

Article



Triple-Threat Natural Hazard Harmonization (Based on Open Science and FAIR Principles): The Foinikas River Drainage Basin (Greece)

George Kaviris ^{1,*}, Angelos Zymvragakis ¹, Vassilis Sakkas ¹, Ioannis Spingos ¹, Hariklia D. Skilodimou ², Stefania Alexandra Andriopoulou-Mounteanou ², Zacharo Paliou ², George D. Bathrellos ², Eleftheria Papadimitriou ³ and Vasileios Karakostas ³

¹ Department of Geology and Geoenvironment, Section of Geophysics and Geothermics, National and Kapodistrian University of Athens (NKUA), Panepistimiopolis 15772 Athens, Greece

² Department of Geology, University of Patras, 26504 Patras, Greece

³ Geophysics Department, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

* Correspondence: gkaviris@geol.uoa.gr

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Abstract: The Foinikas River drainage basin of the Western Gulf of Corinth, Greece, represents a complex tectonic environment that is highly susceptible to multiple natural threats. A high-resolution multi-hazard model is developed by integrating seismic, flood, and ground deformation hazards. Seismic hazard was assessed through a refined Probabilistic Seismic Hazard Assessment (PSHA) using a logic tree approach to incorporate multiple source models and Ground Motion Models (GMMs). Flood susceptibility was represented using an existing flood hazard dataset derived from previous hydrological modeling and past flood events, available through an open-access repository. Ground deformation was quantified using satellite radar interferometry (InSAR) from the Copernicus European Ground Motion Service for the period 2019–2023 and compared with previous InSAR results spanning from 2002 to 2017. Results identified a clear spatial pattern: the southern rocky section of the basin exhibits very low hazard, whereas the northern and northeastern coastal areas show high to very high susceptibility, respectively. The integrated multi-hazard zonation, validated with an Area Under the Curve (AUC) of 0.95, demonstrates high predictive accuracy. The outcome of this study can be exploited by local authorities to enhance the management and urban planning of the hazard-prone sectors. All data used for multi-hazard modeling are open and publicly available through open repositories.

Keywords: multi-hazard analysis; probabilistic seismic hazard assessment; ground deformation

1. Introduction

Natural hazards can affect both natural and built environments and, when their impacts substantially disrupt human life, they are characterized as natural disasters [1]. Their frequency and intensity are controlled by environmental and geomorphological conditions[2], whereas expanding human activity often amplifies their consequences, resulting in considerable socioeconomic losses. Earthquakes and floods are among the current global threats, which have existed throughout geological time [3,4].

Seismic hazard refers to the maximum level of ground motion that is expected to occur at a site during an earthquake [5]. Given that the expected ground motion cannot be predicted with adequate accuracy, seismic hazard



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assessments are conducted to estimate Intensity Measure Types (IMTs), such as Peak Ground Acceleration (PGA), through either probabilistic or deterministic approaches [6]. IMTs are most commonly derived using the probabilistic framework originally formulated by [7] and further advanced by [8], widely known as the Cornell–McGuire Probabilistic Seismic Hazard Analysis (PSHA). Within this framework, IMTs are expressed for a specified Return Period (RP), defined as the time interval associated with a given probability of exceedance. National building regulations, including the current Greek Code [9], typically adopt a RP of 475 years, corresponding to a 10% probability of exceedance within 50 years.

Flooding is a natural phenomenon that has shaped landscapes over geological time and occurs when river flow exceeds channel capacity, inundating normally dry land [10]. Globally, floods are the most frequent natural hazards and account for a significant share of disaster-related mortality, causing major damage to infrastructure, housing, and agricultural land [11,12]. Flood hazard maps are essential tools for identifying vulnerable areas and illustrating variations in flood risk across regions, supporting targeted mitigation measures [13,14].

Ground deformation measurements and monitoring play a crucial role in understanding and reducing the risks posed by natural hazards such as earthquakes, landslides, and subsidence [15]. By monitoring how the Earth's surface moves and deforms over time, it is possible to detect subtle precursory changes, identify unstable areas (especially in landslide-prone or steep terrain, i.e.) [16], and evaluate how strain is accumulating along active fault zones. Ground deformation can be measured using advanced space-geodetic methods. Point-based Global Navigation Satellite System (GNSS) observations measure motion with accuracy in all three motion components [17]. Interferometric Synthetic Aperture Radar (InSAR) maps surface displacement over wide areas, but it is limited to the satellite's Line-of-Sight (LOS) direction. Applied independently or jointly [18], these techniques support hazard assessments, improve early-warning efforts, and contribute to designing safer infrastructure by improving knowledge before, during, and after destructive events.

Geographic Information Systems (GIS) provide an effective framework for integrating and analyzing spatial datasets related to natural hazards [19,20]. By combining multiple hazard layers, GIS enables the identification of hazard-prone areas and the evaluation of interactions that may lead to cascading or compound events [21,22]. Such spatially explicit information supports proactive planning aimed at reducing fatalities and economic losses [23] and constitutes an essential tool for land-use planning and development strategies [24,25]. In regions exposed to multiple hazards, multi-hazard assessments facilitate the simultaneous evaluation of threats and support decision-making, urban vulnerability assessment, and disaster risk mitigation [26–29].

Within the abovementioned framework, research data management aspects are aligned with the target of HOMEROS, an Open Science project which conceptualizes multi-hazard assessment as both a scientific endeavor and an infrastructural undertaking. HOMEROS, funded by OSCARS (Open Science Clusters' Action for Research and Society, <https://doi.org/10.3030/101129751>) exploits resources made available through national and international research and digital infrastructures to demonstrate the added value of open and interoperable ecosystems that facilitate multidisciplinary data exchange, with emphasis on essential geohazard variables. HOMEROS explores how tools, datasets, and services provided by platforms such as EPOS and Copernicus, and related initiatives can be integrated into academic research processes. This approach enables the coordinated analysis of earthquake and flooding hazards through scientific workflows that are harmonized, to the extent feasible, supporting interdisciplinary research. The implementation of structured workflows for data curation, processing, and quality control enhances the consistency, reliability, and interoperability of heterogeneous datasets, while ensuring that research outputs are disseminated through trusted open repositories. In this context, multi-hazard assessment is not limited to the superposition of individual hazard maps; rather, it is formulated as an integrated, data-driven methodology that promotes scientific robustness, reproducibility, and informed hazard management.

The drainage basin of the Foinikas River in southern mainland Greece serves as an ideal study area to harmonize an integrated, open-source multi-hazard framework. By synthesizing our updated seismic hazard model with ground deformation data and high-resolution flood assessments, this study moves beyond traditional single-hazard approaches to provide a holistic view of hazard. The resulting datasets are provided as Open Data under Creative Commons licenses.

The Foinikas drainage basin in southern mainland Greece provides a suitable test site for the development of a multi-hazard assessment framework. Although seismic hazard, flood hazard, and ground deformation have previously been investigated independently in the Western Gulf of Corinth, these datasets have not been harmonized within a common framework for integrated hazard assessment. To address this gap, we combine an updated PSHA model, an openly available flood hazard dataset, and EGMS-based InSAR ground deformation observations within a unified GIS workflow. The proposed framework harmonizes heterogeneous hazard datasets through common spatial resolution.

