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Nationwide exposure modelling and scenario-based seismic risk assessment of school buildings in North Macedonia

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Abstract

Seismic risk assessment is an essential component of disaster risk reduction, enabling the identification of vulnerable structures and the prioritisation of mitigation measures. For educational buildings, this importance extends beyond pre-earthquake risk mitigation, as schools also serve as emergency shelters and community gathering points in the aftermath of seismic events, making their seismic safety a matter of both structural and social resilience. Despite their importance, a comprehensive nationwide exposure model for school buildings did not exist for North Macedonia, limiting the implementation of large-scale seismic risk assessments and evidence-based retrofit planning. This study addresses this gap by developing the first national exposure model of school buildings in the country through the integration of existing datasets, governmental records, cadastral information, and publicly available online sources. The resulting model comprises 1,129 schools and characterises their structural typology using a uniform taxonomy, alongside information on occupancy, floor area, and replacement cost. The exposure model is subsequently combined with vulnerability and fragility functions from the GEM Global Vulnerability Data Repository and employed in two earthquake scenarios, considering the 1963 Skopje and 1931 Valandovo earthquakes, the two most seismically significant historical events in the national territory in terms of impact and recorded magnitude, respectively. The analyses quantify the expected damage distribution, structural losses, and fatalities at the municipal level, identifying the most vulnerable building typologies and municipalities under each scenario. The proposed exposure model represents the first harmonised national inventory of school buildings in North Macedonia and provides a transparent and reproducible framework for future seismic risk assessment, emergency planning, and prioritisation of seismic retrofit interventions for school buildings.

Keywords: School buildings, Exposure modelling, Scenario-based seismic risk, North Macedonia

1. Introduction

Educational buildings represent one of the most critical infrastructure types within the built environment, serving not only as centres of learning and education but also as gathering places and emergency shelters following natural disasters such as earthquakes, making the assessment of their seismic risk a priority for disaster risk reduction. The assessment of seismic risk of school buildings has been studied extensively, at scales ranging from case study building assessments (Monteiro 2001, O'Reilly, et al. 2018), to regional (Apostolaki, Riga and Pitilakis 2022, Ribeiro, et al. 2022, Jeswani, Guo and Christopoulos 2022) and national portfolios (Perrone, et al. 2020, Faravelli, et al. 2023, Cattari, et al. 2024, Karafagka, et al. 2023).

Seismic risk is generally defined as a function of seismic hazard, exposure, and vulnerability (Baker, Bradley and Stafford 2021). Each of these components influences the computed risk estimate, and there are many approaches of defining them depending on the available data and the intended purpose of the assessment. Seismic hazard can be assessed deterministically or probabilistically. Exposure models can be developed at different spatial scales and for different building occupancy classes, ranging from coarse national-level aggregations to detailed asset-by-asset inventories. Vulnerability models can be derived empirically from observed earthquake damage data, analytically through numerical structural modelling, or through hybrid combinations of both (Calvi, et al. 2006). This study addresses two of these components in depth: the development of a detailed, nationally comprehensive exposure model for school buildings in North Macedonia, and the direct impact considering the characteristics of two historical events on school buildings.

An exposure model consists of information about the spatial distribution of buildings, their structural attributes, number of occupants, built-up area, and replacement cost. There are two main approaches for gathering data from large-scale spatially distributed systems, known as the top-down and the bottom-up approaches (Zapata, et al. 2022), while there are also two types of taxonomies used in classification of building data: risk-oriented taxonomies (Grünthal 1998, FEMA 2003, Jaiswal, Wald and Porter 2010) and faceted taxonomies (Brzev, et al. 2013, Silva, et al. 2018, D'Ayala, et al. 2020). Recent large-scale European and global initiatives, such as the European Seismic Risk Model (ESRM20) and the global earthquake risk model, have developed harmonised exposure databases for residential, commercial and industrial buildings (Crowley, et al. 2021, Silva, et al. 2023). However, school buildings are not included in these large-scale models, and their risk assessment consequently relies on national or regional initiatives.

For North Macedonia, information such as the number of schools, pupils and administrative staff is publicly available through the State Statistical Office of North Macedonia (SSO 2025), while more detailed information on school locations and names can be obtained from the Ministry of Education and Sciences (MES) upon request. There are no publicly available datasets that includes typological information on the school building stock, and past studies and projects addressing seismic risk of school buildings are limited to specific regions, with no study providing a national-scale exposure model and risk estimate. The recently concluded CRISIS (*Comprehensive RISk assessment of basic services and transport InfraStructure*) project aimed to enhance cross-border cooperation and coordination in disaster risk management, focusing on seismic risk of important infrastructure including school buildings, covering 57 school buildings (Sheshov, et al. 2023). Building on its conclusions, the ongoing EMERGE (*Rapid multi-risk needs evaluation and planning platform*) project is further strengthening regional disaster and emergency management by developing a platform for scenario-based and near real-time seismic and landslide risk evaluation, with 58 school buildings being assessed (EMERGE 2025). The WB MF-EE (*High-level seismic screening of the structures of municipal buildings in North Macedonia*) project performed high-level seismic screening of municipal buildings including schools in several high seismic hazard areas across the country, covering 30 school buildings (Sheshov, et al. 2022). The UNICEF-funded projects conducted by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje assessed the physical and psychological management of earthquake-related emergency situations in schools in North Macedonia, with findings summarised in five reports, two of which contain inventory data on school buildings: IZIIS Report 2001-46 covering 41 school buildings (Milutinovic, et al. 2001a) and IZIIS Report 2001-47 covering 107 school buildings (Milutinovic, et al. 2001b). There are also individual seismic risk assessments of specific school buildings carried out by IZIIS in Skopje. These initiatives cover only limited groups of school buildings, they differ in methodology, classification taxonomies, and spatial coverage, resulting in fragmented, limited, and for some cases even overlapping or outdated findings. To address this gap, this study develops the first nationwide exposure model of school buildings in North Macedonia by integrating information from previous research projects, governmental databases, cadastral records, and publicly available online sources,

comprising 1,129 school structures with detailed information on their location, structural typology, floor area, occupancy, and replacement cost.

North Macedonia is a seismically active region, and studies on risk assessment have been carried out in the past (Sheshov, et al. 2023, Sheshov, et al. 2022, EMERGE 2025, Mircevska, et al. 2019, Jusufi, et al. 2025, Jusufi and Apostolska 2025, Edip and Apostolska 2022), with national risk estimates on residential, commercial and industrial buildings also provided in the European and global risk models (Crowley, et al. 2021, Silva, et al. 2023).

Scenario-based seismic risk assessment is an important tool for understanding the potential consequences that a future event of similar characteristics may cause (Villar-Vega and Silva 2017) and has therefore been widely used in seismic risk estimation. Considering this, in the second part of this study, two earthquake scenarios are explored to assess the damages and losses on school buildings in North Macedonia. Among many significant earthquakes in the territory of North Macedonia (Djumurdjanov, Milutinovic and Salic 2020), the two most important with epicentres in the national territory are the 1963 Skopje earthquake and the 1931 Valandovo earthquake. The former being the most destructive in terms of impact (Petrovski 2004), and the latter the strongest in terms of recorded magnitude located within the national territory (Milutinovic, et al. 2017). The 1963 Skopje earthquake has been extensively studied over the past decades (Zatopek 1968, McKenzie 1972, Anderson and Jackson 1987, Hadzievski 1988, Suhadolc, et al. 2004, Danciu, et al. 2021). Although interpretations differ regarding the fault geometry and rupture mechanism, most authors agree that the 1963 Skopje earthquake resulted from fault movement along a well-defined tectonic structure, with a primary strike-slip component and evidence of both horizontal and vertical displacements. Some studies (McKenzie 1972, Anderson and Jackson 1987, Hadzievski 1988) suggest a strike-slip faulting with possible overthrusting, while others (Zatopek 1968, Drogreshka 2018, Suhadolc, et al. 2004) highlight variations in orientation and rupture characteristics. On the other hand, the fault crossing the Skopje region described in Danciu, et al. (2021), which is also believed to be the one responsible for the Skopje 1963 earthquake, has the characteristics of a normal fault, because it is considered representative of the overall seismicity in the region, as it accounts for other ruptures that have occurred there. Similarly, the 1931 Valandovo earthquake has been studied by several authors (Papadimitriou, et al. 2007, Drogreshka 2018, Danciu, et al. 2021), all of whom interpret the event as resulting from a normal faulting mechanism, consistent with the extensional tectonic regime of the region. The studies differ primarily in the epicentral location, with (Papadimitriou, et al. 2007) being the only one placing the epicentre above the active fault line assumed to be responsible for the event in the ESHM20 (Danciu, et al. 2021).

Based on the above, this study provides: (i) the first national exposure model of school buildings in North Macedonia, and (ii) the first scenario-based seismic risk assessment of the country's school building stock considering two of the most significant historical earthquakes affecting the territory: the 1963 Skopje and the 1931 Valandovo earthquakes. The developed exposure model offers the first comprehensive overview of the national school building stock and establishes a foundation for future probabilistic seismic risk and damage assessments, as well as for the development of seismic risk mitigation strategies and retrofit prioritisation frameworks for school buildings. The results of the earthquake scenarios provide quantitative estimates of the expected physical damage, economic losses, and human impact associated with each scenario, identifying the most vulnerable school buildings and municipalities and offering a scientific basis for evidence-based decision-making and emergency preparedness.

2. Development of an exposure model of school buildings

According to SSO (2025), for the 2022/23 academic year, there were 1,013 primary and 135 secondary schools, with 255,692 pupils and 26,517 teaching staff. Comparable statistics are available for preceding and subsequent academic years, with only minor variations that are not considered

significant for the purposes of this study. North Macedonia is divided into eight statistical regions and 80 municipalities (urban and rural), ten of which form the City of Skopje, the country's capital. The Skopje region contains approximately one-third of the national population and, consequently, the highest number of pupils and teaching staff. In contrast, the Pelagonia region covers the largest geographical area and, accordingly, contains the highest number of schools. More detailed and relevant information on schools and their locations were provided by MES, which are summarised in the following Table 1.

Table 1. General information on municipalities, population and number of school buildings.

Region	Number of municipalities	Number of urban municipalities	Number of rural municipalities	Population based on the latest census in 2021 [SSO]	Number of primary schools, SY2022/23 [MES]	Number of secondary, schools SY22/23 [MES]	Number of primary and secondary school buildings, SY22/23 [MES]	Number of pupils, SY2022/23 [MES]	Number of teaching staff and administration, SY22/23 [MES]
Eastern	13	8	5	150,234	108	14	122	20,124	2,912
Northeastern	6	3	3	152,982	92	8	100	24,281	2,896
Pelagonia	9	5	4	210,431	173	16	189	30,075	3,643
Polog	9	2	7	251,552	148	13	161	37,237	4,901
Skopje	17	9	8	607,007	156	31	187	81,903	8,787
Southeastern	10	6	4	148,387	118	7	125	18,412	2,318
Southwestern	9	5	4	177,398	125	10	135	24,342	3,230
Vardar	7	5	2	138,772	64	8	72	17,899	1,899
	80	**43**	**37**	**1,836,713**	**984**	**107**	**1,091**	**254,273**	**30,586**

SY=school year, SSO=State Statistical Office of NM, MES=Ministry of Education and Sciences of NM

The absence of a centralized, publicly accessible technical database for school buildings in North Macedonia required a multi-source, bottom-up data collection strategy. Several sources were consulted (see Table 2), spanning from official government registries, cadastral records, prior research projects, and online information. Sources are classified as either research-based, providing complete or near-complete structural classification, or registry-based, providing geometric and locational data only.

