IDENTIFICATION OF POTENTIAL GEOHAZARD AREAS IN WESTERN MACEDONIA BASED ON SEISMIC DATA

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ABSTRACT

Western Macedonia is located within a seismically active zone of the Balkan Peninsula, characterized by complex geological, tectonic and seismotectonic area of active intra-plate tectonics and history of moderate to strong earthquakes.
The identification of potential areas prone to geohazards is therefore essential for seismic hazard assessment, land-use planning, and risk mitigation. This study uses seismic data to delineate potential geohazard areas through spatial and statistical analysis.

Keywords: seismic data, GIS, geohazard ś

INTRODUCTION

Geohazards associated with seismic activity represents a significant threat to population, infrastructure, and economic development. Earthquakes may lead not only to direct ground shaking damage but also to secondary effects such as surface faulting, landslides, and ground deformation. Identifying areas with elevated geohazard potential is therefore a critical step toward effective risk mitigation, urban planning, and the implementation of appropriate building regulations [3]. In regions such as Western Macedonia, where settlements and critical infrastructure are often located near active tectonic structures, this need is particularly pronounced.
Seismic data constitute a fundamental source of information for investigating seismotectonic processes and assessing geohazard potential. Earthquake catalogs provide detailed records of event location, magnitude, depth, and temporal occurrence, allowing

for the analysis of spatial and temporal seismicity patterns. Statistical analysis of seismicity, including frequency–magnitude relationships and spatial density methods, can reveal zones of increased stress accumulation and enhanced seismic activity [15]. When combined with spatial analysis tools, these methods enable the delineation of areas that may be more susceptible to future seismic events [10].

The aim of this study is to identify and delineate potential geohazard areas in Western Macedonia based on the systematic analysis of seismic data. By applying spatial density analysis using Kernel Density Estimation (KDE), statistical seismicity parameters, and Geographic Information System (GIS) techniques, this research seeks to identify areas of increased geohazard potential.

STUDY AREA

The western part of the Republic of North Macedonia, which is defined as the West Macedonian tectonic zone, is an internal massif located in the northeastern part of the Dinaric-Hellenides. To the west it borders the Mirdita zone (on the territory of Albania), it also partially borders the Cukali zone (in the Debar region). Its eastern border, towards the Pelagonia massif, is a regional fault zone [7].

The region is characterized by a complex geological and tectonic setting resulting from the interaction of the Eurasian and African plates with numerous active and potentially active faults. Western Macedonia encompasses several major tectonic units [9], including grabens, horsts, and fault-bounded basins, which contribute to its heightened seismic activity.

The seismotectonic framework of the region is further constrained using the receiver function method, revealing significant lateral variations in crustal thickness and internal structure [12, 13].

The region is intersected by numerous faults, but some of them have high seismicity defining them as active faults: Sharplanina, Elbasan-Debar, Pelister and Peshtansko-Petrinski, Figure 1.

These faults are predominantly of the normal slip type, which reflects the extensional regime of the area. They also represent seismic sources with clearly expressed temporal and spatial continuous seismicity [8]. The geological base consists of a combination of metamorphic, sedimentary and volcanic units, with localized zones of weak sediments in basins that can intensify ground shaking during seismic events [2]. Since the concentration of earthquakes is in the entire region under consideration, we say that it has the characteristics of a true seismic zone.

