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RESEARCH ARTICLE - SOLID EARTH SCIENCES

Seismic hazard assessment in the Podhale region, Poland—zone and smoothed seismicity approach

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Abstract

Poland is characterised by weak natural seismicity. However, the last analysis of the natural seismic hazard in the country was carried out 24 years ago. Therefore, a significant fraction of the recorded seismicity is not included in the hazard estimates currently used, either because recent observations are not taken into account or because of improved seismic network capabilities. Furthermore, Podhale, in the Tatra Mountains, is the only region with recorded permanent natural seismicity. This study aims to create new seismic hazard maps of the Podhale region from a newly compiled database containing information on historical events and two complete instrumental catalogues (regional and local), each at a different level of completeness. The local catalogue was recorded over the last few years. Two seismic hazard assessment techniques were applied, namely the conventional (zone-based) (Cornell in Bull Seismol Soc Am 58(5): 1583–1606, 1968) and the smoothed seismicity model, based on the spatial distribution of seismicity. The earthquake recurrence parameters were estimated using the methodology developed by Kijko et al. (Bull Seismol Soc Am 106: 1210–1222, 2016). The new seismic hazard model incorporates several improvements, such as a comprehensive logic tree and a new set of ground motion models. The new maps provide a more detailed assessment of the seismic hazards of the investigated area. Moreover, they predict higher PGA than previous seismic hazard maps covering Podhale, like global European Seismic Hazard Maps 2013 and 2020.

Keywords Seismic hazard · Zone method · Smoothed seismicity model · Podhale · Carpathians

Introduction

Current knowledge of the seismicity of the Podhale area is considerably superior to that compiled by Schenk et al. (2001) twenty-four years ago. The most recent monitoring shows a clear difference in seismic hazards in the eastern and western parts of Podhale, with a clear gap between the two areas. Figure 1 shows the seismic hazard assessment (SHA) by Schenk et al. (2001) and the current seismicity of Podhale. However, small regions such as Podhale were treated as parts of significantly larger areas for which Schenk et al. (2001) calculated the seismic hazard. The results of this approach differ from the current seismic monitoring results in the region. We aimed to calculate a detailed seismic hazard for a low but recordable seismic area to determine whether doing so would facilitate correcting the local hazard maps.

Poland is known as a region of low tectonic origin seismicity. Knowledge of tectonic seismic activity in Poland has been based on historical reports (Guterch 2009c; Guterch and Kozák 2015) and events M > 2 recorded by the Polish Seismological Network (PLSN) (Draber et al. 1998, 2000a, 2000b, 2001, 2002, 2003a, 2003b, 2004; Guterch 1995, 2006, 2007, 2009a, 2009b, 2009c; Guterch et al. 2005; Guterch and Kozák 2015). The PLSN comprises stations located 100–300 km apart, and the aim of the network is to record teleseismic and mining-induced events (Rudziński et al. 2021). The largest recorded earthquake in the area occurred on 30 November 2004, with $M_w = 4.5$ (Wiejacz and Dębski 2009; Guterch 2006, 2009c; Guterch and Kozák 2015).

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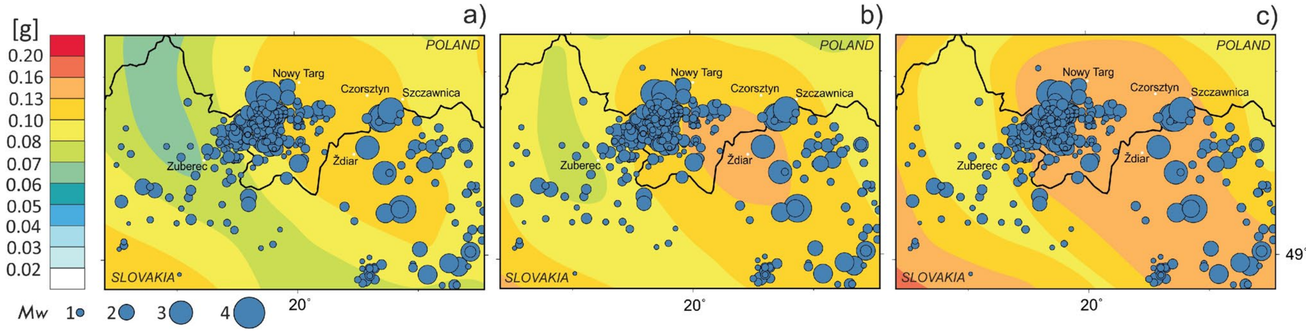

Fig. 1 Current seismicity of Podhale against the background of the seismic hazard map compiled by Schenk et al. (2001). PGA hazard map with a 10% probability of exceedance within **a** 50 years, **b** 105 years, and **c** 527 years; (return period of **a** 475 years; **b** 1 000 years

A project, *Monitoring of Seismic Hazard of the Territory of Poland* (MSHTP), conducted during 2008–2012, focused on detecting minor events in regions of known historical earthquakes (Trojanowski et al. 2015). The project aimed to build a national database of natural seismic activity for SHA. The Podhale region in the Polish part of the Western Carpathians range is the only area where continuous seismic activity is observed. Only sporadic events were recorded in other regions (Plesiewicz and Wiszniowski 2015). After completion of the MSHTP project, seismic monitoring of the Podhale area continued in several projects implemented by the Institute of Geophysics, Polish Academy of Sciences, and commissioned by the Polish Geological Institute—National Research Institute. The projects are: *Permanent Geodynamic Monitoring of Poland* (PMGP)—Stage I (2013–2016); *Geodynamic Monitoring of Poland*—Stage II (2018), Stage III (2019–2021) and, starting from 2022, Stage IV. During network operation, more than 200 earthquakes were recorded, with a tectonic origin event of Mw 0.7–2.4 being recorded once a month on average. However, most events were small, often at the noise level, and imperceptible to humans.

The database of seismic events compiled during the monitoring of the entire Podhale area facilitates compiling a more detailed SHA. Furthermore, the database enables upgrading of the previous SHA that was completed by, e.g. Grünthal et al. (1999), Schenk et al. (2000, 2001), and Giardini et al. (2014). In the approach followed by Schenk and coworkers, the division into seismogenic zones focused on the spatial distribution of seismicity patterns, with the geological criterion being of secondary importance. However, in the Global Seismic Hazard Assessment Program (GSHAP) project (Danciu et al. 2021, 2024), as well as in the Seismic Hazard Harmonisation in Europe (SHARE) project (Giardini et al. 2014), the available information on the seismicity of the investigated area was inferior. Therefore, we used another approach with larger seismic zones for the main geological units, with the first zone including the Podhale synclinorium and the Pieniny Klippen Belt. The main group of earthquakes in this zone is probably correlated with the Peripieninic fault zone inside the first zone. A lack of information on the focal mechanism of events prevented the division of the first zone into smaller sub-zones correlated with minor faults. For instance, the scattered events in the Tatra Massif were included in another zone, the sub-Tatra fault, owing to the complicated geological structure and the small number of events. The aim of our zone approach was comparing the results with another seismic hazard assessment procedure based on smoothing seismic activity. In addition, we aimed to show the superior performance of the smoothed seismicity model (SSM), in which the probability of occurrence of events plays a critical role. The superiority of the zoneless method relates to the outlined seismogenic zones being highly unreliable (e.g. Schenk et al. 2001; Grünthal et al. 2018). However, the new database of seismic events contains a sufficient number of earthquakes, enabling differentiation between the seismological zones. This delineation was not possible in previous studies. In particular, based on the spatial patterns of seismicity, it was possible to determine whether the SHA in Podhale allowed for the location of critical structures such as geothermal power plants.

To assess the earthquake recurrence parameters of the study area, we used the technique developed by Kijko and Sellevoll (1989, 1992) and Kijko et al. (2016). Their approach allows assessment of the required parameters when catalogues are incomplete, the earthquake magnitudes are uncertain, and the earthquake recurrence model is not precisely known. We did not record strong ground motions during the study period. Therefore, we could not develop a characteristic ground motion model (GMM) for our study area, and we used GMMs from regions with similar tectonic environments.

The work aims to update seismic hazard estimates for the Podhale region by applying a logic-tree approach to capture epistemic uncertainties.

Seismic hazard analysis method

Seismic hazards for the Podhale region are computed using the classical technique of Cornell (1968). Probabilistic seismic hazard analysis (PSHA) provides the probability that ground motion in a specified place would be exceeded at least once during a given time (McGuire 2004; Kijko 2020). The probability of exceeding a chosen ground motion value y, $P\left[Y > y\right]$, is evaluated for a specific magnitude of earthquake at a particular distance multiplied by the probability that such an earthquake would occur. The calculations are repeated for possible magnitudes and earthquake locations, and the results are summed. The probability $P\left[Y > y\right]$ is estimated with the support of the Total Probability Theorem (Benjamin and Cornell 1970; Kijko 2020) as:

$$P\left[Y \geq y\right] = \int_{m_{min}}^{m_{max}} \int_{R|M} P\left[Y \geq y|m, r\right] f_M(m) f_{R|M}(r|m) dr dm, \quad (1)$$

where $P[Y \geq y|m, r]$ is the probability described by a ground motion model (GMM) conditional probability that the ground motion will exceed the chosen level y for a given distance r and magnitude m; $f_M(m)$ is the probability density function (PDF) of earthquake magnitude, and $f_{R|M}(r|m)$ is the conditional PDF of the distance from the given magnitude seismic event.