Table 2. Number of school buildings and type of information provided by different sources.

Abbreviation of the source	Source description and reference	Buildings studied	Buildings in model	Type of information
CRISIS	CRISIS Project (Sheshov, et al. 2023)	57	54	location, complete taxonomy string, building area
EMERGE	EMERGE Project (EMERGE 2025)	58	55	location, complete taxonomy string, building area
WB_MF-EE	WB_MF-EE Project (Sheshov, et al. 2022)	30	30	location, complete taxonomy string, building area
UN-46	UNICEF funded IZIIS project (Milutinovic, et al. 2001a)	41	38	location, complete taxonomy string, building area
UN-47	UNICEF funded IZIIS project (Milutinovic, et al. 2001b)	107	103	location, complete taxonomy string, building area
IZIIS	IZIIS individual assessments	18	18	location, complete taxonomy string, building area
AREC	Agency for Real Estate Cadastre of North Macedonia (AREC 2025)	-	773	number of stories, building area

WEB	Online available information	-	710	location, complete or partial taxonomy string
Other	Buildings not available in the any of the mentioned sources	-	128	number of pupils, number of staff provided by MES

Note: Complete taxonomy string = at least: number of stories, design/construction year, material and LLRS.

Rows highlighted in grey are sources that have not been considered in previous research studies or projects.

Research-based sources (EMERGE 2025, Sheshov, et al. 2023, Sheshov, et al. 2022, Milutinovic, et al. 2001a, Milutinovic, et al. 2001b), collectively provide full or near-complete building classifications for 298 school buildings. For the remaining buildings, typological information was supplemented using cadastral records from the AREC and visual interpretation of photographic evidence obtained from school websites. Since these datasets were developed for different projects and at different points in time, discrepancies between them are expected. In some cases, school buildings included in earlier studies have since been permanently closed or replaced by newly constructed buildings, while in other cases the same school building appears in multiple research projects, resulting in overlaps between datasets. Figure 1 presents the contribution and overlap of the different data sources used in developing the exposure model. This figure highlights the complementary nature of these datasets demonstrating that integrating multiple sources was essential for achieving the most complete and reliable classification of the national school building stock.

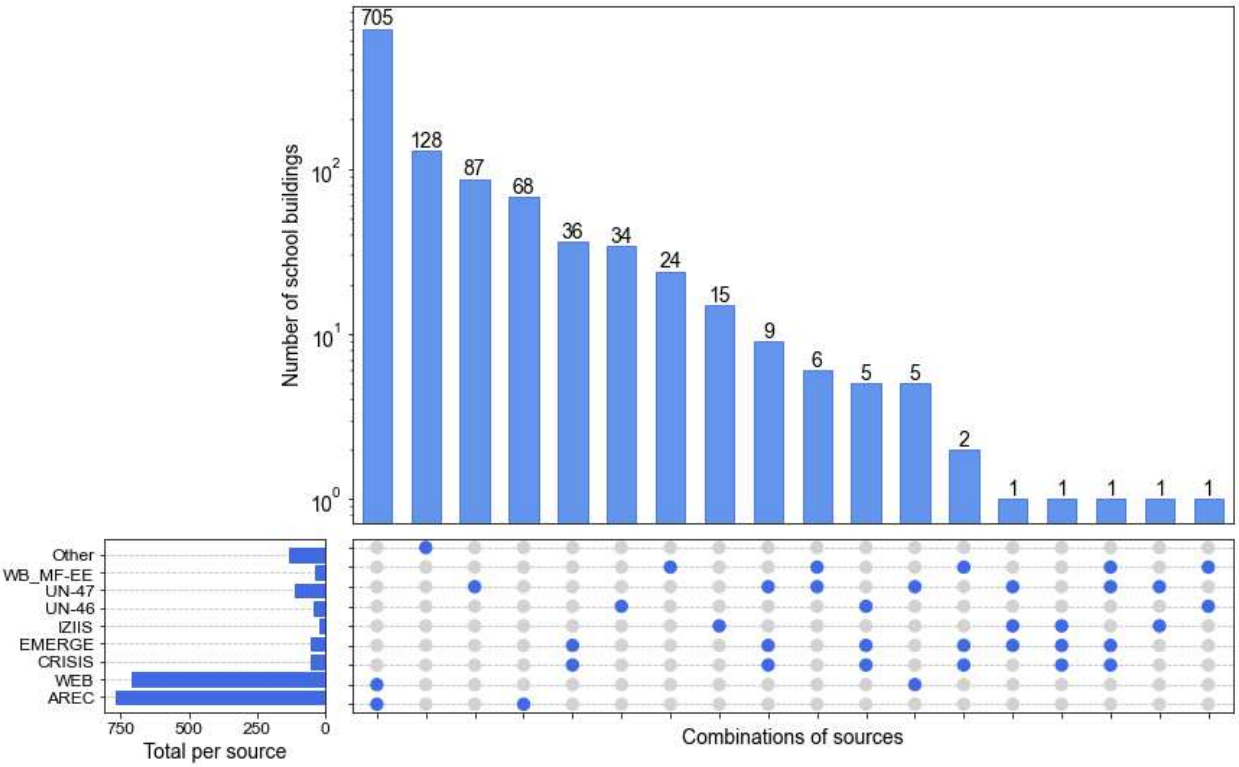


Figure 1. Distribution of number of buildings considered in various sources.

Accounting for all of the above, the total number of school structures considered in the exposure model is **1,129** (1,015 primary and 114 secondary), which differs from both SSO and MES administrative records. The higher number adopted in the exposure model is because, where reliable information was available, additional buildings belonging to the same school complex were explicitly identified and represented as separate structures. In addition, schools officially confirmed as permanently closed were excluded from the model, whereas schools reporting zero enrolled students but without formal closure notices were retained under the assumption that they may resume operation in the future. Figure 2 illustrates the spatial distribution of all school buildings included in the exposure model across the national territory.

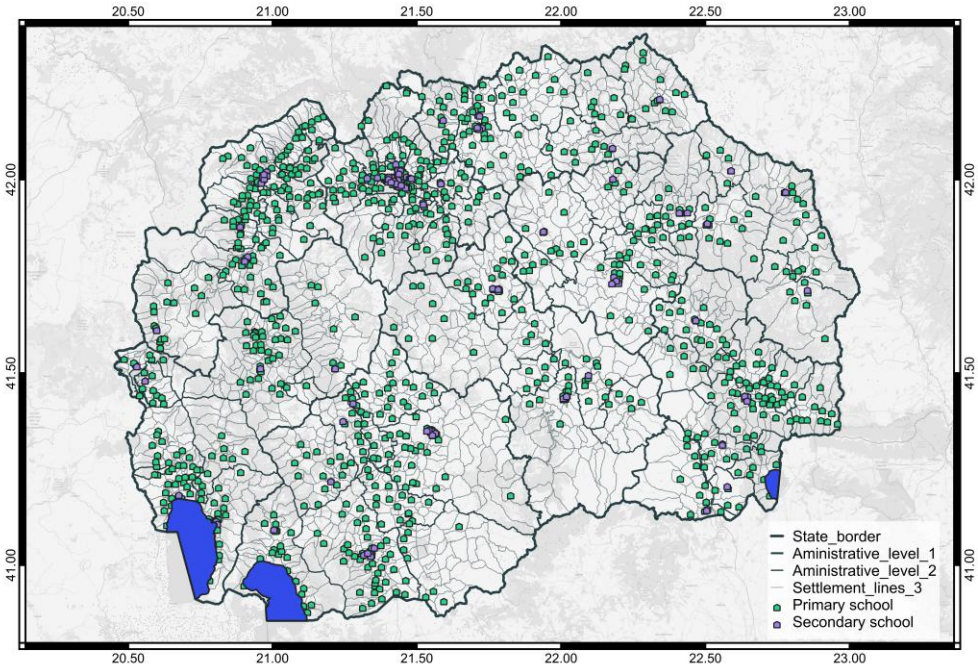
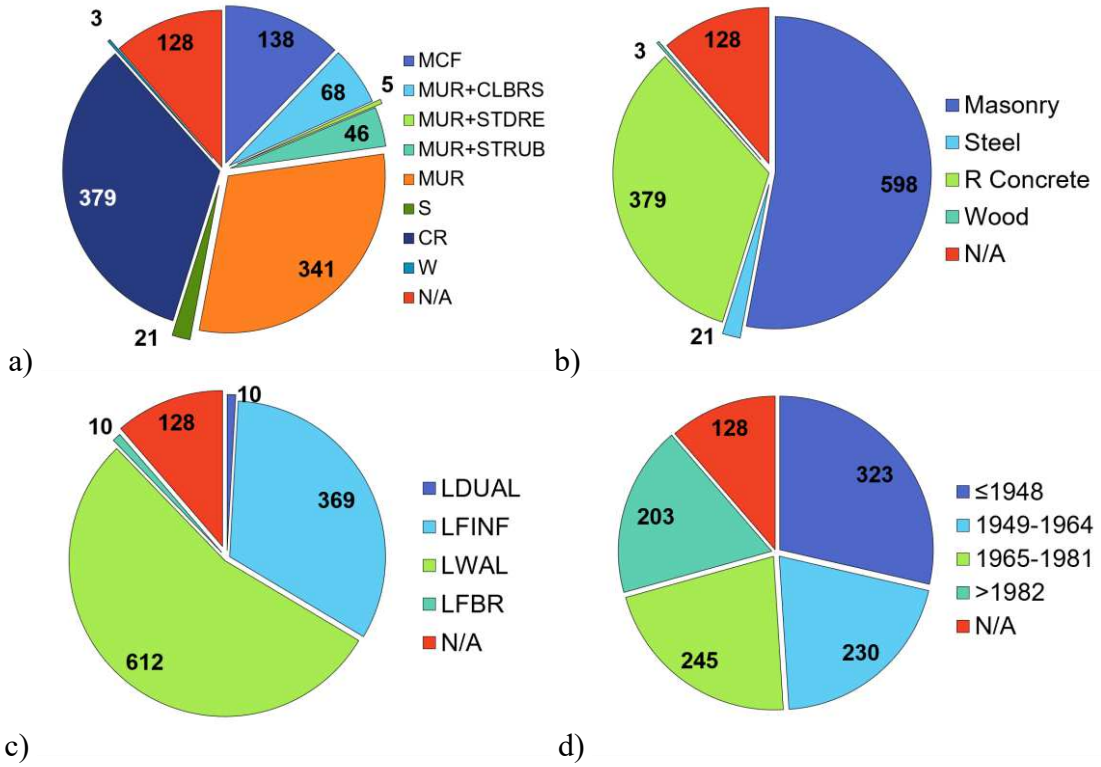
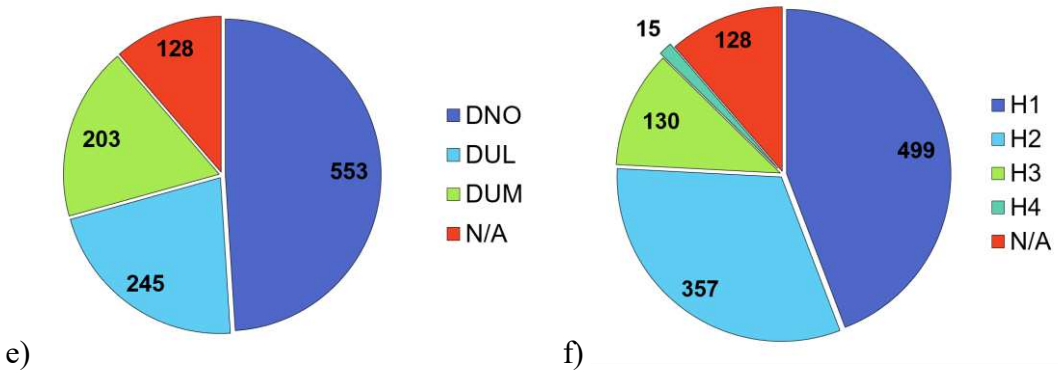


Figure 2. Spatial distribution of school buildings in North Macedonia.

