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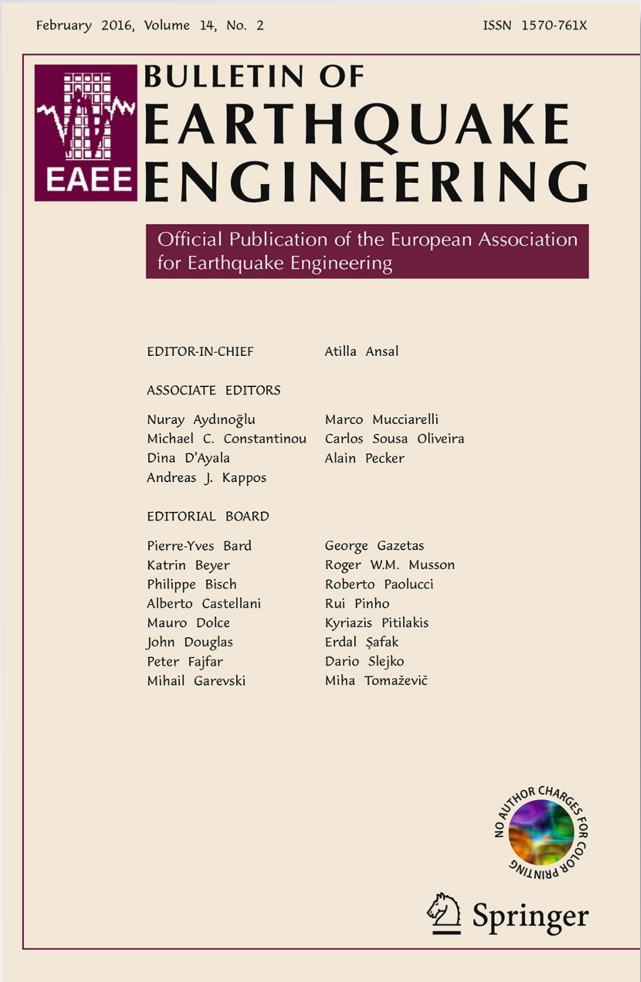
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ORIGINAL RESEARCH PAPER

An updated and unified earthquake catalogue for the Western Balkan Region

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Abstract The Harmonization of Seismic Hazard Maps in the Western Balkan Countries Project (BSHAP) was funded for 7 years by NATO-Science for Peace Program to support the preparation of new seismic hazard maps of the Western Balkan Region using modern scientific tools. One of the most important outputs of the BSHAP is an updated and unified BSHAP earthquake catalogue that is compiled directly from the datasets of earthquake data providers of the region. The BSHAP earthquake catalogue described here covers the geographic area limited by 38.0°–47.5°N, 12.5°–24.5°E and includes 26,118 earthquakes that occurred in the region between 510 BC and 2012. Details of data compilation efforts including the removal of duplicate events, unification of the magnitude scales, declustering of the catalogue and completeness analysis are presented in this manuscript. New magnitude conversion equations for various local magnitude scales of the data providers are developed with the aim of having homogeneous moment magnitude estimates. Completeness time intervals for the catalogue data are provided as inputs to the seismic source models used to obtain updated seismic hazard of Western Balkan Region. The unified and updated BSHAP catalogue is found to be compatible with the current well-established European and world-wide catalogues and represents a sound basis for analysis of the seismicity of this region.

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Keywords Earthquake catalogue · Western Balkan Region · Magnitude conversion equations · Catalogue completeness · Mainshock-aftershock classification

1 Introduction

The Western Balkans is a seismically active region characterized by relatively higher earthquake hazard and risk when compared to the rest of Europe (except for Greece, Italy and Turkey with highest hazard levels). Minimization of the loss of human lives, of property damage, and of social and economic disruption due to earthquakes essentially depends on the reliable estimates of seismic hazard. In September 2007, the Harmonization of Seismic Hazard Maps in the Western Balkan Countries Project (BSHAP—SfP# 983054) funded by NATO Science for Peace (SfP) Program was launched with the main objective of preparing new seismic hazard maps of the Western Balkan Region. In addition to the preliminary seismic hazard maps of the region, an initial BSHAP earthquake catalogue was created by integrating the national catalogues of the participating and neighboring countries. The follow-up project (BSHAP_II—SfP# 984374, Improvements in the Harmonized Seismic Hazard Maps for the Western Balkan Countries) was initiated in October 2012 to further improve the initial seismic hazard maps of the participating countries by implementing the state-of-the art probabilistic seismic hazard assessment techniques and the outputs of the initial BSHAP project. One of the main goals of the BSHAP_II project is to improve the BSHAP earthquake catalogue by: (i) examining and filtering the catalogue for missing or duplicate events and introduction of missing or new earthquake data, (ii) investigating the catalogue completeness time spans and identifying the possible existing gaps in the catalogue, (iii) unification of the magnitude scales and adding available earthquake metadata for the present earthquakes, and finally providing an earthquake catalogue compatible with international standards.

The objective of this paper is to present the updated and unified BSHAP earthquake catalogue for the Western Balkan Region, the outcome of the collaboration among 8 countries and 11 participating institutes for almost 8 years, to the international earthquake engineering community. The BSHAP earthquake catalogue covers the geographic area limited by 38.0°–47.5°N, 12.5°–24.5°E (Fig. 1) and includes 26,118 earthquakes that occurred in the region between 510 BC and 31.12.2012. The following section presents the procedure followed for the compilation of the earthquake database in addition to a brief summary of the earthquake catalogs compiled by multi-national groups between years 1974 and 2007 for the Western Balkan Region. Source information, earthquake parameters and statistical analysis of the BSHAP catalogue is presented in the next section. Since the data is collected from 24 different national and global catalogues, many efforts are made for unification of the local magnitude scales, locating the duplicate events around the national borders, and mainshock-aftershock classification of the events. Such efforts along with the proposed magnitude conversion relationships for the region are elaborated in the subsequent sections. The completeness of the catalogue is homogeneous only for certain time periods, depending on magnitude and region. The temporal and spatial completeness analysis of the final catalogue is discussed in the last section.

Finally, the BSHAP catalogue is compared to the recent established global earthquake catalogues: the GEM (Global Earthquake Model) Instrumental Earthquake Catalogue (Storchak et al. 2013) and the SHARE European Earthquake Catalogue (SHEEC)

