IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

Local Magnitude Conversion to Unified Moment Magnitude in the Croatian Earthquake Catalogue (CEC)

Ljiljana Ivanković[1], Snježana Markušić[2,*], Ines Ivančić[2]
University of Applied Sciences Velika Gorica, Velika Gorica, Croatia[1]
Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia[2]

Abstract: The earthquake catalogue of events that occurred in Croatia (Croatian Earthquake Catalogue – CEC) during the period 373BC–2015 was compiled for achieving homogeneity for magnitudes. The need to use moment magnitudes in hazard analyses (since the moment magnitude characterizes the earthquake size accurately and the selected ground motion prediction equations (GMPEs) employ the moment magnitude (M_W) scale) motivated this work. Using M_W magnitude values obtained by the centroid moment tensor solutions (Harvard GCMT catalog, PDE catalogue) and from RCMT solution (INGV), magnitude conversion equation for local magnitudes (which are reported in CEC for each event) was 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. About 120 GCMT/RCMT solutions for small-to-large events, varying M_W from 3.5 to 5.7, were used to derive the local relationship converting the M_L to M_W. The completeness and homogeneity of the unified catalogue were also analyzed, as well as *a* and *b* value of the Gutenberg-Richter frequency-magnitude relation. A prepared unified homogeneous catalogue can serve as a reference catalogue for seismic hazard estimates and other seismic studies in Croatia and neighbouring areas.

Keywords: Earthquake catalogue, local magnitude, moment magnitude, errors-in-variables, seismicity.

I. INTRODUCTION

The wider area of Croatia is seismically active region characterized by relatively higher earthquake hazard and risk. 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. The basis for the reliable, as much as possible, seismic hazard assessment is unified, homogenous and complete earthquake catalogue. The objective of this paper is to present the updated and unified earthquake catalogue for the wider Croatian territory (the Croatian earthquake catalogue – CEC). The CEC covers the geographic area limited by 42.0 – 47.0 °N and 13.0 – 20.0 °E and includes 78995 events that occurred inside the mentioned area in the period 373BC-2015 (Fig. 1). The following sections present the effort for unification of the local magnitude scales, the magnitude conversion relationship (local to moment magnitudes), the mainshock-aftershock classification of the events, the statistical analysis of the CEC and the temporal and spatial completeness analysis of the final catalogue. The following sections present the effort for unification of the local magnitude scales, the magnitude conversion relationship (local to moment magnitudes), the mainshock-aftershock classification of the events, the statistical analysis of the CEC and the temporal and spatial completeness analysis of the final catalogue.

II. CROATIAN EARTHQUAKE CATALOGUE – CEC

After the great Zagreb earthquake of 9 November 1880, the sporadic earthquake research efforts evolve into systematic ones. Immediately after the earthquake, the Yugoslav Academy of Science and Arts in Zagreb established the “Committee for observation of earthquake-related phenomena”. The main task of the Committee was to study Croatian earthquakes and methodically collect all related data. In the first volume of its Papers, the Academy published the extensive report on the Zagreb earthquake (Torbar, 1882), where the phenomena related to that event are not only described, but also explained. The Academy’s Committee later also collected and published all available information on the Croatian earthquakes for the period 361–1906. This data set was used as solid basis for scientific study of the natural phenomenon (Kišpatić, 1891, 1892, 1895).

The first catalogue compilation was initiated within the framework of the UNDP/UNESCO project “Survey of the seismicity of the Balkan region” (Shebalin et al., 1974). The resulting catalogue was published in two volumes (Part I – earthquakes in the period 1901–1970; Part II – earthquakes before 1901). Its subset consistingof earthquakes on the Croatian territory formed a nucleus of the CEC. It has been revised (e.g. Herak et al., 1996) and supplemented for the years after 1970 (e.g. Herak et al., 1988, 1991; Herak and Cabor, 1989; Markušić et al., 1990, 1993, 1998; Ivančić et al, 2002, 2006). As a rule, new entries were added to the catalogue with a delay of 1–2 years, which could be used to collect relevant data and relocate the earthquakes.

IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

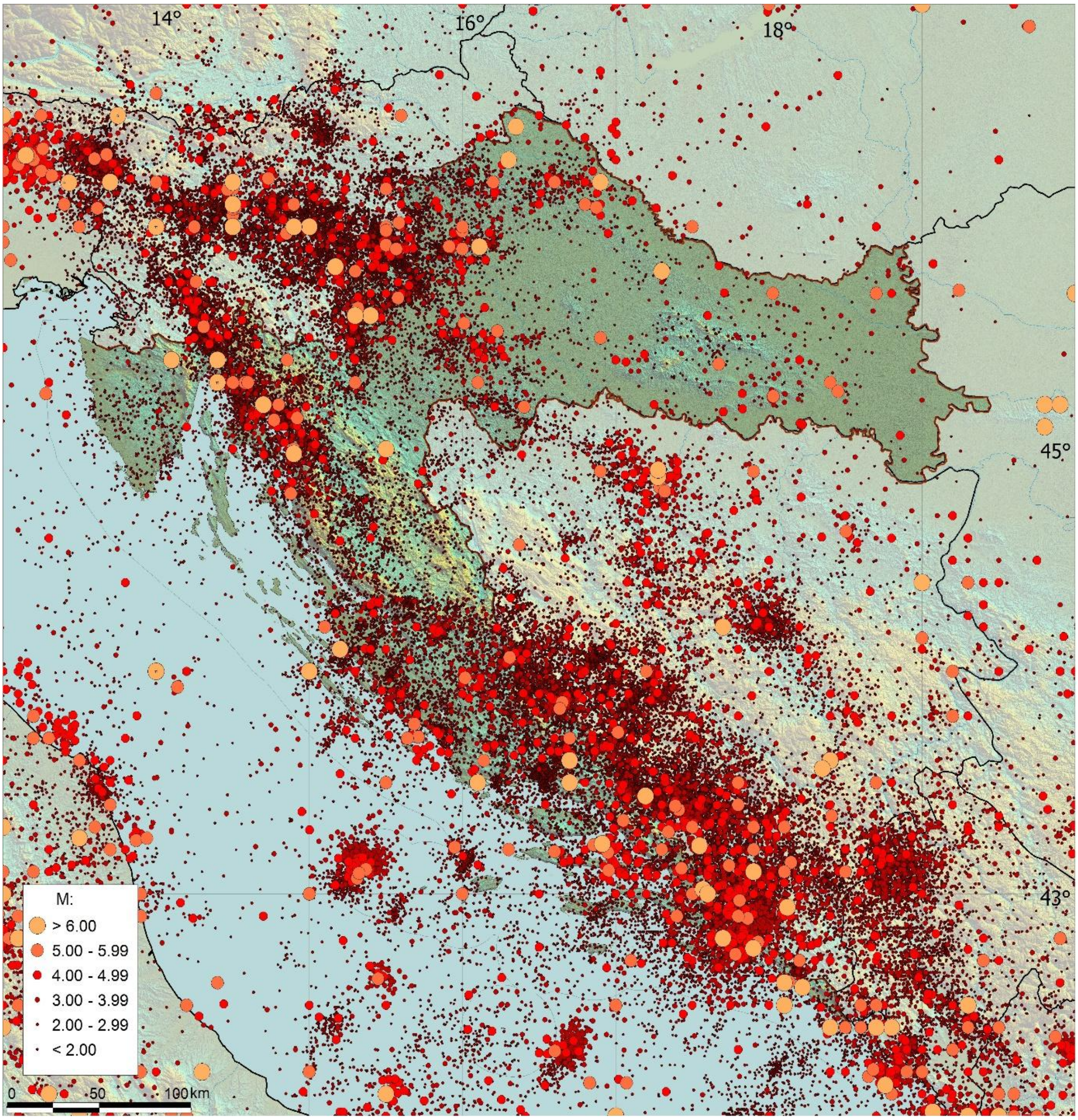

Figure 1. Spatial distribution of the earthquakes in the Croatian Earthquake Catalogue in the period 373BC-2015.

For historical earthquakes only macroseismic information were used. In the early years of 20th century, instrumental data were rare and available only for strong earthquakes. For that period, in the cases when it was impossible to obtain a reliable instrumental, locations of the epicentres were determined also on the basis of macroseismic data.

The final CEC version contains 78995 earthquakes, from which 12838 with magnitudes $M_w \geq 2.5$, in the period 373BC-2015. The magnitude distribution of the catalogue entries (for the period 1900-2015) is presented in Fig. 2. Hypocenter depth values in the earthquake catalogues (and in the CEC) 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. The spatial distribution of focal depths of the events in the CEC is shown in Fig. 3. These depths generaly vary in between 5 and 30 km and the average focal depth of events recorded in the area covered by the CEC after 1900 is found as 11.3 km.

IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

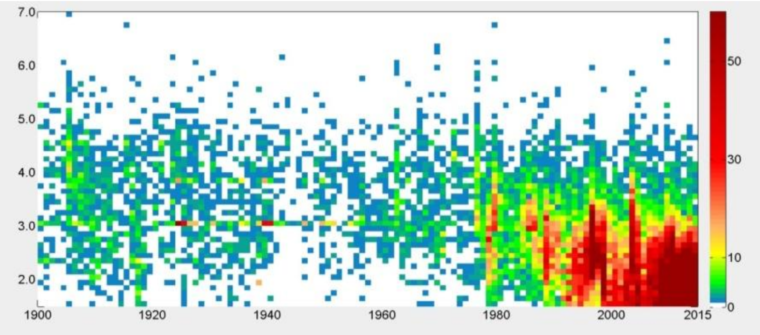

Figure 2. Yearly number of earthquakes in the period 1900–2015, within bins 0.1 magnitude units wide is given by the colour scale.