2.1. Building classification

Since the data collected from multiple sources employ different taxonomies and level of detail, a unified taxonomy was adopted to harmonise the different building typologies. Each school building was characterised using the GEM Building Taxonomy v3.2 (Silva, et al. 2022), which comprises several attributes and levels. The most relevant attributes for seismic risk assessment are the lateral load-resisting system (LLRS), structural material, year of construction, number of stories, and wall material (Dabbeek and Silva 2021). These attributes are therefore considered in defining the taxonomy string of each school building, whereas the distribution of buildings across these attributes is shown in Figure 3.





e) f)

Figure 3. School buildings in North Macedonia, in terms of a) structural material (detailed); b) structural material (general); c) LLRS; d) year of design/construction; e) ductility level; and f) number of stories. The abbreviations indicate: MCF = Confined masonry, MUR = Unreinforced masonry, CLBRS = Fired clay solid bricks, STDR = Dressed stone, RUB = Rubble stone, S = Steel, CR = Reinforced concrete, W = Wood, LDUAL = Dual wall-frame system, LFINF = Infilled frame, LWAL = Wall system, LFBR = Braced frame, DNO = Nonductile, DUL = Low ductility, DUM = Medium ductility, H# = Number of stories above ground.

The dominant structural materials are unreinforced masonry (URM, ~36%) and reinforced concrete (RC, ~34%), with confined masonry (MCF) accounting for approximately 12%. The large share of pre-1964 URM buildings, constructed prior to the introduction of seismic design codes in the former Yugoslavia, represents the most seismically vulnerable fraction of the stock. RC buildings constructed between 1964 and 1981 are classified as medium-code (CDM), reflecting the design standards introduced following the 1963 Skopje earthquake. Buildings constructed after 1981 follow the revised JUS 31/81 (1981) code and are assigned medium ductility (DUM) where applicable.

The full set of taxonomy strings present in the exposure model, along with the number of assigned buildings, is given in Table 3. Eighteen distinct taxonomy classes are identified, covering all 1,129 buildings. Three classes, MUR/LWAL+DNO (three story-height variants), P-R<20, and P-R>20, do not correspond directly to a single GEM fragility curve and are handled through a taxonomy mapping in the risk analysis.

Table 3. Present building taxonomy strings for school buildings in North Macedonia.

	Taxonomy string	No. of stories	No. of school buildings
1	CR/LFINF+CDL+DUL	1-4	56
2	CR/LFINF+CDM+DUL	1-4	140
3	CR/LFINF+CDM+DUM	1-4	173
4	CR/LDUAL+CDL+DUL	4	1
5	CR/LDUAL+CDM+DUL	2-3	6
6	CR/LDUAL+CDM+DUM	2-3	3
7	MCF/LWAL+DUL	1-4	129
8	MCF/LWAL+DUM	1-2	9
9	MUR/LWAL+DNO	1-3	341
10	MUR+CLBRS/LWAL+DNO/RWO	1-3	68
11	MUR+STDRE/LWAL+DNO/RWO	1	5
12	MUR+STRUB/LWAL+DNO/RWO	1-2	46
13	S/LWAL+CDL+DUL	1	7
14	S/LWAL+CDM+DUL	1-3	4
15	S/LFBR+CDM+DUM	1-2	10
16	W+WWD/LWAL+DNO	1	3
17	P-R<20	1	18
18	P-R>20	1-2	110

For buildings where one or more taxonomy attributes were absent, conservative assumptions were applied in a consistent and documented manner, guided by the historical evolution of construction practices and design regulations in North Macedonia, engineering judgment based on available school exterior and/or interior publicly available photographs, and comparison with structurally similar buildings for which complete typological data were available. The assumptions adopted in this study are the following:

- *Missing construction year* – When the year of construction was unavailable, assumptions were made based on the visual characteristics of the building and the historical context of construction practices. If the school was clearly identified as an unreinforced masonry structure, it was assumed to have been built either before 1948 or between 1949-1964. This assumption was also applied to single-story regional schools (i.e., i.e., satellite/branch schools that are smaller in size and occupancy, administratively subordinate to a central/main school, and typically located in rural areas). Confined masonry structures were assigned to the periods 1948-1964 or 1964-1981, while reinforced concrete buildings were assumed to have been constructed either between 1964-1981 or after 1981. This classification also applies to three- and four-story schools. These assumptions are consistent with the evolution of construction practices and the development of design regulations in the country.
- *Definition of ductility level* – The ductility level was defined based on the construction year and the code levels proposed by Milutinovic, et al. (2022), while accounting for the structural material as well. Unreinforced masonry buildings were always classified as DNO (nonductile), irrespective of the construction year and type of masonry, whereas confined masonry and steel structures were assigned a minimum ductility level of DUL (low ductility), regardless of their construction year. These assumptions reflect the inherent seismic performance characteristics of the respective structural systems and are consistent with the adopted GEM taxonomy (Silva, et al. 2022), as well as the GEM vulnerability framework (Silva, et al. 2023, Martins, et al. 2021) later considered in the earthquake scenarios.
- *Missing material* – When material information was unavailable, it was inferred by comparison with similar buildings documented in previous research. This was particularly relevant for confined masonry and unreinforced masonry structures with fired brick blocks. For reinforced concrete schools, the identification was more straightforward, as reinforced concrete columns and beams are often visible on the interior and sometimes the exterior. One-story regional schools constructed before 1948 or between 1949-1964 were assumed to be masonry, while all the buildings built after 1981 were assumed with high confidence to be reinforced concrete. For buildings with three or four stories, the structural system was considered to be either reinforced concrete or confined masonry.
- *Missing LLRS* – For masonry buildings, the LLRS was assumed to be a wall system. For reinforced concrete structures, the LLRS was typically considered to be an infilled frame, with dual systems being a rare exception. Concrete dual/wall systems became characteristic in the late 1970s and early 1980s, during the post-Skopje 1963 earthquake era. This period is strongly associated with the rise of brutalist architecture, where exposed reinforced concrete was extensively used both as a structural and architectural expression. Pure moment frames are considered very uncommon in the case of school buildings, because of the architecture of school buildings the bays of reinforced concrete frames are infilled with masonry. For steel structures, those constructed after 1981 are classified as braced frames, whereas those built before 1981 are classified as wall systems. This assumption reflects the occurrence of prefabricated wall panels with steel framing around 1964. The same classification rule is applied to timber structures.
- *Uncertainty in the number of stories* – The number of stories was primarily obtained from the AREC database and verified using available photographs to account for possible misclassifications in cadastral records. An additional source of uncertainty arises when a school complex comprises several structures with different numbers of stories. In cases where these structures could be identified as separate units, they were treated as individual buildings in the exposure model. This

level of distinction was possible only for buildings included in previous research projects or clearly distinguishable in other sources, as photographic evidence alone is often insufficient to determine such details with confidence.

- *Buildings with limited information (location, number of stories, and number of pupils only)* – All buildings in this category are regional schools, with the exception of three central schools located in rural municipalities. Conservative assumptions were adopted based on school type and occupancy. Regional schools with fewer than 50 pupils were classified as masonry structures of unknown block type, with a wall LLRS and a construction year prior to 1948. For two-story schools, centrally located schools, or those with more than 50 pupils, the same conservative assumption of masonry structures with unknown block type and wall LLRS was applied, but the construction year was set between 1948 and 1964. All buildings in this category were classified as DNO, consistent with statistics derived from comparable schools for which detailed technical information was available in previous research.
- *Buildings with very limited information (location and number of pupils only)* – All buildings in this category are primary regional schools. Out of the total of 128 schools, 110 have fewer than 20 pupils, while 18 have more than 20 pupils. Since no typological information is available for these buildings, two distinct taxonomy strings, P-R>20 and P-R<20 (Table 3), were assigned which can subsequently be linked through a taxonomy mapping scheme to several vulnerability functions derived from statistics of comparable schools with complete technical information.

The exposure model is a dynamic product that can be updated as new inspection or census data becomes available. Despite the assumptions required for incomplete records, the model represents a substantial improvement over existing national and European datasets, none of which previously included school buildings explicitly.

2.2. Occupancy and replacement cost

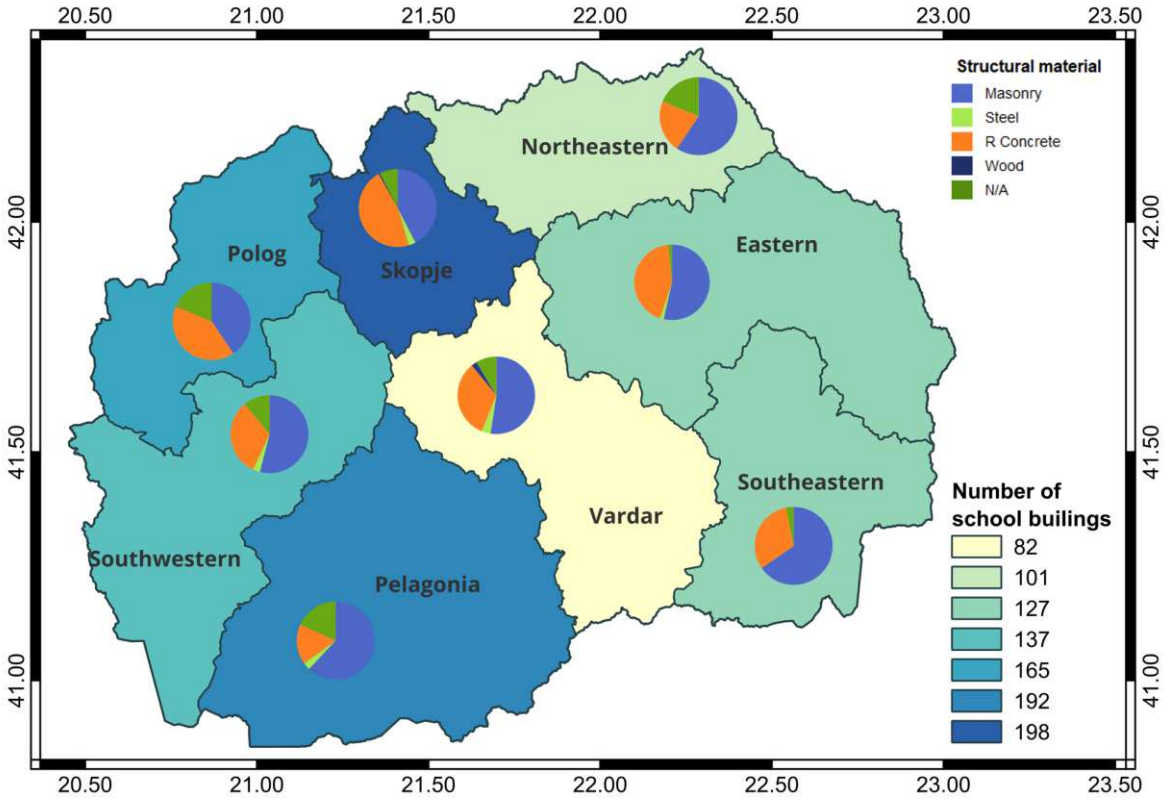
In addition to the general information of school buildings (administrative and locational attributes) and the taxonomy string assigned to them, the model quantifies three complementary metrics that also represent part of the exposure model and are important for the quantification of damage and losses in subsequent risk assessment: occupancy, building area, and replacement cost.