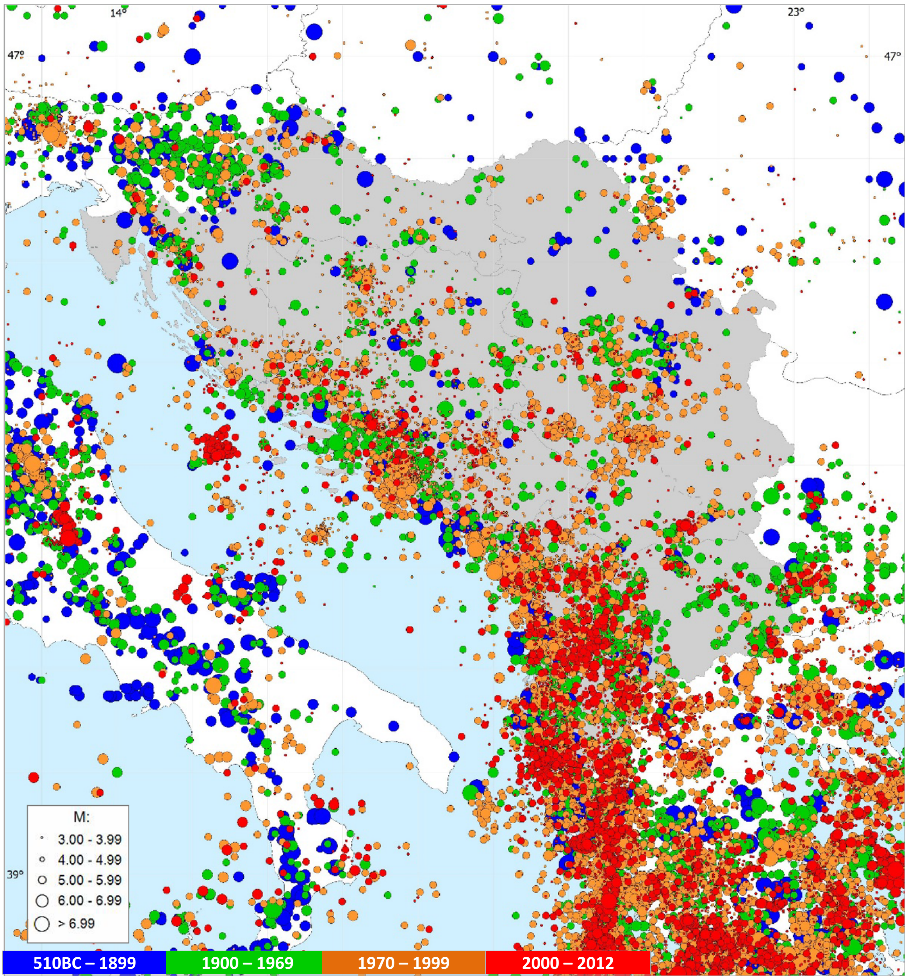

Fig. 1 Spatial distribution of the earthquakes in the proposed BSHAP catalogue (earthquakes $M \geq 3.5$ in the period 510BC–1969, and earthquakes $M \geq 3.0$ in the period 1970–2012. Corresponding timeline of the data is presented at the *bottom* of the map). The countries contributing to the BSHAP_I and BSHAP_II projects are denoted by the *gray* areas

1900–2006 (Grünthal and Wahlström 2012; Grünthal et al. 2013) as a quality check for international standards. We believe that the BSHAP earthquake catalogue presented in this paper is compatible with the current well-established European and world-wide catalogues and that it will provide a solid background for the seismic hazard estimates in the greater Balkan Region and its surroundings in the future.

2 Compilation of the earthquake database

During the past decades, great individual and cooperative efforts were made in all of the Balkan countries to improve the earthquake catalogue databases. Various national or regional earthquake catalogues with different data qualities, completeness intervals, time periods, and data formats have been prepared. These differences arose as the consequence of the implemented methodology, quality of the historical data, and the density of existing national seismic stations. A significant improvement was made during the Survey of the Seismicity of the Balkan Region Project funded by UNESCO/UNDP REM/70/17 (Shebalin et al. 1974): a compilation, verification and unification of all existing earthquake catalogues in the Balkan region was realized. The outcomes of this project include a separate earthquake catalogue with maximum earthquake intensity bigger than five ($I \geq$ V) for the time period 1901–1970, a non-homogeneous earthquake catalogue for $I <$ V for the same time period, and a separate database for the earthquakes with epicentral intensity bigger than seven ($I \geq$ VII) occurred in the time period 1801–1900. The catalogue by Shebalin et al. (1998) that covers the territories of Poland, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Albania, Romania and Bulgaria supersedes the work of Shebalin et al. (1974). This comprehensive catalogue contains 3949 earthquakes in the time interval of 342 BC–1990 within the spatial window of 38°–55°N, 10°–35°E. However, only one magnitude estimate (surface magnitude, M_s or body wave magnitude, m_b) was assigned to the earthquakes in the Shebalin et al. (1998) catalogue. Bayliss and Burton (2007) explained that the M_s values in the Shebalin et al. (1998) catalogue were derived from direct measurements, estimated based on macro seismic and mixed determinations (including estimation from observed maximum intensity, I_{max}, and depth), or converted from SP, LP etc. phases; whereas m_b values were derived from direct measurements.

The Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 and was implemented within the time period 1992–1998 (Giardini 1999). In order to mitigate the earthquake risk, GSHAP promoted a regionally coordinated, homogeneous approach to seismic hazard evaluation. The GSHAP earthquake catalogue was further improved by the follow-up project that covers the western part of the Balkan Region: the GSHAP Seismic Hazard Assessment for the Adria Region (GSHAP-Adria) Project. GSHAP-Adria project highly benefited from the compiled European catalogue in the framework of the EC project-A Basic European Earthquake Catalogue and Database (BEECD, Stucchi 1998). The BEECD catalogue includes 3946 earthquakes that occurred between the years 1022 and 1993 in the Northern Balkan Area. According to Musson (1996), the earthquake catalogue compiled for the BEECD project can be considered as a "working catalogue" because: (i) a couple of new regional catalogues (e.g. Herak et al. 1996) were investigated but not incorporated since they were compilations of other catalogues, and (ii) new and improved national catalogues that were being compiled in the region could not be included since they were kept confidential. At the end of GSHAP and GSHAP-Adria, the first M_w-based earthquake catalogue for the region bounded by 44°–72°N, 25°W–32°E that includes approximately 5000 entries within time interval 1300–1993 with a lower magnitude threshold of $M_w = 3.5$ was created by Grünthal and Wahlström (2003). In the GSHAP catalogue, the data was calibrated into a homogenized M_w magnitude scale through the application of a hierarchical conversion system depending on the data availability in different regions. For Croatia, Bosnia and Herzegovina, and Slovenia regions, highest priority was given to the regional catalogue compiled by Živčić et al. (1996) and Herak et al. (1996) followed by the Oncescu et al. (1999) and Zsíros (1990) regional catalogues. Grünthal and Wahlström (2003) mentioned that the latest date of entry to most of the regional catalogues (especially for the Balkan region) was before 1993, indicating a temporal inconsistency between different geographical locations covered by GSHAP.

One of the major objectives of the BSHAP project was to build a uniform and updated earthquake catalogue for the Western Balkan Region based on the collaboration of "regional data providers": the national seismological surveys and other earthquake related institutes in the region. Therefore, the data from previously compiled catalogues are not directly used in this compilation, except for 48 events taken from Shebalin et al. (1998) catalogue. The first step of the data compilation process was to survey the available national catalogues and unifying the format of the national catalogues (by completing the required parameters such as origin time, location, local magnitude, and assigning a reference for data provider) to create a standard format for the BSHAP catalogue entries. The initial BSHAP catalogue including the earthquakes with magnitudes 3.5 and bigger was compiled from the national catalogues of 12 countries in the region: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Hungary, Italy, Montenegro, Macedonia, Romania, Serbia and Slovenia. In addition to the national catalogues, data from global catalogues (listed in Table 1) were incorporated into the database. The work implied a major challenge due to the large number of events in the national and regional catalogues and variety of the data format. Compiling of this initial earthquake catalogue (including 13,300 events) was achieved with the great contributions of Ll. Duni, M. Herak and S. Radovanović in the frame of the BSHAP_I project (during 2008–2011).

3 The final BSHAP catalogue: short overview

Initial BSHAP catalogue was enriched with more than 12,000 events: $3.0 < M < 3.5$ earthquakes starting from 1970 up to 2012 and $M \geq 3.0$ earthquakes occurred between 2010 and 2012 during BSHAP_II project. For each participating country, the top priority within the national borders was given to the entries in the domestic catalogue. As the complete data for Macedonia for the period 2006–2013 were not available at the time of assembling the catalogue, the $M \leq 3.5$ events are taken from the official Greek Catalogue (Aristotle University of Thessaloniki). Similarly, missing entries in the BSHAP catalogue from the territory of Bosnia and Herzegovina for $3.0 < M < 3.5$ earthquakes occurred between 1970 and 2012 and $M \geq 3.0$ earthquakes between 2010 and 2012 are collected from the national Croatian, Montenegrin and Serbian catalogues. The local and international catalogues contributing data to the final BSHAP catalogue are listed in Table 1.

After merging the national catalogues, events with magnitude smaller than 2.4 were removed from the database to minimize the possibility of creating duplicate events. Still, double entries for some events within the 15 km buffer zone around the national borders were determined. The search for duplicates for small magnitude events was done by an iterative and automated procedure based on two search criteria: (i) epicentral distance ($\Delta d = \pm 40$ km) and (ii) time difference ($\Delta t = \pm 90$ s). Additionally, the search was performed with and without a magnitude difference criteria of $\Delta M = 1$, regardless of the magnitude type. To control the automated procedure, manual and automated quality checks were performed. In the buffer zones, the preference was given to the record from the authoritative catalogue (the catalogue from the country where the epicenter is located). For Bosnia and Herzegovina, whose catalogue (except the few events near Banja Luka) entirely consists of data taken over from global catalogues, the Croatian catalogue was considered authoritative (Herak et al. 1996; Herak and Herak 2009).

