CALIBRATION OF MOMENT MAGNITUDE-LOCAL MAGNITUDE RELATION USING ALBANIAN SEISMIC NETWORK DATA: ENHANCING SEISMIC CATALOGS THROUGH BACK-PROCESSED EVENT DATA

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Abstract

This study focuses on calibrating the moment magnitude-local magnitude (M_w-M_L) relation using seismic data from the Albanian Seismic Network, spanning the last three years. Our approach includes back-processing specific events to expand the dataset, aiming for a comprehensive analysis. Utilizing GISOLA real-time moment tensor inversion software within the Seiscomp (v.4) seismic monitoring system, we compute M_w values. Concurrently, M_L values are derived using SEISAN (v.12), following the methodology of Hutton and Boore (1987), with manual amplitude checks for validation. The findings reveal a strong correlation between M_w values computed through GISOLA, utilizing full waveform data for moment tensor inversion, and M_L values obtained through routine location in SEISAN. Notably, exceptional efforts in back-processing specific events contribute to enriching the dataset, enhancing the reliability of the calibration. The best correlation scores are observed for moment tensor solutions of quality A and B, corresponding to the highest variance reduction. These results are represented by high correlation coefficients and low correlation standard deviations, indicating the robustness of the calibrated M_w-M_L relation. Our study contributes to the development of comprehensive earthquake catalogues for Albania, crucial for seismic hazard assessment and risk mitigation. By refining the M_w-M_L relation, we enhance the accuracy of magnitude estimation, facilitating more informed assessments of seismic hazard.

Key words*: *moment magnitude, calibration, earthquake catalogues, seismic hazard assessment, moment tensor inversion.

Përmbledhje

Ky studim fokusohet në kalibrimin e relacionit magnitudë momenti-magnitudë lokale (Mw-ML), bazuar në të dhënat e tërmeteve nga Rrjeti Sizmologjik Shqiptar. Qasja jonë përfshin një analizë gjithëpërfshirëse. Duke përdorur programin e Inversionit të Tensorit të Momentit GISOLA, përshtatur në kohë reale me sistemin e monitorimit sizmik Seiscomp (v.4), llogariten vlerat për M_w*. Njëkohësisht, vlerat* M_L *vlerësohen në kohë reale në sistemin SEISAN (v.12), duke aplikuar modelin e përshtatur të Hutton dhe Boore (1987), me kontroll manual për rritjen e saktësisë. Gjetjet zbulojnë një korrelacion të fortë midis vlerave të* M_w *dhe* M_L*. Veçanërisht, përpjekjet në përpunimin e ngjarjeve specifike kontribuojnë në pasurimin e të dhënave, duke rritur besueshmërinë e kalibrimit. Rezultatet më të mira të korrelacionit janë vërejtur për zgjidhjet e Tenzorit të Momentit, të cilësisë A dhe B, që korrespondojnë me reduktimin më të lartë të variances, si kriter vlerësues për saktësinë e metodës. Këto rezultate përfaqësohen nga koeficientë të lartë korrelacioni dhe devijime standarde me vlerë të ulët, që tregojnë se modeli I kalibruar* M_w*-*M_L*, është i besuaeshëm statistikisht. Studimi kontribuon në zhvillimin e katalogëve gjithëpërfshirës homogjen, për tërmetet në Shqipëri dhe rreth saj, bazë për vlerësimin e rrezikut sizmik dhe zbutjen e rrezikut. Duke përpunuar lidhjen* M_w*-*M_L*, rritet saktësia e vlerësimit të magnitudës, duke ndikuar në përmirësimin e vlerësimit të rrezikut sizmik.*

Fjalë kyçe*: magnitude e momentit, kalibrimi, katalogu i tërmeteve, vlerësimi i rrezikut sizmik, inversion i tenzorit të momentit.*

Introduction

Quantifying seismic energy release relies on determining earthquake magnitude, historically measured by the Richter scale (M_L). However, the Moment Magnitude scale (M_W) provides a more accurate assessment, particularly for larger earthquakes, as it considers seismic moment (M_0), a physical quantity derived from seismic wave measurements. The seismic moment (M_0) is defined as:

$$M_0 = \mu A \overline{D} \qquad (1)$$

Where: μ is the shear modulus of the rocks involved in the earthquake; A is the area of the fault that slipped and $\overline{D}$ is the average slip on the fault. This seismic moment relates directly to fault slip, source dimensions, and the strength of the geological material involved (Allen, 1978; Boore, 1987). These parameters are critical because they provide a comprehensive picture of the energy released during an earthquake, which is not captured by M_L. Discrepancies between M_w and M_L values have been observed worldwide, necessitating calibration to ensure accurate earthquake magnitude estimation, crucial for seismic hazard assessment and risk mitigation (Boore & Atkinson, 2008).

