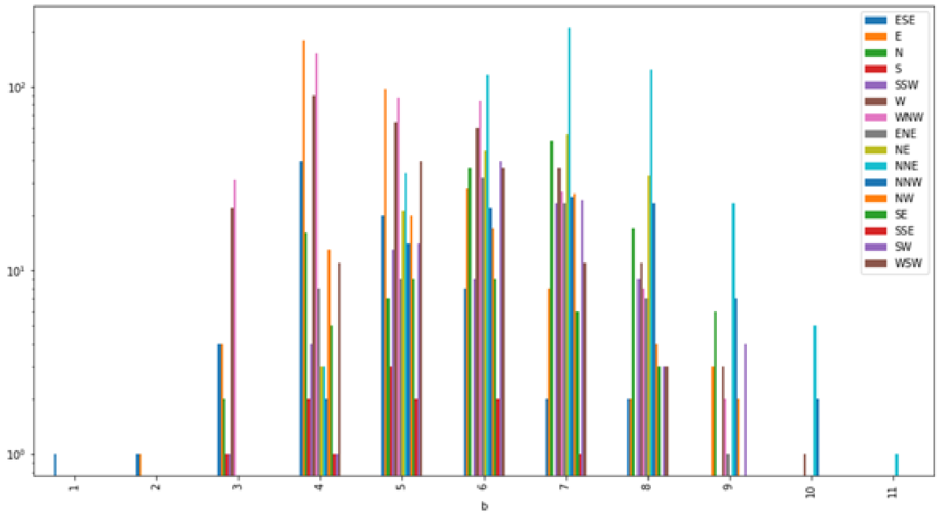

Figure 3- Wind intensity per wind direction in the study area.

[20] https://emergency.copernicus.eu/mapping/list-of-components/EMSN041
[21] https://emergency.copernicus.eu/mapping/list-of-components/EMSN059
[22] http://ocean.space.noa.gr/FireHub
[23] https://climate.copernicus.eu/climate-reanalysis
[24] https://www.meteo.gr/

3.2. Determination of fire ignition points

For the determination of the fire ignition points several datasets have been utilized such as the DEM[25] and its derivatives (aspect, slope), ERA-5 and METEO data related to temperature, wind (velocity, direction), rainfall, along with the adjusted Corine Land Use / Land Cover[26] product and other satellite based spectral indices (e.g. NDVI, EVI). The selection of ignition points is critical to simulate the start and spread of fire scenarios. For this purpose, the Machine Learning model of daily fire risk forecasting, which was developed by the BEYOND Centre, was utilized (Apostolakis et al. 2021). The resulting output (Figure 4) is a set of high fire ignition probability cells (red), based on the model's knowledge gained through the correlations of the input variables with past fire events. Based on these results and the analysis of the worst case wind scenarios in the area, the ignition points were combined with the respective wind intensity and direction that could possibly harm residential areas.

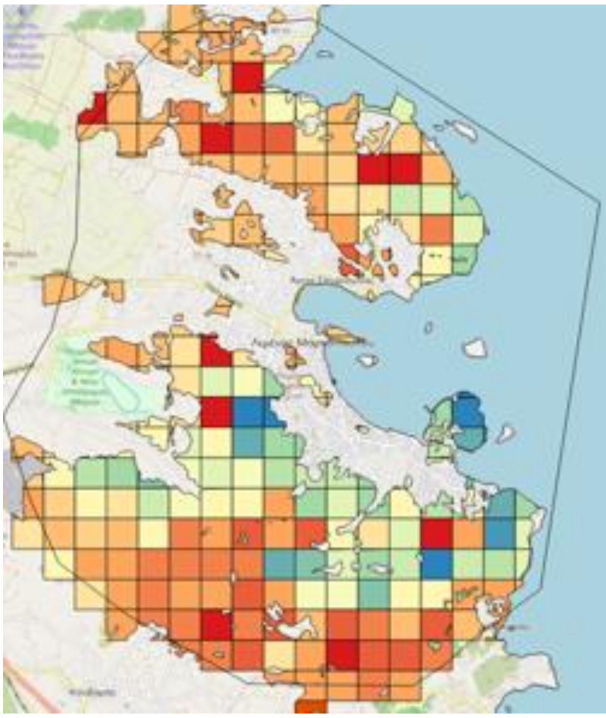

Figure 4- Fire ignition probability cells.