The final version of BSHAP catalogue contains 26,118 earthquakes, from which 5914 earthquakes with magnitudes $M_w \geq 3.5$ in the period 510 BC–1969 and 19,230 earthquakes with magnitudes $M_w \geq 3.0$ in the period 1970–2012. The magnitude distributions of the catalogue entries for these two time intervals are presented in Fig. 2. The magnitude-

Table 1 Regional, national and global data sources for the BSHAP earthquake catalogue

Catalogue notation	Data taken from	Number of data taken	Explanations
Regional and national sources			
TIR	Tirana, Albania	3919	Events with $M \geq 3.0$ up to 31/12/2012
BLY	Banja Luka, Bosnia and Hercegovina	403	Events with $M \geq 3.0$ up to 31/12/2010
SOF	Sofia, Bulgaria	174	Events with $M > 4.0$ up to 1997 (taken from Bayliss and Burton 2007)
ZAG	Zagreb, Croatia	3807	Events with $M \geq 3.0$ up to 31/12/2012
THE	Permanent Regional Seismological Network operated by the Aristotle University of Thessaloniki, doi:10.7914/SN/HT	12,966	Events with $M_W \geq 4.5$ up to 31/12/2010. Events with $M_L \geq 2.0$, 01/01/2010–31/12/2012
BUD	Budapest, Hungary	12	Zsíros, 2000 (tibor@seismology.hu)
ROM	Roma, Italy (CPTI04)	1064	http://emidius.mi.ingv.it/CPTI04/
SKO	Skopje, Macedonia	602	Events with $M \geq 3.4$ up to 31/12/2005
PDG	Podgorica, Montenegro	817	Events with $M \geq 3.0$ up to 31/12/2012
BUC	Bucharest, Romania	168	Events with $M \geq 3.0$ up to 31/12/2012
LJU	Ljubljana, Slovenia	577	Events with $M \geq .3.0$ up to 31/12/2012
BEO	Belgrade, Serbia	1087	Events with $M \geq 3.0$ up to 31/12/2012
Global sources			
EMMA	The database of earthquake mechanisms for European area	57	http://www.emsc.csem.org/Earthquake/emma.php
EMSC	EMSC-CSEM	70	http://www.emsc-csem.org/Bulletin/
ISC	International seismologic center	266	http://www.isc.ac.uk/iscbulletin/search/catalogue/
NEIS	NEIC/NEIS catalogue, USGS, USA	200	http://earthquake.usgs.gov/data/centennial/centennial.pdf
HRV	Harvard GCMT catalog	140	GCMT Catalog (2014) http://www.globalcmt.org
INGV	Regional centroid moment tensor (RCMT)	273	http://www.bo.ingv.it/RCMT/
ETHZ	RCMT from seismological service of Zürich	17	http://www.seismo.ethz.ch/prod/tensors/
PDE	The preliminary determination of epicenters (PDE) bulletin	11	ftp://hazards.cr.usgs.gov/NEICPDE
SHE	Earthquake catalogue for central and southeastern Europe 342 BC–1990 AD	48	http://www.bgr.bund.de/EN/Themen/Seismologie/Erdbebenauswertung_en/Kataloge_en/historisch/EU_centr_south_en.html.

GCMT and RCMT evaluations have priority over other catalogues

time distribution and the cumulative annual number of earthquakes in the period 1970–2012 (Fig. 3) show the significant increase of events with magnitude $M_w \geq 3.0$ starting from the end of the 70s.

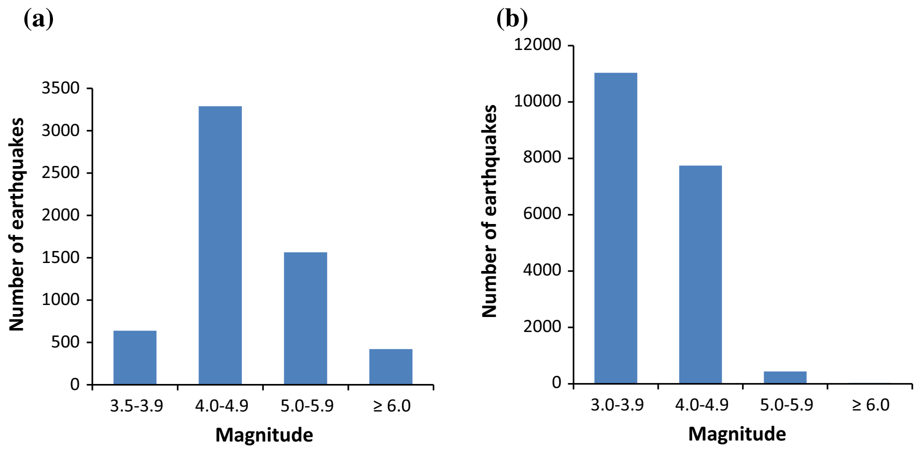

Fig. 2 Magnitude distribution of seismic events: **a** $M_w \geq 3.5$, in the period 510BC–1969 and **b** $M_w \geq 3.0$, in the period 1970–2012

Hypocenter depth values in the earthquake catalogues (and in the BSHAP catalogue) are generally not as well-constrained as the other parameters such as magnitude and epicentral location despite considerable progress due to modern instruments and techniques in the last years. In certain cases, a fixed value is assigned as the focal depth in order to remove the well-known trade-off between origin time and focal depth; therefore, the information about focal depths coming from individual catalogues should be used with caution. Current version of the BSHAP catalogue contains a variety of depth estimates from different national agencies. Histogram of the focal depth distribution shows clear peaks at 0, 10, 30, and 33 km, indicating that the typical fixed depth values used in the original catalogues are transferred to the compiled catalogue. Additionally, a small number of hypocenter depth values provided in the catalogue are "calculated depths" that have been rounded to nearest integer. Therefore, the spatial distribution of focal depths of the events in the BSHAP catalogue (shown in Fig. 4) does not provide systematic and consistent information related to the thickness of the tectonic features of the region. According to Fig. 4, the hypocenter depth generaly varies in between 5 and 30 km for the Western Balkan Region. Average depth of events recorded in the whole BSHAP area after 1900 is found as 8.4 km.

One of the characteristic features of the BSHAP catalogue is the downscaling of the magnitude of 1904 Kresna earthquake, which is estimated as the largest continental European historical earthquake affecting (by intensity V+) at distances of about 100–140 km from its epicenter, including the cities of Skopje (MK), Sofia (BG) and Thessaloniki (GR). The first magnitude estimate of the 1904 earthquake was made by Gutenberg; however, he did not provide a very robust estimate of the long-period body-wave magnitude (of about 7.5) based on the maximum amplitude from the undamped Omori seismograph in Osaka (OSA) and the P and S amplitudes from a Wiechert in Göttingen (GTT). Karnik (1968) calculated the surface-wave magnitude of the larger shocks of Struma sequence using the original Prague formula and ground amplitudes from GTT, Leipzig (LEI) and Potsdam (POT) stations and estimated the M_s value of the mainshock as 7.8. Christoskov and Grigorova (1968) approved that value using trace amplitudes recorded by 10 undamped penduli in Russia (Levitski 1906) and same three seismographs from Europe.