The findings of this study address a critical issue; while individual datasets provide valuable baselines, a combined multi-hazard approach is particularly critical for the Foinikas River drainage basin due to its highly complex, interconnected geodynamic and geomorphological setting within the western Gulf of Corinth. The basin represents a high-risk landscape where disparate natural hazards do not occur in isolation but rather overlap spatially and temporally. The southern steep, rocky topography accelerates torrential surface runoff, focusing intense flood dynamics directly into the low-lying northern and northeastern coastal floodplains. Concurrently, this exact low-lying deltaic zone experiences persistent, long-term ground deformation and subsidence, which inherently compounds the local marine and fluvial flood vulnerabilities. Additionally, the highly active tectonic regime of the Gulf of Corinth imposes a severe and continuous seismic threat to the region's coastal settlements. Mitigating risk in such a complex environment via conventional, single-hazard frameworks creates critical gaps in emergency planning, as it overlooks how a subsiding coastline directly exacerbates flood susceptibility, or how ground motions due to a fault rupture threaten structurally compromised terrains. Consequently, by executing an improved, localized logic-tree probabilistic seismic hazard assessment and integrating it seamlessly with InSAR deformation grids and flood matrices, this study delivers the first harmonized multi-hazard zonation map for the region that provides local authorities with a unified tool that reflects a more accurate hazard profile of the Foinikas basin.

Regarding the study area, the drainage basin of Foinikas River lies in the northern Peloponnese, onshore the Western Gulf of Corinth (WGoC) (Figure 1A). The basin occupies an area of more than 94 km² and exhibits an elongated configuration trending from southwest to northeast. The drainage network originates from the eastern slopes of Mount Panachaiko, flows in a southwest to northeast direction and discharges into the WGoC (Figure 1B). In the southern part of the basin, the landscape is largely mountainous, reaching elevations above 1900 m at Mount Panachaiko (Figure 1B). This high-altitude area is characterized by steep (30–45°) to very steep slopes (>45°). The regional active tectonics, characterized by ongoing uplift, have strongly shaped the drainage basin of Foinikas River, promoting deep incision of the channels and the formation of steep slopes throughout the catchment. In contrast, the northern portion of the basin comprises a low-lying floodplain (Figure 1B), with gentle slopes (<5°).

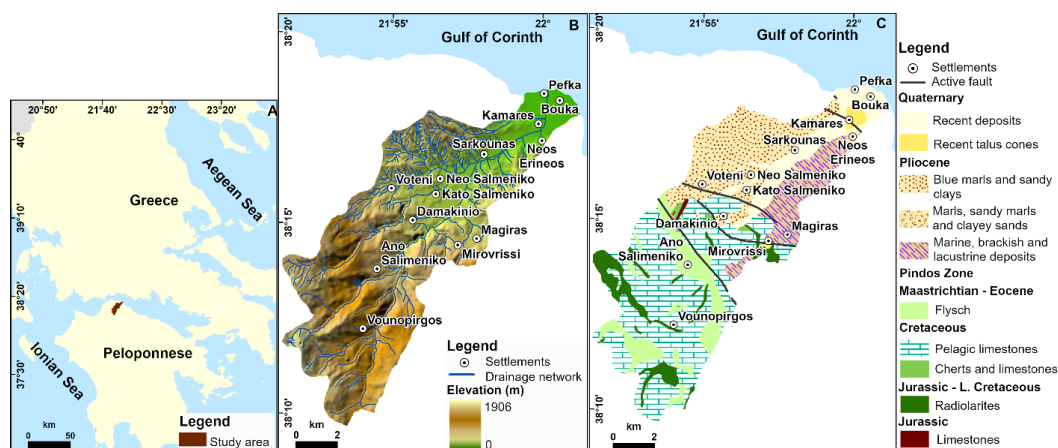


Figure 1. (A) Geographic location of the Foinikas River drainage basin, (B) Morphology, drainage network, major roads, and principal settlements within the study area. (C) The geological formations of the study area along with active faults, the latter adopted from [30].

The geological framework of the southern part of the study area is influenced by formations belonging to the Pindos geotectonic zone (Figure 1C). In contrast, the northern sector is characterized by the presence of Pliocene and Quaternary deposits. According to prior works of [29], the area encompasses the following lithological components:

- Quaternary deposits: Unconsolidated materials including clays, silts, sands, and gravelly layers.
- Pliocene sediments: Comprised of marls, sandy marls, clay-rich marls, and sequences alternating between marls, clays, coarse sandstones, and conglomerates.
- Flysch sequences: Dominated by interbedded sandstones and thin-bedded limestones.
- Carbonate rocks: Including Cretaceous, pelagic limestones that are typically thin- to medium-bedded, folded, and karstified, along with Cretaceous cherts and limestones and Jurassic limestones.
- Radiolarites: Thin siliceous layers dating from the Jurassic to lower Cretaceous.

The WGoC is part of the Gulf of Corinth, which is an active tectonic half-graben [31] that is well-known for its high seismicity in both historical [32,33] and modern eras [3,34]. In the Foinikas area and its surroundings, there have been several strong earthquakes ($M \geq 6.0$) that had social and infrastructure impacts (Figure 2). During

the historical era, a very well-known earthquake is the 373 BCE M 6.6 earthquake whose accompanying tsunami has been considered to be related to the destruction of the city of Helike [35,36]. Destructive earthquakes have been recorded in instrumental era of seismology, with the most recent being the 15 June 1995 M_w 6.2 earthquake, which had an impact on Aigion town, a major settlement of the region [37]. Other strong events are those of 30 May 1909 (M 6.0), 31 March 1965 (M_w 6.4) and 18 March 1993 (M_w 5.9), as reported by [3]. During the first month of 2010 a four-day-delayed doublet occurred in proximity to Efpalio with magnitudes of M_w 5.3 and 5.2 [38,39]. On 23 December 2020 a M_w 4.6 event struck close to Marathias and initiated an earthquake sequence that included an earthquake of M_w 5.0 close to Trizonia Island and terminated with a M_w 5.3 earthquake in February 2021 close to Psathopyrgos [40–44]. Those examples denote that there is significant seismic hazard in the WGoC that also includes our study area, the Foinikas drainage basin. In addition to the high seismicity, the Foinikas drainage basin is vulnerable to flood hazards. According to [29], 11 events that impacted the drainage basin, emphasizing that its low-lying areas are especially vulnerable to recurrent flooding.

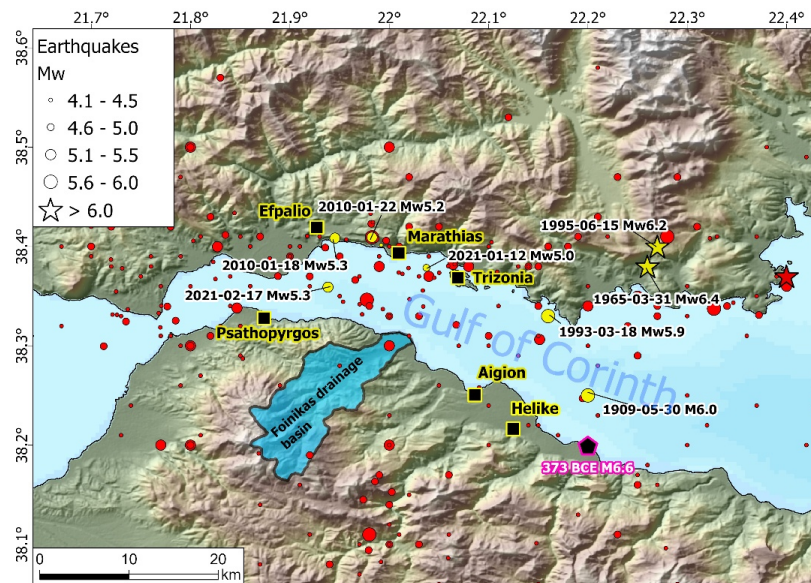


Figure 2. Seismicity Map of the broader WGoC, where Foinikas drainage basin is included. The adopted earthquake catalogue is the updated version of [34] hosted by [45]. Significant earthquakes are shown in yellow with their labels. The historical Helike event is marked by a black pentagon; its coordinates are taken from [46].

