# LOCAL RELATIONS FOR CONVERTING $M_L$ TO $M_W$ IN SOUTHERN-WESTERN BALKAN REGION

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Compilation of a homogenous earthquake catalogue, by expressing the size of the earthquakes in a unified magnitude scale, is an important tool for the seismic hazard evaluation. The most reliable and useful scale of magnitude to be chosen as the common measure of earthquake size, for both historically known and the instrumentally recorded events, is the moment magnitude, $M_W$. We investigate the empirical relationships between local magnitudes ($M_L$) calculated by the seismological agencies operating in the Western Balkan countries, and the relevant moment magnitude $M_W$, derived from the moment tensor analysis of medium-strong Western Balkan earthquakes. As result, regression relations converting $M_L$ to $M_W$ for these countries have been derived. Based on the proposed relations, an estimate of $M_W$ which can be considered as a unified magnitude scale can be calculated for each earthquake of the regional catalogue.

**Keywords:** local magnitude, moment magnitude, regression, earthquake catalog, seismic hazard.

## Introduction

Compilation of a homogeneous earthquake catalog is an essential tool for the seismic hazard evaluation. Many efforts have been put recently, also in the Balkan area, to create a regional catalogue, being homogenous as far as possible with regards to magnitude. A magnitude homogenous earthquake catalogue spanning the twentieth century has been assembled for Greece and adjacent areas (Burton et al. 2004). A new homogenous catalogue covering Bulgaria and surrounding Balkan area has been created with intention of performing a consistent seismic hazard assessment across the region (Bayliss and Burton, 2007). The heart of these works center around appropriate correlation equations between the various magnitude scales, $M_W$, $M_S$, $m_b$, and $M_L$.

Despite various shortcomings, the earthquake magnitude scale is one of the most fundamental parameters to be used for quantification of earthquakes. Although use of a uniform scale is desirable, it is not always possible because of changes in instrumentation, the data reduction method, the magnitude formula, the station distribution, etc. (Kanamori, 1983). As a result, various magnitude scales such as $M_L$, $M_S$, $m_b$, etc., have been developed and are currently in use.

The main problem of the different magnitude scales is that they do not behave uniformly for all magnitude ranges. Another problem is that the $M_L$, $M_S$ and $m_b$ scales exhibit saturation effects at different levels for large earthquakes. Both these limitations could result in under- or over-estimation of earthquake magnitudes (Scordilis, 2006). For these reasons, another magnitude scale, namely moment magnitude, $M_W$, based on seismic moment, is considered as the most reliable magnitude, accurately describing the size of earthquakes. In order to maintain continuity and uniformity of the data, it is important to relate different magnitude scales.

Another important issue, concerned with the seismic hazard evaluation, is the proper choice of predictive ground motion models (PGMM). Due to the scarce strong motion data, an adequate attenuation model is not available so far for the southern-western Balkan area. Hence, we have to consider PGM models from similar tectonic settings, or worldwide used ones. Considering that almost all predictive ground motion models in use today are based on the moment magnitude, it would be very useful that $M_W$ to be chosen as the common measure of earthquake size, for both historically known and the instrumentally recorded events.

The seismological centers that operate in the southern-western Balkan region report their earthquake catalogues in terms of $M_L$, $M_S$, or $M_W$. For the historical events they use the epicentral intensity ($I_0$), and later convert it in $M_S$ or any other equivalent magnitude, using regression models based on $I_0$ and other focal parameters (Karnik 1996, etc.). For the instrumental period, seismological centers of the area quantify the earthquakes size in terms of local magnitude, $M_L$. But the procedures they use for $M_L$ determination are rather different, and the $M_L$ magnitudes reported up to now by them cannot be considered as equivalent. For that reason, it is not possible to define a unique regional relation connecting $M_L$ to $M_W$ or to any other magnitude scale. Therefore local relations have to be derived (Scordilis, 2006). Surely, it would be very good for the future investigations to calibrate $M_L$-$M_W$, so that they give magnitudes that are consistent with the moment magnitude ($M_W$). With the recent advancement to calculate regional centroid moment tensor solutions (RCMT) for medium-large earthquakes in our region, it has become possible to solve adequately these problems.

## Method

Most of investigators apply the standard least-squares fitting to derive appropriate empirical relationships:

$$y = \mathbf{X\beta} + \varepsilon \qquad (1)$$

The standard regression assumes that only dependent variable ($y$) is subject to error, while the independent variables ($\boldsymbol{x}$) are error-free. Since the basic requirement of an uncertainty on the independent variables much smaller than the one on the dependent variable is not satisfied, the ordinary least squares cannot be used a priori to derive these relationships in the magnitude conversion studies, because the input parameters are also in error.