3.3. Fire spread simulations

FlamMap[27] is an open source application that runs in a 64-bit Windows Operating System environment and simulates possible fire behaviour characteristics, such as the rate of spread and its intensity under constant environmental conditions at a given time. By adapting FlamMap in a Linux environment, it was possible to simplify the number of input layers from 8 to 5 as follows: DEM, Aspect, Slope, Fuel and Density. The elevation, the aspect and the slope layers were created through GIS. In this study, the surface fuel, the moisture content of the fuel and the vegetation characteristics of the area, were determined by using an adjusted land use/cover map through GIS, high resolution satellite imagery and photo-interpretation. Each fuel model was assigned to a vegetation type as a combination based on the works of Kalabokidis et al. (2013) and Scott & Burgan (2005). The layer of Density represents the amount of available fuel per unit volume of the surface covered by the canopy space. It is an important factor that affects the probability of starting a fire and the rate of crown fire spread (Johnston, 2012). For the area of interest, this layer was categorized into 4 different classes, concerning the estimated timber volume of the available fuel per m^3.

[25] https://www.ktimatologio.gr/
[26] https://land.copernicus.eu/pan-european/corine-land-cover
[27] https://www.firelab.org/project/flammap

Various hazard scenarios were simulated, based on extensive combinations of ignition points and wind characteristics (direction, speed). Finally, all these scenarios were co-assessed and combined, leading to 4 fire hazard assessments, one per ignition area (ignition areas refer to groups of ignition points depending on their place and impact on the study area).

3.4. Vulnerability

For the estimation of the total vulnerability of the study area, the generation of the population density/age and the building materials datasets from the Hellenic Statistical Authority[28] was a necessary prerequisite. For the generation of the above mentioned datasets, the 2011 Census data were processed along with the support of very high resolution satellite images and orthophoto maps.

3.5. Exposure

The economic exposure layer was generated by using land use and land values data (€ / m^2), very high resolution satellite images and orthophoto maps. These data were obtained from the Ministry of Digital Government[29] and contained polygons with the land value zones. In order to handle areas with no information on land value, polygons of these areas were created and values were manually assigned, through an exhaustive analytical process were the neighbouring land values and the photo-interpretation of high-resolution satellite images and orthophotos were assessed and combined.

3.6. Fire risk

For the risk assessment, the datasets of a) hazard, b) total vulnerability and c) exposure, derived in the previous stages of the methodological approach were fused. Each one of the 4 spatial layers concerning fire hazard were combined with the layer of total vulnerability and economic exposure and the final risk maps were produced for the area of interest.

4. Results

4.1. Fire risk maps

Fire risk maps (e.g. Figures 5, 6) depict the fire risk per building block according to the socio-economic characteristics, the resistance of the buildings and the spatio-temporal spread of fire. Two fire risk maps were produced for each one of the 4 fire ignition areas, with the former presenting the fire risk and the population gathering areas (social and cultural sites, such as schools, museums, etc.), while the latter the fire risk and the essential infrastructure and services of the area (road network, fire brigade, etc.). It is emphasized that building blocks that are shown in red and orange colour are of the utmost importance and priority, as these are of the highest risk during the 1st and the 3rd hour of the fire spread respectively.