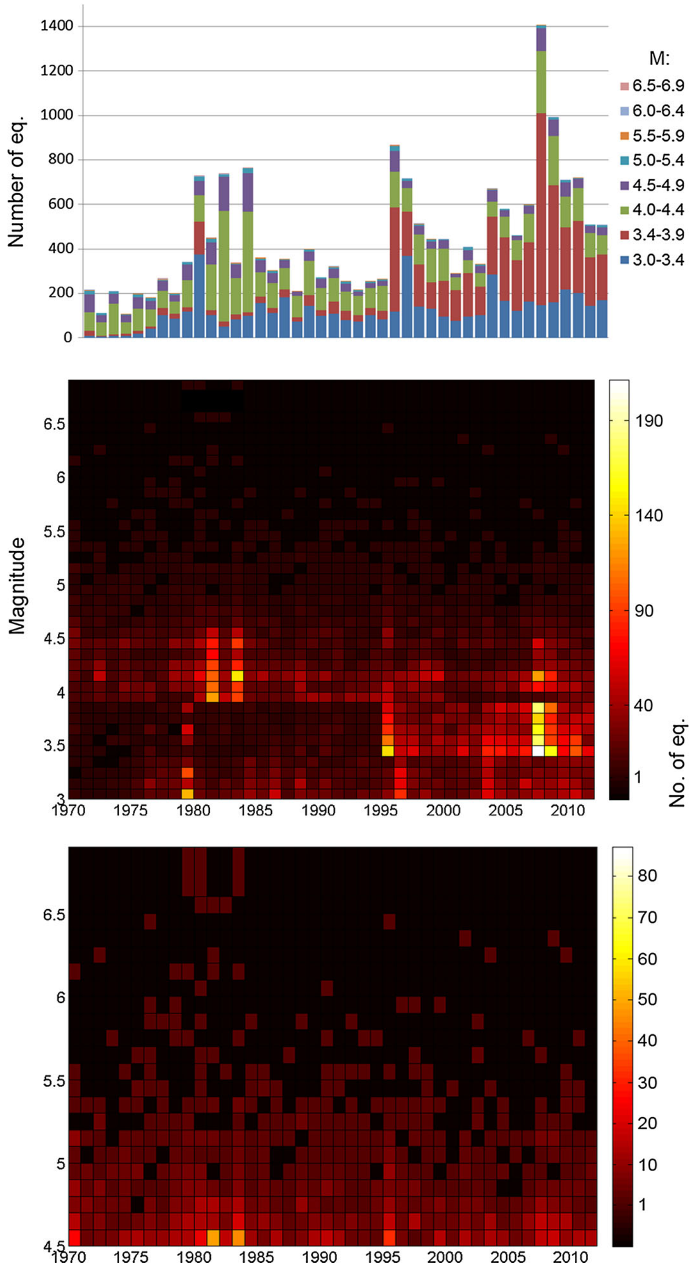

Fig. 3 BSHAP catalogue magnitude timeline (all events) in the period 1970–2012 (*top*) and cumulative annual number of earthquakes in the period 1970–2012 for all magnitudes (*middle*) and just for magnitudes >4.5 (*bottom*)

Abe and Noguchi (1983a, b) demonstrated that the magnitudes of early twentieth century events were significantly overestimated because they were calculated using the records gathered from undamped seismometers. The catalogue for worldwide shallow events with

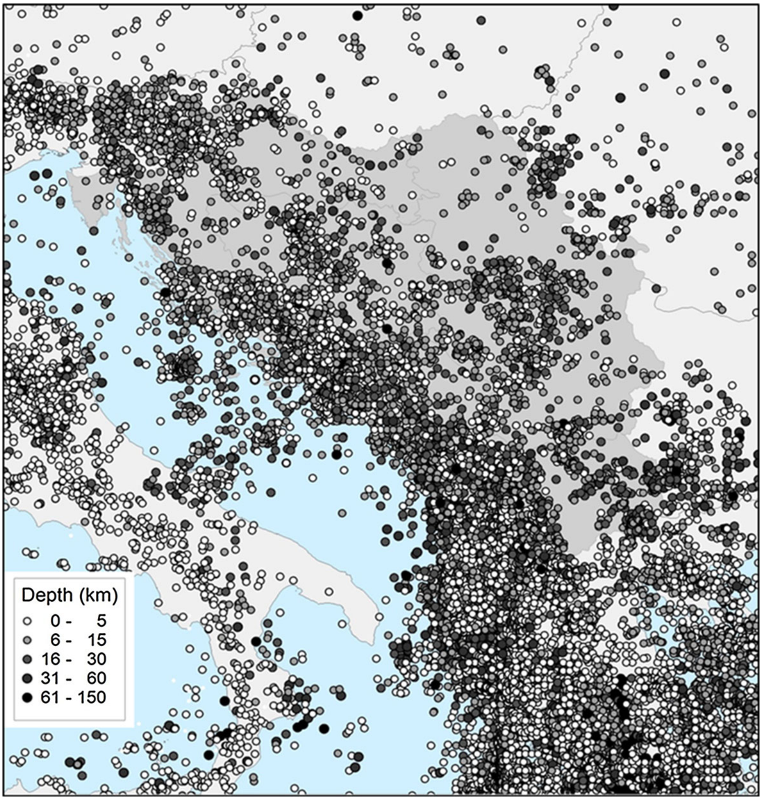

Fig. 4 Spatial distribution of hypocenter depths for all events in the final BSHAP catalogue

$M_s > 7$ prepared by Abe and Noguchi (1983b) accounted for this bias by applying a systematic correction. Doubts about the large magnitude assigned to 1904 Kresna earthquake was also expressed by Miyamura (1988) on the grounds that the data used were not reliable. Meyer et al. (2002) considered that the Krupnik fault is associated with the mainshock of the 1904 earthquake sequence. Assuming an average fault dip of 45°, a 15 km thick seismogenic crust, and the average slip of 2 m on a ~20 km long fault, they calculated the seismic moment (M_o) of the earthquake and estimated the M_s as 6.9 based on the M_o–M_s relationship proposed by Ekström and Dziewonski (1988). Ambraseys (2001) reappraised the instrumental data concerning the 1904 events. Obtaining the value of $M_s = 7.2$, he confirmed that the mainshock was previously overestimated by at least 0.3 magnitude units. Based on the abovementioned corrections on the initial magnitude estimation, the magnitude of the 1904 Kresna Earthquake is downscaled as $M_w = 7.2$ in BSHAP catalogue.

4 Magnitude scales and conversion to moment magnitude

The indispensable fields required for seismic hazard assessment (origin date and time, epicenter location, and all the available data for appropriate magnitude characterization) are included in the BSHAP catalogue. Since the moment magnitude characterizes the earthquake size accurately and the selected ground motion prediction equations (GMPEs) for the seismic hazard assessment employ the moment magnitude (M_W) scale, the latter was chosen as the uniform magnitude scale for the BSHAP catalogue. Various magnitude scales, even from the same data provider, were assigned to the events in the initial catalogue. Therefore, proxy values of M_W had to be obtained using the empirical relationships between the local and other magnitude scales and M_W to fulfill the BSHAP requirements. This task had to be performed not only for the historical and early instrumental period events but also for new earthquakes, because the number of direct measurements of seismic moments was very limited within the source catalogues.

Most of magnitude estimations in the BSHAP catalogue are in terms of local magnitude scales used by several different national seismological agencies of the region. Available magnitude conversion relations for Europe such as Scordilis (2006) are not applicable to those local scales used by the data providers in the Western Balkan area. Therefore, several empirical magnitude conversion relationships were derived using errors-in-variables regression (EIVREG), a least squares data modeling technique in which observational errors on both dependent and independent variables are taken into account (Castellaro and Bormann 2007; Lolli and Gasperini 2012). Recent literature entries suggest that EIVREG performs better than Ordinary Least Square (OLS) regression when one or more of the independent variables are measured with additive noise, as in the case of the magnitude scales (Draper and Smith 1998). The M_W estimation was preceded by a detailed statistical investigation regarding the relationships between different magnitude scales used by local seismic networks, with a view to check the magnitude consistency reported by the above mentioned agencies with the M_W magnitude obtained by the centroid moment tensor solutions (Harvard GCMT catalog, PDE catalogue) or from RCMT solution (INGV, ETHZ).