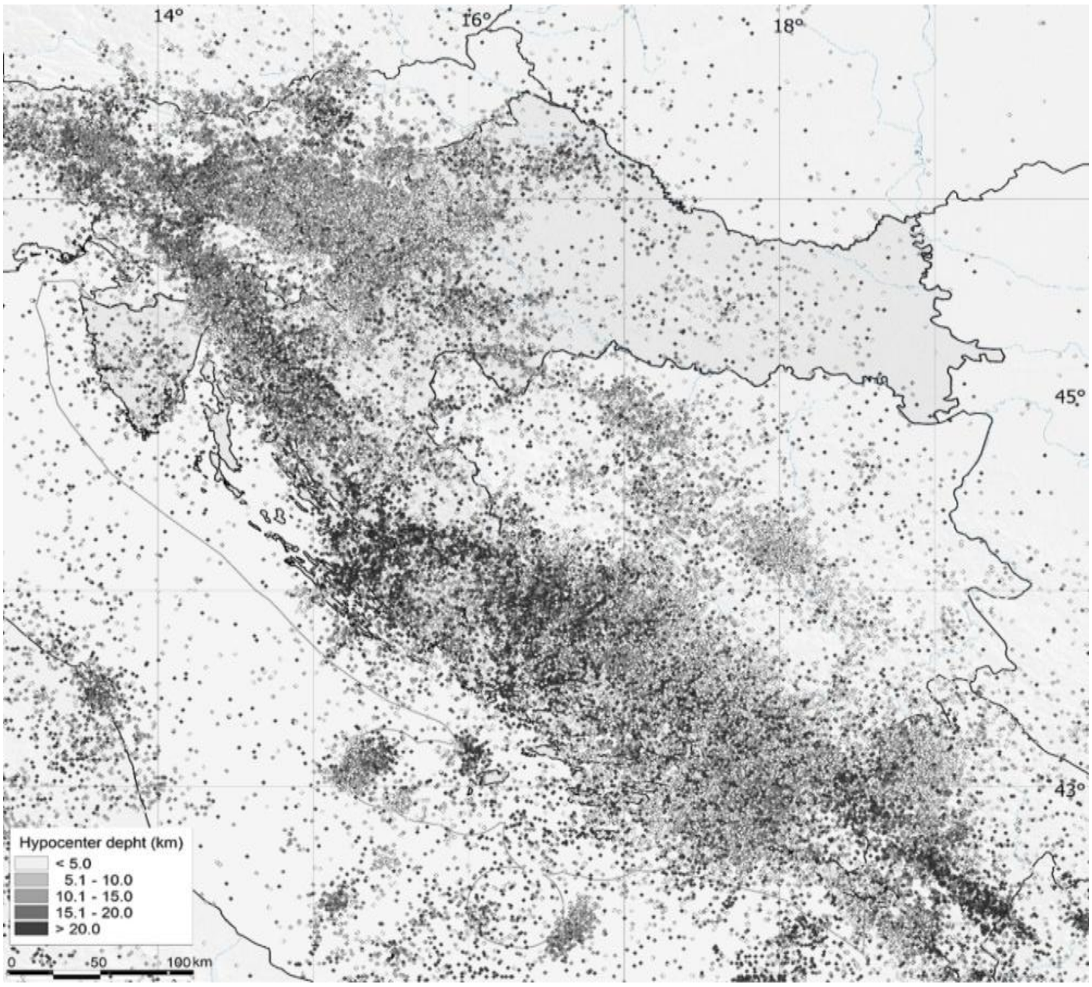

Figure 3. Spatial distribution of hypocenter depths for all events in the CEC.

III. MAGNITUDE CONVERSION TO MOMENT MAGNITUDE

The CEC contains data about origin dates and times, epicentre locations, focal depths, local magnitudes and intensities of earthquakes. Since catalogues with moment magnitudes are used for seismic hazard assessment, it was necessary to determine the conversion relation in order to calculate moment magnitude from local magnitude values. Values of M_W had to be obtained using the empirical relationships between the local and other magnitude scales and M_W. Therefore, 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).

IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

Determination of M_W based on M_{ms}

Until the beginning of the 20th century, earthquake magnitude in the CEC is reported in terms of macro seismic magnitude M_{ms}. The macro seismic magnitudes for the pre-instrumental period, were converted to M_W using the relevant regression relations given by Scordilis (2006).

Local to Moment Magnitude Conversion

To find the relation that converts local magnitude in the CEC to moment magnitude a dataset of moment magnitudes from another catalogues (ISC, ANSS, SHEEC (Grünthal et al., 2013), EMSC, including centroid moment tensor solutions - Harvard GCMT catalog, PDE catalog and RCMT solution - INGV) , for as many events in the CEC as possible, is created. It was possible to find 1956 different events (from which about 120 GCMT/RCMT solutions), with determined moment magnitudes, that existed in the CEC. Coefficients of the empirical relation that converts local to moment magnitude are obtained by a least square method known as EIVREG (errors-in-variables) method, in which observational errors on both dependent and independent variables are taken into account (Fig. 4), and the conversion relation is found to be:

$$M_W = 0.11 + 0.99\, M_L,$$

with determination coefficient (R^2) to be equal 0.8663.