Occupancy data (number of pupils, teaching and administrative staff) are sourced directly from MES for each building. The total school-day occupancy across all 1,129 school buildings (Figure 4a) amounts to 284,859 people (254,273 pupils and 30,586 staff). These values can be used in subsequent fatality loss calculations, where daytime occupancy is assumed. While individual building-level data of occupancy are available for each school in the exposure model, the aggregated regional distribution of occupancy is shown in Figure 4b.

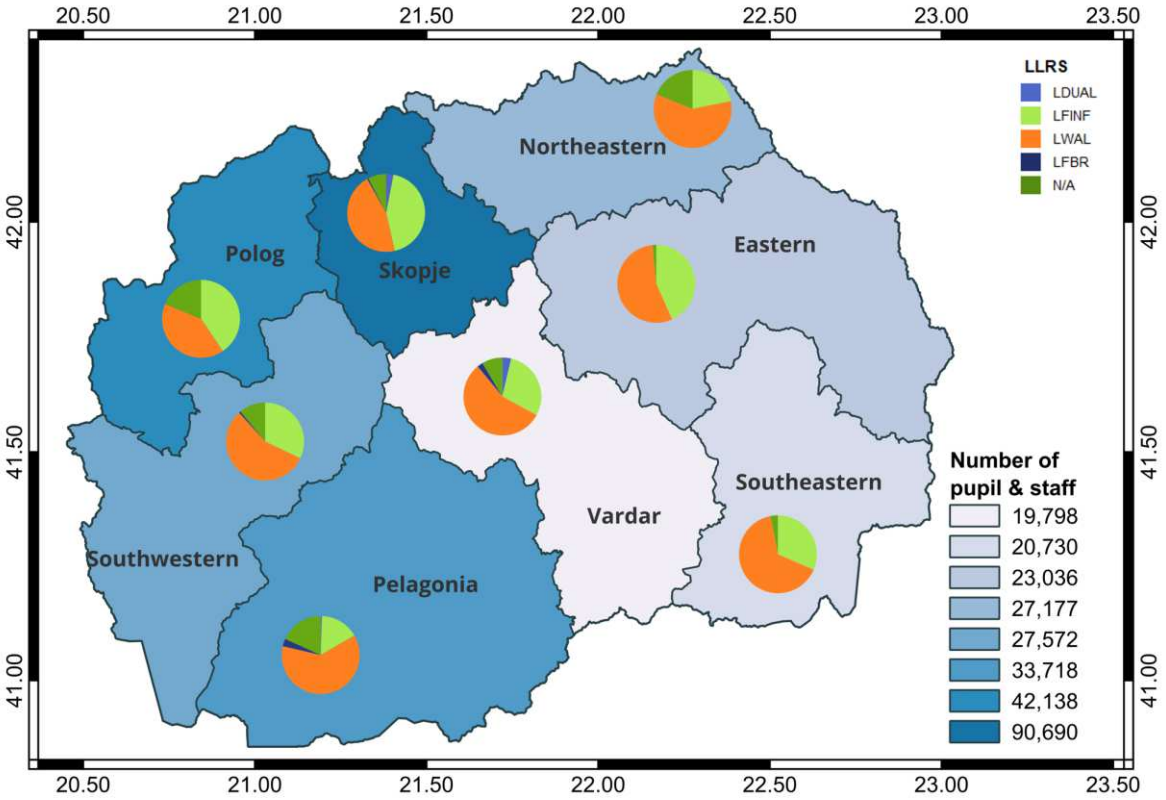
The gross floor area of each school building was determined through a stepwise procedure. For school buildings included in previous research studies, where building area data were already available, the values were compared against cadastral data to ensure accuracy. For buildings that were not part of a previous project, but can be located in the cadastral data, the area was obtained directly from AREC. Since AREC provides only net areas, the gross area was calculated as $A_{gross} = 1.15A_{net}$, where the 15% factor accounts for perimeter and partition walls, determined based on engineering judgment. For buildings with limited datasets (classified as *Other* in Table 2 and Figure 1), the net area was estimated in accordance with the *Regulation for Design Standards and Norms* (Official Gazette of North Macedonia No. 60/2012), which specifies a minimum of 7-10 m^2/student, a corridor area calculated as 0.7*(students + staff)*1.8 m, and a minimum of two sanitary units (5 m^2 each) per classroom. For schools with fewer than five enrolled pupils, a minimum area of 30 m^2 was assumed to ensure a realistic representation of building size. The total gross floor area of the national school building stock is estimated at approximately 1.58 million m^2. The Skopje region accounts for the

largest share (>500,000 m^2), consistent with its demographic predominance, while the Northeastern, Eastern and Southeastern regions each contribute less than 200,000 m^2 (Figure 4c).

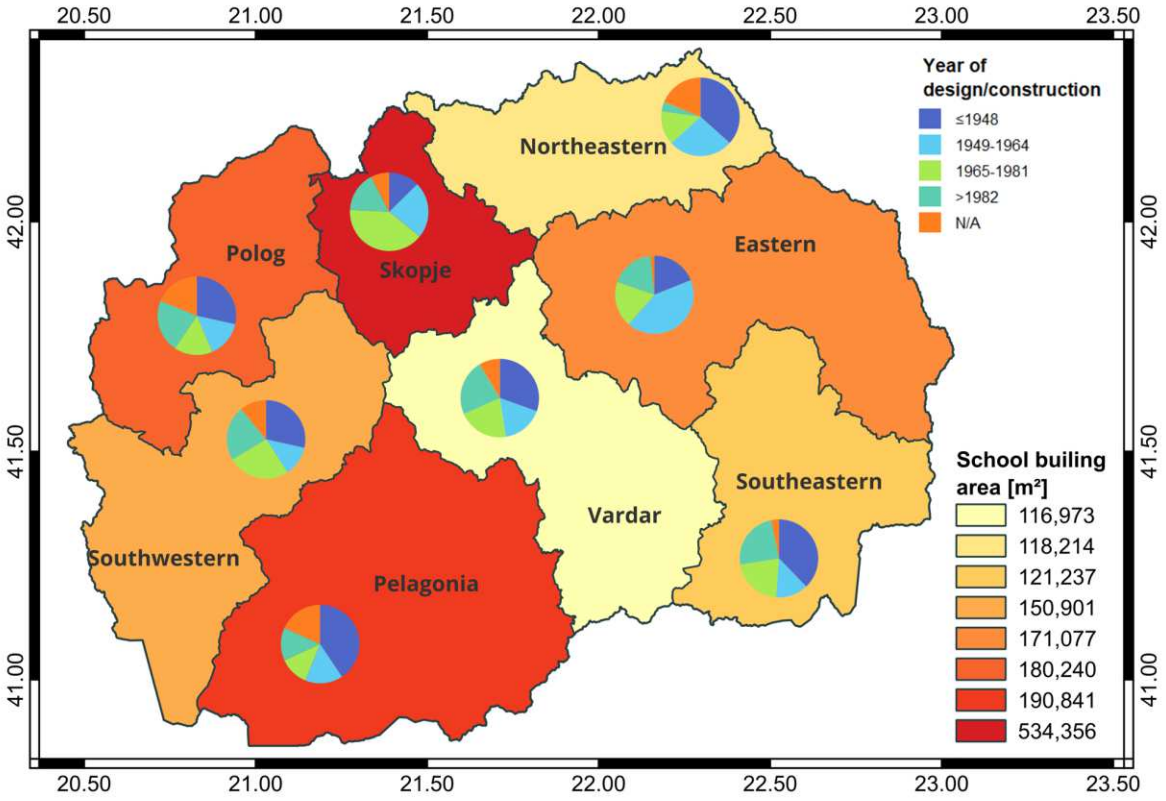
The replacement cost represents the construction cost of a new building with the same capacity but according to the current design regulation, without considering the price of land or the market value (Dabbeek and Silva 2021). A uniform unit cost of 810 €/m^2 (50,220.00 MKD/m^2) is applied to all buildings, derived from the official *Price list for the minimum fee for the services of authorized architects and authorized engineers in the field of building construction* (Official Gazette or North Macedonia no. 54/2023). While this uniform assumption does not introduce variability relevant to location- or typology-specific costs, it provides a consistent and grounded reference for subsequent loss calculations. Only structural replacement costs are presented here, while non-structural and content losses are excluded due to the absence of building-specific data and education-vulnerability fragility functions for these components in North Macedonia. Applied to the total floor area of 1.58 million m^2, the aggregate national replacement cost of school building stock is estimated at about 1.28 billion € (or 79.54 billion MKD). The regional distribution of replacement cost mirrors that of the building area, with the Skopje region accounting for approximately one-third of the national total (Figure 4d).



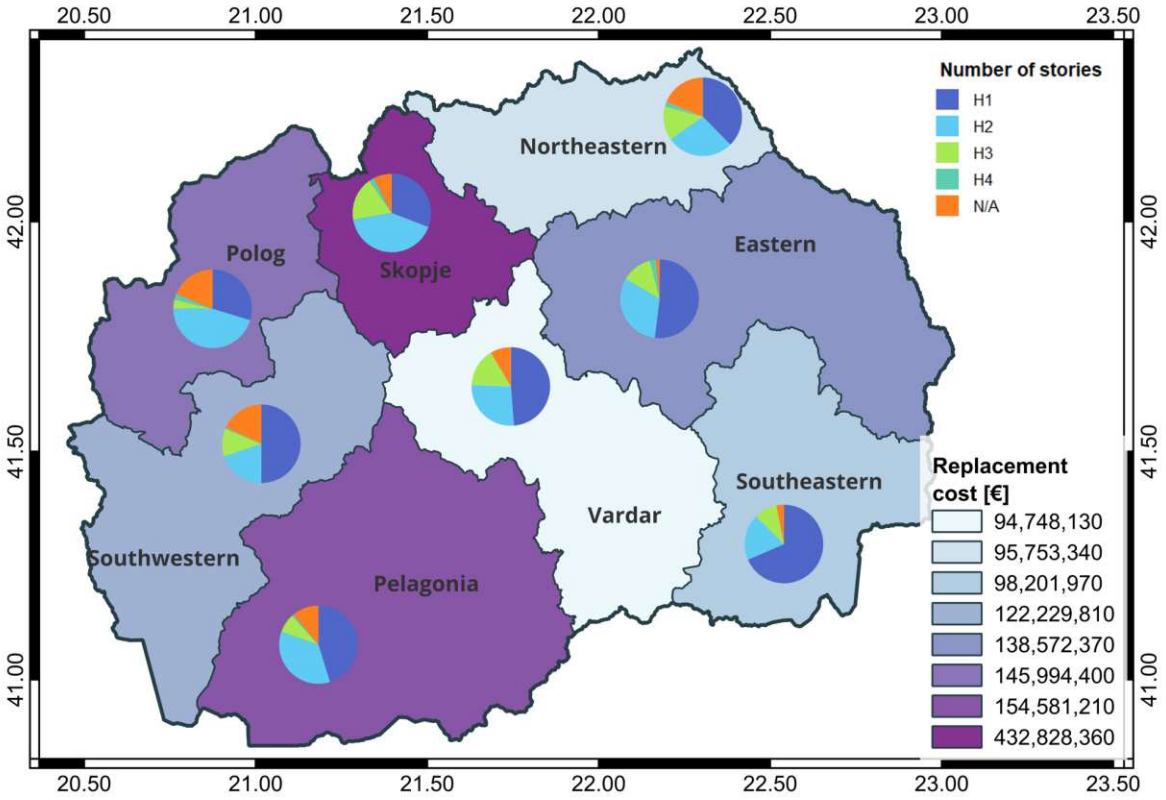
a) Number of school buildings, and structural material



b) Number of pupil and staff, and type of LLRS



c) Total area of school buildings, and year of construction



d) Total replacement cost of all buildings, and story height

Figure 4. Exposure statistics across regions in North Macedonia.