In the context of Albania, situated within the seismically active Alpine-Mediterranean tectonic belt, seismic hazard assessment is of paramount importance due to its geological complexity. Albania represents a continental collision zone where the Adriatic microplate (Adria) interacts with the westernmost margin of the Eurasian plate along the Albanides Orogeny, part of the Hellenides (Dabovski 2006; Jouanne et al., 2012). This region is characterized by complex tectonic processes, including thrusting, normal faulting, and strike-slip faulting, which contribute to its high seismicity (Dushi et al., 2018). Understanding seismicity patterns and assessing seismic hazard in this region are essential for disaster preparedness and resilience. Recent studies by Papazachos and Papazachou (2003), Mihaljević et al. (2017), Duni et al. (2018) and Marcusic et al. (2020), have contributed to the probabilistic seismic hazard assessment of Albania, providing valuable insights into earthquake risk mitigation strategies. Additionally, Markušić et al. (2016) provided an updated earthquake catalogue for the Western Balkan Region, offering essential data for seismic hazard analysis.

Advancements in digital recording technology have facilitated novel attempts to calibrate the M_w-M_L scale, aiming to establish preliminary scaling relations for routine application in Albania (Rama et al., 2021). Building on these advancements, our study focuses on establishing scaling relations between M_w and M_L using seismic data from the Albanian Seismic Network, integrating real-time seismic waveform processing systems like GISOLA and SEISAN.

Our study aims to calibrate the moment magnitude-local magnitude (M_w-M_L) relation using seismic data from the Albanian Seismic Network over the past three years. Employing cutting-edge technology and applications, we utilize GISOLA real-time moment tensor inversion software within the Seiscomp (v.4) seismic monitoring system to compute M_w values, while M_L values are derived using SEISAN (v.12) following established methodology (Havskov et al., 2020; Triantafyllis et al., 2021).

Moment tensor inversion is a robust method for determining the seismic moment and focal mechanisms of earthquakes by inverting the observed seismic waveforms. This novel approach enables real-time data processing, contributing to more accurate M_w computations. We introduce appropriate statistical approaches, such as orthogonal regression, to establish a robust parametric relation between M_w and M_L for routine application (Khan & Lucas, 2018). Orthogonal regression is particularly useful in this context as it accounts for errors in both variables, providing a more reliable calibration model. Our findings demonstrate a strong correlation between M_w values computed through GISOLA and M_L values obtained via routine location in SEISAN, validating the reliability of our methodology. Our research significantly advances the development of comprehensive earthquake catalogues for Albania, essential for effective seismic hazard assessment and risk mitigation.

Literature review

Allen (1978) contributed foundational insights into magnitude scales and moment magnitude, relevant globally including seismic hazard studies in the Balkans and Albania;

Bommer et al. (2003) highlighted the use of logic trees for GMPEs, crucial for addressing uncertainty in seismic hazard assessments in Central Europe and the Balkans, including Albania;

Boore (1987) discussed the historical context of the Richter scale, essential for earthquake parameter estimation worldwide, including the Balkans and Albania;

Boore and Atkinson (2008) developed updated GMPEs for PGA, PGV, and 5%-damped PSA, enhancing seismic hazard assessment capabilities in the Balkans and Albania;

Chiou and Youngs (2014) improved GMPE accuracy with their NGA model updates, benefiting seismic hazard assessments in regions like the Balkans and Albania;

Cotton et al. (2006) proposed criteria for selecting GMPEs, guiding their application in Central Europe and rock sites, crucial for accurate seismic hazard assessments in the Balkans and Albania;

Dimitriadis et al. (2019) provided an overview of the Balkan Seismic Hazard Assessment Programme, enhancing seismic hazard understanding in the Balkans, including Albania;

Duni et al. (2018) reviewed seismic hazard assessment in Albania, emphasizing ongoing research efforts to improve methodologies;

Dushi (2013) applied the Coda Q method in Albania, crucial for developing accurate ground-motion prediction equations for seismic hazard assessments.