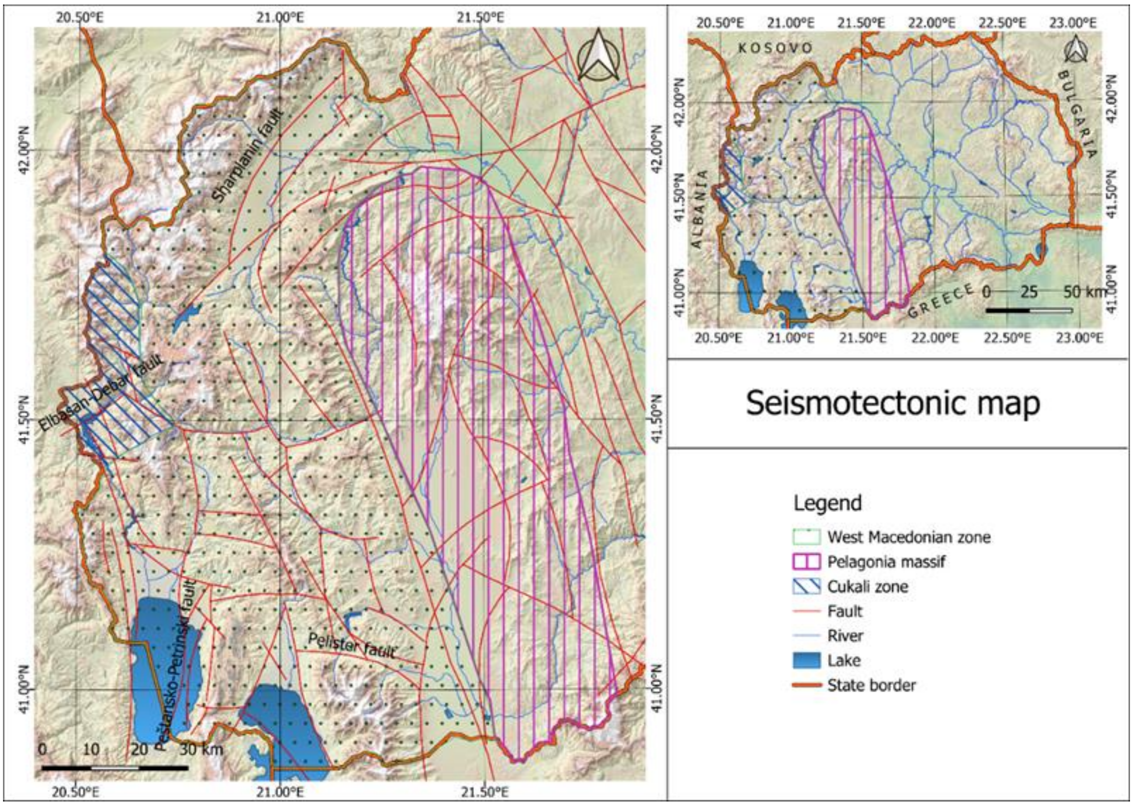


Figure 1. Seismotectonic map of the study region

HISTORICAL AND INSTRUMENTAL SEISMICITY

Seismicity defines the spatial distribution of historical and contemporary earthquakes in a given area over time. The integration of historical and contemporary earthquake data is essential for seismological research. Historical records document catastrophic earthquakes, while modern data provide continuous seismic records and enable precise analyses. This connection facilitates a more comprehensive understanding of the recurrence of strong earthquakes, the identification of active faults, as well as the mapping of areas exposed to seismogeological effects.

The territory of Western Macedonia is characterized by a complex tectonic structure. The interaction of block structures results in pronounced seismicity, manifested through very weak to strong earthquakes, with magnitudes ranging in the interval $0.1 \leq Mw \leq 6.7$. Earthquakes with epicenters located in Western Macedonia are grouped into several epicentral areas, which spatially belong to the Western or Drim, seismogenic zone [4, 9]. Most of them are located entirely on the territory of Western Macedonia, while some extend partially across its borders (they represent border epicentral areas). Epicentral areas with high seismic activity include Debar, Peshtani–Ohrid–Struga and Bitola regions, where the recurrence of earthquakes that produce seismogeological effects is observed. The remaining areas are characterized by moderate to low seismic activity, Figure 2.