4.1 Determination of M_W proxy based on M_{ms}, M_S and m_b

Until the beginning of twentieth century, earthquake magnitude is reported in terms of macro seismic magnitude M_{ms} in the BSHAP catalogue. The macro seismic magnitudes in the catalogue, coming from the source catalogs for the pre-instrumental period, were converted to M_W using the relevant regression relations of Scordilis (2006) given in Eqs. 1–3:

$$M_W = 0.80 \times M_{ms} + 1.31 \quad 4.0 \le M_{ms} < 5.4 \tag{1}$$

$$M_W = 0.70 \times M_{ms} + 1.80 \quad 5.4 \le M_{ms} < 6.3 \tag{2}$$

$$M_W = 1.04 \times M_{ms} - 0.33 \quad 6.3 \le M_{ms} < 8.1 \tag{3}$$

The surface wave magnitude M_S is proven to be a good estimator of M_W since it scales rather well in a wide range of magnitudes (ISC-GEM 2012). Hence, M_S is preferred as the magnitude scale to obtain the proxy M_W in cases where direct measurements of M_W are missing. But when M_S is not available, it would be worthly to use the short-period body-wave magnitude (m_b), although m_b has a larger scatter with M_W, especially for earthquakes with magnitudes above six. The emprical M_S–M_W and m_b–M_W relationships are not linear for the whole magnitude range, therefore, bi-linear functional forms are often used in regressions (e.g. Scordilis 2006). To avoid the shortcoming of choosing the hinge magnitude value (the value where the slope of the line changes) for the bi-linear functional form and the additional uncertainty associated with it, a single continuous functional form in terms of exponential model as shown below is preferred:

$$y = \exp(b_0 + b_1 x) + b_2 \tag{4}$$

The relevant regression coefficients and the standard deviations (shown in Table 2) were obtained using the non-linear least square regression method since the direction of the bias is likely to be more complicated in non-linear functions and the methods for estimating non-linear errors-in-variables models without any extraneous information are not available. A dataset of more than 300 data pairs of M_S–M_W and m_b–M_W available for the BSHAP project area (till April 2014) is compiled for this purpose .

The respective M_S and m_b values are taken from the bulletins of ISC, whereas the corresponding M_W values are taken from the GCMT catalogue of Harvard, or from RCMT solutions (INGV and ETHZ) (please see Table 1 for details). A similar functional form is also used in ISC-GEM (2012) global earthquake catalogue, therefore, regional empirical relations proposed in this study can be directly compared to the analog global models derived in the framework of ISC-GEM project. Figures 5 and 6 show the distribution of the residuals of the proposed models for M_S and m_b, respectively, indicating that the residuals are equally distributed along the zero line for both models. These figures also point out that the proposed regional regression relations fit the data in the BSHAP area better than the relevant global GEM-ISC (2012) relations, especially for magnitudes <5.0. Therefore, Eqs. (5) and (6) (provided in Table 2) are used to calculate the M_W proxy values if direct measurements of M_W are missing, but M_S and/or m_b magnitudes from the bulletins of ISC are available.

4.2 Determination of M_W proxy based on M_L to M_W conversion

To enable conversion of the local magnitudes (M_L) calculated by the seismological centers of the region to M_W, we updated the empirical relations derived by Duni et al. (2010), using the extended dataset for the BSHAP region. The moment magnitude values determined by the Harvard GCMT solutions (Dziewonski et al. 1981) and the regional moment tensor solutions reported by INGV (Rome) and ETHZ (Zürich) (till April 2014) are accepted as the reference data pairs. About 260 GCMT/RCMT solutions for small-to-large events in the BSHAP area, varying from $M_W = 3.5$ to $M_W = 6.9$, are used to derive the local relationships converting the M_L to M_W. The relevant functional form, regression coefficients, and the standard deviations obtained using the EIVREG method are presented in Table 3 separately for each local seismological center. Analysis of the residuals point out no systematic trends or bias in the proposed local magnitude conversion equations (Fig. 7).

Table 2 Derived regional relationships between the moment magnitude M_W, M_S and m_b

Regression model		No. of events	Determination coefficient, R^2	SD of regression, s_e	Application range
$M_w = \exp(-0.044 + 0.227 M_s) + 2.26$ [a] (0.276) (0.030) (0.374)	(5)	322	0.916	0.161	$3.0 \le M_S \le 7.0$
$M_w = \exp(-1.401 + 0.458 m_b) + 2.28$ [a] (0.373) (0.052) (0.271)	(6)	379	0.890	0.197	$3.2 \le m_b \le 6.2$

[a] In the second rows, in parenthesis are given the standard errors of regression coefficients

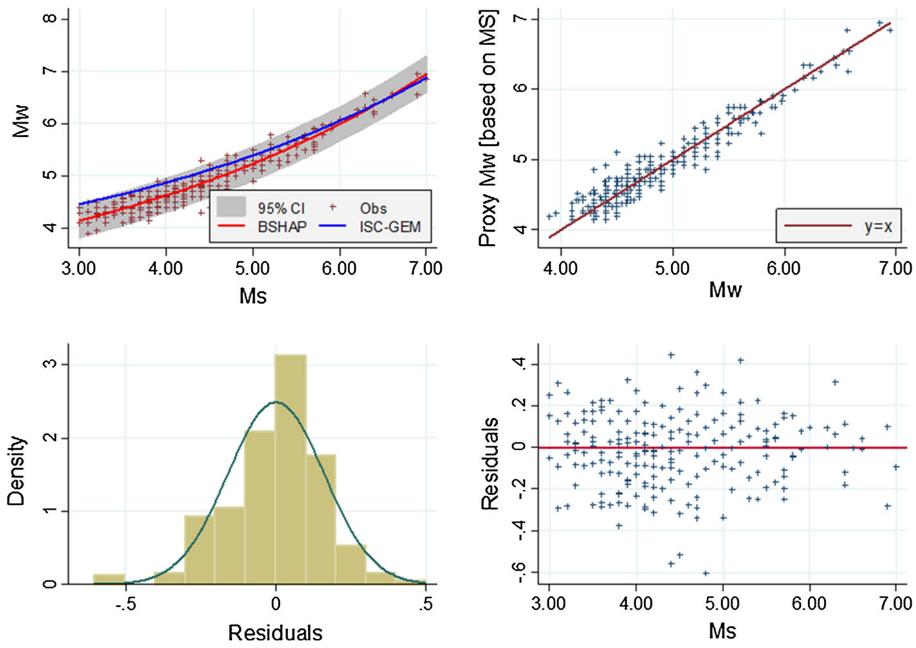

Fig. 5 Proposed M_w–M_s regional regression model (*red*) for the BSHAP project area; ISC-GEM global model (*blue*): $M_w = \exp(-0.22 + 0.23M_s) + 2.86$ and distribution of residuals

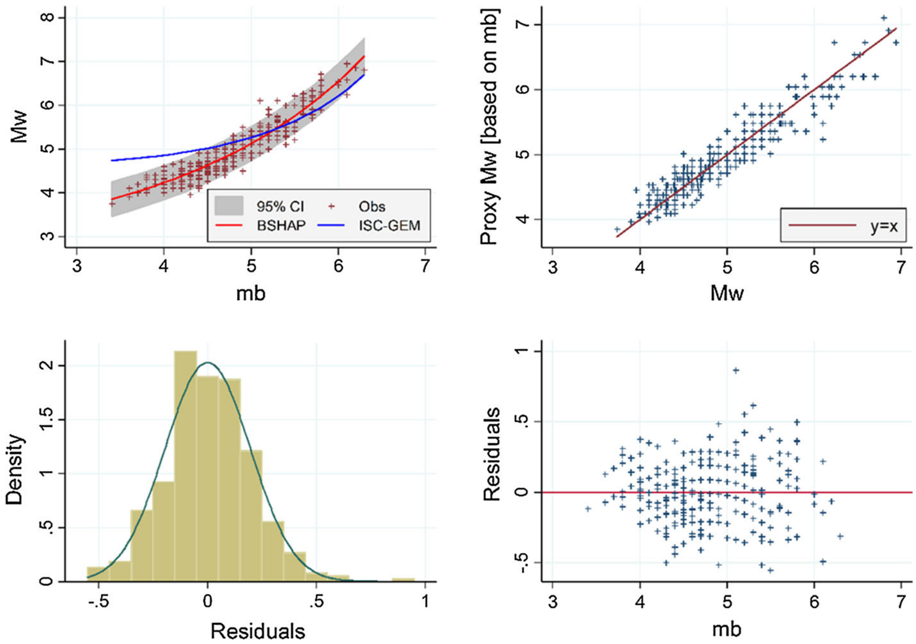

Fig. 6 Proposed M_w–m_b regional regression model (*red*) for the BSHAP project area; ISC-GEM global model (*blue*): $M_w = \exp(-4.66 + 0.86m_b) + 4.56$ and distribution of residuals

Table 3 Empirical relationships between moment magnitude M_W and local magnitude M_L