Fundo et al. (2012) conducted probabilistic seismic hazard assessments in Albania, contributing vital data for seismic risk mitigation;

Muço et al. (2002) developed a moment magnitude relation specific to Albania, essential for seismic hazard assessment and earthquake engineering applications;

Dabovski (2006) reviewed Balkan region geodynamics, providing insights into tectonic processes and seismicity, relevant for interpreting seismic hazard in Albania;

Jouanne et al. (2012) used GPS data to constrain tectonics in Albania, contributing to understanding active tectonic processes and seismic hazard.

Dushi et al. (2018) conducted stress inversion studies in Albania, contributing to seismic hazard assessment and earthquake engineering;

Triantafyllis et al. (2021) introduced GISOLA for real-time moment tensor inversion, and Havskov et al. (2020) detailed SEISAN, both pivotal for advancing seismic hazard assessment methodologies;

Khan and Lucas (2018) discussed orthogonal regression analysis, applicable to determining parametric relations like the Mw-ML relation, crucial for accurate seismic hazard assessments.

Methodology

The methodology employed in this study aims to calibrate a representative model relation between Moment Magnitude (M_w) and Local Magnitude (M_L) following the steps outlined in the following:

- *Mw*: Moment Magnitude (Mw) values are initially determined using real-time inversion techniques implemented in GISOLA (Triantafyllis et al., 2021). This automated procedure is supplemented by a manual revision process, to ensure accuracy and reliability.

This first step of the methodology implied in our work is to describe and evidence the importance, accuracy, and efficiency of obtaining the scalar seismic moment (M_0) and moment magnitude (M_w) source parameters. Through the application of GISOLA system for real-time moment tensor

solutions, we acquire crucial focal mechanism information necessary for understanding the tectonic implications of earthquakes (Figure 1).
The precise determination of M_0 and M_w is integral to the calibration process detailed in this paper, reflecting advanced seismic analysis within our approach.

Data collection spans from 2014 to January 2021, covering a period both before and after the installation of GISOLA at the Institute of Geosciences (IGEO). From this dataset, 163 high-quality solutions were selected for analysis. The selection was based on stringent quality criteria, including the number of recording channels (stations), azimuthal coverage, signal-to-noise ratio (SNR), variance reduction (VR), condition number, and the spatiotemporal stability of the solutions.

The results are depicted in a Kaverina's plot inset within the moment tensor distribution map (Figure 1-inset), highlighting the clustering index.