2. Materials and Methods

2.1. Input Data

This study exploited the following data-resources:

- Geological maps of Nafpaktos, Amygdalea and Khalandritsa sheets (1:50,000 scale) from the Institute of Geology and Mineral Exploration.
- Earthquake catalogue ($M_w \geq 4.1$ earthquakes) from [34], updated to 2023.
- Source area and fault models from the European Seismic Hazard Models 2013 (ESHM13) and 2020 (ESHM20) [47–49].
- Ground Motion Models (GMMs): [50–54].
- Flood datasets are publicly available through Zenodo [55].

2.2. Open Scientific Data and Research Outputs

A key component of multidisciplinary research in Earth and environmental sciences is open scientific data, especially when diverse datasets like geological, geomorphological, seismic, and geodetic data need to be combined under a single research framework. Such datasets must be properly documented, interoperable, and reusable in order to support their long-term integration across scientific domains and research infrastructures as well as to guarantee transparency and reproducibility.

The methodical creation, curation, and distribution of open scientific data and related research products serve as the foundation for studies of geodynamic processes within the HOMEROS project framework. The project introduces structured workflows in line with FAIR (Findable, Accessible, Interoperable, Reusable) principles and

Open Science practices to integrate GNSS observations, remote sensing products, and instrumental measurements. Transparency, reproducibility, and long-term accessibility are ensured by adding all hazard maps, multi-hazard zonation results, and related datasets through rigorous documentation and quality control processes in reliable repositories like Zenodo.

Every research output has a persistent Zenodo identifier (DOI) assigned to it [45,55–57] and is discoverable under the HOMEROS Community repository in Zenodo. Having open data that are findable and described with rich metadata encourages cross-disciplinary reuse in hazard assessment and land-use planning applications and makes it easier to include them in larger research ecosystems in the future.

2.3. Seismic Hazard Assessment

In the probabilistic methodology of [7,8] the primary input consists of two major elements: (a) the seismotectonic model and its parameters and (b) the Ground Motion Model (GMM). A seismotectonic model is a source model that describes the seismotectonic setting of the study area. Ideally, a fault model that includes activity rates and kinematics should be used. However, obtaining such detailed information is not always possible. Thus, the next best option is to use source area models. These divide a region into surface zones within which a homogeneous distribution of seismicity is assumed. Given the inherent uncertainty in these models, it is common practice to adopt multiple source models in seismic hazard calculations [58–60]. For this study, we selected four seismotectonic models: two source-area models and two fault models. Specifically, we adopted zones and faults from the 2013 and 2020 European Seismic Hazard Models (ESHM13 and ESHM20, respectively) [47,49]. By this approach, we aimed to introduce a diversified pool of sources to the modelling process and account for both local (faults) and regional (zones) seismic factors that contribute to hazard.

As it was beyond the scope of the current study to derive them anew, we collected seismicity parameters required for inclusion of the fault models from their metadata. These parameters included the associated preferred focal mechanism (strike, dip, and rake), the a and b values of the Gutenberg-Richter (GR) law [61] and the maximum magnitude that can be produced by the rupture of the fault, as derived from empirical relationships [62]. On the contrary, the seismicity parameters of the source areas, i.e., the magnitude of completeness, M_c , the a and b values of the GR law, and the maximum expected magnitude, M_u , were recomputed. The first was determined through the Maximum Curvature method [63], which estimates M_c through the maximum of the first derivative of the Frequency Magnitude Distribution (FMD). Using M_c as a threshold, the a and b values were estimated via the maximum likelihood method of [64]. M_u was computed using two approaches: by adding a constant factor of 0.5 to the maximum observed magnitude [65], and second, via the R-W-C equation [66,67], which estimates M_u by taking into account the maximum and the second-largest observed magnitudes within each source zone. Both M_u values were incorporated in the logic tree structure, as detailed below.

GMMs are empirical relationships which estimate IMTs, in our case PGA, as a function of an array of independent variables (e.g., magnitude, distance, fault type and soil conditions). We selected GMMs that were developed using mostly strong motion data recorded by seismic stations in Greece and that have been successfully implemented in previous seismic hazard studies. Specifically, we selected the models of [51–54,68]. It must be noted that for the fault models, only the GMM proposed by [54] was selected because it is the only one among the five abovementioned GMMs that uses the Joyner and Boore type of distance [69], which considers the ruptured plane in the estimation of IMTs. For zone sources, we adopted the approach of creating sub-logic trees per GMM to account for normal and non-normal faulting types, according to prior seismic hazard-related works [3,70,71]. Specifically, the sub-logic tree splits the selected GMM into normal and non-normal (reverse and strike-slip) branches and weighs them according to the relative percentages of normal and non-normal focal mechanisms that have been determined in each zone. We used the validated focal mechanism catalogue of [72] to collect the rake values in order to compute the percentages. Regarding the soil conditions, we used the rock type to remain consistent with the framework of the Greek National Building Code [9].

The described ensemble of seismotectonic models and GMMs was integrated into a logic tree scheme (Figure 3), to combat epistemic uncertainty by combining alternative seismic hazard calculations. The four source models were set as the major branches of the tree. For each source area, minor branches consisted of the two types of M_u and the five GMMs. As a result, we aimed to capture the variability of the principal sources of epistemic uncertainty, i.e., source model, maximum magnitude, and GMM selection. Each branch was assigned an equal weight, as there was no definitive reason to assign higher confidence to any specific branch.

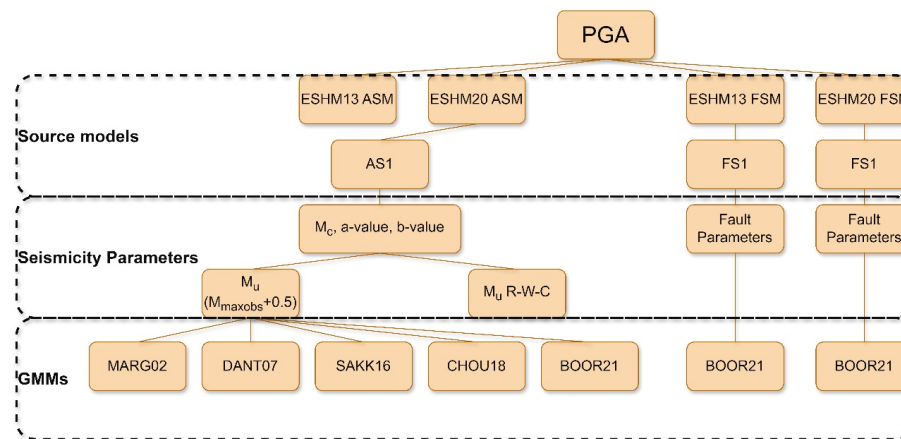


Figure 3. The logic tree which was constructed to obtain PGA (RP = 475 yr). For clarity, the minor branches are shown only for the first area source of the ESHM20 model. GMM abbreviations: MARG02 = [50], DANT07 = [51], SAKK16 = [52], CHOU18 = [53], and BOOR21 = [54]. We used equal weighting on all seismic hazard outputs.