If, in the area of interest, we could distinguish n_S seismic sources with the annual average rate of seismic event magnitudes ν_i, then the entire average annual rate of earthquakes takes the form:

$$\lambda(y) = \sum_{i=1}^{n_S} \nu_i \int_{m_{min}}^{m_{max}} \int_{R|M} P\left[Y \geq y|m, r\right] f_{M,i}(m) f_{R|M,i}(r|m) dr dm. \quad (2)$$

Relying on the assumption that the ground motion parameter y is a log-normal random variable $\ln(y) = g(m, r) + \varepsilon$, where ε is random error. The standard choice is that the probability $P\left[Y \geq y|m, r\right]$ is a normal, complementary cumulative distribution function (CDF) with a known mean and standard deviation, which are defined as $\overline{\ln(y)}$ and $\sigma_{\ln(y)}$, respectively. In most PSHA applications, it is assumed that earthquake magnitudes follow the Gutenberg–Richter relation, which implies that $f_M(m)$ is a negative, exponential distribution shifted from zero to m_{min} and truncated from the top by m_{max} (Page 1968):

$$f_M(m) = \frac{\beta \exp\left[-\left(m - m_{min}\right)\right]}{1 - \exp\left[-\left(m_{max} - m_{min}\right)\right]}, \quad (3)$$

where $\beta = b$ ln10 and b is the parameter of the frequency-magnitude Gutenberg–Richter relation.

Cornell's approach (Cornell 1968) to seismic hazard assumes that the occurrence of an earthquake in time follows the Poisson distribution. Therefore, before the computation of PSHA, the dependent events, such as foreshocks and aftershocks, must be removed.

Seismic data

Seismic hazard assessment for the Podhale region is based on earthquake databases, such as the historical catalogue (Guterch and Kozák 2015), bulletins of the Institute of Geophysics Polish Academy of Sciences (Draber et al. 1998, 2000a, 2000b, 2001, 2002, 2003a, 2003b, 2004; Guterch 1995, 2006, 2007, 2009a, 2009b, 2009c), the catalogue of seismicity of Podhale recorded by the MSHTP project (Trojanowski et al. 2015), analysis of the seismicity recorded by PMGP projects, and the Slovak seismic catalogue. The Slovak catalogue was made available to us by the Department of Seismology of the Earth Science Institute of the Slovak Academy of Sciences (Cipciar et al. 2024; ESI SAS 2004).

Seismic hazard studies in Podhale include only seismicity of tectonic origin and do not consider anthropogenic seismicity generated by the Czorsztyn Reservoir (Białoń et al. 2015; Rudziński et al. 2021). The investigated area was divided into two parts, namely the western one, with tectonic-origin seismicity, and the eastern one, with seismic activity triggered by the Czorsztyn Reservoir (Fig. 1). Consequently, our analysis includes only the western part of Podhale.

Unfortunately, seismic events in the available catalogues were expressed in different magnitudes, M_w, M_L, and intensity I_0 conventions. Therefore, converting them into one magnitude type was necessary before conducting any computation. Following Grünthal and Wahlström (2003), all magnitudes were converted into moment magnitudes M_w. Magnitude M_L was converted to M_w employing the formula by Grünthal et al. (2009) for Central Europe:

$$M_w = 0.0376 M_L^2 + 0.646 M_L + 0.53, \quad (4)$$

with error:

$$\sigma^2 = \left(0.97 M_L^4 - 12.4 M_L^3 + 58.4 M_L^2 - 120 M_L + 921\right) \cdot 10^{-4}.$$

Intensity I_0 was converted into M_w in two steps. In the first step, M_L is calculated employing the formula by Grünthal et al. (2009):

$$M_L = 0.81 I_0 + 0.49 \log h - 0.85, \quad (5)$$

$$\sigma^2 = \left(2.82 I_0^2 + 3.99 I_0 \log h + 57.2 \log^2 h - 31.1 I_0 - 132 \log h + 293\right) \cdot 10^{-4},$$

Table 1 Completeness magnitudes of instrumental catalogues

Mc estimation procedure	c1	c2
Mc estimation by the goodness of fit test at 90% confidence bounds	2.3	0.8
Mc estimation by maximum curvature method	2.4	1.1
Mc estimation by modified goodness of fit test	2.2	0.9

Table 2 Events recorded in instrumental Podhale seismic catalogues

Catalogue	Number of all events	Completeness magnitude M_C	Number of $M_W \geq M_C$ events	Number of events after declustering	Number of $M_W \geq M_C$ events after declustering
h0	4	–	4	4	4
c1	75	2.4	55	24	18
c2	243	1.0	171	141	112

where h is the depth. In the next step, M_w is calculated according to (4).

After magnitude type unification, the earthquakes were grouped into three catalogues (Supplement A):

h0:Historical earthquakes, containing the largest events,

c1:Earthquakes recorded by the PLSN during 1966–2007 and supplemented with events recorded by the Czechoslovak and later Slovak National Seismic Network,

c2:Earthquakes recorded from 2008 by the local seismic network as part of project MSHTP and the subsequent PMGP projects.

Catalogues c1 and c2 are complete but at different levels of completeness. The completeness of both catalogues was estimated according to a procedure developed by Wiemer and Wyss (2000) and modified by Leptokaropoulos et al. (2013), Table 1. Declustering of c1 and c2 was performed using the procedure developed by Gardner and Knopoff (1974). The chi-square test showed that the Poisson distribution of the declustered catalogue could not be rejected. Ultimately, for all computations, the levels of completeness Mc 2.4 and 1.0 were used, for which the catalogues passed the test of Poissonian distribution. The results are shown in Table 2.

Earthquake recurrence parameters of Podhale seismicity

A highly incomplete and uncertain database of Podhale seismicity allowed assessment of the recurrence parameters only for the entire region. The parameters, b-value of Gutenberg–Richter, the main activity rate ν, and the maximum possible magnitude m_{max} were estimated by a procedure developed by Kijko–Sellevoll (Kijko and Sellevoll 1989, 1992; Kijko et al. 2016). As an alternative, we assumed m_{max} to be equal to the largest observed magnitude, $m_{max}^{observed}$, increased by 0.5. The following estimates were obtained (Table 3). The starting magnitude is $m_c = 1.0$.

Table 3 Seismicity parameters

Estimation method	β	b	$\nu(m_c = 1.0)$	m_{max}
Declustered catalogues, estimated m_{max}	1.94 ± 0.17	0.84 ± 0.07	7.02 ± 1.52	5.19 ± 0.53
Declustered catalogues, $m_{max} = m_{max}^{observed} + 0.5$	1.98 ± 0.17	0.86 ± 0.07	6.95 ± 1.50	5.50 ± 0.54

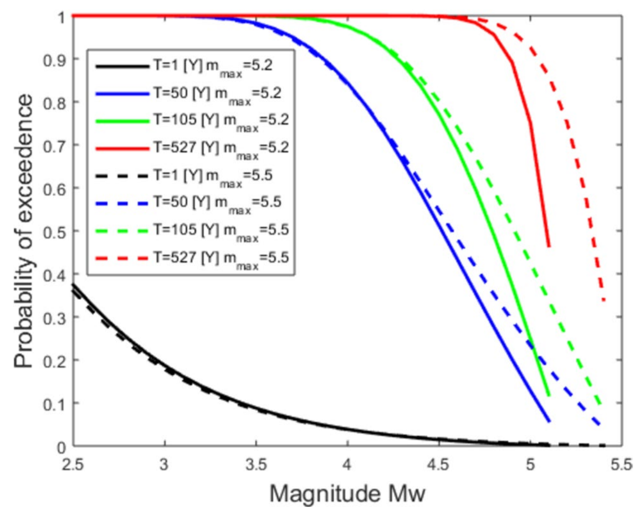

Fig. 2 Probability of exceeding a given magnitude within 1, 50, 105, and 527 years

The probability of exceedance of a specified magnitude at least once within the period of 1, 50, 105, and 527 years is presented in Fig. 2. Based on the estimated ν, β, and m_{max}, within 50 years, an earthquake of $M > 4.5$ would occur at least once with a probability of approximately 65%, whereas the occurrence of such event is almost inevitable within 470 years. Events with $M > 4.5$ can cause losses to infrastructure in the epicentral region with a radius of several kilometres. Such was the event on 30 November 2004, which caused damage to buildings approximately 6 km from the epicentre. The mean return period of seismic events with a magnitude range of 1.0 to 5.0 is shown in Fig. 3. For example, the average return period of an event of $M = 4$ is approximately 20 years. The annual probability of exceeding the specified magnitude is shown in Fig. 4. Therefore, the probability of exceeding magnitude 4.0 is approximately 5%, and magnitude 2.0 is almost 75%. The above assessments are consistent with the seismic activity recorded in the Podhale region.