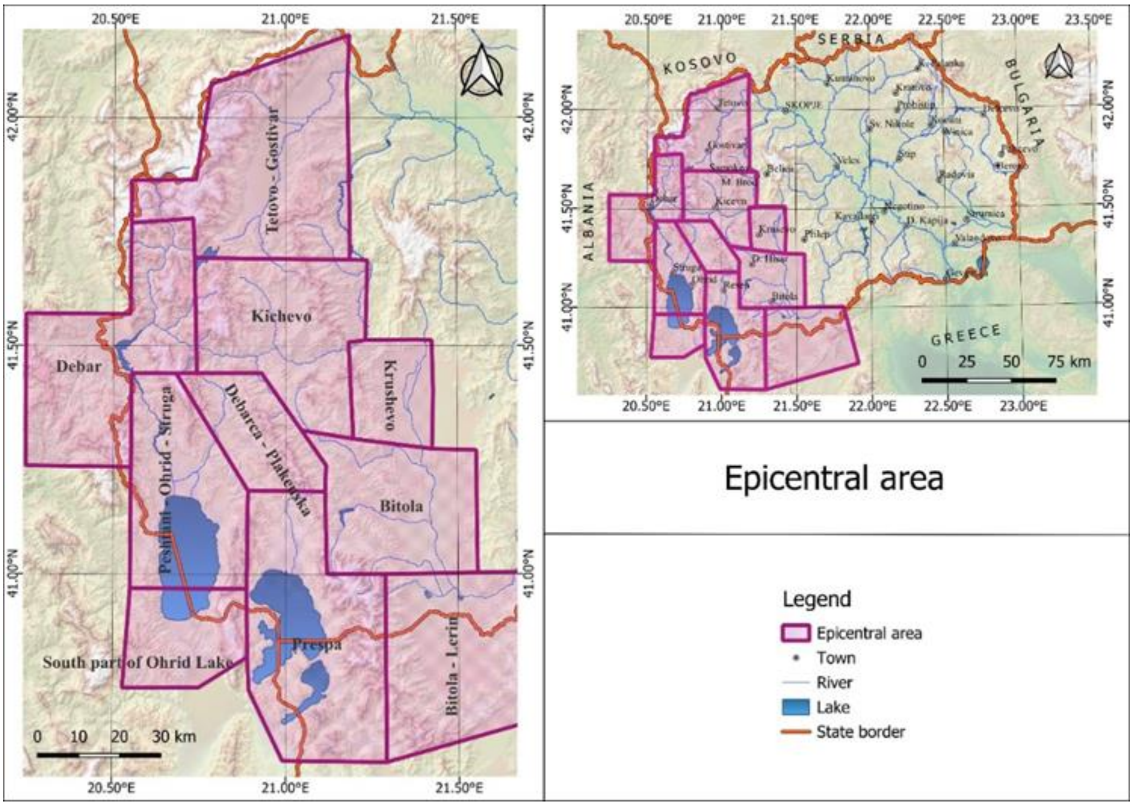


Figure 2. Epicentral areas in Western Macedonia

Faults responsible for seismic activity with magnitudes ML ≥ 5.0 (or moment magnitudes Mw ≥ 5.0), classified as active and representative faults for the epicentral areas to which they spatially belong, include the Shar Planina Fault, the Elbasan–Debar Fault, the Peshtani–Petrino Fault system, and the Pelister Fault [4].

Considering both historical and contemporary seismicity, it is evident that epicentral areas with increased seismic activity are most often associated with earthquakes capable of generating pronounced seismogeological effects. For example, in the epicentral area Peshtani–Ohrid–Struga, significant events include the historical earthquake of 527, as well as more recent earthquakes in 1911 and 2017. Similarly, in the epicentral area Debar, notable earthquakes occurred in 1967 and 2020. In the epicentral area Bitola, the historical earthquake of 1858 and the event of 1994 are particularly significant.

Historical seismicity for the period 525–1900 is characterized by seven earthquakes, all with magnitudes Mm ≥ 5.0 (Mm—magnitude determined from macroseismic data), while contemporary seismicity covering the period 1901–2023, includes a total of 12 736 earthquakes with magnitudes ranging from 0.1 ≤ Mw ≤ 6.7. Spatial distribution of seismicity for the period 1901-2023 are presented in Figure 3.

Figure 4, illustrates the number of earthquakes with magnitude intervals of one unit each.