2.4. Flood Hazard Assessment

Flood hazard conditions within the Foinikas River drainage basin were evaluated using the flood events and hazard assessment framework, as well as the corresponding hazard index values reported by [29]. A spatial representation of flood events and flood hazard for the same area has also been published in the Zenodo repository [55]. For the objectives of the present study, this dataset was utilized as the principal flood hazard layer describing the spatial distribution of potential flooding across the basin.

The map was developed from openly available geospatial datasets, which ensures transparency and facilitates the reproducibility of the methodological workflow. In addition, the dataset provides a continuous spatial representation of flood hazard, enabling the identification of variations in hazard intensity throughout the drainage basin.

Within the methodological framework of this research, the flood hazard map was incorporated into a GIS-based analytical environment where it served as a fundamental input layer for spatial evaluation. Through this process, the study area was classified according to continuous hazard index values, allowing a systematic interpretation of flood hazard patterns. Elevated hazard index scores represent zones with a high potential for flooding, while lower scores denote areas with comparatively low flood susceptibility.

2.5. Ground Deformation

The broader Foinikas drainage river area was investigated using InSAR, aiming to quantify spatial ground motion on a local scale. Ground deformation was derived from products provided by the Copernicus pan-European InSAR service, the European Ground Motion Service (EGMS) platform.

The broader Foinikas drainage basin was investigated using InSAR data for the period 2019–2023 to quantify local-scale spatial patterns of ground motion. Previously published InSAR products covering 2002–2017 are also discussed to extend the temporal perspective. Recent ground deformation for 2019–2023 was derived from products provided by the Copernicus European Ground Motion Service (EGMS) (<https://egms.land.copernicus.eu/> (accessed on 19 March 2026)). EGMS delivers freely accessible, harmonized ground-motion velocity maps and displacement time series based on Sentinel-1 radar observations, with millimeter-level accuracy. Three product levels are available: (i) Basic (L2a), which provides relative ground-motion measurements along the satellite LOS; (ii) Calibrated (L2b), which consists of LOS measurements calibrated to a GNSS-derived regional reference frame; and (iii) Ortho (L3), that includes decomposed Vertical (Up–Down) and East–West motion components obtained by combining ascending and descending geometries on a 100 m grid. However, the calibration using the regional GNSS velocity field with respect to the ETRF2020 reference frame imports a strong horizontal component to the decomposed motion. The latter estimates the overall deformation pattern but may attenuate the local deformation amplitudes. To better resolve both the magnitude and the spatial expression of deformation within the Foinikas River drainage basin, the basic (L2a) EGMS products were used. A local reference-point calibration procedure was applied, and the measurements were subsequently decomposed into Vertical and East–West components.

To locally reference the L2a InSAR products, a stable point within the urban area of Patras was selected. This point was chosen in the vicinity of a permanent GNSS station for which daily RINEX observations were available over a long period, enabling, if required, an absolute calibration approach. The InSAR reference was placed near station PAT1 (HxGN SmartNet network), ensuring consistency with a reference point adopted in an

independent dataset (Multi Scale and Multi Hazard Mapping Space based Solutions, project of European Space Agency, MEMpHIS project) that is discussed later. A second GNSS site, PAT0 (EUREF Permanent GNSS Network), was also evaluated as a potential reference point; however, it was excluded because it is located close to the active Rio–Patras fault zone [73], where local deformation may bias the referencing.

Daily observations from PAT1 GNSS station were processed over multiple years to estimate the regional GNSS velocity field. Raw 30 s RINEX data were analyzed using Bernese v5.4 GNSS software [74], yielding a velocity vector of $V_{\text{East}} = -15.15 \pm 0.03$ mm/yr, $V_{\text{North}} = -21.06 \pm 0.03$ mm/yr, and $V_{\text{Up}} = -0.46 \pm 0.20$ mm/yr in the ETRF2020 reference frame. The noticeable horizontal motion, combined with the relatively large incidence angles of the Sentinel-1 acquisitions ($\sim 41^\circ$ and $\sim 45^\circ$ for ascending and descending geometries, respectively), would strongly affect any calibration that projects the GNSS velocity into the LOS direction [75], as is the case in the L3 EGMS products. This consideration further supports the use of a locally defined reference point for the InSAR analysis.

The L2a EGMS InSAR products used in this study span the period 2019–2023 and include both ascending and descending Sentinel-1 orbital geometries, with more than 250 scenes available. Deformation maps in the Vertical and East–West directions were generated through a two-step workflow. First, each LOS dataset was locally referenced by subtracting the LOS velocity of the selected reference point from all remaining measurement points. Second, the locally referenced LOS velocities were decomposed into Vertical and East–West components on a 100 m grid. Since ascending and descending acquisitions do not result in the same ground targets, a representative LOS velocity was computed for each grid cell by averaging the LOS measurements within the cell and assigning the result to the cell centroid for each geometry. The paired LOS velocities were then decomposed into Vertical and East–West motion using the incidence and track angles computed at each centroid [76]. Decomposition was performed only for cells containing observations from both geometries and only where at least three data points were available in the original L2a dataset. An analogous procedure was applied to the displacement time series. The resulting locally calibrated and decomposed dataset was used to derive velocity fields, while acceleration was estimated by fitting a second-degree polynomial to the decomposed time series.

For the final InSAR products presented in this study, uncertainty was assessed using the quality indicators associated with each measurement point, mainly the RMSE of the displacement time series and the standard deviation of the estimated mean velocity. According to EGMS specifications, the nominal mean-velocity standard deviation is 0.7 mm/yr (1σ), while the displacement standard deviation is 8 mm (1σ) for the calibrated and ortho products. The local calibration and ascending/descending decomposition procedures applied in this study did not alter these uncertainty values; therefore, the reported velocity uncertainty for each point was retained and used as the formal uncertainty of the fitted deformation field. Long-term velocities were estimated using robust least-squares linear regression with bisquare weighting, minimizing the influence of outliers and anomalous observations. Point reliability was further controlled by applying a temporal coherence threshold >0.7 . Uncertainty related to the decomposition was reduced by requiring at least three measurement points within each 100 m cell for each orbital geometry. Cells with strongly unbalanced point distributions between the two geometries, for example, 20 points in one geometry versus only 3 to 5 in the other, were excluded from the decomposition to avoid biased estimates. Remaining uncertainty may be associated with measurement-point distribution, land-cover conditions, particularly in densely vegetated areas, and error propagation during decomposition. These effects are especially relevant for the east-west component, while the north-south motion is not resolved by the Sentinel InSAR viewing geometry.