Standard regression would underestimate the effect of error-in variables, and the other coefficients in the model can be biased to the extent that they are correlated with the poorly measured variables. This is avoided by using the errors-in-variables regression models (Draper and Smith, 1998; Treiman 2009).

## The data

Seismicity studies depend largely on the available information, completeness and reliability of the earthquake data, expressed on the earthquake catalogue used. Several projects are underway in the southern-western Balkan area for the seismic hazard assessment and the necessity for a unified earthquake catalogue in terms of magnitude is evident. For this reason we utilized all the available information for the damaged earthquakes of the region, such as the earthquake catalogues of Albania, Montenegro, Croatia, Serbia, Macedonia, Greece (Thessaloniki), as well as the earthquake bulletins of the International Seismological Centre (ISC).

The earthquake catalog used for PSHA in Albania is that of Sulstarova et al. (2005), which contain about 700 events with $M_S \geq 4.5$, covering the period 58 BC-2005 AC, and the area between 18.5-21.5°E and 39-43°N. A new working-file was compiled by merging the Sulstarova's catalog with the new data ($M_L \geq 3.5$) provided by the above mentioned agencies. The resulting catalog covers a larger area, 18-24°E and 38-44.4°N.

## Results of analysis

Since the moment magnitude characterizes more accurately the earthquake size, it was chosen as a uniform magnitude scale for seismic hazard investigations. The $M_W$ estimation was preceded by a detailed statistical investigation regarding the relationships between different magnitude scales used by the seismic networks of the region, 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.

Magnitudes $M_S$ and $m_b$ of ISC were converted in $M_W$ using the relevant regression relations of Scordilis (2006):

$$M_W = 0.67 \times M_S + 2.07 \qquad 3.0 \le M_S \le 6.1 \qquad (2)$$

$$M_W = 0.99 \times M_S + 0.08 \qquad 6.2 \le M_S \le 8.2 \qquad (3)$$

$$M_W = 0.85 \times m_b + 1.03 \qquad 3.5 \le m_b \le 6.2 \qquad (4)$$

In the same way was proceeded for the historical earthquakes, generally quantified in terms of the macroseismic intensity *I* (MSK-64) and converted to the $M_{SK}$ (Kárnik's magnitude) by using local or regional empirical relations (Gutdeutch et al. 2002). Based on the catalogue of historical earthquakes published by Kárnik in 1996, which covers one century of the seismic history of Central and Southern Europe, Scordilis (2006) proposes the following relations:

$$M_W = 0.80 \times M_{SK} + 1.31 \qquad 4.0 \le M_{SK} \le 5.3 \qquad (5)$$

$$M_W = 0.70 \times M_{SK} + 1.80 \qquad 5.4 \le M_{SK} \le 6.2 \qquad (6)$$

$$M_W = 1.04 \times M_{SK} - 0.33 \qquad 6.3 \le M_{SK} \le 8.1 \qquad (7)$$

To enable conversion to $M_W$ of the local magnitudes $M_L$ calculated by the seismological centers of the region, we initiated a detailed statistical investigation regarding the relationships between $M_L$ magnitudes reported by them, and the moment magnitude $M_W$. A considerable dataset from the above mentioned agencies was used, accepting as reference the moment magnitude obtained from the Harvard centroid moment tensor solutions (Dziewonski *et al.*, 1981) and the regional moment tensor solutions (INGV-Rome and ETHZ-Zürich). More than 260 moment tensor solutions for medium-strong events in the Western Balkan region, varying from $M_W=4.0$ to $M_W=7.0$, have been calculated for 1977-2008. These data enable deriving of consistent local relations to convert the local magnitudes $M_L$ to $M_W$.

The summary results are presented on the Table 1 and Figure 1. The method used is that of errors-in-variables regression.