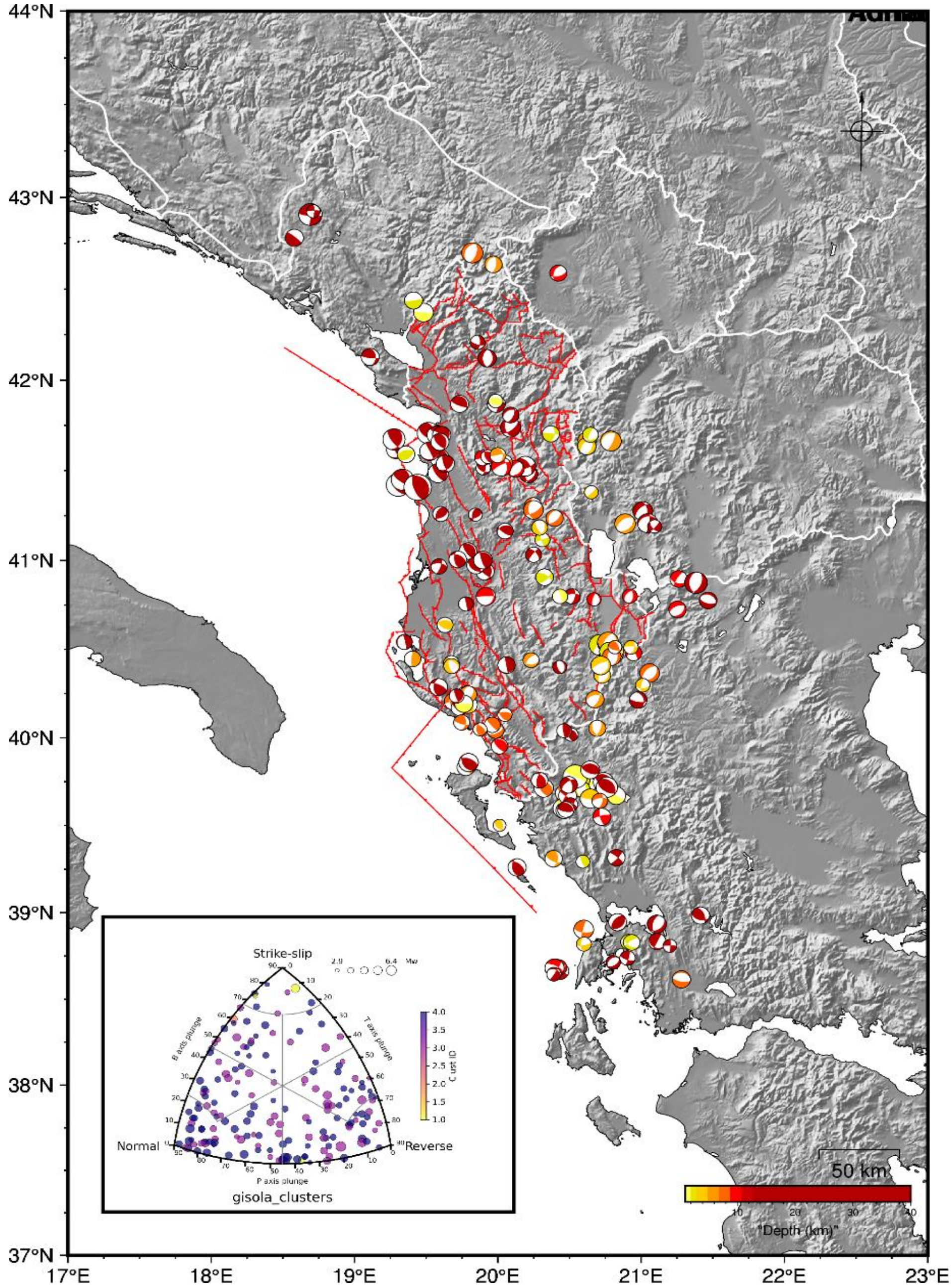

Figure 1. Moment tensor solutions obtained from GISOLA real-time moment tensor inversion software (quality A and B) for earthquakes (Mw≥4.0) recorded during the period 2014-2024.

- *ML determination*: As the second step of the methodology, our investigation into seismic activity from 2014 to 2024 involved analysing approximately 1700 seismic events with magnitudes $M_L \geq 3.0$. The determination of M_L values was executed within the SEISAN (v.12) framework (Hutton & Boore, 1987), utilizing the NETDET program (Havskov et al., 2020). Adjustments were made to align these values with those reported by the Euro-Mediterranean Seismological Canter (EMSC). The parametric form of the formula used is as follows:

$$M_L = log\ (A) + 1.11log(D) + 0.00189D - 1.686 \qquad (2)$$

where:

A (*nm*) is the maximum amplitude of the S (S subscript g/S subscript n) phase on the vertical component (HHZ/EHZ), after correction for the system response and conversion to Wood-Anderson (WA) displacement trace.

D (*km*) is the hypocenter distance, accounting for the depth effect.

Figure 2 presents a cumulative depiction of seismic events over time, highlighting the impact of the 2019 Durres Earthquake (M_w 6.4). This significant event led to a dramatic increase in seismic activity, with over 500 events recorded within a few months following the earthquake. The insets in Figure 2 provide additional statistical insights, showing the temporal distribution of these events and emphasizing the surge in seismicity post-2019.

As part of our methodology, we aim to assess predominant natural seismicity and related parameters. This analysis constrains minimal anthropogenic and environmental interference, particularly within the considered magnitude range ($M_L \geq 3.0$). These observations, supported by insets within Figure 2, underscore the reliability of our M_L values in discerning seismic signals from background noise.