2.6. Multi-Hazard Analysis

The hazard maps generated in the previous sections were used to produce a single multi-hazard map. The values of each hazard map were processed and classified into five ordinal categories to enable consistent GIS-based overlay and comparison. The use of a common five-level ordinal classification ensured that hazard layers originally expressed in different physical units and value ranges could be transformed into a comparable scale, allowing their subsequent integration within a unified GIS framework [1,2,11,14,28,30,77]. More specifically, the values of seismic and flood hazard maps were classified into five classes using a quantile classification, ensuring an approximately equal distribution of grid cells in each category. This approach is widely adopted in the creation of hazard assessment maps, as it effectively manages data that are approximately linearly distributed, allowing for reliable assignment of hazard categories [28]. To evaluate ground deformation hazard, the absolute values of deformation were considered. These values were subsequently divided into five categories, reflecting progressively higher levels of ground instability. The classification thresholds were based on previous studies that identified and delineated hazard zones [78–80]. All hazard layers were converted to a common ordinal scale of 1

to 5. As described by [1,11,14,28,30,77], 1 indicates a very low level of hazard, whereas 5 represents a very high hazard. Before the overlay analysis, all raster layers were resampled to a common spatial resolution and aligned to the same raster grid to ensure spatial consistency and cell-by-cell correspondence throughout the GIS analysis. This preprocessing eliminated discrepancies arising from different raster resolutions and enabled direct comparison of the hazard layers. Since the objective of the study was to identify areas where multiple hazards spatially coincide, an equal-weight overlay was adopted. Following standardization, each hazard layer contributed equally to the final multi-hazard index. This approach has been applied in previous GIS-based multi-hazard assessments [81,82] and provides a straightforward framework for integrating hazard layers expressed on a common ordinal scale. By overlaying these normalized layers, areas where multiple hazards coincide were identified, building on the GIS-based framework for spatial hazard assessment. The approach employs a simple summation of hazard levels across layers, producing a composite map that highlights zones of highest cumulative hazard that consistently identifies zones of high cumulative hazard and areas where seismic, flood, and ground deformation hazards spatially coincide. The advantages of the applied method include ease of implementation, rapid visualization of high-hazard areas, straightforward interpretation, and compatibility with diverse hazard types as noted by [83].

The predictive performance of the multi-hazard map was assessed using ROC analysis and the Area Under the Curve (AUC). For validation purposes, hazard occurrences were considered as positive observations, while an equal number of randomly generated non-event points were created within areas without recorded hazard occurrences. To ensure spatial independence between positive and negative samples, a 100 m buffer was applied around all hazard occurrence points, and the non-event points were generated only outside these buffer zones. Hazard occurrences and randomly selected non-event points were sampled from the map. ROC curves plotted the cumulative proportion of the multi-hazard area against the study area per class. This approach, commonly applied in hazard map validation [84], calculates true and false positive rates, while AUC provides a measure of the map's discrimination ability, from 0 (no predictive power) to 1 (perfect prediction).

3. Results

3.1. Seismic Hazard Assessment

The probabilistic seismic hazard modeling revealed that the highest levels of PGA for a 475-year return period are identified in the northeastern part of the basin, while the lowest are in the southwestern part (Figure 4). The location of the higher PGA values can be attributed to their proximity to active fault systems and to the higher seismicity located within the Gulf. While these values are obtained for reference rock conditions, they indicate the substantial seismic loading at the base of the basin, which would be further modified by the overlying sedimentary fill in a site-specific analysis. The results show a maximum PGA of 3.5 m/s^2 and a minimum of 3.0 m/s^2 . When these values are reduced by 25% to obtain effective PGAs to allow for direct comparisons with the regulations proposed by the Greek National Building Code [9], then the maximum value becomes approximately 2.6 m/s^2 , having a minor increase over the regulatory value of 2.4 m/s^2 , whereas the minimum value drops to 2.25 m/s^2 . This observation indicates that the seismic hazard modeling for the Foinikas Basin produced PGA values that follow or are slightly higher than the ones proposed by the current Greek National Building Code.

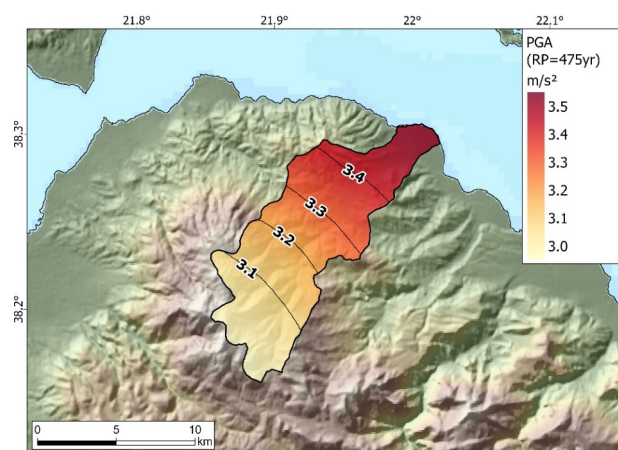


Figure 4. The seismic hazard modeling of the Foinikas drainage basin. The IMT is the PGA for a return period of 475 years.

3.2. Flood Hazard Map

Figure 5 depicts the spatial distribution of flood hazard across the Foinikas River drainage basin as derived from the published dataset by [55]. Examination of the map reveals that regions experiencing the highest flood hazard are largely aligned with the main river channel, predominantly in the northern and central portions of the basin. Moderate hazard areas are primarily located within the central basin but also extend intermittently toward the northern, western, and southern sectors. By contrast, the peripheral areas in the southern, western, and eastern parts of the basin generally correspond to low or very low hazard levels, indicating reduced vulnerability to flooding in these zones.

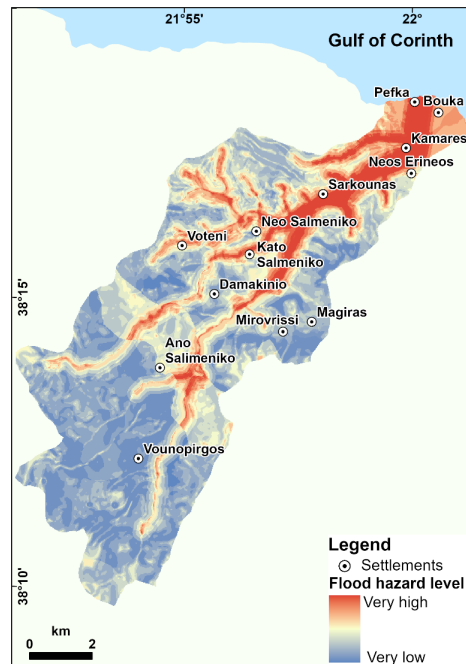


Figure 5. Map illustrates the distribution of flood hazard within the Foinikas River drainage basin.

3.3. Ground Deformation

Two ground-motion velocity maps, covering the period 2019–2023, were generated for the broad study area, representing the Vertical and East–West components, respectively (Figures 6 and 7). In addition, the acceleration field (in mm/yr^2) was estimated to describe the temporal changes in the deformation rate, i.e., whether the motion is accelerating or decelerating. The interpretation of acceleration should consider the sign of the corresponding velocity component. For the Vertical direction, positive velocity combined with positive acceleration indicates accelerating uplift, whereas negative velocity with positive acceleration corresponds to decelerating subsidence, and vice versa. For the East–West component, the sign convention is relative: positive velocity indicates eastward motion, and positive or negative acceleration denotes accelerating or decelerating motion along that direction, respectively.