Agency	Regression equation $M_W = b_0 + b_1 M_L$	Number of events	Determination coefficient, R^2	SD of regression, s_e
Tirana	$M_w = 1.22 + 0.813 M_L$ [a] (0.25) (0.056) (7)	96	0.715	0.256
Podgorica	$M_w = -0.01 + 1.028 M_L$ [a] (0.16) (0.033) (8)	75	0.930	0.184
Zagreb	$M_w = -0.11 + 1.011 M_L$ [a] (0.38) (0.080) (9)	31	0.852	0.229
Belgrade	$M_w = 0.70 + 0.858 M_L$ [a] (0.21) (0.049) (10)	50	0.953	0.182
Skopje	$M_w = 0.56 + 0.913 M_L$ [a] (0.48) (0.101) (11)	28	0.773	0.267

[a] In the second rows, in parenthesis are given the standard errors of regression coefficients

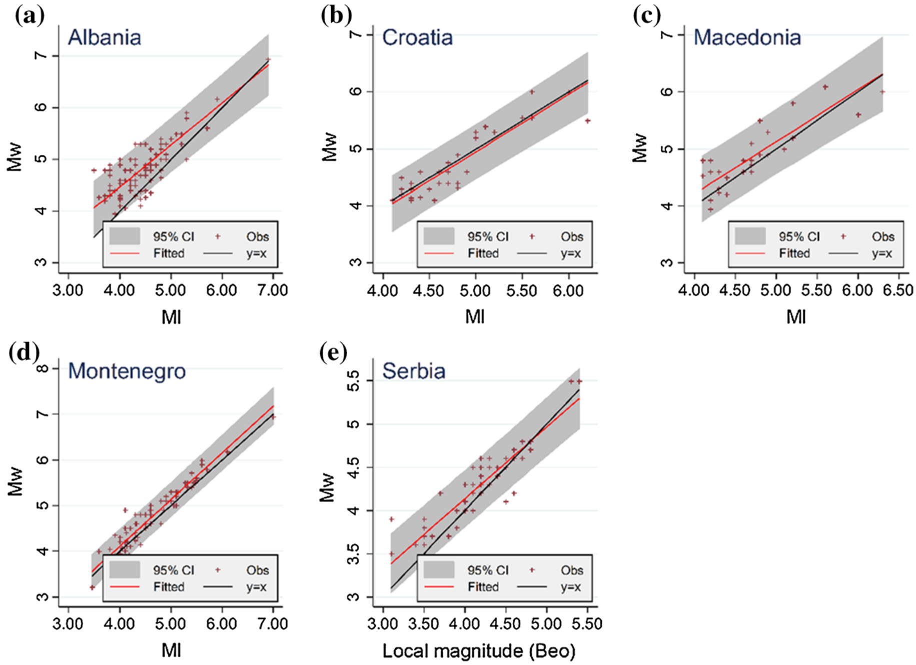

Fig. 7 Magnitude conversion relationships used to compute the proxy-M_w based on the local magnitude scales for **a** Albania, **b** Croatia, **c** Macedonia, **d** Montenegro and **e** Serbia

In order to obtain the most reliable proxy M_W value for the entries in the catalogue, the following scheme is employed:

1. Equations (1)–(3) are used for the events occurred in the historical period (510 BC up to 1907), as well as for events characterized by macro seismic intensity, when the instrumental magnitude determinations are not available;

2. If the direct measurement of M_W based on the original waveform analysis is available, it is included according to the following priority order: GCMT, ISC-GEM, PDE, RCMT (INGV, ETHZ, etc.), or M_W determined from bibliographic search (EMMA, etc.);
3. M_W proxy based on M_S using Eq. (5) is used if M_W is not available, but M_S is;
4. M_W proxy based on local magnitude M_L using the regression models $M_W = f(M_L)$ of the country where the event occurred is included if M_W and M_S are not available, but M_L is;
5. M_W proxy based on m_b using Eq. (6) is used if M_W, M_S and M_L are not available, but m_b is.

5 Earthquake mainshock-aftershock classification and catalogue completeness intervals

In probabilistic seismic hazard assessment (PSHA) calculations, the magnitude recurrence model parameters (generally the a- and b-values of the truncated exponential magnitude-frequency relationship) are estimated by considering the time intervals of catalogue completeness for different magnitude ranges. Before regressing for the recurrence parameters, the foreshocks and aftershocks should be removed from the catalogue since they violate the assumption that the earthquakes are independent events (Bender and Perkins 1987). Foreshocks and aftershocks are both spatially and temporally dependent of the mainshock; however, the identification of dependent events is subjective since no physical differences are known to exist between foreshocks, mainshocks, and aftershocks. Therefore, earthquake clusters are usually defined by their proximity in time and space. There are many algorithms and methods proposed for declustering, and here we used the temporal and spatial windows whose size increases with the magnitude of the mainshock as shown in Table 4. All events occurring within time T_w after the mainshock, and within D_w km from its epicentre were declared as aftershocks. The foreshocks were identified using the same spatial windows, but with a 5-times shorter time span. The particular window sizes used are selected based on the judgement and experience in years of analyses (M. Herak, personal communication) and turned out to produce the mainshock catalogues whose complete parts are Poissonian at least on the 0.95 level of significance when tested by the Anderson–Darling or the χ^2-tests. The time windows preferred for this study are placed in between the values suggested by Gardner and Knopoff (1974) and Knopoff (2000). The same approach (with somewhat smaller windows) was used to study the seismicity of NW Croatia (Herak et al. 2009). Using the above described algorithm 2523 clusters of earthquakes including 16,118 events were identified and the declustered catalogue contains 10,000 mainshocks.

One of the most fundamental problems encountered in statistical analyses of any catalogue is the estimation of its completeness intervals. It is self-evident that completeness levels will vary with time. For the pre-instrumental era, catalogues report only the most important events of large magnitude. The shift of completeness levels to lower magnitudes is caused by development of seismographs and their increased sensitivity and by the significant and constant increase of the density of station networks during the 20th century. Clearly, the rate of instrumental quality and coverage increase was quite inhomogeneous thus causing catalogue inhomogeneity which must be reduced as much as possible prior to any calculations. Identifying completeness thresholds and their temporal and spatial variations is a controversial task, and the problem does not have a unique solution. In evaluating the incompleteness, we have chosen to follow the simplified approach proposed

Table 4 Windowing parameters used to decluster catalogues

M	D_w (km)	T_w (days)
3.0	20.0	25.0
3.2	21.6	30.1
3.4	23.2	36.2
3.6	25.1	43.5
3.8	27.0	52.3
4.0	29.1	62.9
4.2	31.4	75.6
4.4	33.9	90.9
4.6	36.5	109.3
4.8	39.4	131.5
5.0	42.4	158.1
5.2	45.7	190.1
5.4	49.3	228.7
5.6	53.2	275.0
5.8	57.3	330.7
6.0	61.8	397.6
6.2	66.6	478.2
6.4	71.8	575.0
6.6	77.4	691.5
6.8	83.5	831.6
7.0	90.0	1000.0

For $M < 3.0$ and $M > 7.0$, the parameters are estimated by log-linear extrapolation

D_W radius of circular window, T_w duration of aftershocks, $T_{w,for}$ duration of foreshocks

by Mulargia et al. (1987), which involves a visual inspection of the cumulative plot of the number of events as a function of time. This method appears to be very efficient and accurate even when applied to small sets of data.