**Table 1**. Correlative relationships between moment magnitude $M_W$ and local magnitude $M_L$.

| Agency | Regression equation $M_W = b_0 + b_1 \times M_L$ | Number of events | Determination coefficient, $R^2$ | Stand. dev. of regression, $s_e$ |
|---|---|---|---|---|
| Tirana | $M_W = 1.624 + 0.743M_L$ | 102 | 0.74 | 0.301 |
| Pogdorica | $M_W = 0.218 + 0.985M_L$ | 46 | 0.93 | 0.163 |
| Zagreb | $M_W = 0.165 + 0.979M_L$ | 34 | 0.92 | 0.167 |
| Belgrade | $M_W = 0.324 + 0.963M_L$ | 18 | 0.87 | 0.200 |
| Skopje | $M_W = 0.912 + 0.880M_L$ | 23 | 0.85 | 0.210 |
| Thessaloniki | $M_W = 0.383 + 1.010M_L$ | 109 | 0.83 | 0.220 |

Considering the results of this statistical analysis, we conclude:

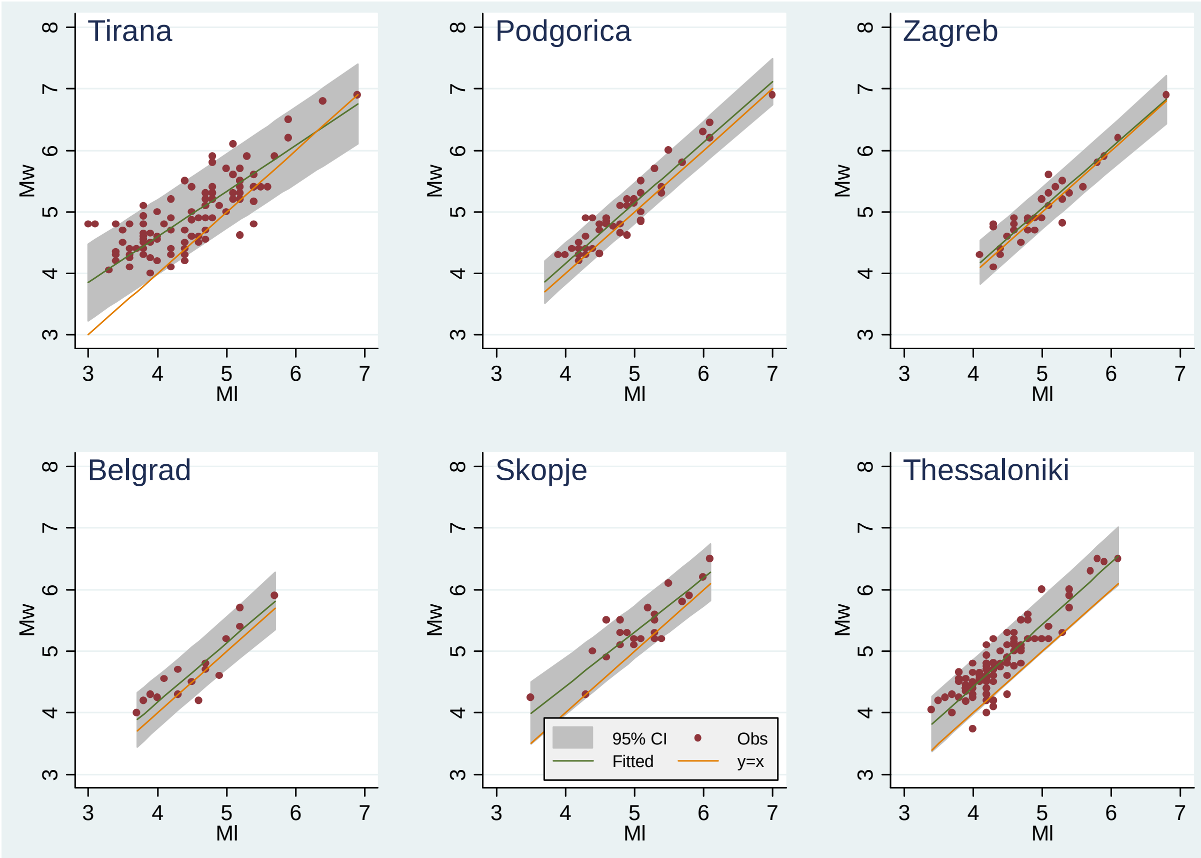


**Fig. 1.** Relationships between moment magnitude $M_W$ and the local magnitude, $M_L$.

- $M_L$ calculated by Podgorica and Zagreb are very well calibrated and almost consistent with $M_W$; a very small underestimation is observed; standard deviation of regression is 0.16.
- $M_L$ calculated by Belgrade is also well calibrated, with a small underestimation especially for small events; regression error is slightly higher, 0.20.
- $M_L$ reported by Skopje is systematically smaller than $M_W$ for $M_L$ <6.0; standard deviation of regression, *Se* =0.21.
- $M_L$ calculated by Tirana is systematically smaller than $M_W$ for $M_L$<6.2, and larger for $M_W$>6.0; standard deviation of regression is quite large, *Se* =0.30. A new calibration of local magnitude for Tirana, consistent with the moment magnitude $M_W$, is required.