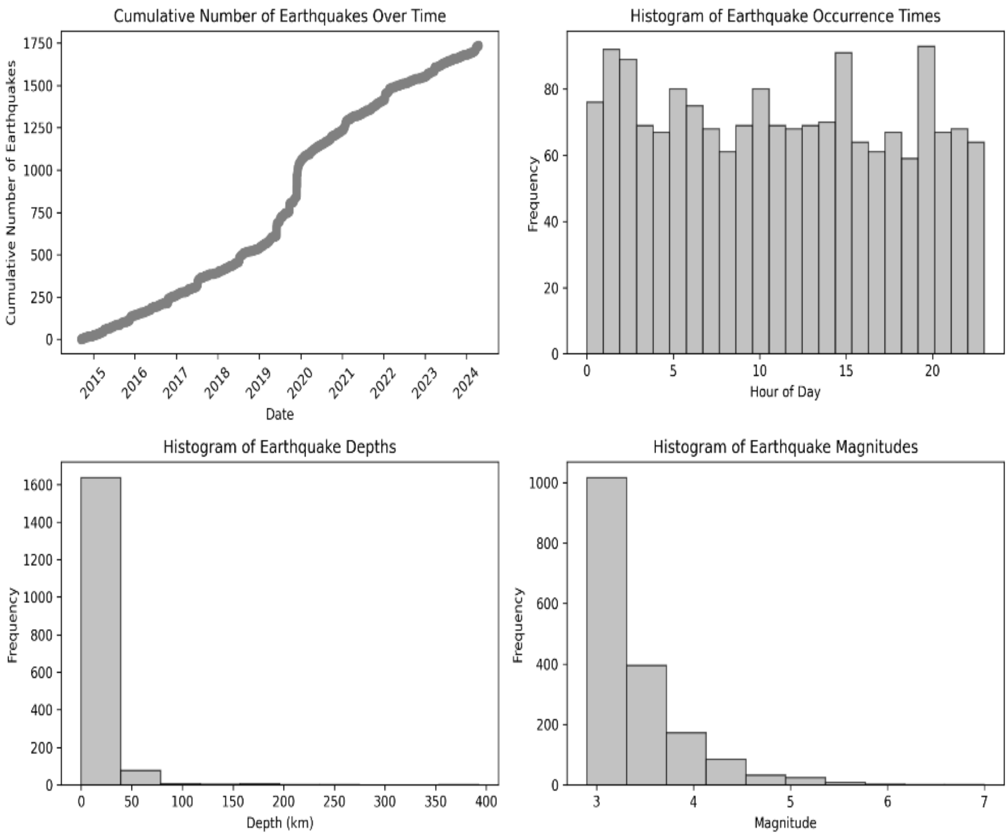

Figure 2. Statistical overview of the earthquake data (ML ≥ 3.0), processed through SEISAN (v. 12), covering the period 2014-2024.

Further investigation into seismic depth and magnitude distributions unveiled important insights relating seismic activity and active tectonics, in Albania and surrounding. Variations in depth parameters indicated predominantly shallow seismic activity, predominantly associated with dynamic processes within the upper and lower crust. Similarly, the magnitude distribution, depicted in Figure 3, provided evidence of dataset completeness within the specified range, constrained by our selection, increase in the recording and processing accuracy and the normalization of the M_L model. This is still far from calibrating a M_L local scale for the studied region.