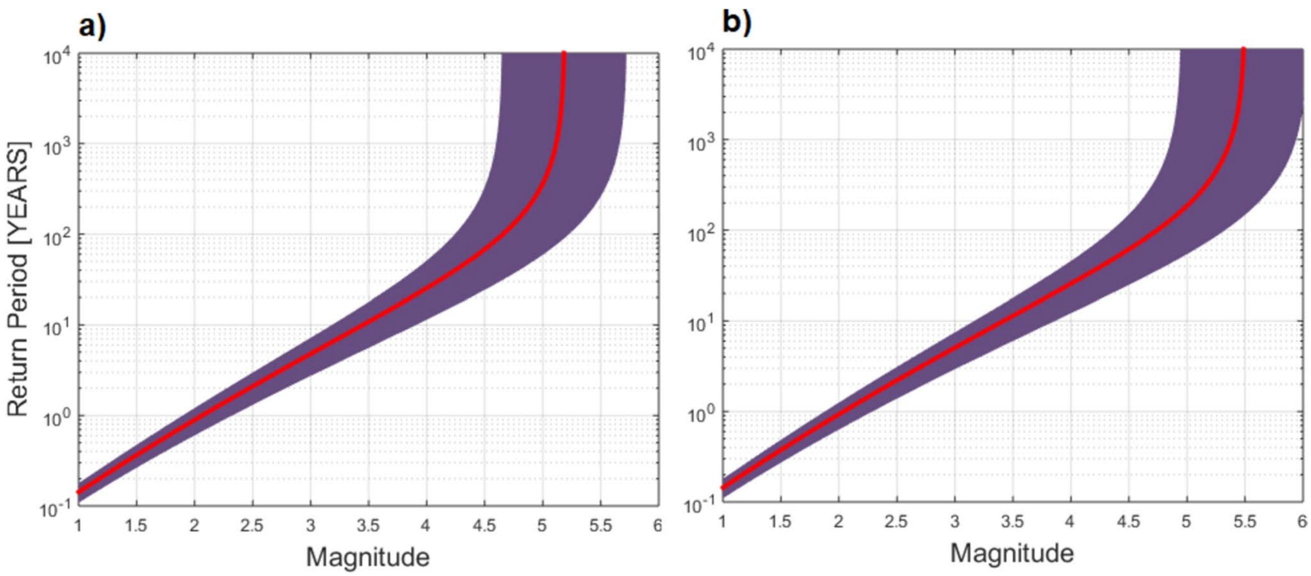

Fig. 3 Mean return period of an event with a certain magnitude (purple colour indicates the uncertainty range of determining the period): **a** $m_{max}=5.2$; **b** $m_{max}=5.5$

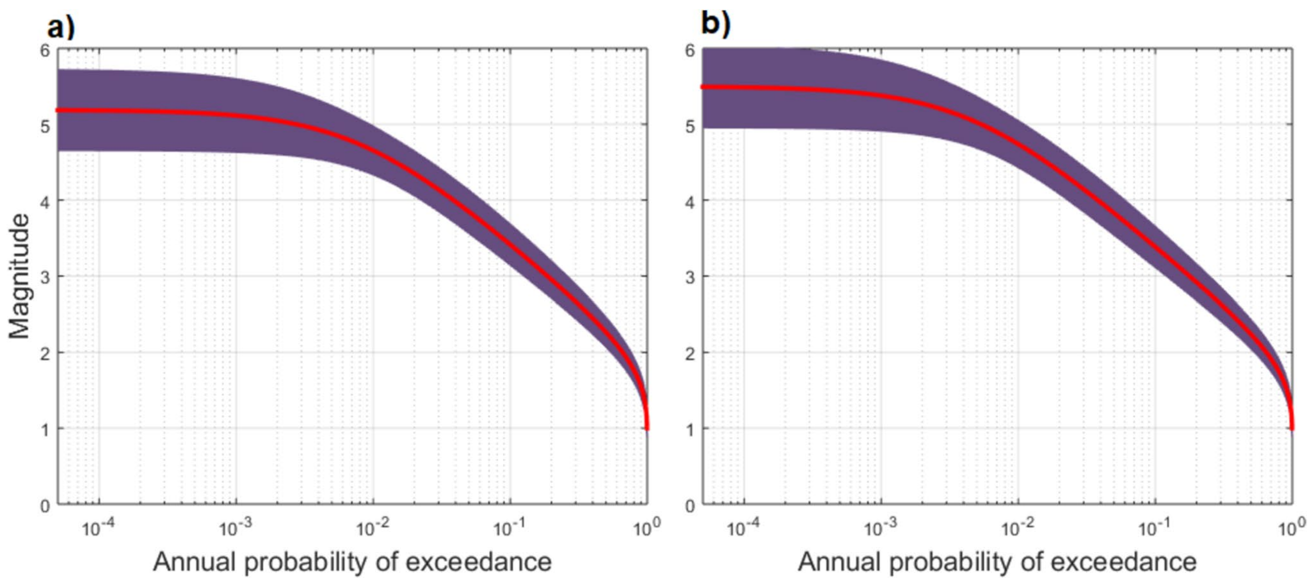

Fig. 4 Annual probability of a seismic event stronger than a given magnitude (purple colour indicates the uncertainty range of determining the probability): **a** $m_{max}=5.2$; **b** $m_{max}=5.5$

Applied ground motion models

Owing to a lack of GMMs for the Polish territory, we applied the relationships derived for other stable continental areas. Generally, three categories of GMMs are available, each applicable to a different tectonic area. These GMMs are appropriate for stable continental regions (SCR), subduction zones, and shallow crustal tectonically active regions.

In our attempt to assess the seismic hazard in the Podhale region, eleven SCR GMMs were considered. They are the GMM by Atkinson (2008); Atkinson and Boor (2006); Campbell (2003); Douglas et al. (2006); Frankel et al. (1996); Pezeshk et al. (2011); Raghu Kanth and Iyengar (2006, 2007); Silva et al. (2002); Somerville et al. (2009); and Toro (2002).

Finally, for the assessment of seismic hazard in the Podhale region, five GMMs for SCR were selected, which are those of Campbell (2003), Toro (2002), Akkar and Bommer (2010), Cauzzi and Faccioli (2008) and Chiou and Youngs (2008). Our selection was guided by the SHARE (Seismic Hazard Harmonization in Europe) project (Delavaud et al. 2012). In addition, in our analysis, we used a more recent GMM developed for shallow crustal seismicity in Europe by Kotha et al. (2020), which was used in the European Seismic Hazard Map 2020 (ESHM20) project (Weatherill et al. 2020). One thing to note is that the European Seismic Hazard Map 2013 (ESHM13) (Giardini et al. 2014), as well as its ESHM20 (Danciu et al. 2021, 2024), do not contain up-to-date and detailed data on seismicity in our study area used in this work.

The GMM developed for Poland, the Czech Republic and Slovakia (CZ-PL-SK) was presented by Schenk et al. (2000, 2001). It has the form:

$$\ln PGA = a_1 + a_2 m + a_3 \ln\left(R_{hypo} + d\right), \quad (6)$$

where PGA is in cm/s^2, $a_1 = 6.15 \pm 0.32$, $a_2 = 0.65 \pm 0.02$, $a_3 = -1.3 \pm 0.16$, and $d = 17$. Schenk et al. (2000, 2001) criticise the GMMs suggested by the GSHAP team (Grünthal 1997). However, it should be noted that the alternative, the European GMMs such as those of Ambraseys et al. (1996), Sabetta and Pugliese (1996), and Spudich et al. (1997) are based on strong seismic earthquakes occurring in areas with orogenic geological structures (Turkey, Iran, Greece, or Italy). In contrast, the CZ-PL-SK area is built of old crystalline rocks (Schenk et al. 2000). The seismic hazard map compiled with the application of GMM (6) is presented in Supplement C.