Completeness time intervals are estimated for the BSHAP earthquake catalogue for different magnitude intervals. Figure 8 shows the plot relative to the classes of magnitudes larger than 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0 and 6.5 from year 1800 up to 2012 and Fig. 9 the plot relative to the classes of magnitude $M \geq 5.5$, $M \geq 6.0$ and $M \geq 6.5$ from year 1100 (1200) up

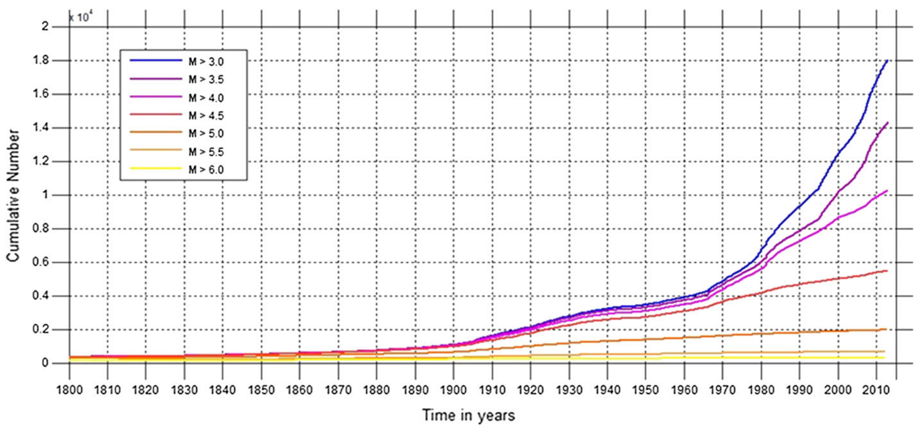

Fig. 8 Cumulative number of earthquakes above the given reference magnitude versus time

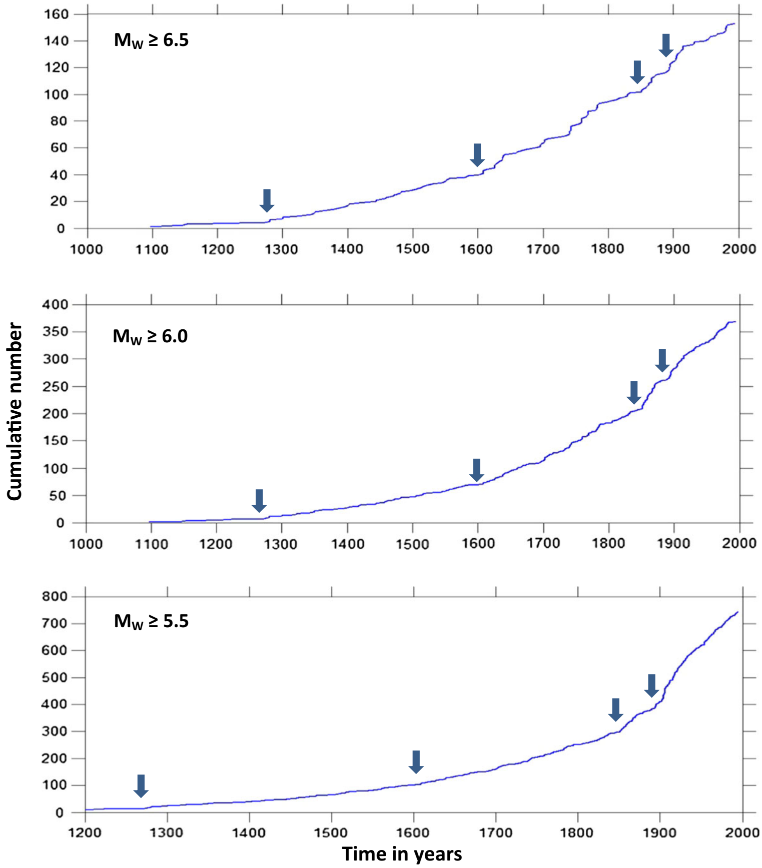

Fig. 9 Closer look at the completeness of events with magnitudes bigger than 6.5, 6.0 and 5.5; the *arrows* indicate the points in time, where a change in slope occurs

to 2012. Assuming that the most recent change in slope occurs when the data became complete for magnitudes above the reference magnitude (Gasperini and Ferrari 2000), completeness intervals for different magnitude ranges are tabulated in Table 5. The completeness time intervals presented in Table 5 are in good agreement with the values proposed by Duni et al. (2010). We would like to underline that the catalog completeness intervals presented in this manuscript are not directly adopted in the calculation of the recurrence parameters for BSHAP seismic hazard maps. Earthquake recurrence parameter are calculated for super zones defined in Mihaljević et al. (2015) using the modified maximum likelihood method that considers the unequal completeness intervals for different magnitude bins proposed by Weichert (1980) (details provided in Mihaljević et al. 2015).

6 Comparison with other global earthquake catalogues

The common events in the BSHAP catalogue are compared to the ISC-GEM Global Instrumental Earthquake Catalogue (1900–2009) (Storchak et al. 2013) and SHARE European Earthquake Catalogue (SHEEC ver. 3.3) (Giardini et al. 2013; Grünthal et al.

Table 5 Catalogue completeness intervals of BSHAP catalogue to be used in seismic source characterization models of BSHAP area

Earthquakes with	$M_W \geq 3.0$	$M_W \geq 3.5$	$M_W \geq 4.0$	$M_W \geq 4.5$	$M_W \geq 5.0$	$M_W \geq 5.5$	$M_W \geq 6.0$	$M_W \geq 6.5$
Complete from year	1982	1978	1965	1945	1900	1850	1605	1280

2013; Grünthal and Wahlström 2012; Stucchi et al. 2012) with the purpose of identifying any temporal and spatial discrepancies between the BSHAP catalogue and these well-established global catalogues. The ISC-GEM catalogue contains the data with magnitudes $M_S \geq 7.5$ for the period 1900–1917, events with $M_S \geq 6.25$ during 1918–1959, and $M_S \geq 5.5$ for the period of 1960–2009.

All events from ISC-GEM catalogue in the BSHAP region are identified and the differences in the event origin times and locations are calculated. For those events, the moment magnitudes are directly taken from GCMT (Harvard) and RCMT (INGV, ETHZ) catalogues. Figure 10a presents the spatial distribution of data from ISC-GEM catalogue within the BSHAP project region in comparison with the locations provided in BSHAP catalogue. For the majority of the common earthquakes, the time difference between both catalogues is <5 s. The maximum time difference between same earthquakes from both catalogues was 25 s (Fig. 10b), and maximum distance difference up to 35 km (Fig. 10c), with the exception of few earthquakes from southern Italy and Greece.

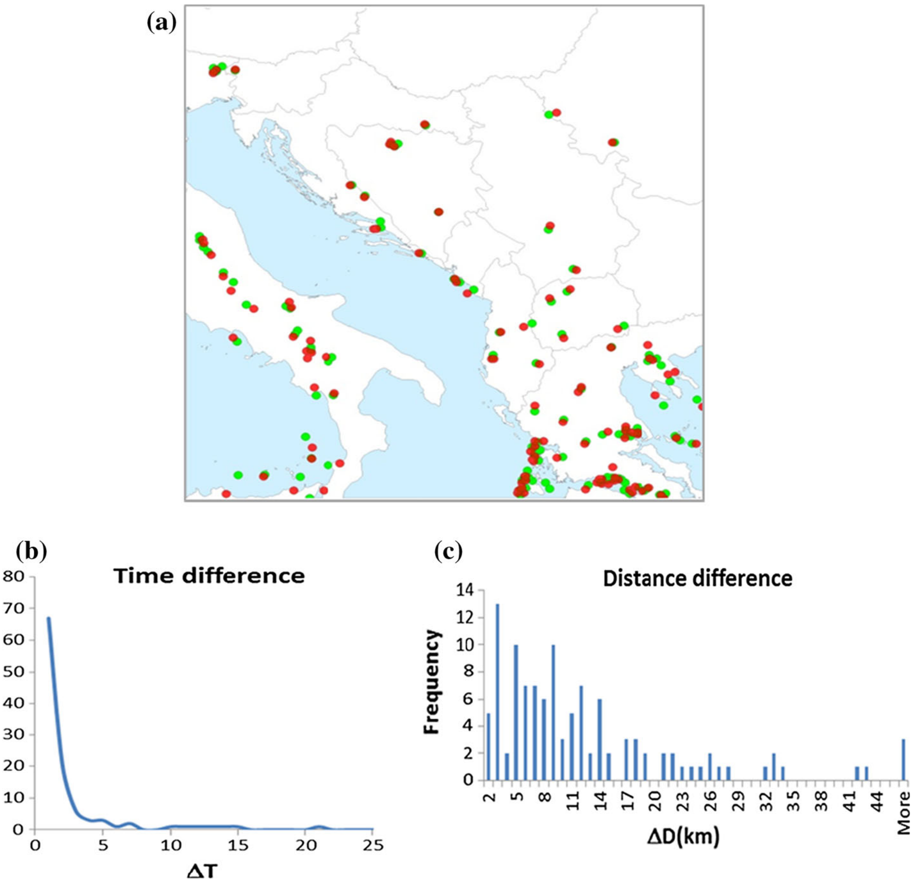

Fig. 10 BSHAP catalogue compared to the ISC-GEM catalogue for common events: **a** map with epicentres for identical earthquakes from both catalogues; **b** time difference and **c** distance difference between same events from both catalogues