[28] https://www.statistics.gr/
[29] https://www.minfin.gr/

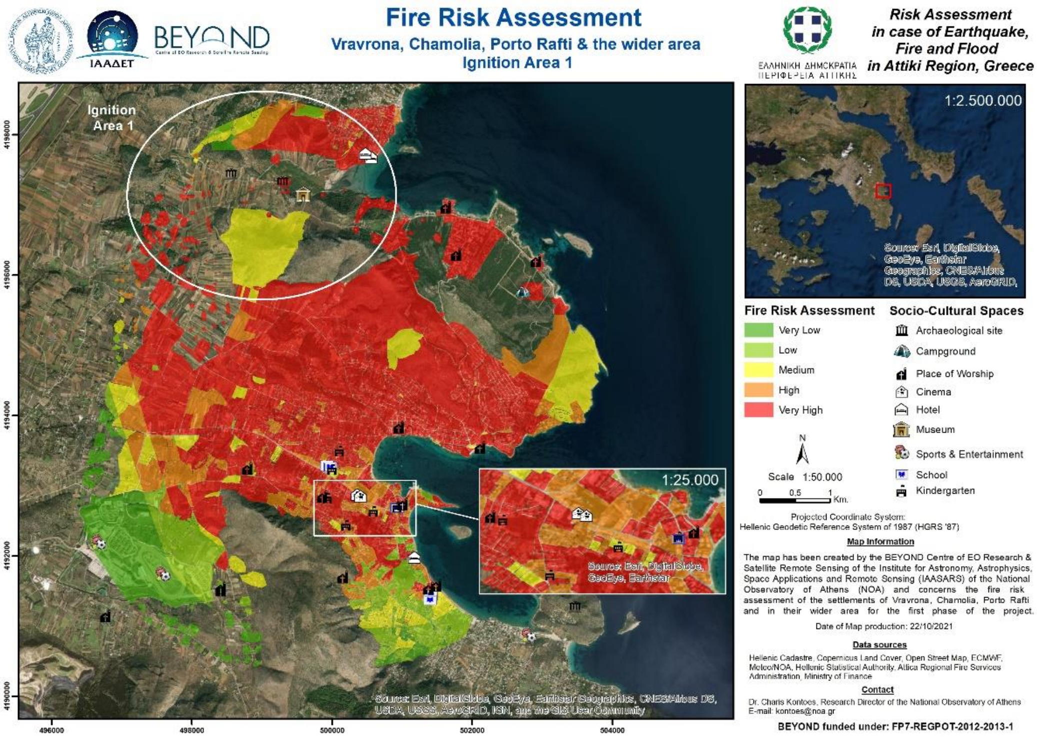

Figure 5- Fire risk assessment for the ignition area 1 (Socio-cultural Places).