An alternative GMM applicable to the Podhale region was developed by Trojanowski et al. (2015):

$$\log Y = a_1 + a_2 m + a_3 \log\sqrt{d^2 + h^2}, \quad (7)$$

where Y is the horizontal peak ground acceleration [m/s^2], m is the M_L magnitude, and d is the hypocentral distance [km]. The GMM (7) was developed by applying the two-stage regression technique (Joyner and Boore 1993) and data obtained from the MSHTP project. The coefficients of the GMM (7) are $a_1 = -2.17$, $a_2 = 1.1$, $a_3 = -2.4$, $h = 4.87$, and $\sigma_{logY} = 0.25$ ($\sigma_e = 0.096$). However, the GMM (7) is based on relatively low-magnitude events, as only such events were available. The only significant earthquake occurred in 2004 (Wiejacz and Dębski 2009); however, it was recorded only by distant stations. Consequently, the GMM (7) is reliable only for small magnitudes. Nevertheless, we applied it as one of the models in the logic tree.

The parameters of the GMMs are shown in Table 4. Initially, the weight of all GMMs was the same in all our computations. However, as some applied GMMs are suitable only for small distances and low magnitudes and others are suitable for larger distances and high magnitudes, the applied events often exceeded the prescribed applicability range of GMM predictors (Fig. 5). Therefore, different weights were assigned to the different magnitude ranges and

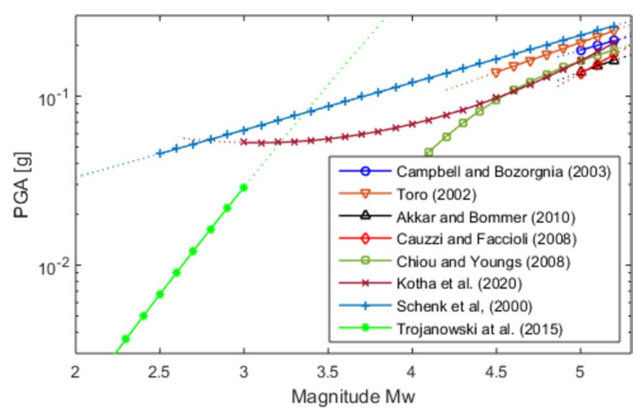

Fig. 5 GMMs used to calculate the seismic hazard of the Podhale region depending on the magnitude range (Delavaud et al. 2012; Douglas 2022; Schenk et al. 2001; Trojanowski et al. 2015)

Table 4 GMMs used in the logic tree for the Podhale region (Delavaud et al. 2012; Douglas 2022; Schenk et al. 2001; Trojanowski et al. 2015).

GMMs	Area	Number of earthquakes	M_{min}	M_{max}	Magnitude scale	r_{min}	r_{max}	r_{scale}
Campbell and Bozorgnia (2003)	Eastern North America	36	5.0	7.5	M_w	10	130	r_{rup}
Toro (2002)	Central and Eastern North America	–	4.5	8	M_w	1	500	r_{jb}
Akkar and Bommer (2010)	Europe and Middle East	131	5.0	7.6	M_w	0	99	r_{jb}
Cauzzi and Faccioli (2008)	World (shallow crust)	60	5.0	7.2	M_w	6	150	r_{hypo}
Chiou and Youngs (2008)	World (shallow crust)	125	4.2	7.9	M_w	0.2	70	r_{rup}
Kotha et al. (2020)	Europe and the Middle East	–	3.0	7.4	M_w	0	545	r_{jb}
Schenk et al. (2001)	Czech Republic, Slovakia, and Poland	–	2.5	6.5	M_s	2	600	r_{hypo}
Trojanowski et al. (2015)	Podhale region	81	0	2.5	M_L	2	20	r_{epi}

m_{min}—minimum magnitude; m_{max}—maximum magnitude; m_{scale}—magnitude scale; r_{min}—minimum epicentre distance; r_{max}—maximum epicentre distance; r_{scale}—epicentre distance scale (r_{jb}—Joyner–Boore distance); r_{hypo}—hypocentral distance (focal); r_{rup}—distance to the rupture zone; r_{epi}—epicentral distance.

epicentral distances (Table 4). The applied GMMs and associated weights are shown in Table 5.

In the GMM branch of the tree, the $P\left[Y \geq y|m,r\right]$ in (1) is calculated according to the formula:

$$P\left[Y \geq y|m,r\right] = \frac{\sum_{i=1}^{8} P^{(i)}\left[Y \geq y|m,r\right] w_M^{(i)}(m) w_R^{(i)}(r)}{\sum_{i=1}^{8} w_M^{(i)}(m) w_R^{(i)}(r)}, \tag{8}$$

where $w_M^{(i)}$ is the magnitude-dependent weight (Table 5), $w_R^{(i)}$ is the distance-dependent weight (Table 5), and $P^{(i)}\left[Y \geq y|m,r\right]$ is the probability associated with the ith GMMs.

Development of seismic hazard maps for Podhale

Zone approach

Following Cornell (1968), seismogenic zones are areas where seismicity is distributed uniformly. An example of seismic hazard assessment for the Podhale region based on an assumption of uniform seismicity distribution is the work of Schenk et al. (2000, 2001), where historical seismicity patterns delineate the zones. However, it is advisable to define zoning on both seismic data and geological/tectonic information.

Based on the current knowledge of seismicity and only recently available information on the geology of the investigated area, it was advisable to revise the delineation of seismogenic zones of the Podhale region (Fig. 1). In Podhale, three major geological units are identified, namely the Pieniny Klippen Belt (PKB), the Podhale synclinorium, and the Tatra Mountains massif (Żelaźniewicz et al. 2011; Narkiewicz and Dadlez 2008) (Fig. 6a). Based on this new information, new seismogenic zones were defined (Fig. 6d). The shape of seismogenic zones was developed by considering the boundaries of the main geological units and the envelope of seismic areas. Our approach to delineating seismogenic zones differed from that of Grünthal et al. (2018), where the designated area of Europe was divided into adjacent zones, and our study area was not included in any of the zones. Accordingly, we had to develop seismogenic zones in this study.

Different geology forms the bounds of the zones from the north and south, whereas the zones to the west and east are defined by earthquake occurrences. The first zone partially covers PKB and the Podhale synclinorium, and the highest natural seismicity was recorded here. The zone also includes a fragment of the Peripieninic fault zone, which is probably responsible for most seismic events in this zone. Several clusters of seismicity are also present. However, owing to a lack of mechanism solutions and information on the activity of the tectonic fault, all clusters were assumed to belong to the same zone. The second zone partially covers the structures of the Tatra Mountains and, from the south, is limited by the sub-Tatra fault, which appears inactive. The seismicity in the second zone is low and diffuse.

Smoothed seismicity model

When calculating an SSM, we considered that the data comprise three catalogues of different completeness levels. The catalogue of the most minor events provides the most spatial information, and other catalogues would be neglected if we directly applied the magnitude-independent method (Helmstetter et al. 2007). Therefore, we compared three approaches. First, we used a technique similar to that applied by Grünthal et al. (2018). The spatial distribution of seismic hazard is defined by magnitude-dependent kernels (Vere-Jones 1992):

$$K(r,M) = \frac{1}{\pi H_z^2(M)} \left(1 + \frac{r^2}{H_z^2(M)}\right)^{-2}, \tag{9}$$

where $H_z^2(M)$ denotes a kernel bandwidth function (e.g., Woo 1996; Molina et al. 2001):

Table 5 Weights of applied GMMs

GMMs	M_w							R [km]		
	6.0	5.0	4.5	4.0	3.0	2.5	0	0	50	> 100
Campbell and Bozorgnia (2003)	0.14	0.14	0	0	0	0	0	0	0.14	0.12
Toro (2002)	0.14	0.14	0.25	0	0	0	0	0.15	0.14	0.18
Akkar and Bommer (2010)	0.14	0.14	0	0	0	0	0	0.15	0.14	0.12
Cauzzi and Faccioli (2008)	0.14	0.14	0	0	0	0	0	0	0.14	0.16
Chiou and Youngs (2008)	0.14	0.14	0.25	0.1	0	0	0	0.15	0.14	0.06
Kotha et al. (2020)	0.14	0.14	0.25	0.45	0.4	0	0	0.20	0.14	0.18
Schenk et al. (2001)	0.16	0.16	0.25	0.45	0.4	0.3	0	0.15	0.14	0.18
Trojanowski et al. (2015)	0	0	0	0	0.2	0.7	1	0.20	0.02	0