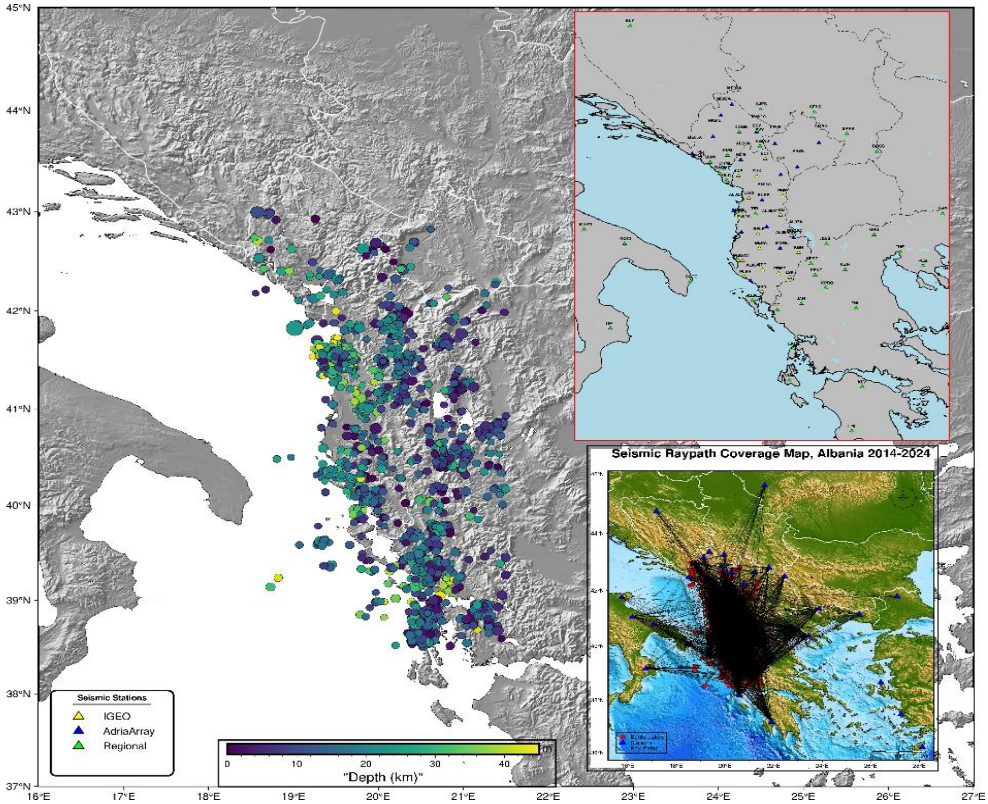

Figure 3. Spatial distribution of earthquake hypocenters in Albania and surrounding ($M_L \geq 3.0$) recorded during the period 2014-2024; the seismic network used to record the data and the ray-path coverage map is also shown, on the map.

Our analysis benefits significantly from the comprehensive deployment of seismic stations, inclusive of both local and regional networks, supplemented by stations integrated through the AdriaArray initiative. Insets within Figure 2 highlight the expansive coverage offered by this network, facilitating broad sampling of the entire crustal volume under investigation. This network, integrated into SEISCOMP (v. 4) and SEISAN systems, furnishes invaluable data for a better M_L determination and seismic analysis.

- *Data Matching and Merging*: to integrate the M_w and M_L data into a cohesive dataset, we developed a custom Python script tailored for this study. The script precisely aligns and merges records from two primary data sources:

GISOLA for the MT parameters and SEISAN for the remaining parametric data, including the earthquake catalogue with coordinates, depth, M_L, and other attributes. The merging process is necessary due to the differences in how source parameters are determined by the two systems for the same set of earthquakes. In the first step, we read data using ***pandas.read_csv*** and ensured temporal alignment with a precision of less than a minute using ***pandas.to_datetime*** and ***pandas.Timedelta***. The script iterates over each row of the merged dataset with ***DataFrame.iterrows***, identifying corresponding entries in the GISOLA data and appending relevant columns using conditional selection and assignment.

Similarly, another script handles merging data from *corf.csv* and *report.csv*, allowing for a (±1 minute) tolerance in date and time matching. This is achieved using conditional selection and time window comparisons within ***pandas.DataFrame***. By stripping leading spaces from column names with ***DataFrame.columns.str.strip*** and checking for optional fields using conditional checks, the script enhances the robustness and flexibility of the merging process. These detailed scripting processes, utilizing operators such as ***pandas.DataFrame***, ***pandas.Series***, and ***pandas.Timedelta***, are crucial for maintaining data integrity and ensuring that the patterns and nuances within the dataset are adequately captured (McKinney, 2010).

- *Orthogonal Regression Analyses*: The merged dataset undergoes orthogonal regression analyses to determine the best representative parametric relation between M_w and M_L (Khan & Lucas, 2018). In this procedure 163 M_L-M_W and M_L-M_0 couples, are analysed. This statistical method is particularly useful for analysing relationships between seismic magnitudes while accounting for measurement errors. The orthogonal regression model can be represented by the equation:

$$M_L = \beta_0 + \beta_1 \cdot M_W \qquad (3)$$

where:

M_L is the local magnitude,

M_w is the moment magnitude,

β_0 is the intercept of the regression line,

β_1 is the slope of the regression line.

The parameters β_0 and β_1 are estimated using a method that minimizes the sum of squared perpendicular distances, implemented in a dedicated Python script developed for this study.

By applying orthogonal regression, we account for errors in both variables, providing a more accurate depiction of the relationship between M_w and M_L.