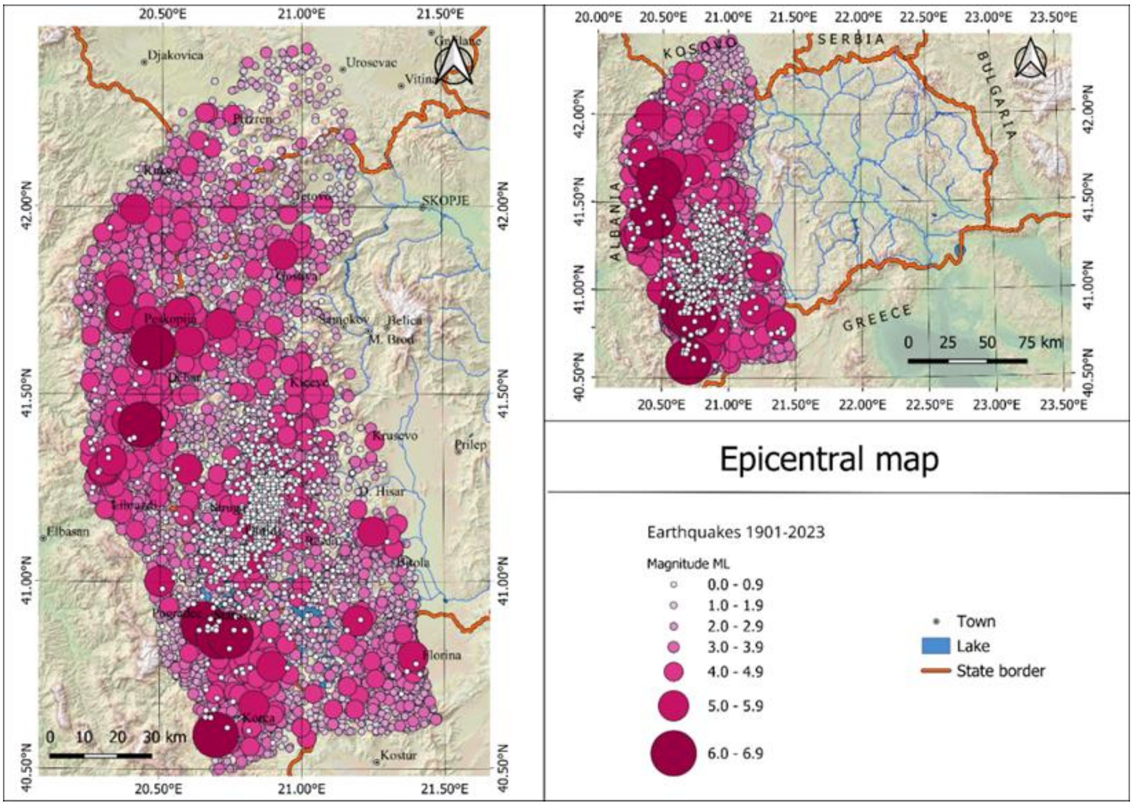


Figure 3. Epicentral map of the study region

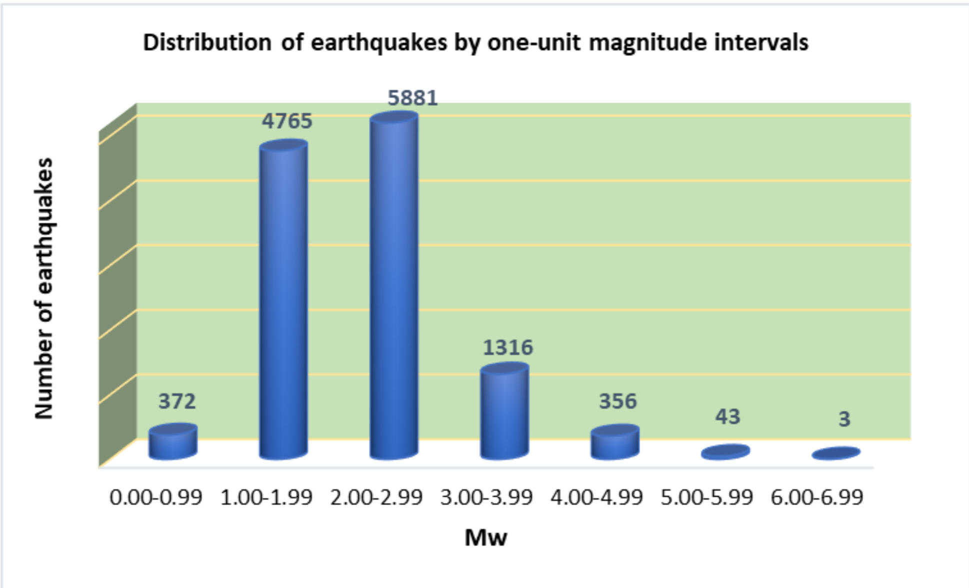


Figure 4. Distribution of earthquakes by one-unit magnitude intervals

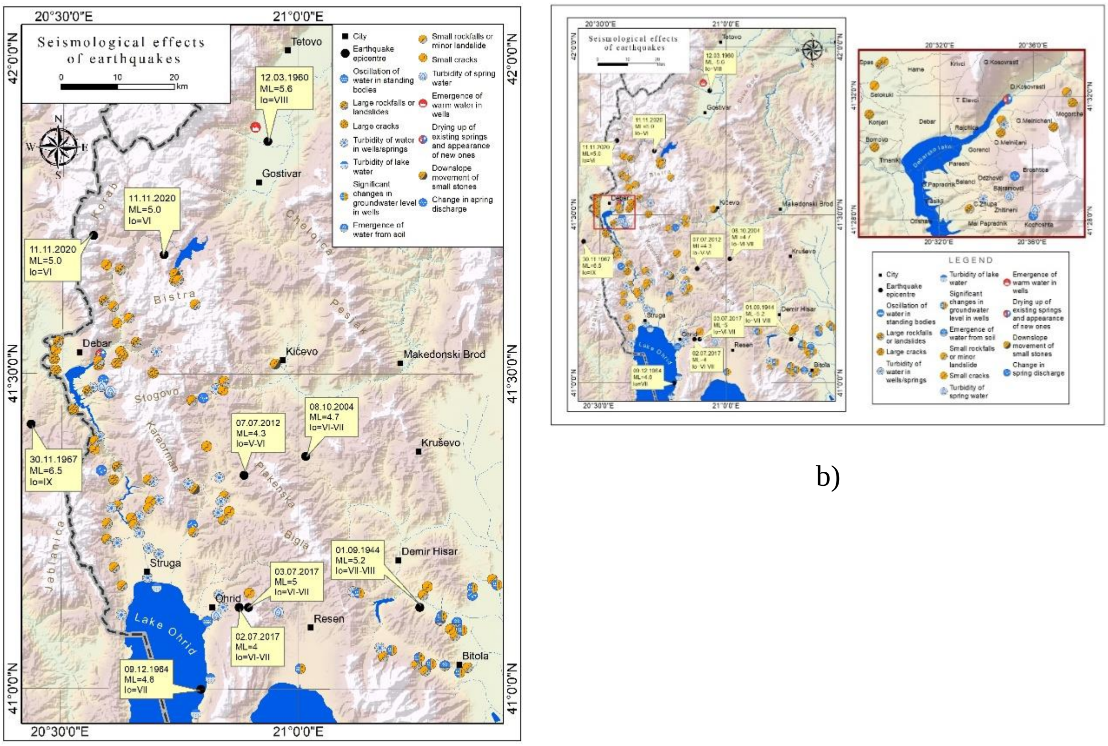
METHODOLOGY

The assessment of seismic geohazards in the study area was carried out using an integrated methodological approach that combines seismological, geological, and spatial analyses. The analysis is based on the application of the frequency-magnitude relationship, spatial density analysis and multi-criteria evaluation in GIS.

Seismological data includes analysis of an earthquake catalog covering the period 1901–2023 [5], contains historical and contemporary (instrumental) events. Based on this dataset, the Gutenberg–Richter relationship [6] was applied to estimate the parameters a and b, as well as the maximum expected magnitude (Mmax), [14]. The b-value was calculated using the maximum likelihood method, proposed by [1], considering only events above the magnitude of completeness (Mc), in order to ensure the reliability of the frequency–magnitude distribution. The spatial variation of b-values was subsequently interpreted as an indicator of relative stress accumulation within the crust.

To estimate the spatial distribution of seismogeological environmental effects caused by earthquakes, a Kernel density estimation (KDE) approach was applied using data on documented seismogeological effects. These include surface ruptures, landslides, liquefaction, and other ground deformation phenomena associated with earthquakes. KDE was used to transform the observed effects into a continuous density surface, highlighting areas with a higher concentration of such effects. The resulting map represents the spatial probability of seismogeological effects from observed seismicity [15, 16]. The final phase of the analysis involved the integration of several thematic layers within the GIS: (i) spatial distribution of densities obtained from KDE, (ii) geological features of the terrain, (iii) isoseismic patterns and their sensitivity, and (iv) distribution of seismically sensitive soils. By overlapping and combining these layers, it was possible to identify areas with different levels of seismic geohazard. As a result, the study area was classified into three categories: high, moderate, and low seismic geohazard.

The analyzed earthquakes with seismogeological effects are presented in Figure 5 (a and b).



b)

a)

Figure 5. Earthquakes with seismogeological effects of nature. a) Seismogeological effects of Western Macedonia (left figure); b) Seismogeological effects of the strongest earthquake in Western Macedonia, Debar 1967 (right figure)