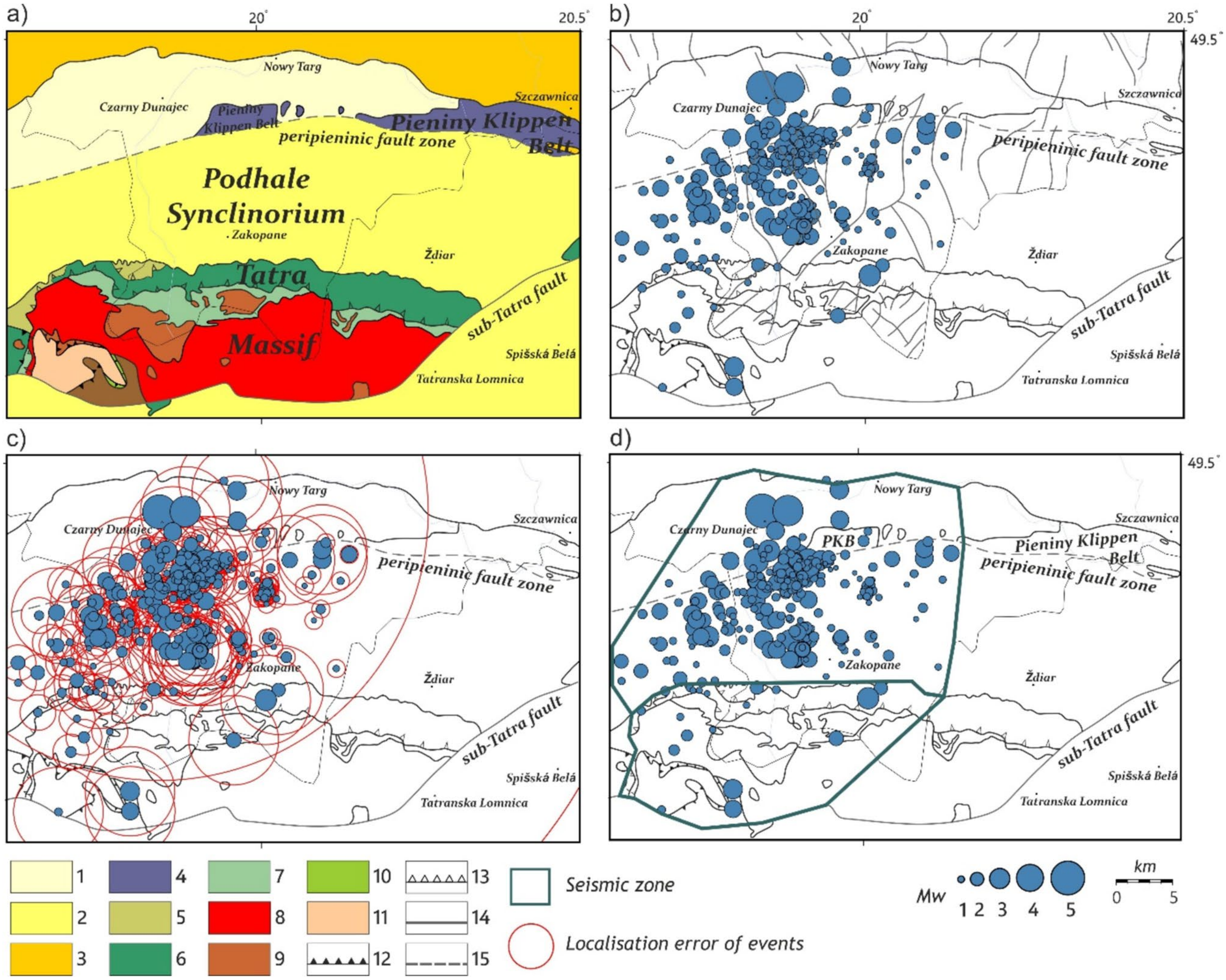

Fig. 6 Process of creating seismic zones on the background of the geology and seismicity of Podhale: **a** tectonic sketch of the Tatra Mountains, Podhale synclinorium, and Pieniny Klippen Belt (Żelaźniewicz et al. 2011; Narkiewicz and Dadlez 2008); **b** seismicity with marked faults based on data from the Central Geological Database of the PGI-NRI (Marks et al. 2022); **c** seismicity with location errors; and **d** seismicity and two seismogenic zones proposed within larger geological units in Podhale. Legend: 1—Neogene sediment; 2—Central Carpathian Paleogene; 3—Magura Nappe; 4—Pieniny Klippen Belt; 5—Choč Nappe; 6—Križna Nappe; 7—High-Tatric Nappes; 8—Granitoids; 9—Rocks of the upper Tatra migmatic complex; 10—Amphibolites with Eclogite relics; 11—Rocks of the lower complex; 12—Mesozoic nappe overthrusts; 13—Ráztoki–Baranca overthrust; 14—faults; and 15—fault zones

$$H_z(M) = d_1^{(z)} \exp\left(d_2^{(z)} M\right). \tag{10}$$

Parameters $d_1^{(z)}$ and $d_2^{(z)}$ of the kernel bandwidth function (10) are estimated for each applied catalogue, c1 ($z=1$), c2 ($z=2$), or h ($z=3$). According to Woo (1996), these parameters are region-specific and should be estimated based on knowledge of geology and seismicity. Molina et al. (2001) suggest assessing d and e from a regression between the mean value of epicentral distances and magnitudes within some magnitude bins. During our SHA for the Podhale region, we used increased epicentral distances depending on location errors. The location errors for historical earthquakes are estimated at 50 km, and the location errors for events registered regionally in the second catalogue are significantly larger than those in the catalogue of local events. The location error counteracts the influence of the magnitude in (9). The final SSM is a weighted mean distribution calculated from all catalogues (see Supplement B).

In the second approach, we applied the method proposed by Helmstetter et al. (2007) and Moschetti et al. (2016), which is independent of magnitudes. The method was modified because we employed three catalogues with various location errors and completeness magnitudes.

Spatial distribution maps

The seismic hazard for the Podhale region was compiled using the classical Cornell (1968) procedure, which requires knowledge of seismogenic smoothness and the zoneless SSM, which smooths the seismicity by magnitude-dependent kernels. The zone approach led to the hazard distribution spread over a larger area (Fig. 7a), whereas earthquake clusters largely control the hazard characteristics for the zoneless area of SSM. Although the hazard is concentrated in a small area, its value is high (Fig. 7b and c).

Logic tree

The application of logic tree formalism in PSHA is designed to deal with the uncertainties of input parameters (Kulkarni et al. 1984; Coppersmith and Youngs 1986). The logic tree comprises a series of nodes and branches, where the nodes represent the input parameter values and the branches are the normalised weights reflecting the rightness of the selected model. Two approaches were used, namely smoothed seismicity (Woo 1996; Molina et al. 2001) and the conventional procedure, which requires delineating seismogenic zones (Cornell 1968; McGuire 2004) (Fig. 8). The applied logic tree is similar to the one used in the SHARE project (Delavaud et al. 2012).

PGA maps

Our hazard assessment is expressed in terms of PGAs with a 10% probability of exceedance in 50, 105, and 527 years (Figs. 9, 10, 11 and Table 6). We do not have any V_{S30} values for the study area. We assumed the typical rocky subsoil in a deeper part of the Podhale region. Ground motion prediction

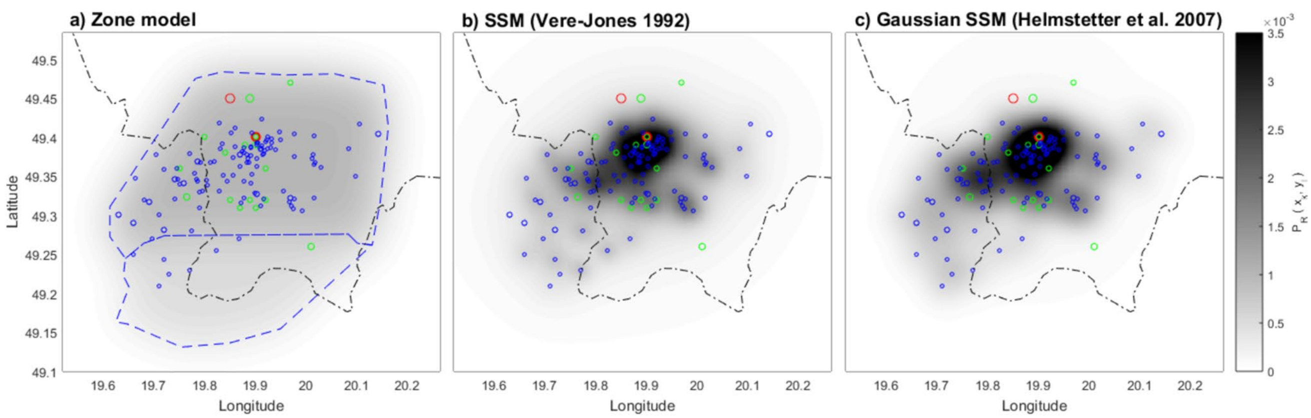

Fig. 7 Spatial distribution maps of earthquake occurrence probabilities in 1 km^2 areas estimated by the **a** zone model, **b** SSM magnitude-dependent kernels (Vere-Jones 1992), and **c** SSM magnitude-independent Gaussian kernels (Helmstetter et al. 2007)