3. Scenario-based seismic risk assessment

In the second part of this study, two earthquake scenarios were explored to investigate the expected damage and losses in the school building stock. Among many significant earthquakes in the territory of North Macedonia (Djumurdjanov, Milutinovic and Salic 2020), the scenario-based risk is computed for two most significant ones: the 1963 M6.1 Skopje and the M6.7 1931 Valandovo earthquakes. For each scenario, the definition of the ground shaking, exposure model and the vulnerability functions are described in the following sections.

3.1. Seismic hazard and ground motion fields

Ground motion fields (GMFs) for both scenarios were generated using the Scenario Calculator of the OpenQuake Engine (Silva, et al. 2014). Site amplification was incorporated using the Vs30-based site condition model from ESRM20 (Crowley, et al. 2021), which provides spatially distributed Vs30 values on a 30 arc-second grid across Europe. The spatial distribution of Vs30 values across the territory of North Macedonia is shown in Figure 5, where the dashed rectangles indicate the two regions considered in the scenario analyses: the Skopje region for the 1963 scenario and the Southeastern/Vardar regions for the 1931 scenario.

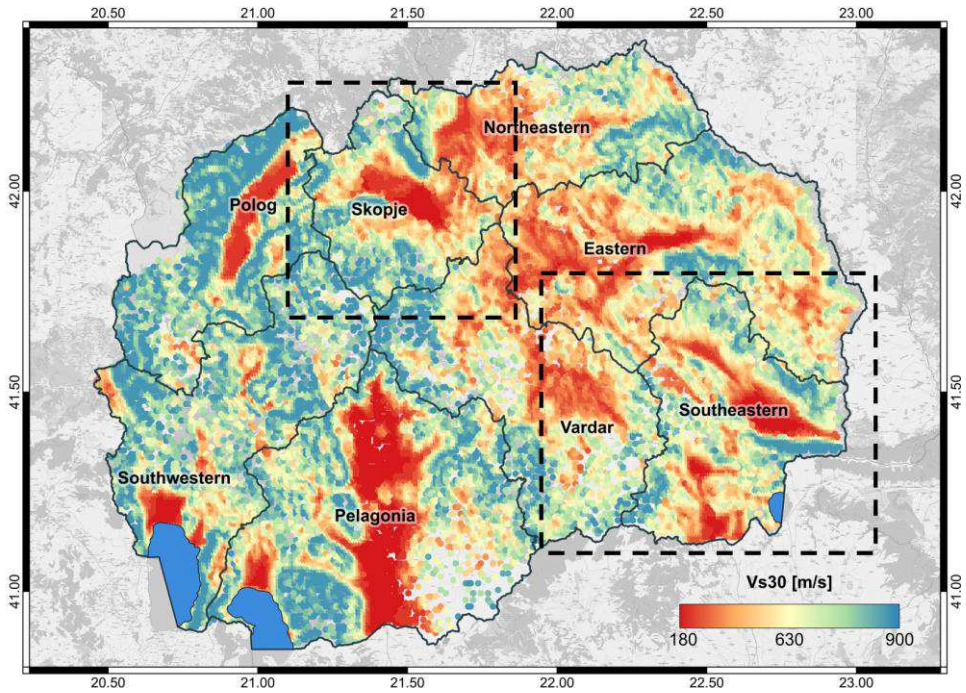


Figure 5. Spatial distribution of Vs30 values across the territory of North Macedonia (Crowley, et al. 2021), with the dashed rectangles indicating the regions considered in the scenario analysis.

The implemented ground motion prediction equations (GMPEs) follow the logic tree proposed by (Salic, et al. 2017), which was implemented in the official national seismic hazard model for North Macedonia (Milutinovic, et al. 2016). The logic tree consists of four active shallow crustal GMPEs (Boore, et al. 2014, Chiou and Youngs 2014, Akkar, Sandikkaya and Bommer 2014, Bindi, et al. 2014), with weights of 0.30, 0.30, 0.20 and 0.20, respectively. To account for the aleatory variability, a truncation level of 3 was adopted and 1000 GMFs were generated per GMPE, yielding 4000 realisations per scenario.

3.1.1. 1963 Skopje earthquake

Fault parameters for the 1963 Skopje earthquake vary across the literature (Zatopek 1968, McKenzie 1972, Anderson and Jackson 1987, Hadzievski 1988, Suhadolc, et al. 2004, Drogreshka 2018, Danciu, et al. 2021), reflecting the limited availability of instrumental recordings. Four fault models are considered (see Table 4), spanning strike-slip and normal faulting interpretations. A sensitivity analysis examining the influence of magnitude, depth, and kinematics on the resulting GMF was conducted and is discussed in detail in Jusufi (2026). The selected fault model adopts a strike-slip mechanism based on Drogreshka (2018), consistent with the official interpretation of the Seismological Observatory of Skopje, with a shallower rupture depth of 9 km (Suhadolc, et al. 2004). This combination produces a conservative PGA distribution while remaining consistent with the source parameters reported in the literature (Figure 6).

Table 4. Input parameters for scenario-based hazard analysis of 1963 Skopje earthquake.

	Reference	Strike	Dip	Rake	Depth	M_w	Kin.
1	Drogreshka (2018)	303	77	-1	15	6.01	SS
2	Anderson and Jackson (1987)	303	74	-21	5	5.30	SS
3	Suhadolc, et al. (2004)	298	79	22	9	5.90	SS
4	ESHM20, Danciu, et al. (2021)	209	70	-55	10	5.96	NF
	Adopted	**303**	**77**	**-1**	**9**	**6.01**	**SS**

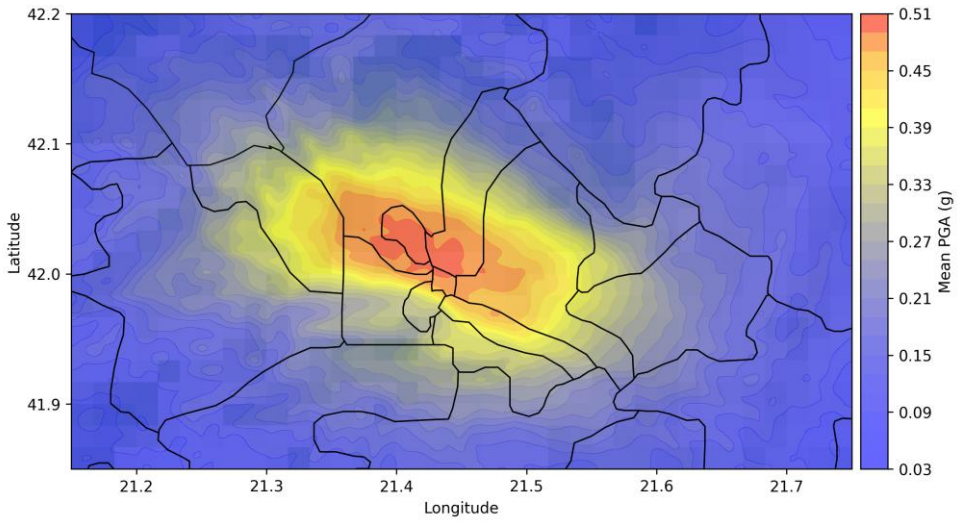


Figure 6. Mean distribution of PGA for the 1963 Skopje earthquake.

3.1.2. 1931 Valandovo earthquake

In contrast to the 1963 Skopje earthquake, the source parameters of the 1931 Valandovo earthquake show general consistency across the available literature (Papadimitriou, et al. 2007, Drogreshka 2018, Danciu, et al. 2021), indicating a normal-faulting mechanism. Two fault models were considered (see Table 5), and the model proposed by Papadimitriou, et al. (2007) was adopted, as it provides a more conservative representation through a broader spatial distribution of high PGA values and is based on the most detailed fault geometry dataset available for this event (Figure 7).

Table 5. Input parameters for scenario-based hazard analysis of 1931 Valandovo earthquake.

	Reference	Strike	Dip	Rake	Depth	M_w	Kin.
1	Papadimitriou, et al. (2007)	270	53	-93	9	6.70	NF
2	ESHM20, Danciu, et al. (2021)	103	45	-60	11	6.73	NF
	Adopted	**270**	**53**	**-93**	**9**	**6.70**	**NF**

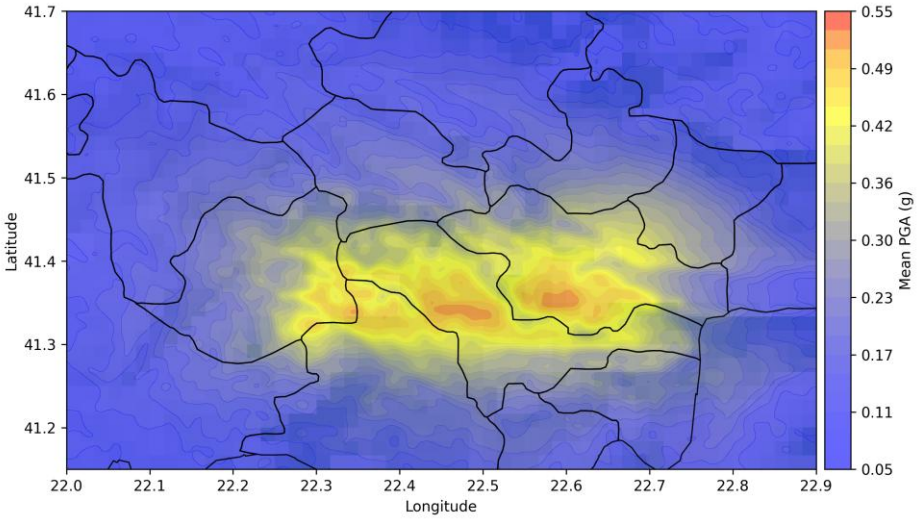


Figure 7. Mean distribution of PGA for the 1931 Valandovo earthquake.

3.2. Exposure models considered in the risk analysis

The exposure of school buildings considered in each scenario is extracted directly from the national exposure model developed in Section 2, retaining only the buildings located within the affected regions.

The Skopje region comprises 198 school buildings (165 primary and 33 secondary), of which 134 are central and 64 are regional schools, distributed across 17 municipalities. The total floor area amounts to 534,356 m², with an estimated replacement cost of €432,828,360, approximately one-third of the national total. Total school-day occupancy in the region is 90,690 persons (81,903 pupils and 8,787 staff). All secondary schools, with the exception of two in the rural municipalities of Saraj and Ilinden, fall under the direct administration of the City of Skopje. The spatial distribution of school buildings across the affected municipalities is shown in Figure 8.