Based on the data available, to verify consistency of the obtained results, we re-estimated the regression equation used to convert the local magnitude $M_L$ reported by Thessaloniki to the $M_W$, and then compared it with the regression equation $M_W=0.97M_L+0.58$ used by this center in its routine practice. Aside from errors-in-variable regression, we used also the standard least-squares fitting. Using the standard regression we obtained the following empirical relation: $M_W=0.96M_L+0.60$, with *Se* =0.24. As it can be seen, the two relations are quite identical, thus confirming the consistency and reliability of the regression relations we derived for Tirana, Podgorica, Zagreb, Belgrade and Skopje, based on the same dataset and values of $M_W$ magnitude. On the other hand, as it is expected, the standard regression underestimates the effect of error-in variable ($M_L$), and leads to slightly larger errors of $M_W$ estimate, compared with the errors-in-variable regression. Using the second model we find that the slope of regression is almost 1, and a slightly smaller regression error, *Se* =0.22. $M_L$ calculated by Thessaloniki leads to a systematic underestimation of about 0.4 magnitude units in all the magnitude range.

We applied the standard regression also for the other seismological centers of the region. In all the cases investigated, standard regression leads to a considerable bias in the slope estimate of the regression equation, and to larger errors in the $M_W$ estimate. The results obtained by the two methods agree completely at the centre of gravity of the dataset. With increasing distance to the centre of gravity the discrepancy between both increases. The errors-in-variables regression is found to be superior, and its general use is recommended for magnitude conversion related problems.

Above regression relations can be used to convert $M_L$ reported by the relevant agencies to the moment magnitude, $M_W$. This will allow the Western Balkan earthquake database to be used more effectively for seismic hazard evaluation.

## Data completeness

A prerequisite for a successful seismic hazard evaluation is to assess the data completeness, that is to find the magnitude above which the catalogue can be considered as reasonably complete, or alternatively to assign time intervals in which a certain magnitude range is likely to be completely reported. Data completeness levels are estimated from the earthquake catalogue, by using the cumulative number of events *versus* time graphs, in order to evidence slope changes, assuming that the most recent change in slope occurs when the data became complete for magnitudes above the reference (Gasperini and Ferrari, 2000).