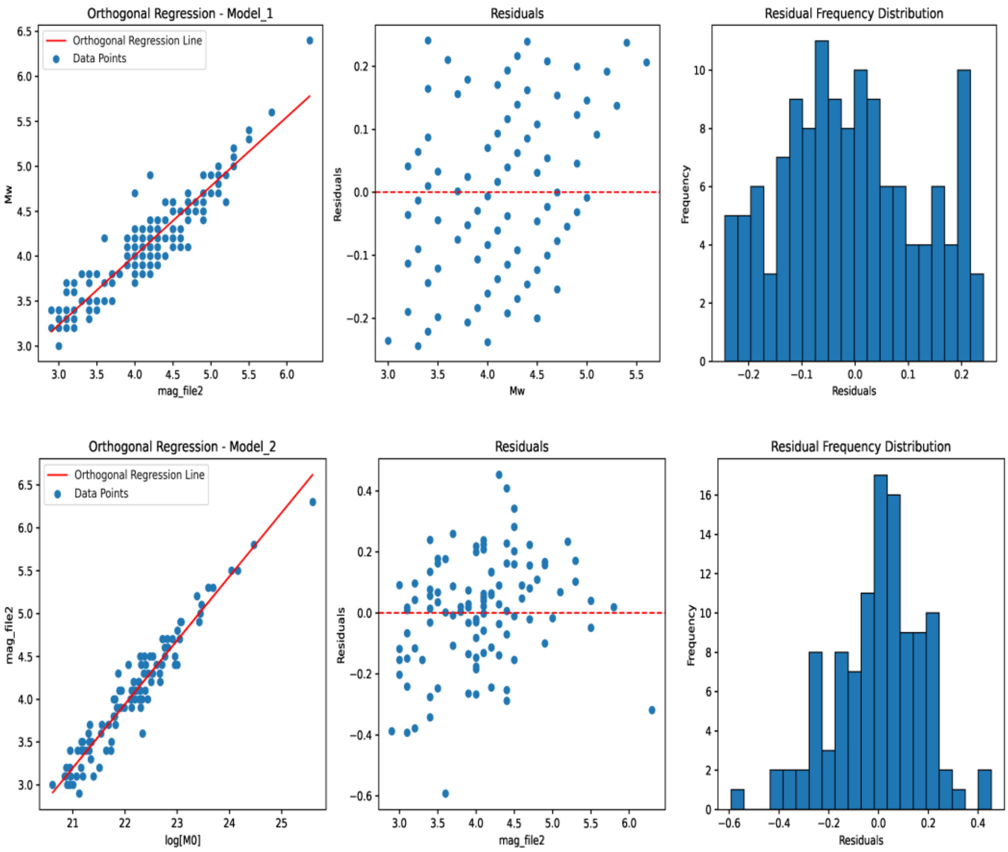

Figure 4. Orthogonal regression graphical results representing two parametric models, M_L-M_W and M_L-Log(M_0), respectively.

This method, is involved to minimize the orthogonal distances between data points and the regression line, aiming a more accurate relationship by accounting for errors in both M_w and M_L. By applying this analysis, we are confident to ensures a robust correlation, enhancing the reliability of our seismic magnitude evaluations

Analysing & Discussion

In this study, we highlight the significance of parameters M_L and M_w as crucial metrics for earthquake size quantification. We establish the relationship between these magnitudes and $\log_{10}(M_0)$, a fundamental aspect reflecting the underlying physical processes of earthquake generation and rupture.

Statistical modelling plays a central role in our data analysis approach. When assessing statistical significance in regression analysis, we meticulously evaluate the reliability of observed relationships between variables. A statistically significant correlation between M_L, M_w, and $\log_{10}(M_0)$ underscores a meaningful connection in line with our understanding of seismic phenomena. This suggests that variations in one magnitude reliably correspond to changes in another, reflecting consistent patterns in earthquake characteristics.

Orthogonal regression, a key method employed in this study, is essential for modelling linear relationships between variables affected by measurement errors, such as seismic magnitude estimations and moment calculations. Unlike traditional least squares regression, orthogonal regression minimizes perpendicular distances between data points and the regression line, ensuring more accurate estimates despite uncertainties in both variables.

However, if the observed correlation lacks statistical significance, it may indicate uncertainties or limitations in our data or analysis methods. In the context of our regression models, a high p-value suggests that the observed relationship between seismic variables may be subject to random variation and may not accurately represent underlying physical processes.

Thus, while the strong correlation coefficients between M_L, M_w, and $\log_{10}(M_0)$ yields promising results, it's crucial to acknowledge the importance of carefully assessing the data quality, analysis techniques, and underlying assumptions. This meticulous evaluation ensures the robustness and scientific validity of our findings, leading to an improved seismic hazard assessment, particularly relevant to the routine data processing in the Department of Seismology, at the Institute of Geosciences.