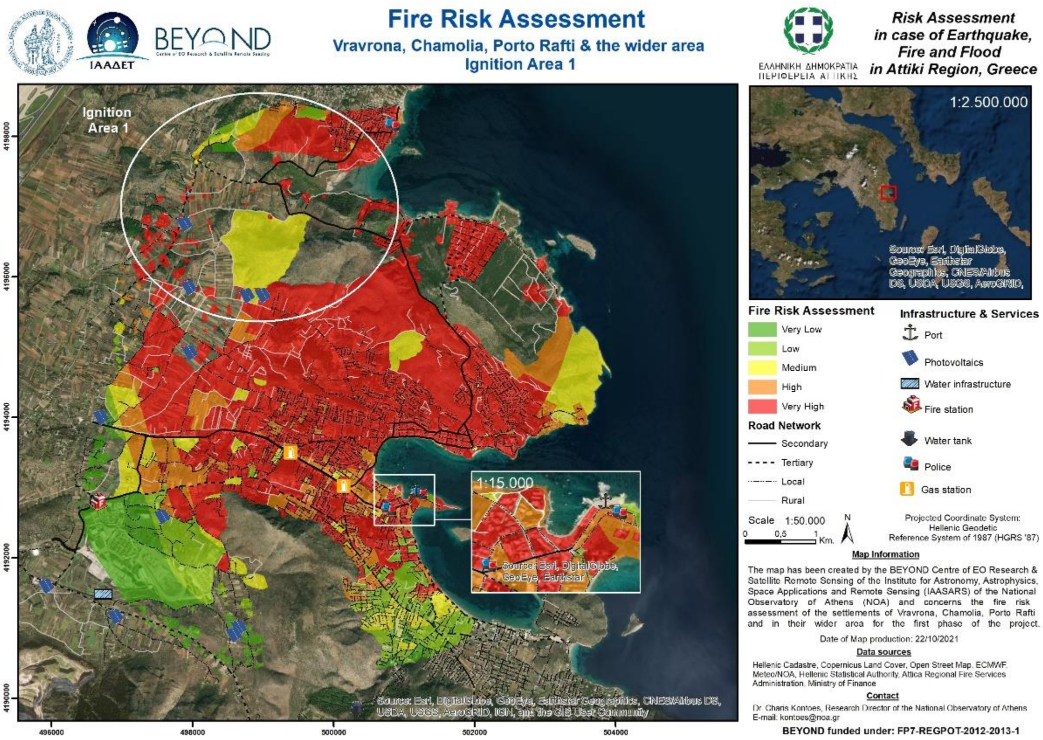

Figure 6- Fire risk assessment for the ignition area 1 (Infrastructure & Services).

4.2. Field observations/Management planning

The study area was divided into sectors for the optimization of field work and the proposed management plans. These sectors were selected according to the produced risk maps and autopsies as the most prone to fire in the area. Priority in each sector was high population gathering areas such as schools, hospitals, nursing homes, etc., as noted in the fire risk maps presented in the previous section. During the field-work, several critical characteristics of the area were recorded like for example road dead ends, high slopes, suitability of roads, possible escape routes, existence of fire protection infrastructure, properties that are surrounded by trees, yards and roofs covered by pine needles or waste, etc. All these contributed to the creation of evacuation maps (e.g. Figure 7) for the defined ignition areas, with assembly points in case of emergency and escape routes. Moreover, proposed fire protection zones were also mapped as an extra measure of fire protection followed by a list of management suggestions such as the placement of fire alarm and protection systems and cleaning of roads and properties.