The velocity fields for both components indicate generally low deformation rates across the larger part of the study area, with values of -3 to $+3$ mm/yr . Similarly, the limited acceleration magnitudes (-2 to $+2$ mm/yr^2) indicate that deformation is predominantly near-linear over much of the Foinikas Basin area. The Vertical component (Figure 6) is characterized mainly by modest subsidence along the northern coastal zone, north of linear fault-controlled structures such as the Rio–Patras fault. The Foinikas delta exhibits the strongest subsidence, with velocities reaching ~ 8 mm/yr , accompanied by an increased (negative) acceleration of approximately -3 mm/yr^2 . To the south, the corridor along the riverbed shows low-amplitude uplift (~ 2 – 3 mm/yr), whereas the mountainous area farther south is dominated by mild subsidence (~ 3 mm/yr) with small acceleration values (typically within ± 1 mm/yr^2). In the western part of the maps, near the urban area of Patras, the most pronounced subsidence pattern aligns closely with the tectonic expression of the Rio–Patras fault. The East–West velocity map (Figure 7) shows predominantly small westward motion (~ 2 to -3 mm/yr), locally disrupted by scattered zones of higher magnitude. The corresponding East–West acceleration field is generally small (-1 to $+1$ mm/yr^2), consistent with an overall near-linear deformation regime.

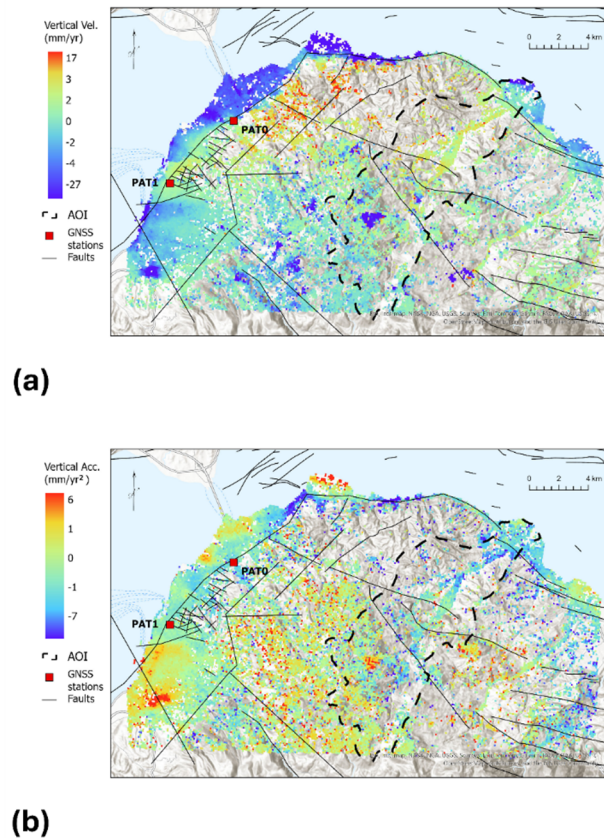


Figure 6. Vertical ground motion field for the broad Area of Interest (AOI), showing (a) velocity and (b) acceleration. The local InSAR reference point coincides with the PAT1 GNSS station (red square). Fault traces are from [30].

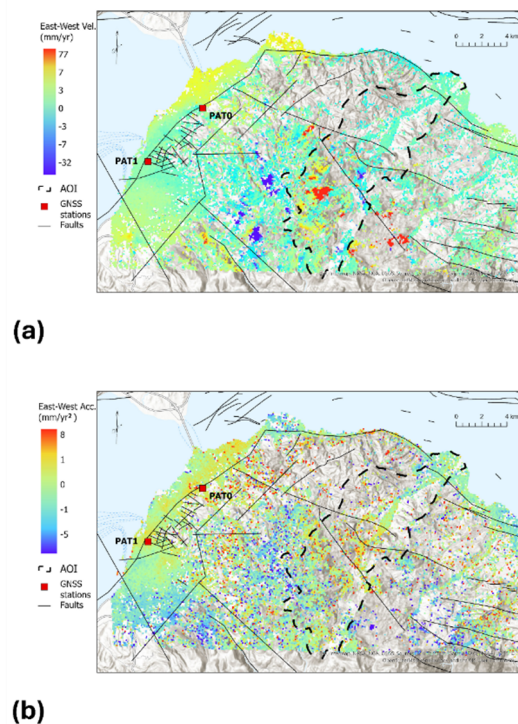


Figure 7. East–West ground-motion field for the broader AOI, showing (a) velocity and (b) acceleration. Positive velocity values indicate eastward motion. The local InSAR reference point coincides with the PAT1 GNSS station (red square). Fault traces are from [30].

3.4. Multi-Hazard Analysis

The multi-hazard map was assigned to discrete categories using the quantile method. According to [28] this method is a common approach for hazard maps due to its suitability for approximately linear data distributions. Thus, the hazards values on the map were grouped into five discrete hazard classes.

High and very high hazard zones dominate the northern and central areas of the study area. Moderate hazards occupy the central sector of the region. In contrast, low to very low hazard areas are mainly situated in the south (Figure 8).

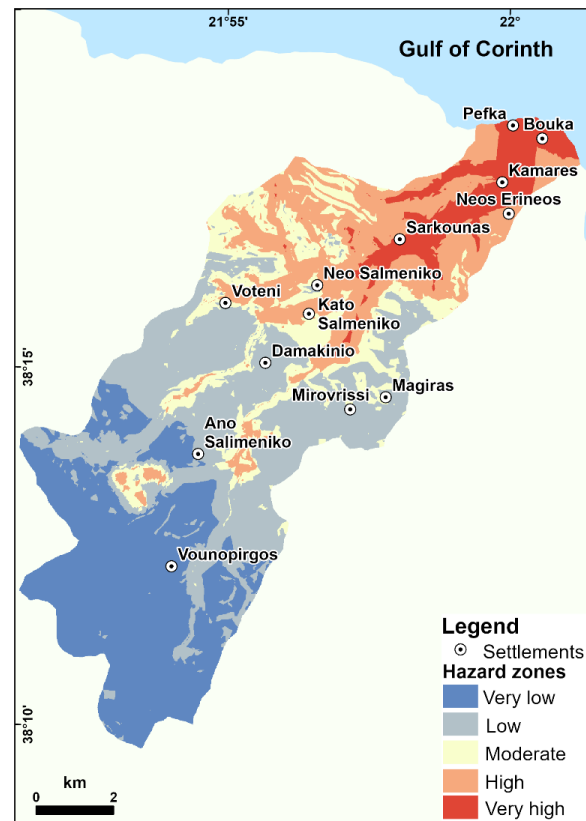


Figure 8. Spatial distribution of multi-hazard levels within the Foinikas River drainage basin.

The multi-hazard map was validated using a ROC curve (Figure 9). The AUC was 0.95, indicating an outstanding discriminative performance of the model in distinguishing between positive and negative samples.