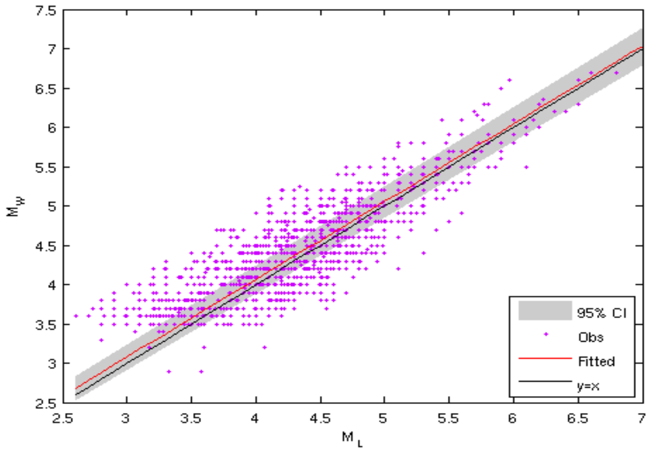

Figure 4. Empirical relation for conversion local to moment magnitudes in the CEC.

The only previous relation that converts local to moment magnitude for Croatia was derived by Markušić et al. (2016). By comparing the moment magnitude values calculated using these two relations it can be seen that M_W values are slightly greater if calculated using conversion relation obtained in this paper. The difference are temporarly dependent (based on the instrument regime – mechanical Wiechert, electromagnetic Sprengnether and digital Guralp seismographs) as displayed in Fig. 5.

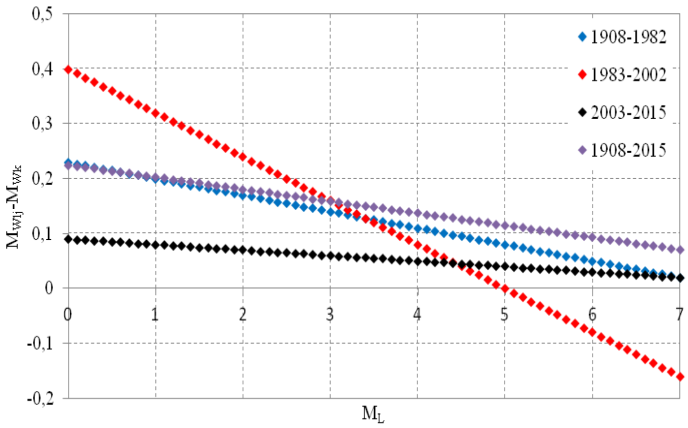

Figure 5. Difference between M_W values calculated from M_L using relation derived in this paper and M_W calculated using relation from Markušić at al. (2016) for three different time periods.

IV. MAINSHOCK-AFTERSHOCK CLASSIFICATION AND CATALOGUE COMPLETENESS INTERVALS

After calculating moment magnitude for every event in the CEC, statistical analysis is performed: catalogue declustering, determining catalogue completeness for ten different magnitude thresholds and, for every complete catalogue were determined the coefficients a and b from Gutenberg – Richter relation (Gutenberg and Richter, 1956):

$$\log_{10}[N(>M)] = a - bM,$$

where N is a number of earthquakes with magnitudes greater than M, a is seismicity level and b is Gutenberg – Richter relation gradient.

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 approach described in Markušić et al. (2016). Based on this approach 8542 foreshocks and 35696 aftershocks were identified, and the declustered catalogue contains 34463 mainshocks which spatial distribution is shown in Fig. 6.