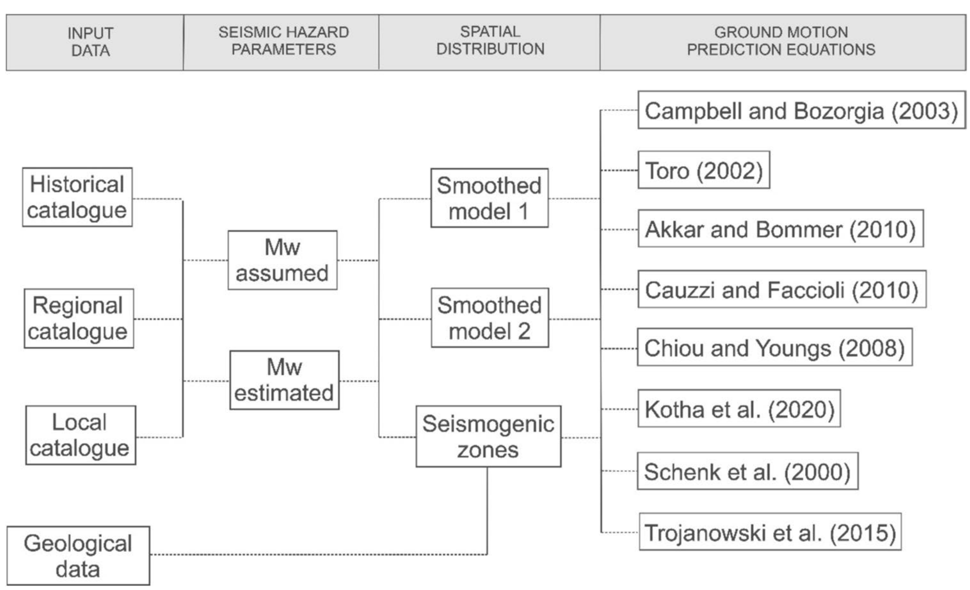

Fig. 8 Thought diagram of the logic tree of seismic hazard development for Podhale

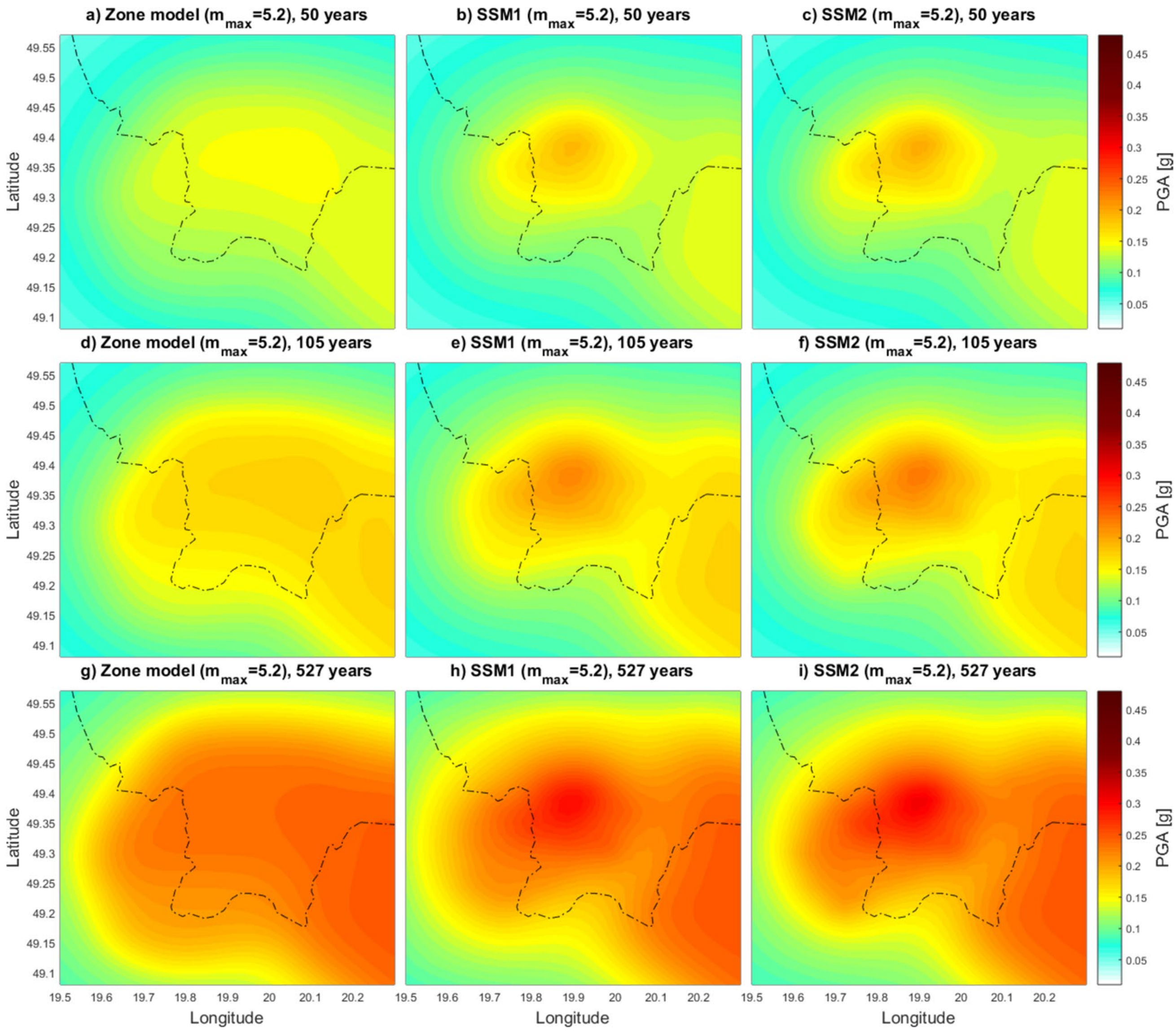

Fig. 9 Seismic hazard maps of Podhale calculated for estimated $m_{max}=5.2$ with the zone approach (**a**, **d**, and **g**); the smoothed seismicity approach with magnitude-dependent kernel (SSM1) (**b**, **e**, and **h**); and the smoothed seismicity approach with magnitude-independent Gaussian kernel (SSM2) (**c**, **f**, and **i**), describing PGA with a 10% probability of exceedance within 50 years (**a**, **b**, and **c**), 105 years (**d**, **e**, and **f**), and 527 years (**g h**, and **i**)

models are calculated for the rock background, $V_{S30} \approx$ 800 m/s. The same parameters are adopted for the Podhale area by the Global Seismic Hazard Assessment Program (Giardini et al. 1999), ESHM13 (Woessner et al. 2015), and ESHM20 (Danciu et al. 2021, 2024). The choice of time intervals of 50, 105, and 527 years facilitated comparing our results with those shown by the current hazard maps for the Czech Republic, Poland, and Slovakia (Schenk et al. 2001, Fig. 1). We considered the influence of the remaining part of Pieniny Mountains zone (Schenk et al. 2001), with a cut of our Podhale zones. Low seismicity to the west of our study area has not been studied and requires investigation. No previous work (Schenk et al. 2000; Badová 2016; Hók et al. 2016) indicates a seismic zone close from the west to Podhale. However, we additionally considered Central Slovakia zone (Schenk et al. 2001), the closest from the southwest to Podhale.

Discussion

Regarding the two applied seismic hazard assessment procedures (zones and smoothing), the smoothed approach, independent of geological information, appears more accurate.