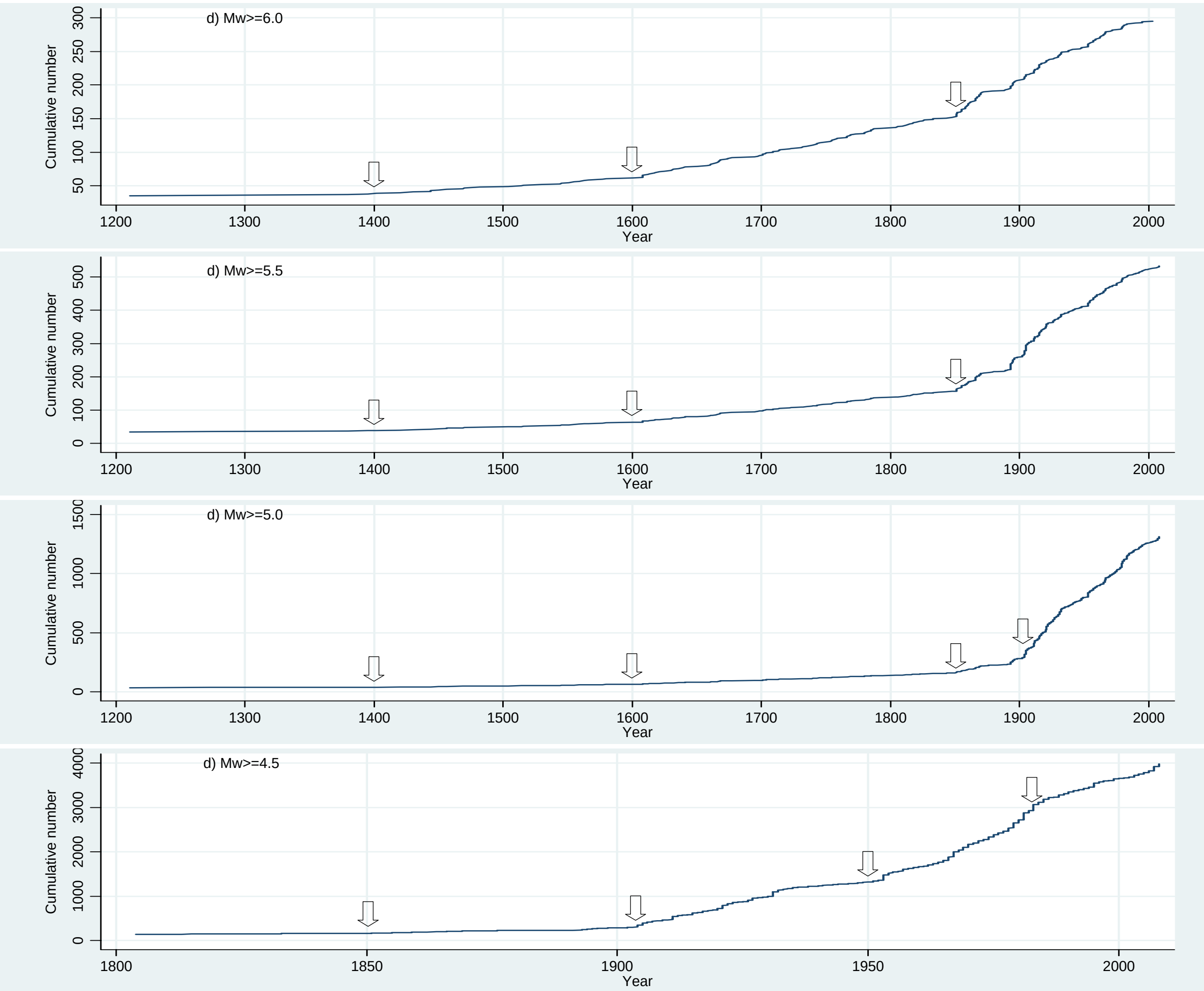


**Fig. 2**. Cumulative number of seismic events with magnitude larger or equal to *4.5*, *5.0*, *5.5* and *6.0*; the arrows indicate the points where changes the curve slope.

Inspecting the cumulative number *versus* time graphs (Figure 2) for the area [18.5-21.5°E, 39-43°N], we identified five magnitude intervals: *4.5*, *5.0*, *5.5*, *6.0,* and *6.5*. The relevant catalogue can be considered complete since 1950 for earthquakes with $M_W \geq 4.5$, since 1905 for earthquakes with $M_W \geq 5.0$, since 1850 for earthquakes with $M_W \geq 5.5$, and since 1600 for earthquakes with $M_W \geq 6.0$. Finally, no earthquake with magnitude 6.5 or greater seems to be omitted for the period after 1400.

## Conclusions

Generally, $M_L$ magnitudes reported by different seismological data centers cannot be considered as equivalent and, therefore local relations connecting them with $M_W$ are required. Regression analysis are carried out to estimate the correlation between $M_W$ and $M_L$ magnitudes reported by Tirana, Podgorica, Zagreb, Belgrade, Skopje and Thessaloniki. $M_W$ values, corresponding to the events used in the relevant datasets, are taken from Harvard CMT catalog and RCMT catalogs from INGV and ETHZ, for medium-strong earthquake occurred in the Western Balkan region. Results obtained by this investigation confirm that the local magnitudes $M_L$, calculated by different centers, not always are consistent with the moment magnitude $M_W$. In some cases, the discrepancies are very large, so the empirical relations converting $M_L$ to $M_W$ may be very useful.

We applied both, the standard regression and the errors-in-variables regression, in our analysis. In all the cases investigated, standard regression leads to a considerable bias in the slope estimate of the regression equation, and to larger errors in the $M_W$ estimate. The results obtained by the two methods agree completely at the centre of gravity of the dataset. With increasing distance to the centre of gravity the discrepancy between both increases. The errors-in-variables regression is found to be superior, and its general use is recommended for magnitude conversion related problems.

The empirical relations derived, are proposed to be used to convert $M_L$ calculated by the seismological data centers of the Western Balkan region to the moment magnitude, $M_W$. The $M_W$ estimate obtained using these relations for each earthquake of the regional catalogue may be considered as a unified magnitude scale, and would be useful for compiling a homogenous earthquake catalogue for Western Balkan region in terms of the moment magnitude.

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