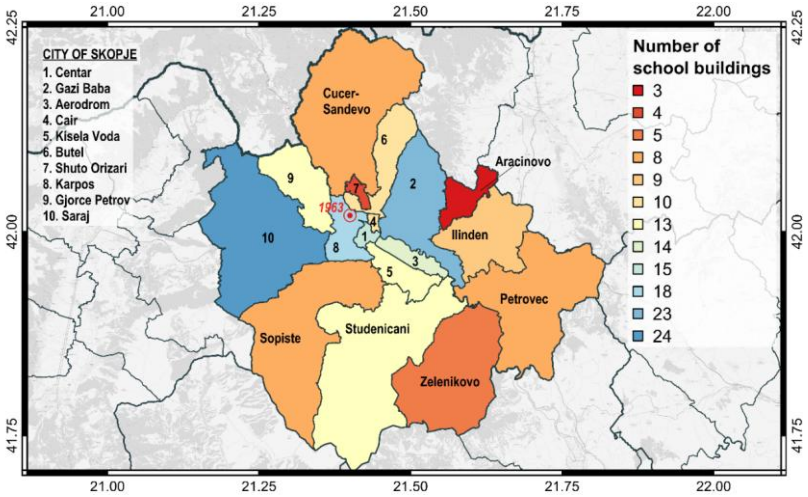


Figure 8. Spatial distribution of school buildings across the municipalities affected by the 1963 Skopje earthquake scenario.

The 1931 Valandovo earthquake affects the South-Eastern region and part of the Vardar region, collectively comprising 164 school buildings (152 primary and 12 secondary), of which 56 are central and 108 are regional schools distributed across 13 municipalities (10 in the South-Eastern region; Kavadarci, Negotino, and Demir Kapija in the Vardar region). The total floor area is 176,042 m², with an estimated replacement cost of €142,594,020. Total school-day occupancy amounts to 31,196 persons (27,937 pupils and 3,259 staff). The municipal distribution of school buildings in the affected area is shown in Figure 9.

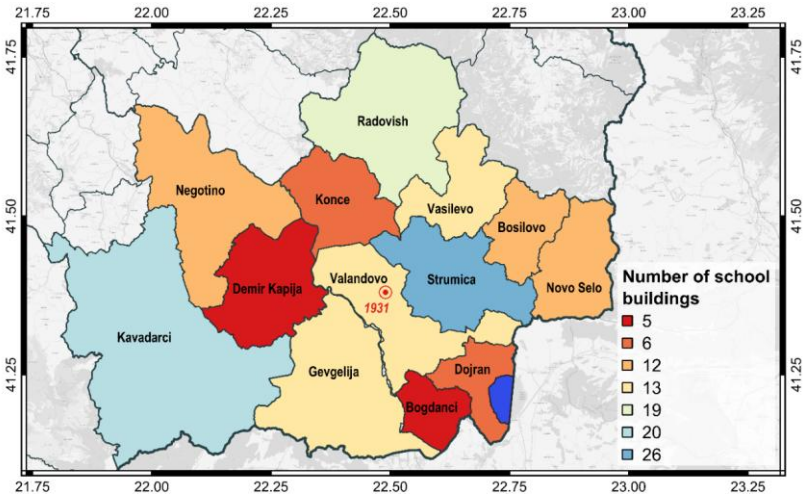


Figure 9. Spatial distribution of school buildings across the municipalities affected by the 1931 Valandovo earthquake scenario.

3.3. Vulnerability model and taxonomy mapping

The availability of fragility and vulnerability functions for North Macedonia remains limited. Existing functions include the vulnerability models developed under the RISK-UE project (Milutinovic and Trendafiloski, 2003) for the building classes defined accordingly to the GEM Taxonomy (Brzev, et al. 2013), CR/LFM+CDL/HEX:2,6,10 and CR/LFM+CDM/HEX: 2,6,10, as well several fragility functions for residential RC buildings (Dumova 2000) for the classes CR/LFM+DUC/HEX:6 and CR/LDUAL+DUC/HEX:16. These functions are not compatible with the dominant school building classes in North Macedonia, which are predominantly masonry structures of one storey (see Figure 3). Recent initiatives towards the development of locally derived consequence models for North Macedonia are presented in Milkova, et al. (2025).

Given the limited availability of locally calibrated functions, the fragility and vulnerability functions from the GEM Global Vulnerability Model (Silva, et al. 2023, Martins, et al. 2021) were adopted in this study. The fragility functions are derived from nonlinear cloud analysis on equivalent SDOF oscillators using ground motion datasets from different tectonic environments, with capacity curves modelled as trilinear or quadrilinear backbone models depending on the structural system, and P-Delta effects incorporated through height-dependent reduction factors (Silva, et al. 2023). The structural loss calculations are based on four damage states defined in terms of spectral displacement thresholds, as described in Martins and Silva (2020).

Of the 42 building classes represented in the exposure model, 37 were directly matched to existing GEM vulnerability and fragility functions, accounting for 660 buildings (~58%) of the total exposure model of school buildings in North Macedonia. The remaining five classes, which have no direct GEM equivalent class, were assigned vulnerability and fragility functions through a taxonomy mapping scheme. For each unmapped class, the assignment was based on the statistical distribution of structurally comparable school buildings with known taxonomy class, ensuring complete coverage of the exposure model while minimising subjective assumptions. The 469 buildings assigned via the mapping scheme represent ~42% of the total stock. The adopted mapping scheme and weighting factors are summarised in Table 6.

Table 6. Taxonomy mapping scheme for building classes without a direct GEM equivalent.

Building taxonomy	Converted building taxonomy	Weight
MUR/LWAL+DNO/H1-R	MUR+CLBRS/LWAL+DNO/RWO/H1	0.47
	MUR+STRUB/LWAL+DNO/RWO/H1	0.47
	MUR+STDRE/LWAL+DNO/RWO/H1	0.06
MUR/LWAL+DNO/H1-C	MUR+CLBRS/LWAL+DNO/RWO/H1	0.60
	MUR+STRUB/LWAL+DNO/RWO/H1	0.40
MUR/LWAL+DNO/H2-R	MUR+CLBRS/LWAL+DNO/RWO/H2	0.60
	MUR+STRUB/LWAL+DNO/RWO/H2	0.40
MUR/LWAL+DNO/H2-C	MUR+CLBRS/LWAL+DNO/RWO/H1	0.94
	MUR+STRUB/LWAL+DNO/RWO/H1	0.06
MUR/LWAL+DNO/H3	MUR+CLBRS/LWAL+DNO/RWO/H1	1.00
P-R<20	CR/LFINF+CDM+DUM/H1	0.38
	MUR+CLBRS/LWAL+DNO/RWO/H1	0.22
	MUR+STRUB/LWAL+DNO/RWO/H1	0.31
	S/LFBR+CDM+DUM/H1	0.09
P-R>20	CR/LFINF+CDM+DUM/H1	0.35
	CR/LFINF+CDM+DUM/H2	0.09
	MCF/LWAL+DUL/H1	0.12
	MCF/LWAL+DUL/H2	0.09
	MUR+CLBRS/LWAL+DNO/RWO/H1	0.20
	MUR+STRUB/LWAL+DNO/RWO/H1	0.15

3.4. Scenario-based seismic risk: 1963 Skopje earthquake

The scenario-based damage and loss estimates for the 1963 Skopje earthquake are derived using the Scenario Damage and Scenario Risk Calculators of the OpenQuake Engine (Silva, et al. 2014), considering the 4000 GMFs generated from the hazard analysis, the exposure model of schools in the Skopje region (Figure 8) and the adopted vulnerability functions described in the previous section.

3.4.1. Damage assessment

Approximately 48% of the 198 school buildings in the region are expected to sustain no damage. The probability of reaching any single damage state above slight is generally below 30%. Complete damage is estimated for approximately 13% of the stock (26 buildings), with the breakdown by school level and administrative status given in Table 7 and Figure 10.

Table 7. Mean damage distribution for the 1963 Skopje earthquake.

		Complete	Extensive	Moderate	Slight	No damage
Level	Primary	20	8	15	37	85
	Secondary	7	2	4	9	11
Status	Central	22	9	16	35	52
	Regional	4	2	4	10	44

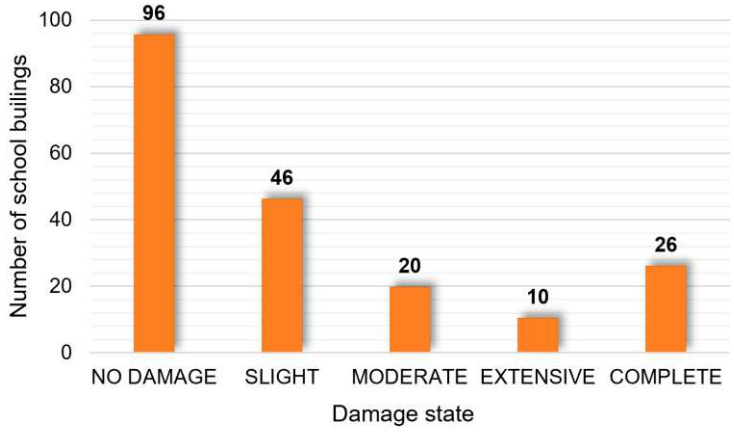


Figure 10. Mean damage distribution from the 1963 Skopje earthquake scenario.

A direct comparison with historically observed damage from the actual 1963 event is not straightforward. According to Jurukovski (1997), eight primary and 11 secondary school buildings were destroyed, and a further 22 primary and 13 secondary schools were extensively damaged, with a large number of additional buildings reported to have sustained moderate or slight damage. The current model projects a different distribution for three main reasons: i) the exposure model reflects the post-1963 building stock, repaired, retrofitted, or replaced, and includes buildings designed according to two successive seismic design codes introduced after the event, JUS 39/64 (1964) and JUS 31/81 (1981); ii) the globally derived GEM fragility functions are less efficient than locally calibrated functions would be; and iii) the estimated ground shaking is a modelled approximation of the historical event rather than a recorded ground motion. Since no instrumental recordings exist for the 1963 Skopje earthquake, the ground motion fields rely on source parameters derived from the literature and should be viewed as one plausible representation of the event rather than an exact reconstruction. Such discrepancies between modelled and observed damage are inherent to scenario-based analysis. Despite these limitations, the results confirm that seismic risk to school buildings in the Skopje region remains significant under a recurrence of a comparable event.

The spatial distribution of damage by municipality is shown in Figure 11. Municipalities forming the City of Skopje, particularly those closest to the epicentre in Karpos, show the highest concentrations

of complete and extensive damage, with complete damage probabilities comparable to slight damage probabilities in the innermost municipalities. This contrasts with the outlying rural municipalities, where distance from the epicentre and a smaller building stock yield comparatively lower damage levels.

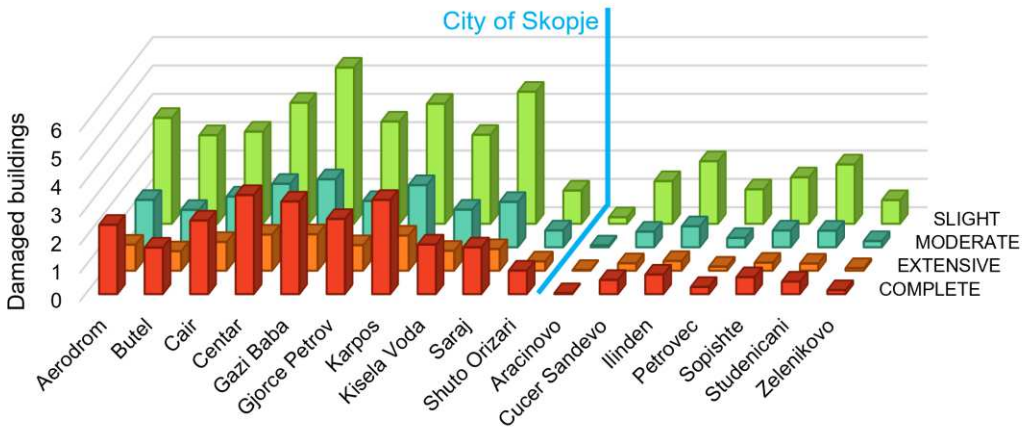


Figure 11. Mean damage distribution by municipality for the 1963 Skopje earthquake scenario.