Analysing the provided orthogonal regression results, we observe notable trends in the relationships between seismic variables. In the first regression model (Table 1), a positive slope of 0.7707 and an intercept of 0.9238 indicate a strong positive linear relationship between M_L and M_w. However, the relatively high p-value of 0.3514 suggests that the observed correlation may lack statistical significance.

Regarding the second regression model (Table 2), we note a similar positive slope of 0.7521 but with a distinct intercept of -12.5994. The correlation coefficient increases to 0.9601, indicating a more robust positive linear relationship between M_L and $\log_{10}(M_0)$, which is anticipated. Yet, the persistent high p-value of 0.337 raises concerns regarding the statistical significance of the correlation.

These results (Table 1 and 2), necessitate a thorough examination of the robustness of our regression models and the underlying data. While the strong correlation coefficients suggest meaningful relationships between variables, the elevated p-values underscore the need for further investigation and potential adjustments to our analysis methodology.

Table 1. The orthogonal regression results for the regression model 1: M_W-M_L

Parameter	**Value**	**Physical Interpretation**
Slope (Orthogonal Regression)	0.7707	The rate of change in M_w with respect to M_L
Intercept (Orthogonal Regression)	0.9238	The baseline M_w value when M_L is zero
Correlation Coefficient	0.9319	Strength and direction of linear relationship between M_L and M_w
P-value	**0.3514**	Statistical significance of the correlation coefficient

Table 2. The orthogonal regression results for the regression model 1: M_L-$\log_{10}(M_0)$

Parameter	**Value**	**Physical Interpretation**
Slope (Orthogonal Regression)	0.7707	The rate of change in M_w with respect to M_L
Intercept (Orthogonal Regression)	0.9238	The baseline M_w value when M_L is zero

Correlation Coefficient	0.9319	Strength and direction of linear relationship between M_L and M_w
P-value	**0.3514**	Statistical significance of the correlation coefficient

Addressing uncertainties, particularly those related to the M_L scale and local characteristics such as site-specific seismic characteristics and station corrections, will be imperative for enhancing the reliability and validity of our seismic data analysis. The last is also supported by the approximate p-value of both models, having in common the M_L scale.

Conclusions

In summary, this analysis employed orthogonal regression to model relationships between various seismic variables. This technique, adept at handling errors in both independent and dependent variables, yielded more accurate estimations of slope and intercept compared to traditional linear regression methods, particularly when faced with uncertainty in both variables.

The dataset utilized comprised moderate to strong earthquakes recorded by the Albanian Seismological Network of the Department of Seismology at the Institute of Geosciences (IGEO), affiliated with the Polytechnic University of Tirana (PUT). These data, derived from waveform recordings used in Moment Tensor Inversion, facilitated the evaluation of Seismic Moment (M_0) and corresponding Moment Magnitude (M_w) through total waveform modeling and calibrated Green Functions, spanning Albania and its surrounding region.

The observed depth distribution of earthquakes underscores the shallow active crust of Albania and highlights recent seismic activity along the Adria microplate's boundary with the Eurasian plate, particularly along the Albanides-Hellenides structures.

Integration of GISOLA with SEISCOMP (v.4.0) marks a notable technological advancement in deploying real-time monitoring and processing systems within the routine operations of the Albanian Seismological Network.

The M_w-M_L model stands pivotal in recent enhancements to seismogenic and attenuation models utilized in local and regional seismic hazard studies across Albania. Orthogonal regression proved suitable for accommodating variations in both scales.

Results revealed strong linear relationships between variables in both the M_w and M_L models, as evidenced by high correlation coefficients. However, elevated p-values suggest potential issues with the statistical significance of observed relationships, possibly due to dataset limitations.

Potential factors contributing to non-significant p-values include the presence of outliers in the data and variations in sample size and variability. Despite these challenges, further investigation, incorporating additional data, may yield more reliable and interpretable results.

Looking ahead, expanding the database of Moment Tensor (MT) solutions, enhancing real-time processing capabilities, and refining local attenuation models will be paramount in improving the robustness of future analyses.

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Notes on Contributors

Prof. Asoc. Dr. Edmond Dushi: Senior seismologist researcher. Contributed to theoretical aspects, data interpretation, and Python scripting for figures and writing of this paper.

Dr. Besian Rama: Instrumentation and software management specialist. Managed data formats, conversions, and maintenance.

MSc. Klajdi Qoshi (PhD candidate): Mathematician researcher. Involved in statistical interpretation.

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