The SHEEC catalogue contains 6609 earthquakes with magnitudes $M \geq 3.0$ (373 BC–2006) in the BSHAP project region, whereas the BSHAP catalogue contains more than 21,267 earthquakes in the same region and in the same time period (Fig. 11a). We determined 5344 common events from both catalogues using the criteria: $\Delta T \pm 60$ s and

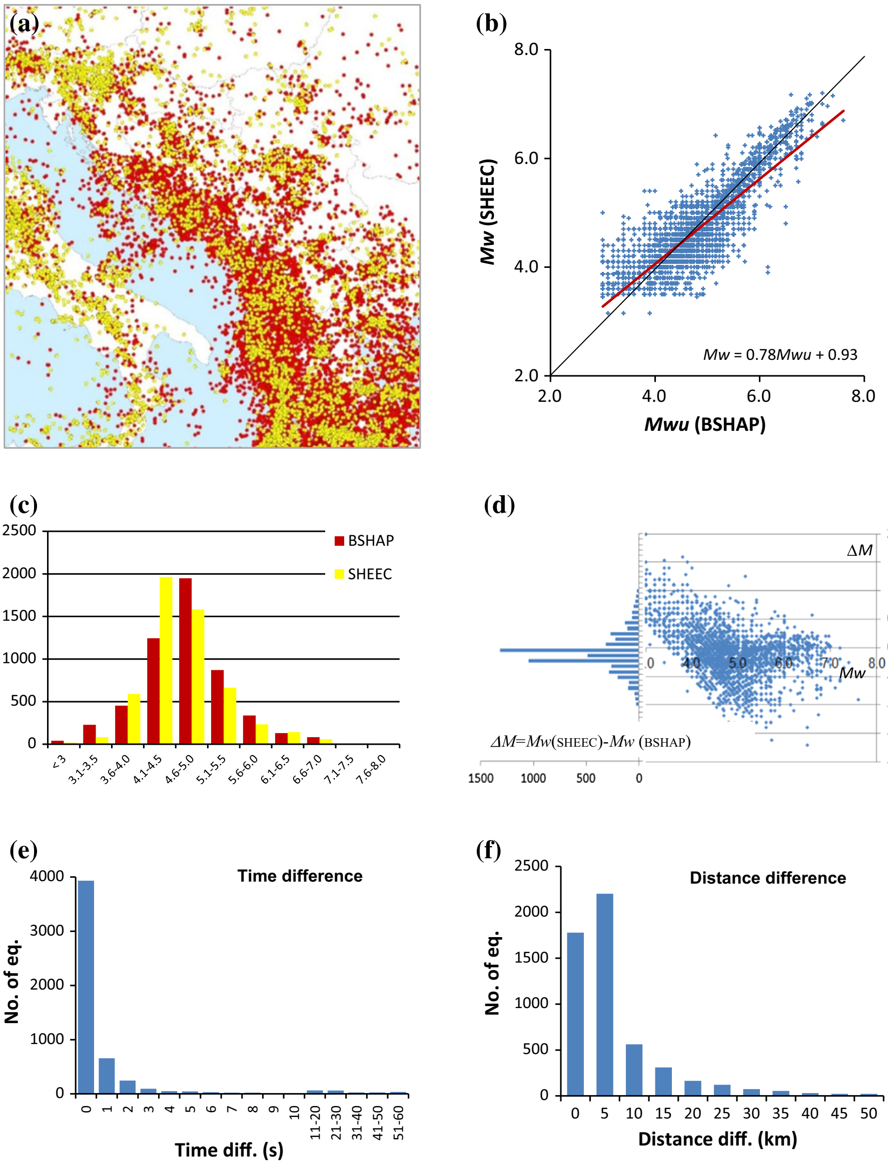

Fig. 11 BSHAP catalogue compared to the SHEEC catalogue: **a** map with epicentres from both catalogues (*yellow*: SHEEC, *red*: BSHAP), **b** magnitude regression between M_w values for identical earthquakes from both catalogues, **c** magnitude distribution for different magnitude bins (*yellow*: SHEEC, *red*: BSHAP) for identical earthquakes from both catalogues, **d** magnitude-difference distribution, **e**, **f** time difference and distance difference between same events from catalogues

$\Delta D \pm 50$ km for time and location differences. The correspondence between the moment magnitudes in both catalogues is close to the 1:1 relationship (Fig. 11c, d). The magnitude regression analysis (Fig. 11b) shows that BSHAP moment magnitudes are slightly overestimated when compared to the SHEEC magnitudes for the same events. 87,5 % of the common earthquakes from BSHAP and SHEEC catalogues have a magnitude difference within the range of $-0.5 \leq \Delta M \leq 0.5$, 49 % of them being overestimated, 28 % are identical and 23 % are underestimated compared to SHEEC magnitudes. For the selected common events, distributions of time and distance differences are shown in Fig. 11e, f, respectively. About 95 % of the selected common earthquakes have a time difference between -0.6 and 0.6 s, and a distance difference up to 20 km. Analysis results show that the proposed BSHAP catalogue is consistent with the current global catalogues in terms of magnitude, time and location of the common entries.

7 Summary and conclusions

The Harmonization of Seismic Hazard Maps in Western Balkan Countries Project (BSHAP), the collaboration among 8 countries and 11 participating institutes, was funded for 7 years by NATO-SFP Program to support the preparation of new seismic hazard maps of the Western Balkan Region. One of the most important outputs of the BSHAP project is the updated and unified BSHAP earthquake catalogue that is compiled directly from the datasets of earthquake data providers of the region. For this purpose, the national earthquake catalogues of 12 countries in the region; Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Hungary, Italy, Montenegro, Macedonia, Romania, Serbia and Slovenia were accessed and assembled together based on the procedures described in this paper. The compiled catalogue is enriched with data from global catalogues, especially for large magnitude events. One of the biggest challenges was to build a standard data format due to the large number of events in the national and regional catalogues and variety of the data format. During last 3 years, the BSHAP catalogue is significantly improved by examining and filtering the catalogue for duplicate events, fulfillment of missing earthquake parameters for the past events and addition of available earthquake metadata for the recent earthquakes.

The final BSHAP earthquake catalogue covers the geographic area limited by 38.0°–47.5°N, 12.5°–24.5°E and includes 26,118 earthquakes that occurred in the region between 510 BC and 2012. Since the primary objective is to provide input to the PSHA and seismic hazard maps, the M_w proxy is estimated for all entries in the BSHAP catalogue. Various magnitude scales, even from the same data provider, were assigned to the events in the compiled catalogue; therefore, separate empirical relationships between the local and other magnitude scales and M_W are developed for Albania, Croatia, Macedonia, Montenegro and Serbia using errors-in-variables regression technique. The data pairs collected from regional and global catalogues are employed in the regression analysis. The catalogue completeness thresholds are analyzed and incorporated into the seismotectonic model developed within the BSHAP Project. The unified and updated BSHAP catalogue, as demonstrated, is fully compatible with the current well-established European and worldwide catalogues.

The BSHAP catalogue represents a step forward from many points of view, which was made possible by the collaborative efforts of national seismological surveys and other earthquake related institutes in the Western Balkan Region. Currently, the BSHAP catalogue is being implemented in the seismo-tectonic model developed for the BSHAP area (Mihaljević et al. 2015) and development of an advanced approach for seismic hazard assessment for the Republic of Macedonia (Šalić 2015). The catalogue will be used as input to the PSHA calculations and updated seismic hazard maps of Western Balkan Area (Šalić et al. 2015) and for Seismic Zoning of Macedonia for developing the Eurocode 8 National Annex of Macedonia. The events that are significant for future seismic hazard studies (the events with $M_w > 5$) in the region are disseminated through the project website (http://wbalkanseismicmaps.org/) for public use.

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