Concerning the damage distribution based on the type of construction (Figure 12), the highest probability of complete damage is associated with infilled reinforced concrete (CR/LFINF) structures. This class is the most prevalent in the Skopje region (86 buildings, ~43% of the stock), of which 56 exhibit low ductility. Significant probabilities of complete damage are also observed for unreinforced masonry (MUR/LWAL) and confined masonry (MCF/LWAL) structures. This outcome is expected, as these structural systems correspond to schools designed and constructed prior to 1964, under either no seismic code or low code requirements, which inherently limits their seismic resistance and increases their likelihood to damage.

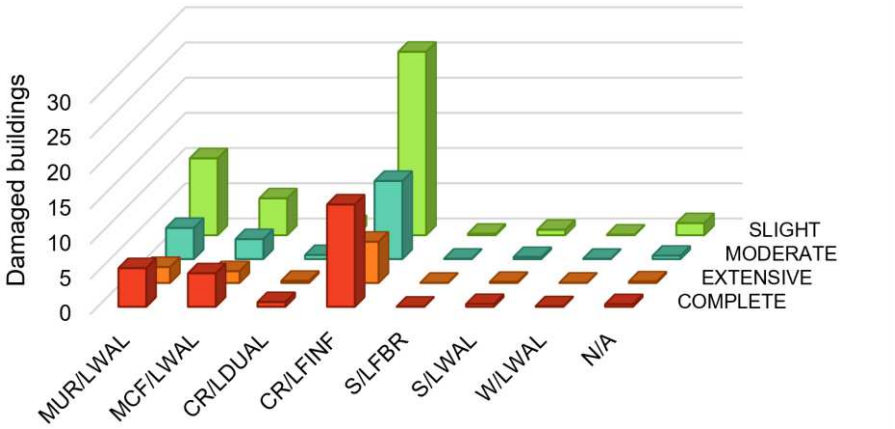


Figure 12. Mean damage distribution by building material and LLRS for the 1963 Skopje earthquake scenario.

3.4.2. **Loss assessment**

The mean economic loss for the Skopje region is €113,852,462, corresponding to approximately 26% of the total replacement cost of the school portfolio. The mean estimated loss of life is 163 occupants. Loss statistics disaggregated by school level and administrative status are summarised in Table 8, while the distribution of economic losses and fatalities by municipality and settlement are presented in Figure 13 and Figure 14.

Table 8. Loss statistics for the 1963 Skopje earthquake scenario.

		Structural losses	Fatalities
Level	Primary	€ 79,068,746	124
	Secondary	€ 34,783,716	39
Status	Central	€ 109,984,780	159
	Regional	€ 3,867,682	4

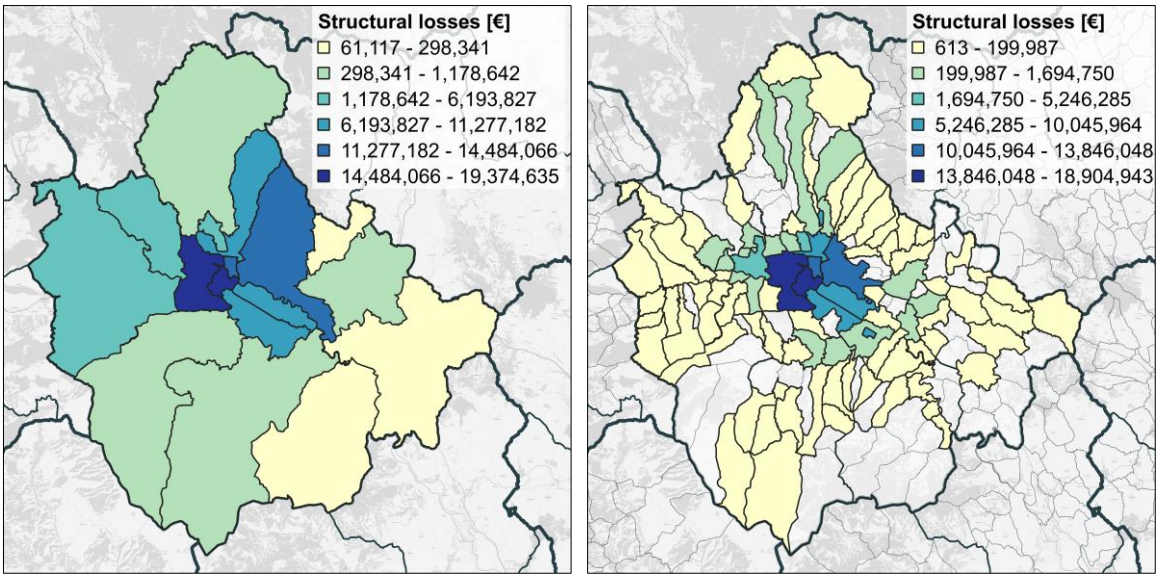


Figure 13. Mean structural losses by municipality (left) and settlement (right) for the 1963 Skopje earthquake scenario.

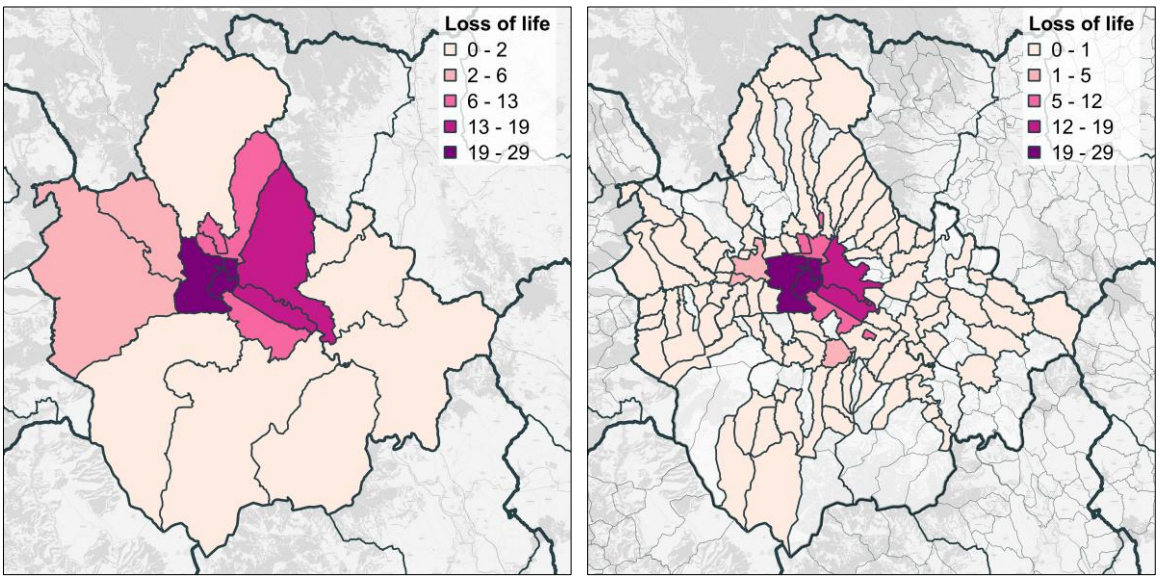


Figure 14. Mean loss of life by municipality (left) and settlement (right) for the 1963 Skopje earthquake scenario.

Both the economic and human losses are concentrated in the urban core of Skopje, most notably in the municipalities of Karpos and Centar, the closest to the epicentre and the most densely built-up. Despite their relatively small geographic areas, these municipalities account for a disproportionate share of losses due to the high density of school buildings and occupants.

With respect to fatalities, the analysed scenario assumes only daytime occupancy. The 1963 earthquake struck at 04:22AM during a school holiday period (26 July), when school buildings were

unoccupied, and even though 1,070 fatalities were reported (Petrovski 2004), they were almost entirely attributable to residential building collapse. The fatality estimates presented here are therefore not intended for comparison with historical records but rather represent the potential human impact of a similar event occurring during school hours today. Fatality vulnerability functions carry significant uncertainties arising from secondary factors beyond structural damage state (Manfredi, et al., 2023) and should be interpreted accordingly.

The municipal-level patterns in Figure 13 and Figure 14 are particularly relevant from a governance perspective, as for North Macedonia, both primary and secondary schools fall under the administration of their respective municipalities. Identifying which municipalities face the highest projected losses can directly inform local authorities on where to prioritise seismic retrofit investment and emergency preparedness measures.

3.5. Scenario-based seismic risk: 1931 Valandovo earthquake

3.5.1. Damage assessment

Approximately 61% of the 164 school buildings are expected to sustain no damage. Complete damage is estimated for less than 10% of the stock (14 buildings). Unlike the Skopje scenario, where central schools dominated the complete damage category, here the pattern is reversed: regional schools account for the majority of the completely damaged buildings (Table 9 and Figure 15).

Table 9. Mean damage distribution from the 1931 Valandovo earthquake scenario.

		Complete	Extensive	Moderate	Slight	No damage
Level	Primary	13	5	11	29	94
	Secondary	1	1	1	3	6
Status	Central	5	2	5	13	31
	Regional	9	4	7	19	69

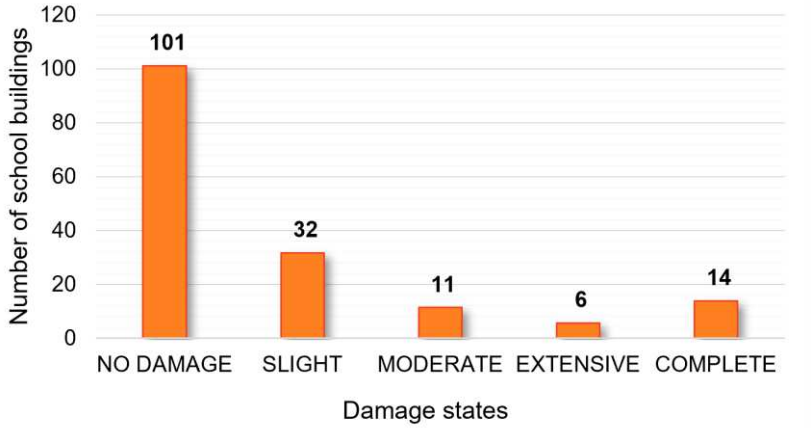


Figure 15. Mean damage distribution from the 1931 Valandovo earthquake scenario.

The municipal damage distribution (Figure 16) shows that Strumica, Valandovo, and Bosilevo are the most affected municipalities, reflecting their proximity to the epicentre and their relatively larger school building counts. The three municipalities located in the Vardar region, being more distant, show comparatively lower damage levels. An additional factor is that these municipalities are rural municipalities, and their settlement pattern is quite dispersed: school buildings are spread across villages, meaning that even within a single municipality, individual schools may experience substantially different shaking intensities depending on their distance from the rupture.