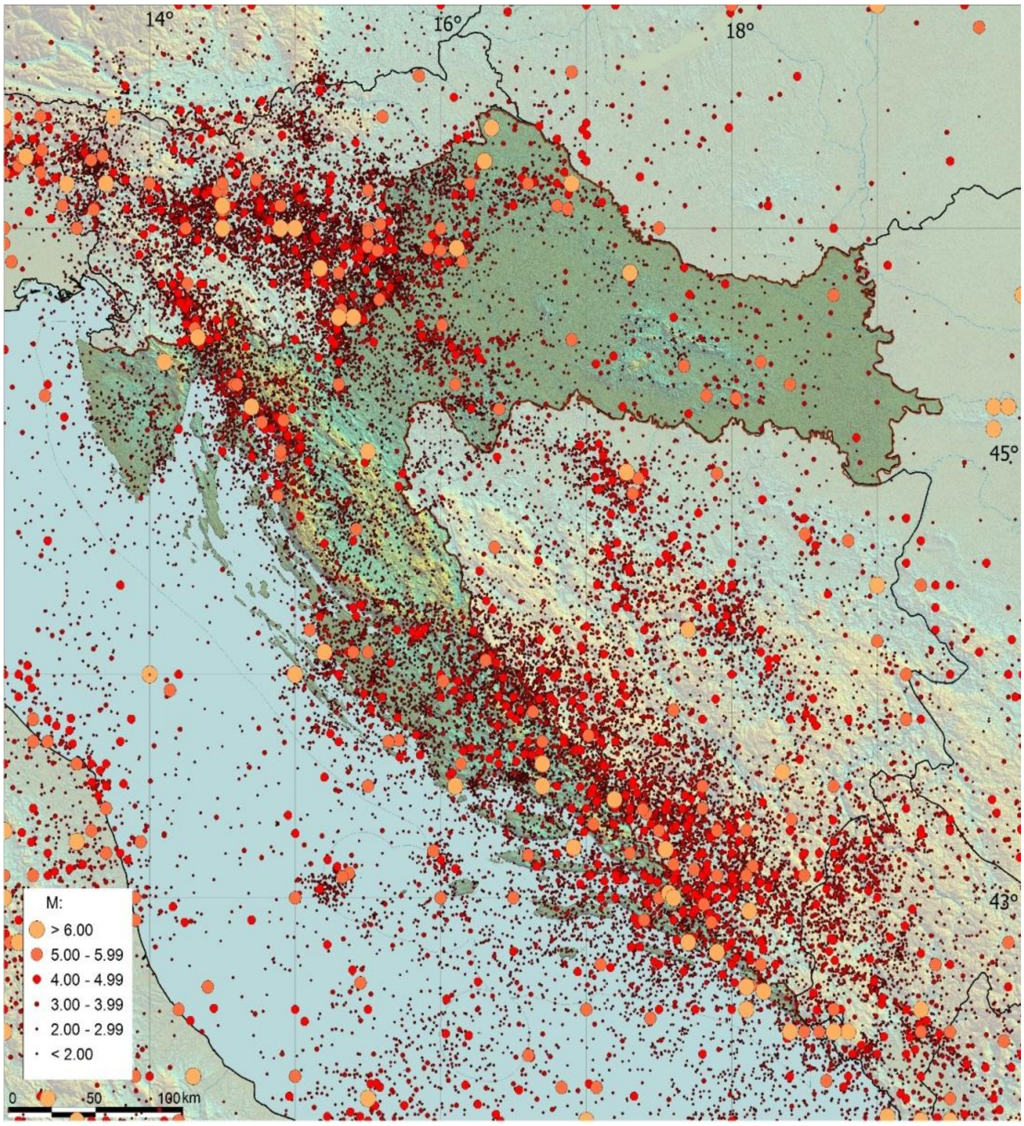

Figure 6. Spatial distribution of mainshocks in the area covered with the CEC.

IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

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 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 CEC for different magnitude intervals. 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 1.

Table 1: Years of completeness for ten magnitude thresholds.

Magnitude threshold	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**
Year of completeness	2004	1996	1980	1970	1900	1850	1800	1750	1500	1400

The year of completeness for certain magnitude threshold also shows a spatial change. This change is displayed in Figures 7 - 9. (for magnitude thresholds 4.0, 5.0 and 6.0, as an illustration).

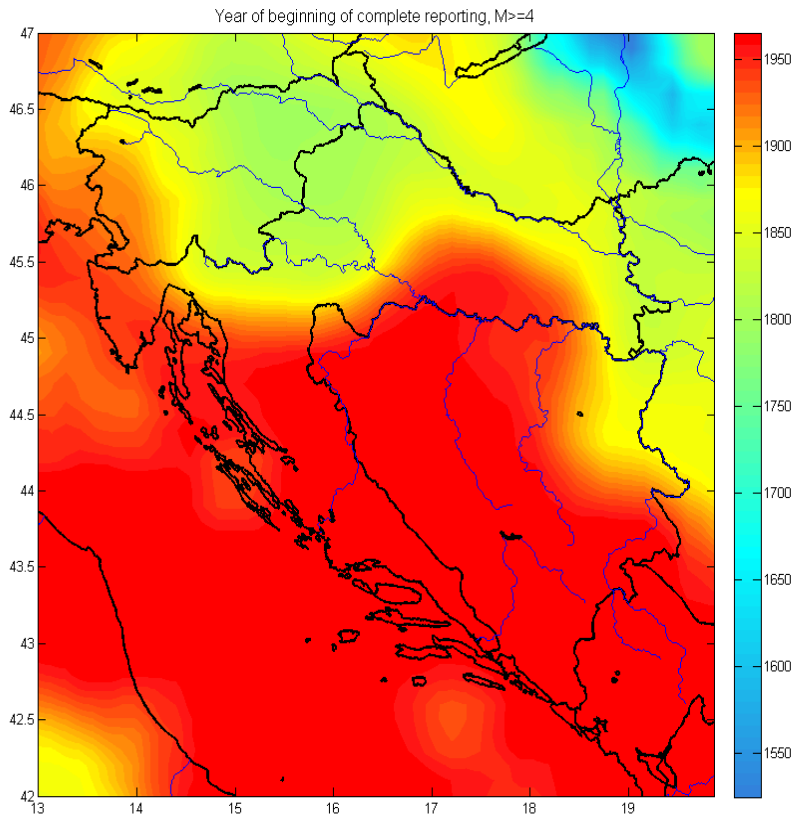

Figure 7. Year of completeness for the magnitude threshold $M_W = 4.0$.

IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

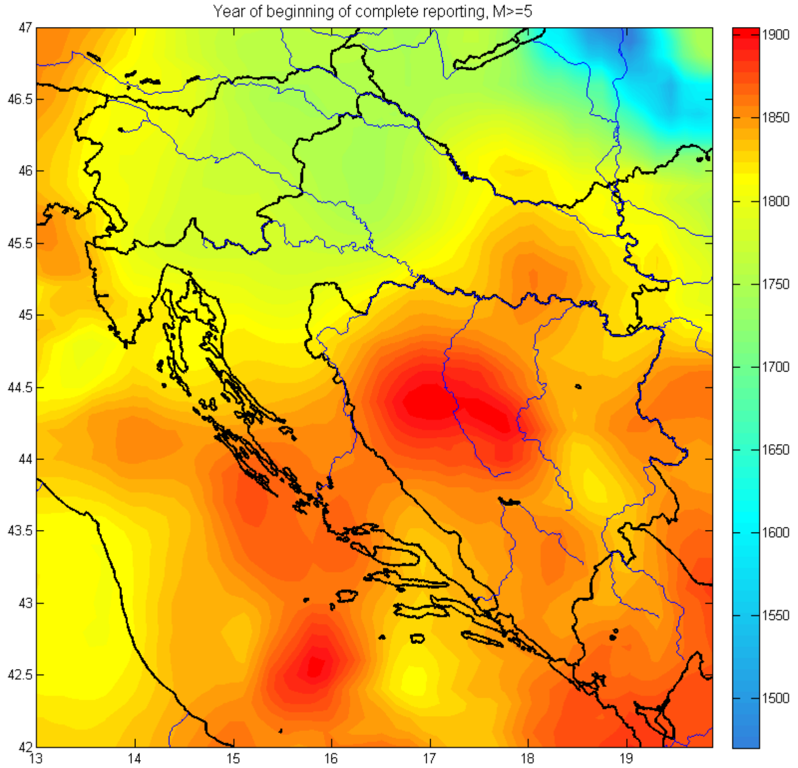

Figure 8. Year of completeness for the magnitude threshold $M_W = 5.0$.

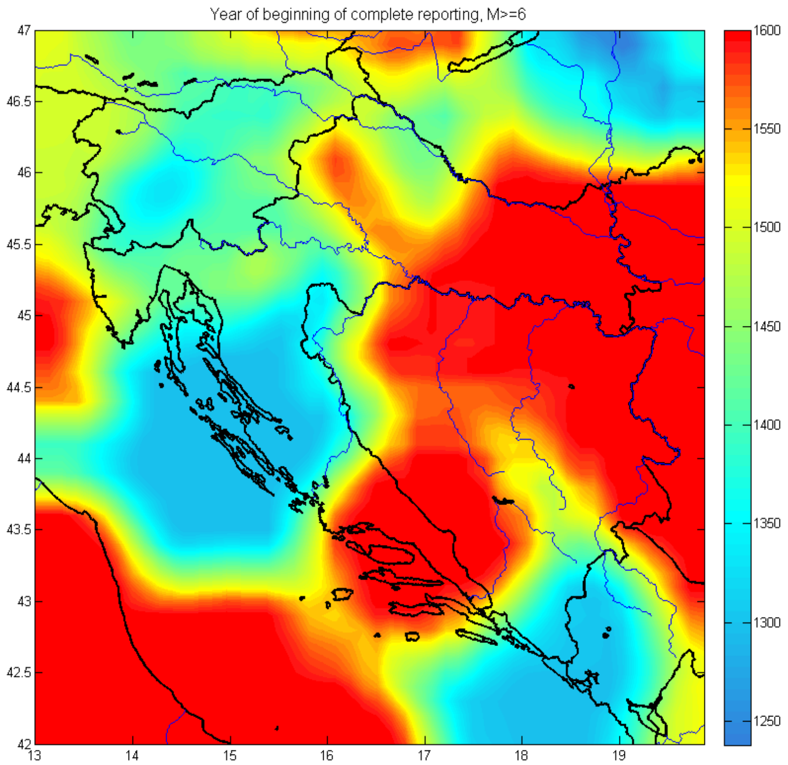

Figure 9. Year of completeness for the magnitude threshold $M_W = 6.0$.

V. STATISTICAL ANALYSES OF THE UNIFIED CROATIAN EARTHQUAKE CATALOGUE

For the complete catalogues parameters *a* and *b* in Gutenberg – Richter relations are calculated using maximum likelihood method. Values of these parameters are presented in Table 2. The Gutenberg – Richter relation gradient *b* is near 1, as expected. Exception is the catalogue with magnitudes above 6.5. This can be explained by taking into account that the majority (26 out of 30) of earthquakes in this catalogue are historical. Local magnitudes of historical earthquakes are determined from intensities, which are not very reliable.

IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

Table 2. Gutenberg – Richter coefficients *a* and *b* for ten different complete catalogues.

Magnitude	Year of completeness	Number of earthquakes	*a*	*b*
2.0	2004	5287	5.68	0.95
2.5	1996	2948	5.93	0.96
3.0	1980	1753	6.14	0.94
3.5	1970	815	6.13	0.90
4.0	1900	817	6.36	0.85
4.5	1850	436	6.76	0.91
5.0	1800	195	6.76	0.89
5.5	1750	77	6.82	0.89
6.0	1500	60	8.10	1.05
6.5	1400	30	10.30	1.36

As an illustration, the spatial distribution of Gutenberg – Richter coefficient *b* for magnitude threshold $M_W \geq 3$ (since 1980, see Table 2) is displayed in Fig. 10. The lowest *b* value is in the coastal part of Croatia, which is expected because this is seismically the most active area of Croatia (as seen in Fig. 1.).

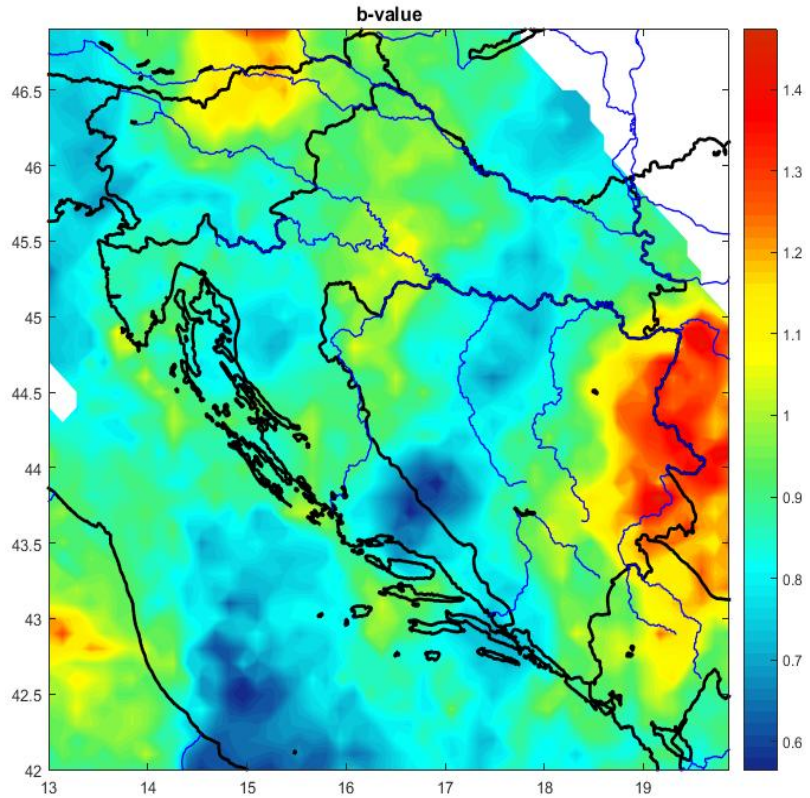

Figure 10. Spatial distribution of Gutenberg – Richter parameter b for the mainshock catalogue complete for $M_W \geq 3$ (since 1980).

VI. CONCLUSION

Earthquake catalogues are one of the most important products of seismology. They provide a comprehensive database useful for numerous studies. Because of that the Croatian Earthquake Catalogue (CEC) is harmonized by determining unified moment magnitude for every earthquake in the catalogue from empirical relation derived in this paper. Based on the relation for calculating the values of moment magnitude can be concluded that the values of local magnitude with sufficient accuracy coincide with the values of moment magnitude. The deviation is slightly higher for smaller magnitudes but does not exceed 0.1. Also, it can be seen that the difference between moment magnitudes calculated in this paper and those given in Markusic et al. (2016) is variable in time and can be related to the regime of instruments (depending on the type of installed seismographs). The final CEC covers the geographic area limited by 42.0°–47.0 °N and 13.0°–20.0 °E and includes 78995 events that occurred in the period 373BC-2015. The statistical analysis is performed on the mainshock catalogue (which contains 34464 events), the catalogue completeness thresholds are analysed and the parameters *a* and *b* in Gutenberg – Richter relation are determined.

IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified
Vol. 4, Issue 11, November 2017

REFERENCES

1. ANSS Composite Catalogue Search: http://www.ncedc.org/anss/catalog-search.html/
2. Bender, B., Perkins, D. M. (1987): SEISRISK III: a computer program for seismic hazard estimation. US geological survey. Bulletin 1772, pp 48.
3. Castellaro, S., Bormann, P. (2007): Performance of different regression procedures on the magnitude regression problem. Bulletin of the Seismological Society of America, 97, 1167–1175.
4. Draper, N., Smith, H. (1998): Applied regression analysis. 3rd edition, Wiley, New York.
5. EMSC-CSEM: http://www.emsc-csem.org/Bulletin/
6. Gasperini, P., Ferrari, G. (2000): Deriving numerical estimates from descriptive information: the computation of earthquake parameters, in ‘‘catalogue of strong Italian earthquakes from 461 B.C. to 1997’’. Annali di Geofisica, 43(4), 729–746.
7. Grünthal, G., Wahlström, R., Stromeyer, D. (2013): The share European earthquake catalogue (SHEEC) for the time period 1900-2006 and its comparison to the European-Mediterranean earthquake catalogue (EMEC). Journal of seismology. 17/4, 339-1344.
8. Gutenberg, B., Richter, C. F. (1956): Magnitude and Energy of Earthquakes. Annali di geofisica, 9/1, 1-15.
9. Harvard GCMT catalog: http://www.globalcmt.org
10. Herak, D., Herak, M., Cabor, S. (1988): Some characteristics of the seismicity and the earthquake catalogue of the wider Dinara mountain area (Yugoslavia) for the period 1979–1988. Acta Seismologica Iugoslavica, 14, 27–59.
11. Herak, D., Cabor, S. (1989): Earthquake catalogue for S. R. Croatia (Yugoslavia) and neighbouring regions for the years 1986 and 1987. Geofizika, 6, 101–121 (in Croatian with English abstract).
12. Herak, D., Herak, M., Sović, I., Markušić, S. (1991): Seismicity of Croatia in 1989 and Kamešnica Mt. earthquake. Geofizika, 8, 83–99.
13. Herak, M., Herak, D., Markušić, S. (1996): Revision of the earthquake catalogue and seismicity of Croatia, 1908–1992. Terra Nova, 8, 86–94.
14. ISC (International Seismological Center) Earthquke Catalogue: http://www.isc.ac.uk/iscbulletin/search/catalogue
15. Ivančić, I., Herak, D., Markušić, S., Sović, I., Herak, M. (2002): Seismicity of Croatia in the period 1997–2001. Geofizika, 18–19, 17–29.
16. Ivančić, I., Herak, D., Markušić, S., Sović, I., Herak, M. (2006): Seismicity of Croatia in the period 2002–2005. Geofizika, 23/2, 87–103.
17. Kišpatić, M. (1891): Earthquakes in Croatia. Work of Yugoslav Academy of Sciences and Arts (abbrev. JAZU), CVII, Zagreb (in Croatian).
18. Kišpatić, M. (1892): Earthquakes in Croatia. Work of Yugoslav Academy of Sciences and Arts (abbrev. JAZU), CIX, Zagreb (in Croatian).
19. Kišpatić, M. (1895): Earthquakes in Croatia. Work of Yugoslav Academy of Sciences and Arts (abbrev. JAZU), CXXII, Zagreb (in Croatian).
20. Lolli, B., Gasperini, P. (2012) A comparison among general orthogonal regression methods applied to earthquake magnitude conversions. Geophysical Journal International, 190(2), 1135–1151. doi:10.1111/j.1365-246X.2012.05530.x
21. Markušić, S., Sović, I., Herak, D. (1990): Seismicity of Croatia and the surrounding areas in 1988. Geofizika, 7, 121–134.
22. Markušić, S., Herak, D., Sović, I. (1993): Seismicity of Croatia in the period 1990–1992. Geofizika, 10, 19–34.
23. Markušić, S., Herak, D., Ivančić, I., Sović, I. (1998): Seismicity of Croatia in the period 1993–1996 and the Ston-Slano earthquake of 1996. Geofizika, 15, 83–101.
24. Markušić, S., Gülerce, Z., Kuka, N., Duni, L., Ivančić, I., Radovanović, S., Glavatović, B., Milutinović, Z., Akkar, S., Kovačević, S., Mihaljević, J., Šalić, R. (2016): An updated and unified earthquake catalogue for the Western Balkan Region. Bulletin of Earthquake Engineering, 14/2, 321-343.
25. Mulargia, F., Gasperini, P., Tinti, S. (1987): Contour mapping of Italian seismicity. Tectonophysics, 142, 203–216.
26. PDE, The preliminary determination of epicenters (PDE) bulletin: ftp://hazards.cr.usgs.gov/NEICPDE
27. RCMT, Regional centroid moment tensor: http://www.bo.ingv.it/RCMT/
28. Scordilis, E. M. (2006): Empirical global relations converting MS and mb to moment magnitude. Journal of Seismology, 10(2), 225–236.
29. Shebalin, N. V., Kárník, V., Hadžievski, D. (Eds.) (1974): Catalogue of Earthquakes, Part I, 1091–1970; Part II, prior to 1901. UNESCO, Skopje.
30. Torbar, J. (1882): Report on the Zagreb earthquake of 9 November 1880. Work of Yugoslav Academy of Sciences and Arts (abbrev. JAZU), I, Zagreb, 141 pp (in Croatian).