RESULTS

This section presents the results of the analysis of macroseismic data with seismogeological effects, and earthquake epicenter distributions for the purpose of identifying geohazard prone areas in Western Macedonia.
It can be observed that the entire study area is characterized by a widespread distribution of earthquake epicenters, indicating that seismic events of different magnitudes—from minor to strong—have occurred throughout the analyzed period, Figure 3. This pattern reflects a persistently high level of seismic activity, confirming that the area can be classified as highly seismically active.
This spatial pattern is consistent with the results obtained from the Kernel Density Estimation (KDE), which highlights zones of increased concentration of seismic activity.
The Kernel Density Estimation (KDE) analysis revealed a non-uniform spatial distribution of seismogeological effects, with clearly defined zones of increased density. The highest density values are concentrated in specific areas, indicating spatial clustering of earthquake-induced environmental effects. These zones correspond to areas with repeated occurrence of seismogeological effects and represent the most affected parts of the study area, Figure 7.
Furthermore, the relatively low b-value (b = 0.62 ± 0.01) shows us that earthquakes of higher magnitude dominate in these areas, indicating increased stress accumulation conditions in the crust, Figure 6.
The combined interpretation of the distribution of seismogeological effects, KDE results, and b-value analysis confirm that the identified areas in Western Macedonia show a high level of seismic activity and represent a region with significant potential for seismic geohazards.