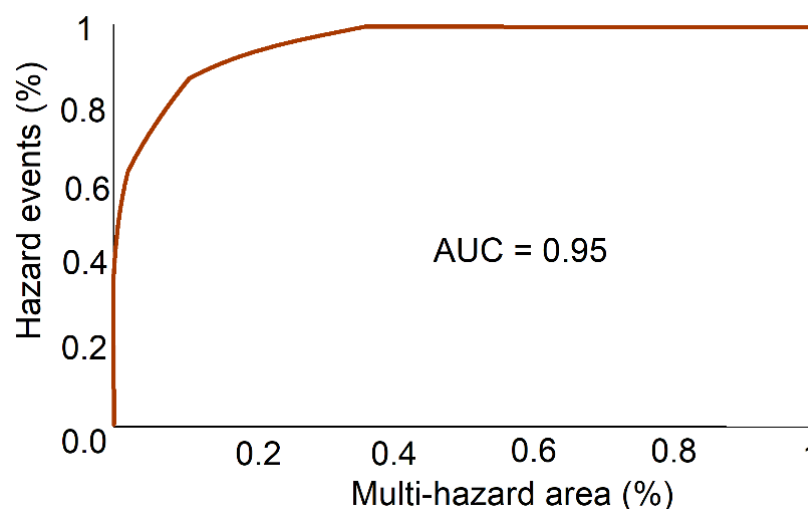


Figure 9. ROC curve of the multi-hazard map showing AUC, with the x-axis representing cumulative multi-hazard area and the y-axis representing cumulative hazard events.

4. Discussion

The main objective of this study is the development of a multi-hazard model for the Foinikas drainage basin, situated in the western Gulf of Corinth. The analysis integrates three sub-hazard layers: seismic, flood, and ground deformation. Given the region's pronounced exposure to these hazards, the generation of a zonation model that ranges from 'very low' to 'very high' susceptibility is a critical tool to inform decision making and resilient urban planning.

Regarding the first thematic layer, i.e., seismic hazard, we modeled PGA values for a return period of 475 years using the classic probabilistic approach of [7,8]. Ref. [3] modelled seismic hazard through both probabilistic and deterministic approaches for the WGoC. However, in the current study, seismic hazard is remodeled by taking into account a variety of seismotectonic models, an extended earthquake catalogue and the newer GMM of [54]. Our results indicate that the northeastern edge of the drainage basin has the highest PGA (Figure 4), attributable to the active seismotectonic setting within the Gulf of Corinth. However, it must be noted that the herein seismic hazard model adheres to the regulations proposed by the current National Building Code [9].

Figure 5 illustrates that areas with elevated flood hazard are predominantly aligned with the main channel of the drainage network, whereas regions situated at higher elevations or farther from the channel generally exhibit lower hazard levels. This distribution pattern underscores the dominant influence of the drainage network on flood-prone areas. These areas correspond largely to low-lying terrain characterized by gentle slopes. Both the morphological stability of the main channel of the hydrographic network and the specific geomorphological characteristics of the basin contribute to an increased likelihood of flooding, as reported by [77]. Additionally, the Mediterranean climate of the area, marked by intense, short-duration rainfall events, frequently triggers flash floods [85]. These events are amplified by the narrow coastal strip of the drainage basin and the rapid response of its hydrological networks, which can result in significant sediment transport and infrastructure damage.

The deformation field within the Area of Interest (AOI) highlights accelerating subsidence concentrated in the Foinikas delta. This behavior is plausibly explained by compaction of unconsolidated sediments, which commonly drives progressive subsidence in deltaic environments. In addition, a localized zone of noticeable, accelerating subsidence in the southern AOI, combined with a strong eastward motion component (>20 mm/yr), may reflect slope-related deformation processes and could be associated with the steep terrain in this part of the AOI. Finally, the main tectonic lineaments mapped in the area appear to coincide with changes in the deformation pattern observed in both components, suggesting differential motion across these structures. Envisat InSAR results for 2002–2010 [73] and Sentinel-1 observations for 2014–2017 (Figures S1 and S2 from the Supplementary file) reveal a deformation pattern that is broadly consistent in both type and spatial distribution with the one identified in this study. The 2014–2017 interferometric product was generated within the framework of the MEMpHIS project, adopting the same local reference point used for the EGMS-based analysis. Minor differences among the three datasets in terms of motion amplitudes and estimated accelerations can be attributed to variations in processing strategies, calibration approaches (e.g., [73] relied on an extended local GPS network), and acquisition periods. However, the dominant result is the strong temporal persistence of the deformation signal over more than two decades (2002–2023) across the entire study area. This long-term consistency is particularly noticeable given the intense seismicity affecting the region during this time span, as well as substantial land-cover changes linked to wildfires and general climatic impacts. The observed diachronic consistency of the ground deformation characteristics likely reflects the control applied by tectonic structures (faults), topography (slopes), and geological conditions (sedimentary deposits), which appear to dominate over shorter-term surface-layer changes.

Our multi-hazard model predicts that, in general, the southern portion of the drainage basin falls within the 'very low' hazard zone, whereas the northern sector is classified within the 'high' zone. The 'very high' zone peaks in the northeastern portion of the basin. This spatial distribution is consistent with the geological and seismotectonic framework of the study area. The influence of the river channel is evident in the central and northern sectors and when combined with low topographic gradients, this amplifies the level of flood hazard. On the other hand, the deltaic environment at the northeastern tip faces the highest rates of subsidence, contradicting the rocky regions to the southern part of the basin. Finally, seismic activity is concentrated within the gulf; when integrated with the fault source models applied across the primary branches of the logic tree approach, the elevated seismic hazard of the northern sector becomes geographically consistent. So, given the geological, seismological and tectonic context of the region, it is evident that the settlements of the NE part of the basin, i.e., Pefka, Bouka, Kamares, Neos Erineos, and Sarkounas have a very high multi-hazard. With regard to the model accuracy, we implemented a ROC analysis, which is commonly used in such studies for model validation [86]. The latter analysis produced an AUC of 0.95, highlighting excellent predictive accuracy (Figure 9).

Beyond the individual hazard analyses, the principal contribution of this study lies in the harmonization of heterogeneous natural hazard information within a common assessment framework. Previous investigations in the

Western Gulf of Corinth have primarily focused on individual hazards, such as seismic hazard, flood susceptibility, or ground deformation, whereas the present work integrates these complementary datasets into a unified multi-hazard product using consistent spatial resolution, classification scheme, and GIS workflow.

Another aspect of this study is the use of open data in the development of the sub-hazard thematic layers that feed into multi-hazard assessment. In line with the HOMEROS project framework, these data are produced and managed through structured workflows that promote transparency and reproducibility. This not only strengthens the scientific robustness of the results but also facilitates access to hazard-related information by civil protection authorities, engineers, and other relevant stakeholders.

To replicate the PSHA model, the user needs to construct a source model logic tree file and a GMM logic tree file. For the source model logic tree, we used the European Seismic Hazard Models of 2013 and 2020, including both areal sources and faults, which are accessible through the European Facilities for Earthquake Hazard and Risk (EFEHR) website. We selected the effective seismic sources by applying a 100 km distance criterion from the study area, retaining only the areal sources and faults located within this distance. The seismicity parameters of the faults were kept unchanged, whereas the parameters of the Gutenberg-Richter law were recalculated using the maximum likelihood method implemented in the open-source software ZMAP, which is available through the Swiss Seismological Service (SED). For the GMM logic tree, we used the built-in GMM of [54] for the fault sources. For the areal sources, we used the GMM proposed by [54] together with five Greek-specific GMMs, which are described in the corresponding publication (refer to Figure 3). The Greek GMMs were implemented in HDF5 format following the “GMPETablePSHA” demonstration provided by the OpenQuake engine repository: <https://github.com/gem/oq-engine/tree/master/demos/hazard/GMPETablePSHA> (accessed on 23 March 2026). Regarding the configuration file, we performed the PSHA calculations using 10,000 logic tree samples generated through a Monte Carlo sampling approach.