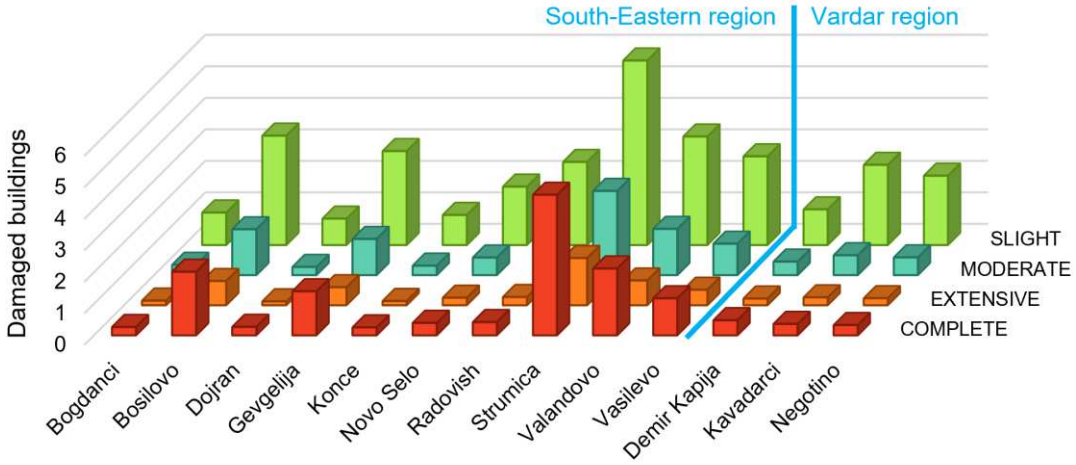


Figure 16. Mean damage distribution by municipality for the 1931 Valandovo earthquake scenario.

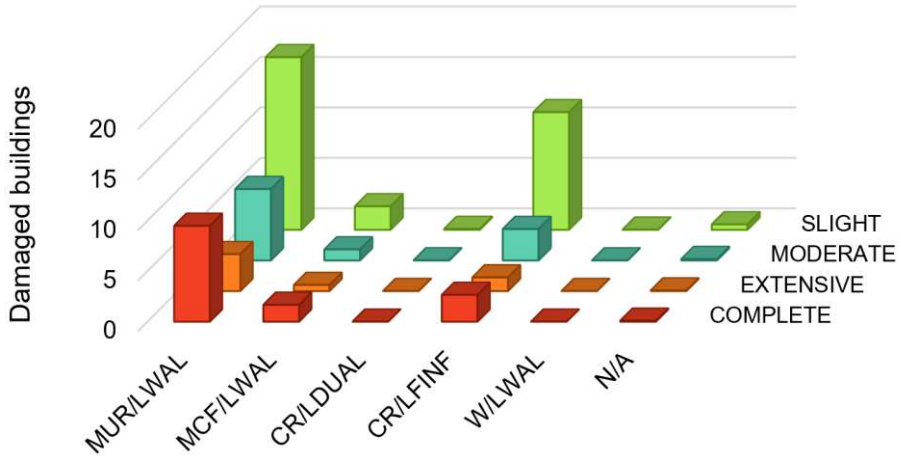


Figure 17. Mean damage distribution by building material and LLRS for the 1931 Valandovo earthquake scenario.

By building class (Figure 17), MUR/LWAL buildings show the highest probability of complete damage. This class is particularly common among regional schools throughout North Macedonia and corresponds predominantly to pre-1964 construction with no seismic code provisions. CR/LFINF buildings, while present in the affected region, largely sustain only slight or no damage, consistent with their more robust structural characteristics and later construction dates.

A direct comparison with historically observed damage from the actual 1931 event is informative but limited. According to Milutinovic, et al. (2017), approximately 45 settlements were affected by the earthquake sequence, with 89% of the total building stock destroyed or severely damaged in the immediate epicentral area and 39% in the surrounding region. The current model projects a substantially lower damage fraction for two main reasons: the exposure model reflects the current building stock, repaired, retrofitted, or entirely replaced since 1931, rather than the stock that existed at the time of the event, which consisted almost entirely of unreinforced stone masonry rural construction of very low seismic resistance.

3.5.2. Loss assessment

The mean structural loss for the affected region is €21,144,094, corresponding to approximately 15% of the regional replacement cost. The mean estimated loss of life is 31 occupants. Loss statistics disaggregated by school level and administrative status are given in Table 10, while the distribution of structural losses and fatalities by municipality and settlement are given in Figure 18 and Figure 19.

Table 10. Loss statistics for the 1931 Valandovo earthquake scenario.

		Structural losses	Fatalities
Level	Primary	€ 13,644,301	20
	Secondary	€ 2,901,700	7
Status	Central	€ 17,105,494	29
	Regional	€ 4,038,600	1

The estimated losses from the scenario-based risk analysis are considerable in terms of both economic damage and fatalities. They are less severe than those observed for the Skopje scenario but remain significant. The spatial distribution of losses confirms Strumica as the most affected municipality in both structural and fatality terms, driven by its larger and denser urban school stock and its proximity to the epicentre. Valandovo, though similarly close to the epicentre, sustains lower absolute losses due to its smaller population and fewer school buildings.

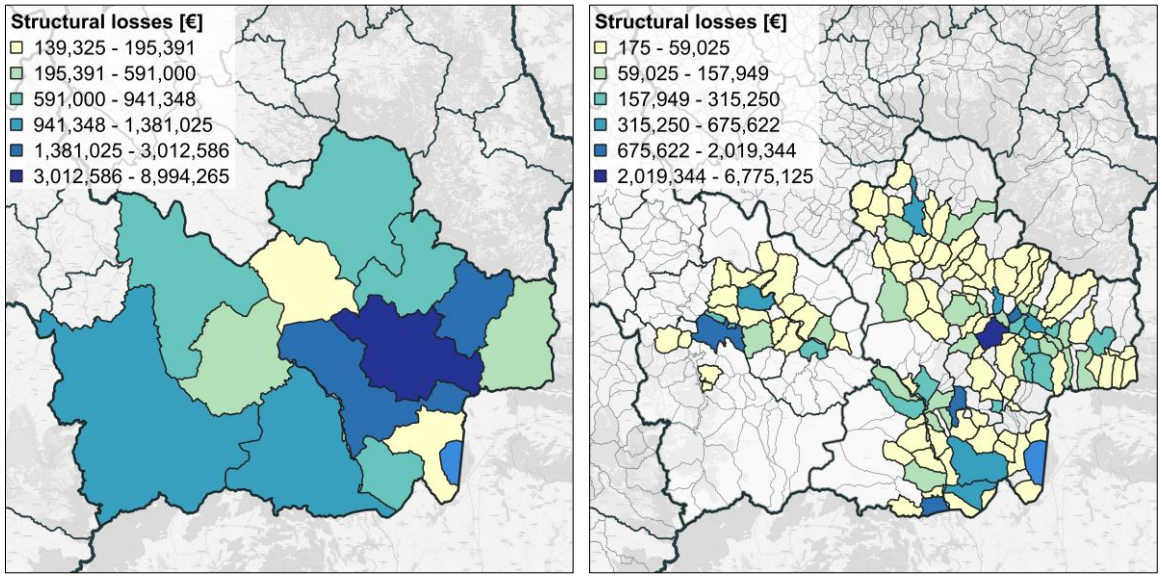


Figure 18. Mean structural losses by municipality (left) and settlement (right) for the 1931 Valandovo earthquake scenario.

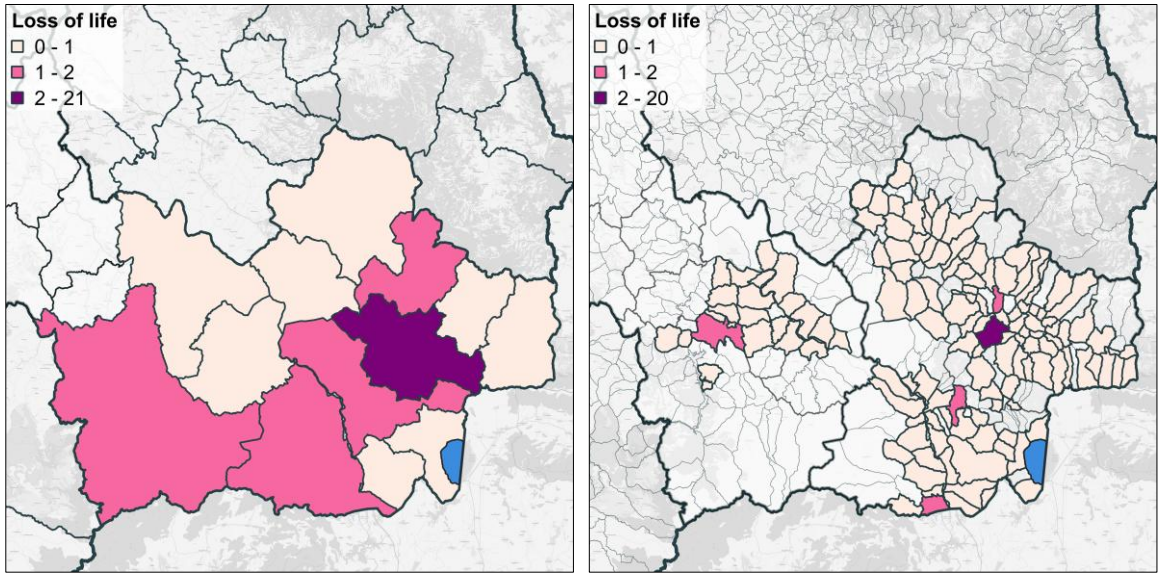


Figure 19. Mean loss of life by municipality (left) and settlement (right) for the 1931 Valandovo earthquake scenario.

Regarding fatalities, nearly all are concentrated within the municipality of Strumica, with only few exceptions Valandovo, Vasilevo, Gevgelija and Kavadarci. According to Milutinovic, et al. (2017), the event caused 31 fatalities and 82 injuries across the affected region, a disproportionately low toll given the extent of structural destruction, largely attributed to the foreshock sequence that preceded the main shock on 8 March, which prompted much of the population to evacuate their homes. The highest concentration of fatalities occurred in the village of Pirava (municipality of Valandovo), where 19 of the 31 deaths resulted from residents returning indoors due to rainfall before the main shock struck. None of the reported fatalities is attributed to the collapse or damage of a school building. This is consistent with the timing of the event, which occurred at 01:50:24 am, when school buildings were unoccupied. The modelled estimate of 31 fatalities therefore represents the potential human impact of a comparable event occurring during school hours and cannot be directly compared to historical records.

4. Conclusions

This study makes two complementary contributions to the seismic risk assessment of school buildings in North Macedonia. The first is the development of the first nationwide exposure model of school buildings, integrating multiple data sources to characterise 1,129 primary and secondary school buildings according to a uniform classification system. The developed model provides the geographic location, administrative classification, building class, floor area, occupancy and replacement cost for each asset, representing approximately 1.58 million m² of school floor area with an estimated national replacement cost of €1,283 million. The exposure model indicates that unreinforced masonry buildings and low-ductility reinforced concrete infilled frame buildings together constitute approximately 70% of the national school building stock, highlighting the significant seismic vulnerability of school buildings in the country.

The second contribution is a scenario-based seismic risk assessment for the 1963 Skopje and 1931 Valandovo earthquakes, representing the two most significant historical events in the national territory in terms of impact and recorded magnitude, respectively. The Skopje scenario produces substantially higher losses due to the higher density, larger floor area, and greater occupancy of the affected building stock, while the Valandovo scenario, though producing lower absolute losses, shows a higher proportion of rural schools reaching complete damage. Both scenarios consistently identify pre-1964 unreinforced masonry buildings and low-ductility reinforced concrete infilled frame buildings as the most vulnerable school typologies, and both demonstrate that seismic risk is spatially concentrated in the municipalities closest to the respective epicentres.

The results provide the first comprehensive overview of the scenario-based seismic risk of the national school building stock and establish a scientific basis for evidence-based decision-making in seismic risk mitigation. The identification of the most vulnerable building typologies and municipalities under both scenarios offers directly actionable information for prioritising seismic retrofit investment, updating emergency preparedness plans, and guiding future probabilistic seismic risk assessments for educational facilities in North Macedonia.

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