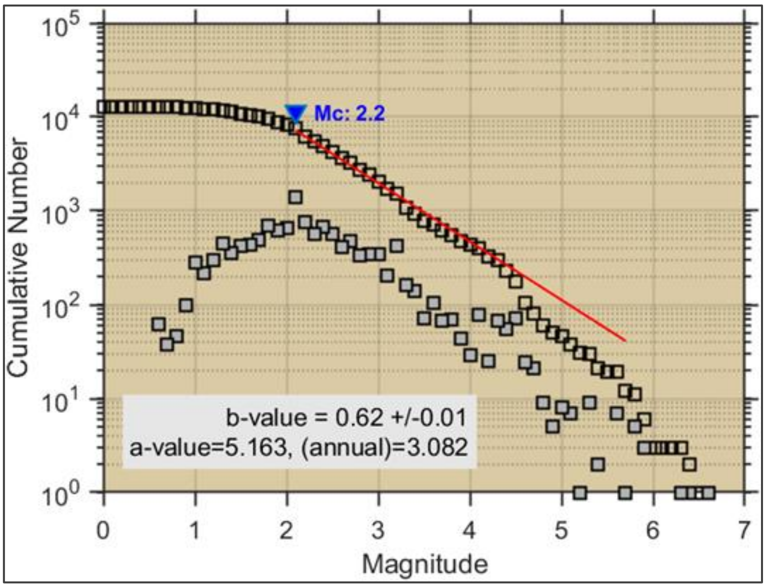


Figure 6. Frequency–Magnitude distribution

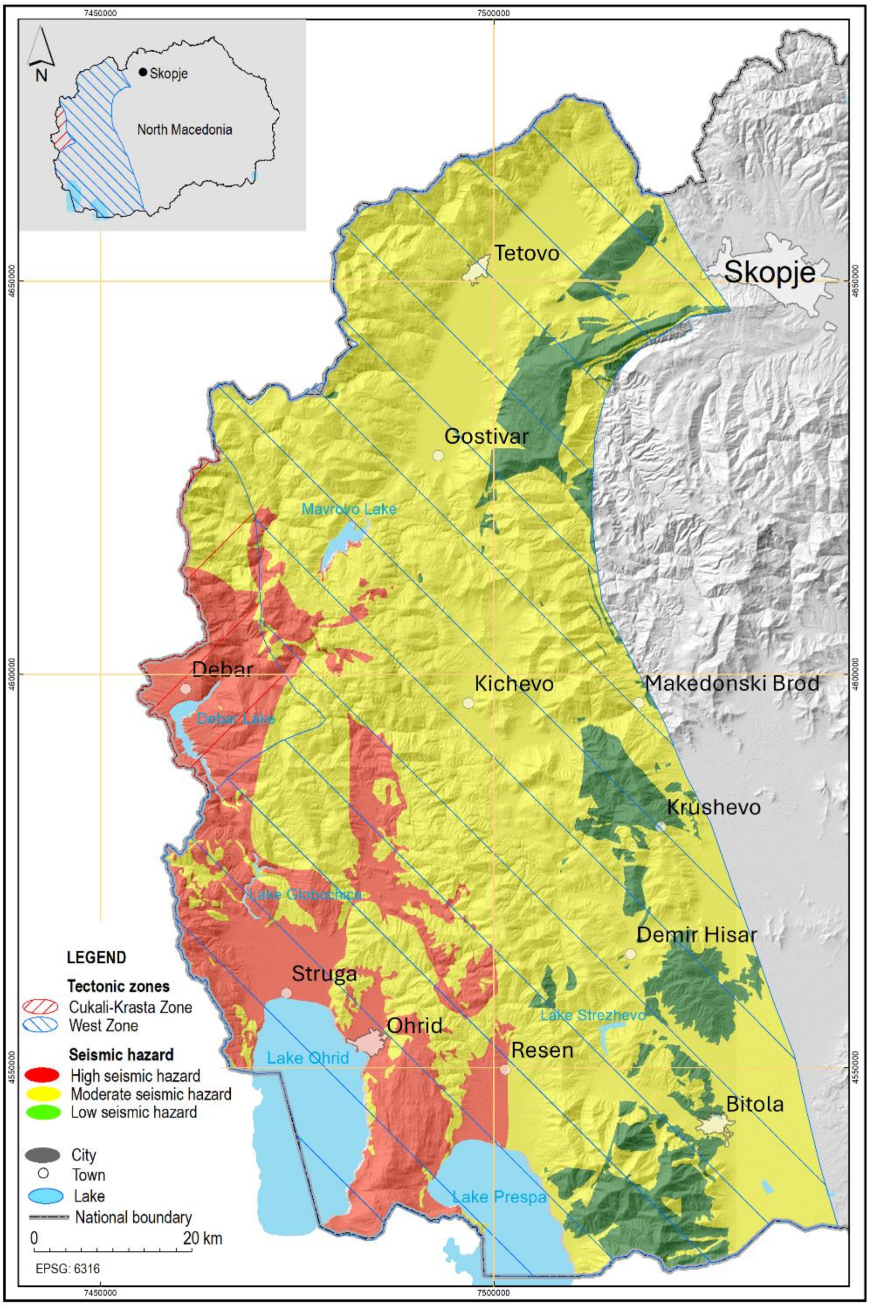


Figure 7. Identification of potential geohazard areas
in Western Macedonia based on seismic data

DISCUSSION

The spatial distribution of earthquake epicenters throughout the region confirms a continuously active seismic regime, with events of different magnitude.

This model is further supported by the spatial clustering of seismological effects, identified through the Kernel Density Estimation (KDE), which highlights the different zones of concentrated seismic effects caused by earthquakes.

The obtained b-value ($b = 0.62 \pm 0.01$) indicates relatively high stress conditions in the crust, which is usually associated with the dominance of seismic events of higher

magnitude followed by seismogeological effects. It follows that, a low b-value depicts the region as a potential zone of future strong seismic activity [11].
The result is strongly supported by the global trend of decreasing b-value with depth in the continental crust and subduction zones.
This is confirmed by the analysis of the seismicity of Western Macedonia, which indicates that the hypocenters of earthquakes are generally located at depths of up to 30 km.
The Geographic Information System (GIS) enabled the identification and classification of geohazard areas.
The results show a strong spatial correlation between the identified areas of high geological risk, areas of increased seismic activity (Fig. 3) and the main active fault structures (Fig. 1), strengthening the reliability of the applied methodological framework. From this correlation, the areas colored in red (Fig. 7) are exposed to a high seismic risk from earthquakes with seismogeological effects. Based on the observed seismicity and seismotectonic characteristics of the region, these areas have historically been affected by strong earthquakes (Fig. 5b), associated with significant seismogeological effects and therefore it is considered that these areas are likely to experience future strong earthquakes capable of generating significant seismogeological effects. Areas colored yellow is exposed to moderate earthquakes, without pronounced effects on the natural environment. Areas exposed to very weak earthquakes with seismogeological effects are colored green. The proposed methodology provides reliable identification and classification of seismic geohazard zones.

CONCLUSSION

This study presents methodological framework for identifying, assessing and spatially delineating areas of seismic geohazard by combining seismicity analysis, Kernel Density Estimation (KDE), F -M distribution, and geological-tectonic data within the Geographic Information System (GIS).
In this way, areas exposed to seismological effects of earthquakes in Western Macedonia were identified.
Identification of high geohazard zones show a strong correlation with active fault structures, high seismic density, and KDE values, while low geohazard zones are characterized by lower seismic activity and more stable geological conditions.
The proposed methodology provides a scientifically sound and spatially explicit framework for assessing seismic geological risk. It is suitable not only for academic research, but also for practical applications in spatial planning, seismic risk management and disaster mitigation strategies

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