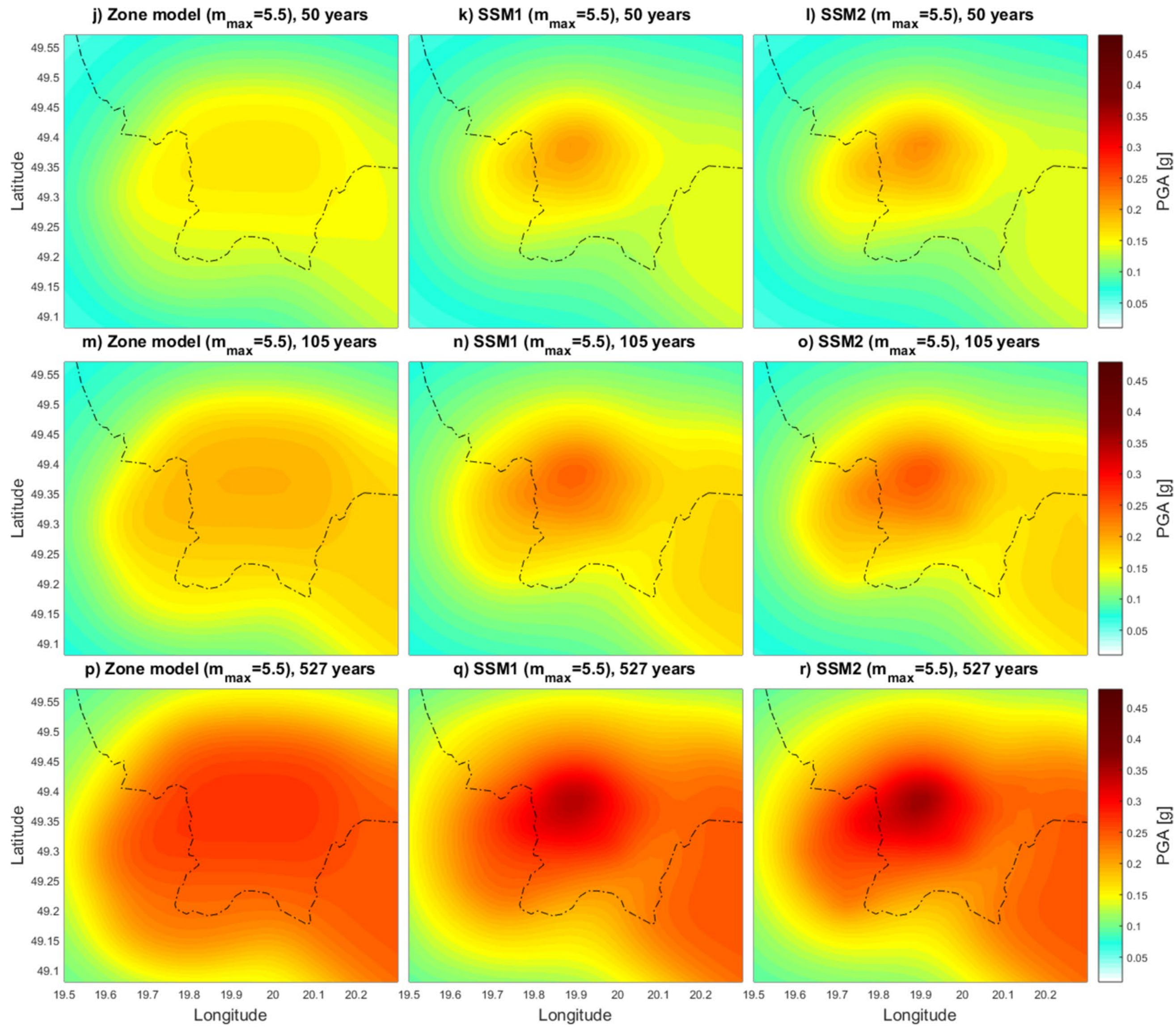

Fig. 10 Seismic hazard maps of Podhale calculated for assumed mmax=5.5 with the zone approach (**j**, **m**, and **p**); smoothed seismicity approach with magnitude-dependent kerne1 (SSM1) (**k**, **n**, and **q**); and the smoothed seismicity approach with magnitude-independent Gaussian kernel (SSM2) (**l**, **o**, and **r**), describing PGA with a 10% probability of exceedance within 50 years (**j**, **k**, and **l**), 105 years (**m**, **n**, and **o**), and 527 years (**p**, **q**, and **r**)

The spatial distribution of the computed hazard considers the empirical distribution without the unnecessary distortion caused by the highly subjective delineation of seismogenic zones.

This entire study was focused on seismic hazard analysis for the Podhale region. Although there are reasons to assume that high seismicity occurs between the eastern part of the Pieniny Mountains and Podhale, it is irrelevant to this study. However, it does require a comprehensive investigation.

The earthquake recurrence parameters β and λ were calculated from all available seismic event catalogues for the entire Podhale region. Assessments of β and λ for each zone were not conducted because of insufficient data. The estimates of β and λ differ significantly from those obtained by Schenk et al. (2001), calculated for the Pieniny Mountains region ($\beta = 1.34 \pm 0.05,\ b = 0.58 \pm 0.02,\ \lambda = 0.16 \pm 0.04$) (Fig. 12).

The maps compiled by Schenk et al. (2001) do not include an account of the site effects. In addition, only one GMM was used, whereas our computations were based on seven GMMs and the logic tree formalism. Therefore, comparing the map compiled by Schenk et al. (2001) with ours is challenging, as is explaining the reason for the maps of the Schenk group indicating a seismic hazard larger than

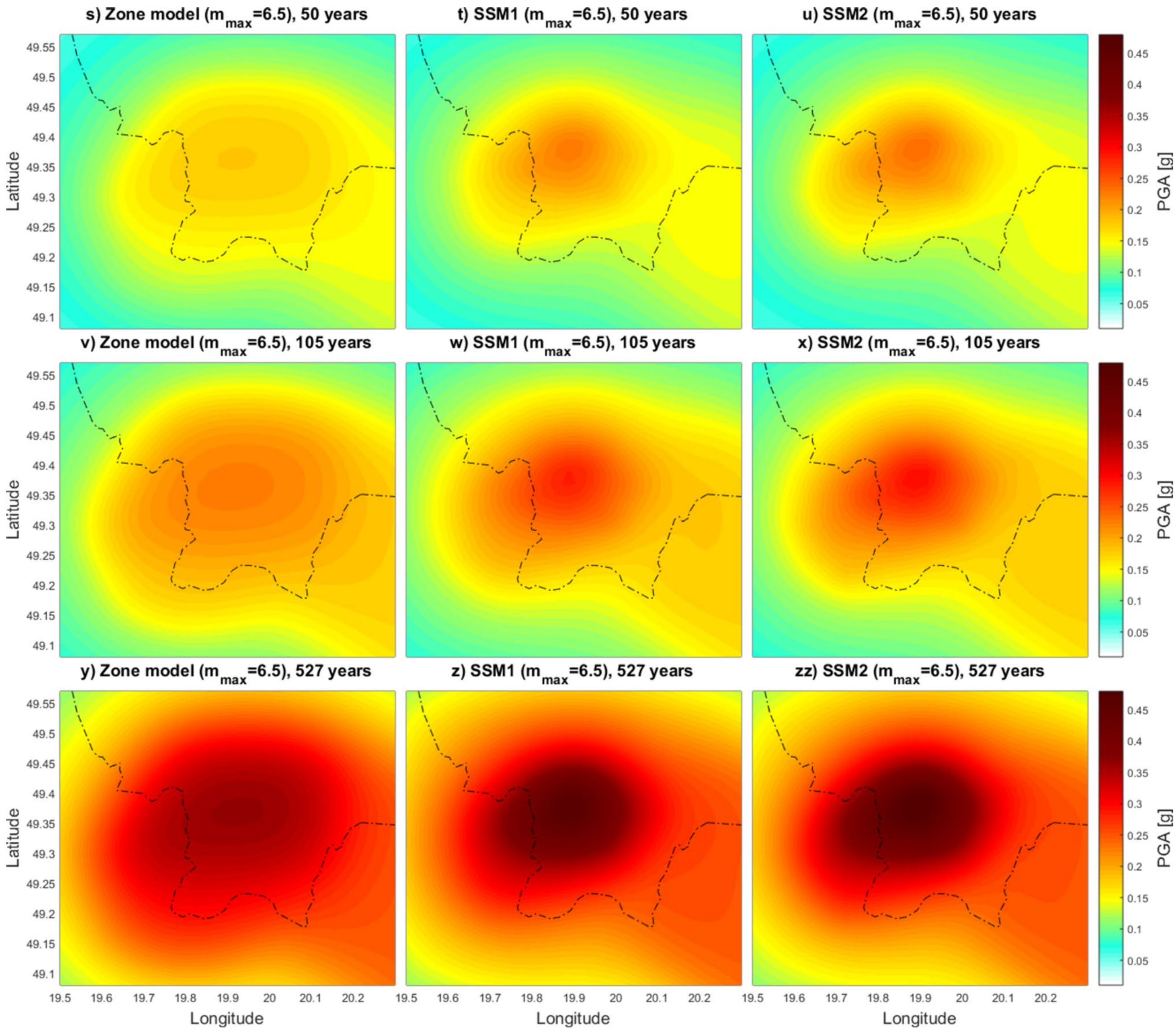

Fig. 11 Seismic hazard maps of Podhale calculated for assumed $m_{max}=6.5$ with the zone approach (**s**, **v**, and **y**); smoothed seismicity approach with magnitude-dependent kerne1 (SSM1) (**t**, **w**, and **z**); and the smoothed seismicity approach with magnitude-independent Gaussian kernel (SSM2) (**l**, **o**, and **r**), describing PGA with a 10% probability of exceedance within 50 years (**j**, **k**, and **l**), 105 years (**m**, **n**, and **o**), and 527 years (**u**, **x**, and **zz**)

Table 6 Max PGA of all localities in Podhale with a 10% probability of exceedance within 50, 105, and 527 years for the zone and smoothed seismicity approaches

Spatial distribution map	Max PGA with a 10% probability of exceedance [g]								
	$m_{max}=5.2$			$m_{max}=5.5$			$m_{max}=6.5$		
	Years								
	50	105	527	50	105	527	50	105	527
Zone model	0.15	0.17	0.25	0.16	0.19	0.27	0.18	0.23	0.36
SSM, magnitude-dependent kernels	0.19	0.22	0.30	0.21	0.24	0.35	0.23	0.28	0.47
SSM, magnitude-independent Gaussian kernels	0.20	0.23	0.31	0.22	0.25	0.36	0.24	0.30	0.49