To reproduce the main ground deformation InSAR maps, EGMS ascending and descending products for 2019–2023 should be downloaded for the study area and be locally calibrated using the selected reference point. The calibrated LOS velocities were aggregated into 100 m cells, requiring at least three measurement points per orbital geometry, while cells with strongly unbalanced ascending/descending point distributions were excluded. The remaining velocities were decomposed into vertical and east-west components using Sentinel-1 viewing geometry, and long-term trends were estimated by robust least-squares regression with bisquare weighting. The derived georeferenced velocity fields were then used to generate the final deformation maps and profiles. The following Zenodo repository contains the vertical and east-west velocity products used in the final figures: <https://doi.org/10.5281/zenodo.19113437> (accessed on 19 March 2026).

To independently replicate the final hazard map and verify the model’s predictive performance, researchers can execute a continuous technical workflow using open-source Geographic Information Systems (e.g., QGIS) or Python-based spatial libraries. This process involves extracting the individual seismic, flood, and ground deformation matrices from their respective DOIs and spatially harmonizing all heterogeneous input layers to a unified resolution of 10 m × 10 m utilizing bilinear interpolation to guarantee satisfactory grid alignment. Subsequently, the continuous values of each individual hazard layer are standardized into an integer-based susceptibility index ranging from 1 (Very Low) to 5 (Very High) using the deterministic classification thresholds defined in the methodology section. Those layers are then overlaid through a GIS-based framework by employing a simple summation of hazard levels across layers, which later produces a composite map, where the highest cumulative hazard is depicted. Finally, model validation is performed as a separate step using a binary Receiver Operating Characteristic (ROC) curve analysis. The continuous composite matrix is cross-referenced against the independent validation event and non-event vectors to assess the model’s ability to discriminate between positive and negative samples.

Nevertheless, some limitations of this study should be acknowledged, while also highlighting opportunities for future research. The spatial integration of the seismic, flood, and ground deformation layers through an equal-weight framework implies a possibly simplified approach, as it assumes equal contribution of the different hazard components, a linear relationship during the overlay process, and independence between the individual hazard mechanisms. Although this approach provides a transparent and reproducible first-order assessment of multi-hazard spatial patterns, it does not fully capture the complex interactions between processes that operate across different spatial and temporal scales. In particular, it may not distinguish between low-frequency catastrophic events and more persistent environmental processes with different impacts and recurrence characteristics. Future studies can build upon this baseline framework by incorporating more advanced risk assessment methodologies. For example, multi-criteria decision-making approaches, such as the Analytic Hierarchy Process, could be used to derive hazard-specific weights based on local exposure, vulnerability, and historical damage information. Additionally, dynamic numerical modelling approaches that simulate cascading hazard interactions could further

improve the representation of temporal dependencies and potential chain effects between hazards. Such developments would enhance the applicability of multi-hazard assessments and provide more refined decision-support tools for local authorities, while the present framework offers a valuable foundation for identifying spatial patterns and prioritizing areas for further investigation.

5. Conclusions

A high-resolution multi-hazard model for the Foinikas drainage basin is developed through the integration of seismic and flood hazards and ground deformation. By providing a robust methodology that includes PSHA, InSAR deformation monitoring, and hydrological modeling, this research provides a critical tool for resilient urban planning in a region characterized by complex geodynamic activity.

PSHA was refined through the integration of [54] GMM, an expanded earthquake catalogue and the fault sources of ESHM13 and ESHM20. The results indicated that the northeastern edge of the drainage basin has the highest PGA, but it is consistent with the regulations of the Greek Building Code. The flood hazard map, available through an open-access repository, highlighted the dominant influence of the primary drainage network and the significance of the low-lying topography in flood susceptibility. Furthermore, interferometric observations for the period 2002–2023 revealed a persistent deformation field where accelerating subsidence in the Foinikas delta and slope-related processes in the southern sector are correlated with long-term tectonic and geological controls rather than transient surface changes.

The synthesized multi-hazard model demonstrates a clear spatial gradient: the southern portion of the basin is characterized by ‘very low’ hazard levels, while the northern and northeastern sectors exhibit ‘high’ to ‘very high’ susceptibility. These peak hazard zones directly encompass the settlements of Pefka, Bouka, Kamares, Neos Erineos, and Sarkounas, identifying them as priority areas for civil protection interventions. The reliability of these findings is supported by a ROC analysis, which yielded an AUC of 0.95, confirming the model’s excellent predictive accuracy.

A cornerstone of this research is the application of open and FAIR data principles. By ensuring the transparency and reproducibility of the sub-hazard thematic layers, this study provides a scalable framework that allows civil protection authorities, engineers, and the public to access vital safety information. Ultimately, the results presented herein serve as a scientific foundation for mitigating geohazard risks and enhancing the socio-economic resilience of the Foinikas drainage basin.

The integrated multi-hazard zonation map provides information for risk management and urban planning within the Foinikas River basin. For the high-to-very-high hazard northern and northeastern coastal settlements, specifically Pefka, Bouka, Kamares, Neos Erineos, and Sarkounas, local authorities can utilize these outputs to establish strict land-use zoning regulations that restrict new residential development within the flood-prone central hydrographic networks. Regarding the northeastern basin sectors, where the highest PGA values are identified, municipal planning departments should prioritize targeted seismic retrofitting programs for critical infrastructure and older building stocks that may not comply with the current Greek National Building Code provisions. Furthermore, the persistent, accelerating subsidence identified by the InSAR time-series within the Foinikas delta dictates that any future development, including underground utility networks, port facilities, and transportation infrastructure, must incorporate specialized geotechnical mitigation measures to withstand long-term ground deformation. Finally, at an operational level, civil protection agencies can overlay this multi-hazard matrix with local demographic data to optimize evacuation routes.

6. Statements and Declarations

All figures presented in this manuscript are original and have been created by the authors. No copyrighted material has been reproduced without permission, and there is no copyright issue related to the content of this manuscript.

Supplementary Materials

The additional data and information can be downloaded at: <https://media.scilitp.com/articles/others/2609041417179695/JHRR-26050198-Supplementary.pdf>. Figure S1: Vertical velocity field for the broad area of interest (AOI) for the period 2014–2017. The local InSAR reference point coincides with the PAT1 GNSS station (red square). Fault traces are from Ganas et al. (2025). Figure S2: East–West velocity field for the broad area of interest (AOI) for the period 2014–2017. Positive velocity values indicate eastward motion. The local InSAR reference point coincides with the PAT1 GNSS station (red square). Fault traces are from Ganas et al. (2025).

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by A.Z., V.S., I.S., S.A.A.-M. and Z.P. The first draft of the manuscript was written by A.Z., H.D.S. and V.S. Supervision and review were done by H.D.S., G.K., G.D.B., V.K. and E.P. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

Data used for seismic hazard modeling: Source models from <http://hazard.efehr.org/en/home/> (accessed on 19 March 2026), Earthquake catalogue from <https://doi.org/10.5281/zenodo.18494500> (accessed on 19 March 2026), Data used for flood hazard modeling: <https://doi.org/10.5281/zenodo.15745262> (accessed on 19 March 2026), InSAR and GNSS: <https://doi.org/10.5281/zenodo.19113437> (accessed on 19 March 2026).

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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