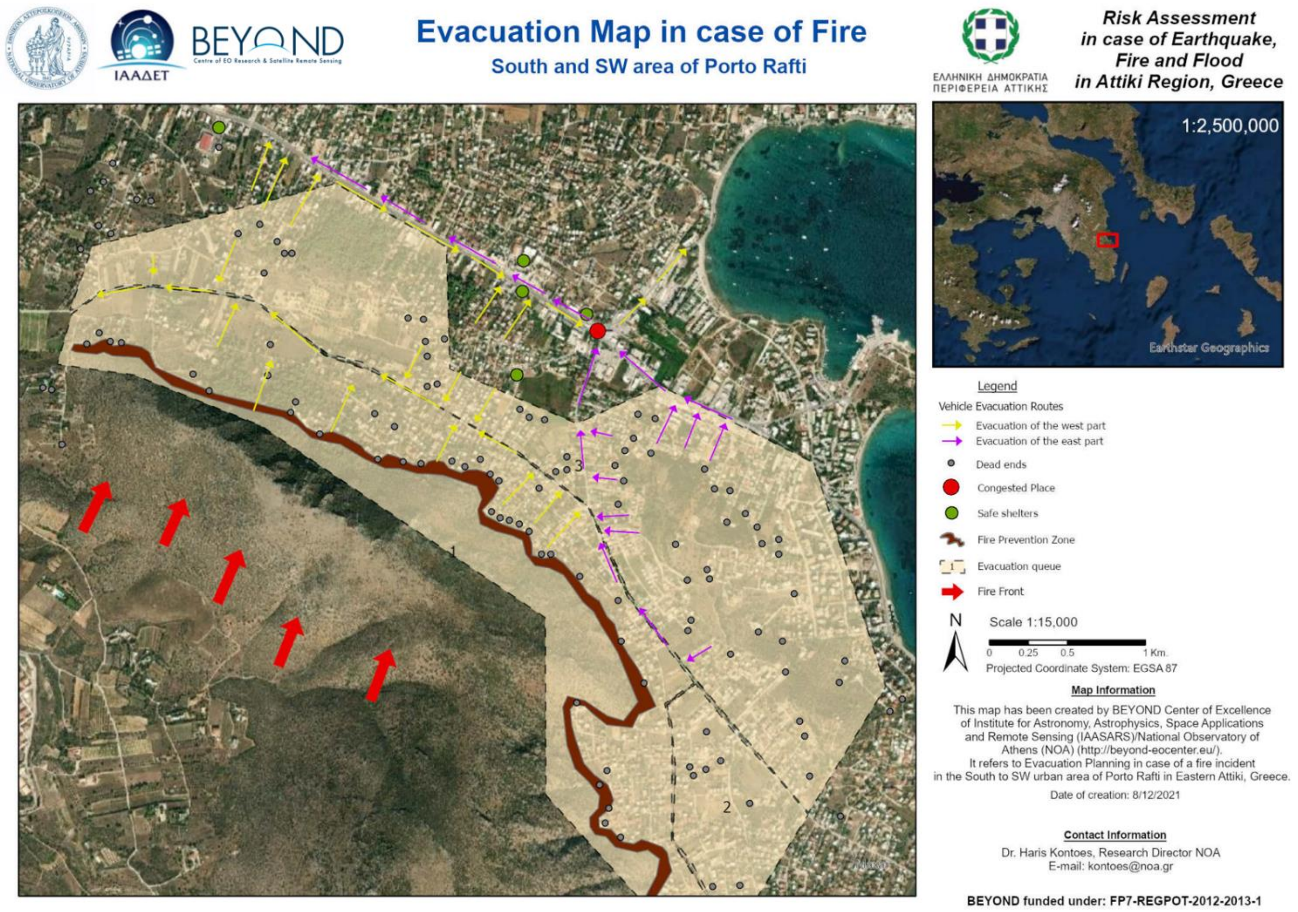

Figure 7. Example of evacuation map.

5. Conclusions

Demographic data, such as population density and age distribution per building block and the buildings' fire resistance characteristics yielded the foundation for a robust approach to estimate the fire vulnerability of each block. In addition, the combination of vulnerability with land values (as a level of economic exposure) composed a comprehensive socio-economic assessment of building-blocks in the event of fire. The combination of the above with the numerous simulations of fire spatio-temporal propagation scenarios led to the overall fire risk assessment of the study area. The two settlements of augmented fire risk, identified through the risk maps and distinguished during the field campaign are the eastern part of the settlement of Hamolia and the settlement of Vravrona (mainly south of Vravronos Avenue on the slopes of the hill). Both of these areas are in direct contact and within the forest, which penetrates into the properties and is adjacent to roofs, power cables, etc. The road network of the areas consists of poor quality roads with significant slopes and many dead ends. In addition, the roads are covered by pine needles, dry side grasses and many of them are used as parking lots. No, or poorly maintained, firefighting and fire protection systems were recorded in those areas. Finally, it is crucial that all civilians take the necessary precautions (e.g. cleaning their roofs and yards from foliage) and follow the instructions of the responsible actors in combination with the development of the appropriate fire preventive measures and fire protection infrastructure.

The presented methodology signifies the importance of coupling innovative technologies (ML modelling, geoinformatics, etc.) and contemporary data (e.g. EO data) with field-work, in service of human life and infrastructure protection. It is an integrated approach of fire risk assessment and management at a very high-resolution level of analysis (building-block), that is produced for Greece and sets a precedent for the first time.

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