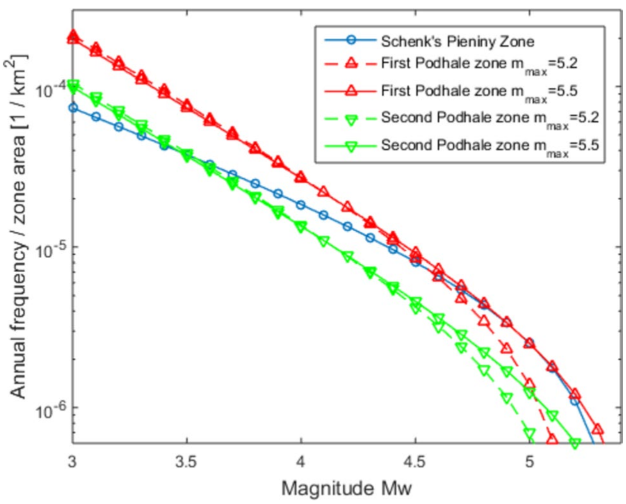

Fig. 12 Unitary (per km^2) annual frequency of magnitude exceedance in two zones in Podhale and the Pieniny Mountains zone of Schenk et al. (2001)

that obtained by our study. However, to make it partially possible and find the reason for the differences, we minced the Schenk computations by applying only one, the GMM applied by Schenk et al. GMM. The comparison is shown in Supplement C. Our hazard assessments after using the Schenk GMM are significantly larger than the seismic hazard calculated with the help of the logic tree (Fig. 8). One thing to note is that our comparison was not ideal because our approach considers the site effect, which was not included in the Schenk computations.

Our hazard assessments (with zones and smoothed seismicity) show a relatively high seismic hazard in the north-western part of Podhale. Moreover, our estimates provide a higher hazard than those of Schenk et al. (2001) (Fig. 1).

Our hazard assessments provided higher hazards for several reasons. One being that we applied more recent and more complete seismic event catalogues. The new catalogues contain new events that occurred in the eastern and western parts of the Podhale region, which significantly affected the estimated hazard spatial distribution, mainly when the smoothed seismicity approach was applied. The most significant effect of the new data was observed in the vicinity of Czerwienne Village in the Peripieninic fault zone.

We present hazard curves for two towns in Podhale: Ciche (49.377°N, 19.848°E) and Zakopane (49.297°N, 19.952°E). Zakopane is the primary urban centre in this area, whereas the most seismic events were recorded close to Ciche town. The probability of strong PGA exceedance in Ciche was

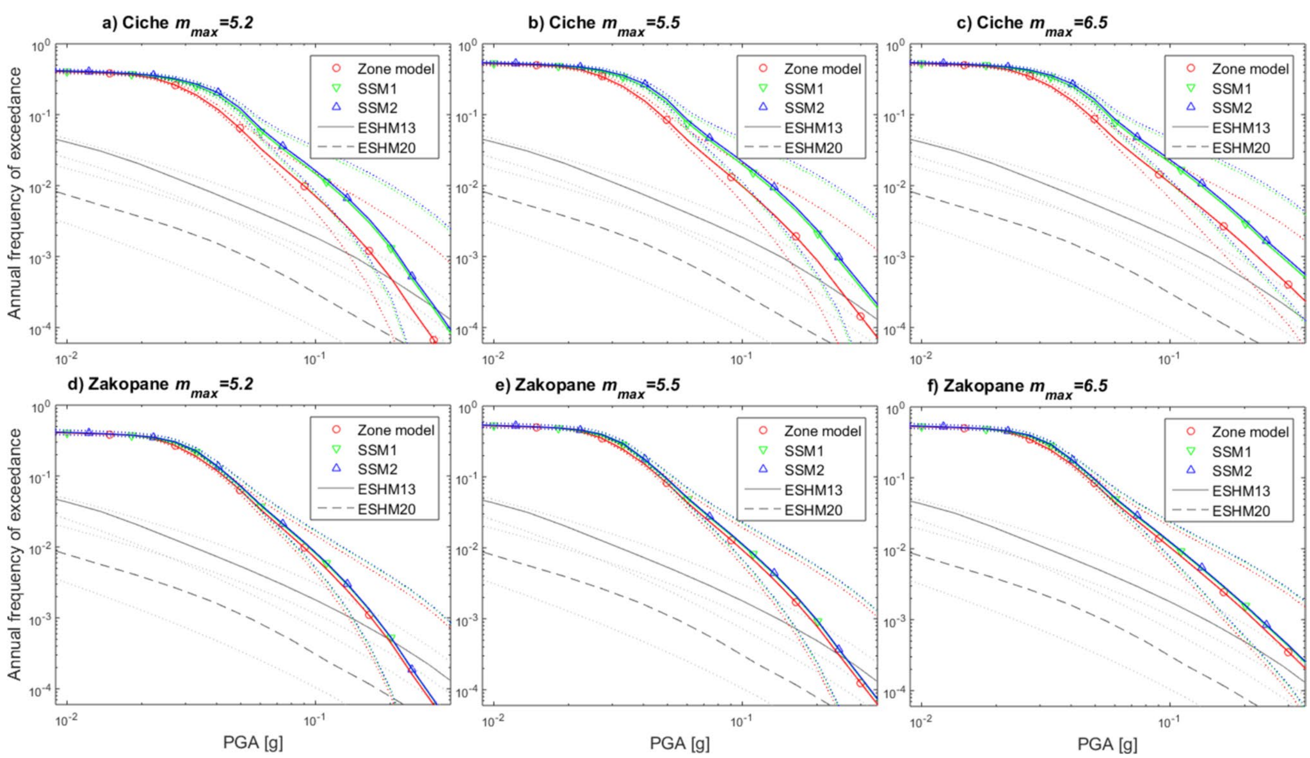

Fig. 13 Hazard curves for two towns in Podhale: Ciche (**a**, **b**, and **c**) and Zakopane (**d**, **e**, and **f**); for maximum magnitudes $m_{max}=5.2$ (a and d), $m_{max}=5.5$ (b and e), and $m_{max}=5.5$ (c and d), for zone and smoothed models. For comparison, hazard curves of the European Seismic Hazard Model 2013 and 2020 are shown for selected locations (grey). The dotted lines indicate 0.05 and 0.95 quantiles of probability

higher than in Zakopane when we used the SSM. The kernels of SSMs do not significantly affect PGA distributions (Figs. 9, 10, 11, 13).

The probability of PGA values occurrence for Podhale is higher than in ESHM, especially for average values (0.01–0.1 g). This results from adopting the local GMPE, which is characterised by greater amplification for weak events than global models for larger magnitudes (Tables 4 and 5). Magnitude recurrence probability is also higher for magnitudes below m_{max}. The assessed maximum magnitude for Podhale causes the higher PGA probability for Podhale to be equal to or lower than the ESHM probability. Assuming the maximum magnitude of 6.5, similar to ESHM, causes the probability to be higher in the entire PGA range.

The assessment of m_{max} requires additional discussion. Having insufficient geological and tectonic data, which results from the low interest in the seismicity of Podhale, we must focus only on seismic data. Realising that there are many but no generally accepted methods for estimating the m_{max} value and that observations from the last 1000 years confirm that no stronger earthquake occurred in the study area, we chose the magnitude assessment method based on seismic data. On the one hand, we used the Kijko–Sellevoll method, which has a solid statistical basis but may be sensitive to the data, and on the other hand, we assumed a magnitude larger than the maximum observed magnitude by 0.5. There is no evidence from the available data to assume larger magnitudes. One could assume arbitrarily larger m_{max} based on other assumptions, such as the ESHM data. Figures 11 s—zz, 13c and f present the result for $m_{max} = 6.5$. However, this is beyond the scope of our analysis.

Conclusions

Based on an extended monitoring period of Podhale seismicity, we conclude that the investigated area should be considered a separate seismic zone that requires an individual seismic hazard study. Despite extremely limited information, obtaining the spatial distribution of the seismic hazard for the Podhale area was possible. This study shows the presence of 'hot spots' of seismicity where the effects of earthquake occurrence cannot be ignored. Our study results differ significantly from the earlier findings of Schenk et al. (2001), Giardini et al. (2014), and (Danciu et al. 2021, 2024).

The earthquake concurrence parameters estimated for the Podhale region differ from those of the Pieniny Mountains zone (Schenk et al. 2001), which covers the area of Podhale. The difference confirms the need for seismic hazard studies at the local scale.

The largest ground motions could be experienced in the area of Czerwienne, where, with a 10% probability of exceedance in 50 years, the predicted PGA exceeds 0.2 g. Civil engineers should consider such a ground motion, as it constitutes the limit of heavy construction damage (PN-B-02170 2016).

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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