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Magnitude Conversion Relations for Nepal Himalaya Region

S. N. Shrestha¹, P. N. Maskey², G. B. Motra³

^{1,2,3} Tribhuvan University

Abstract

Magnitude conversion is a critical step in the compilation of earthquake catalogues and the assessment of seismic hazard. Given Nepal's high seismic hazard and the limited availability of Nepal region-specific magnitude conversion relations, there is a need to develop empirical relationships that account for the unique tectonic and geological characteristics of the Nepal Himalaya region. This study used existing earthquake catalogues from various institutions to develop new magnitude conversion relations for Nepal Himalaya Region. In this study, we develop new empirical relations for conversion of other magnitudes to moment magnitude. We compare and validate the relations with existing global and regional relations available in the literatures. These relations are then used to compile homogenous earthquake catalogue for Nepal Himalaya region and to perform seismic hazard analysis.

Keywords: Magnitude Conversion, Nepal Himalaya, Moment Magnitude, Regression

1. Introduction

Nepal lies in one of the most seismically active regions in the world, situated at the boundary between Indian and Eurasian tectonic plates. The ongoing collision of these plates results in significant crustal deformation, making Nepal highly prone to large and devastating earthquakes (Bilham et al., 1997). The 2015 Gorkha earthquake (Mw 7.8) highlighted the country's vulnerability, causing nearly 9,000 deaths, displacing millions, and causing extensive damage to infrastructure (Eberhard et al., 2015). The seismic risk in Nepal is further exacerbated by rapid urbanization, inadequate building codes, and poor enforcement of construction standards (Dixit et al., 2013). In a country like Nepal, where rapid urbanization and poor construction practices exacerbate seismic risk, understanding seismicity and recurrence parameters is vital for mitigating the potential loss of life and economic damage from future earthquakes (Parajuli & Koirala, 2019).

In this context, understanding seismicity, compiling accurate earthquake catalogues, and ensuring consistency through magnitude conversion are essential tools for appropriately quantifying earthquake hazard and risk in Nepal, and ultimately for saving lives and reducing economic losses.

The compilation of a comprehensive and accurate earthquake catalogue is a critical step in seismic hazard assessment. An earthquake catalogue provides a historical record of seismic events, including their locations, magnitudes, depths, and times of occurrence. In Nepal, where historical records of earthquakes are limited and instrumental data is relatively recent, compiling a reliable catalogue is challenging but essential (Ambraseys & Douglas, 2004). A well-curated catalogue allows seismologists to identify seismic source zones, assess fault activity, and understand the tectonic processes driving earthquakes (Pandey et al., 1999). It also serves as the foundation for statistical analysis, such as determining recurrence intervals and magnitude-frequency relationships (Kijko & Sellevoll, 1992). Without a robust earthquake catalogue, it would be impossible to accurately model seismic hazards or predict the likelihood of future earthquakes. Given Nepal's high seismic risk and the devastating consequences of past earthquakes, such as the 1934 Bihar-Nepal earthquake and the 2015 Gorkha earthquake, the compilation of a reliable earthquake catalogue is indispensable for informed decision-making and risk mitigation (Bollinger et al., 2016).

Magnitude conversion is a crucial step in earthquake catalogue compilation because seismic events are often reported using different magnitude scales (e.g., local magnitude M_L , body wave magnitude m_b , surface wave magnitude M_S , moment magnitude M_w). These scales are based on different measurement techniques and may not be directly comparable (Kanamori, 1977). In Nepal, where earthquake data is sourced from various national and international agencies, inconsistencies in magnitude scales can lead to inaccuracies in hazard assessments (Chaulagain et al., 2015). Magnitude conversion ensures uniformity in the catalogue by converting all magnitudes to a consistent scale, typically the moment magnitude (M_w), which is the most reliable measure of an earthquake's size (Hanks & Kanamori, 1979). This standardization is essential for accurate statistical analysis, such as calculating the Gutenberg-Richter relationship or estimating ground motion parameters (Grünthal, 2011). M_w is derived from the seismic moment (M_0), which quantifies the total energy released by an earthquake based on fault area, slip displacement, and rock rigidity (Hanks & Kanamori, 1979). Unlike other scales, it does not saturate for large earthquakes. Traditional scales (e.g., M_S , m_b) saturate at higher magnitudes (~8.0), underestimating the true size of very large earthquakes (Kanamori, 1977). M_w remains accurate for all earthquake sizes. M_w provides a uniform standard for comparing earthquakes globally, improving seismic hazard modeling and engineering design (Bormann & Di Giacomo, 2011). Since M_w relates directly to fault mechanics, it is preferred for tectonic and geodynamic research (Ekström et al., 2012).

The GCMT project (formerly Harvard CMT) is a leading global source of moment tensor solutions and is considered the most suitable for M_w conversions. GCMT uses long-period seismic waves to compute the full seismic moment tensor, providing stable and reliable M_w estimates (Dziewonski et al., 1981; Ekström et al., 2012). It systematically reports M_w for earthquakes worldwide since 1976, ensuring consistency in catalogs. Unlike short-period magnitudes (e.g., m_b , M_L), GCMT's M_w is less affected by wave frequency limitations, making it ideal for converting older earthquake records (Scordilis, 2006). Most international agencies (USGS, ISC, EMSC) use or cross-reference GCMT solutions for homogenizing earthquake catalogs.

Therefore, in this study, we focus on determining magnitude conversion relations for conversion of other magnitude scales to equivalent GCMT-based M_w .

With an objective of determining a homogeneous earthquake catalogue for Nepal Himalaya Region, we reviewed several earthquake catalogues relevant for the region. We mainly reviewed the catalogues of following agencies for Nepal region – International Seismological Center (ISC), ISC-Global Earthquake Model (ISC-GEM), National Earthquake Information Center, USGS (NEIC), National Earthquake Information Center, India (NDI), Beijing Seismic Network, China (BJI), Moscow Seismic Network, Russia (MOS), International Data Centre, CTBTO (IDC), Harvard Global Centroid Moment Tensor (GCMT), and Department of Mines and Geology, National Seismological Centre, Nepal (DMN).

Global catalogues like ISC, ISC-GEM, GCMT and NEIC provide comprehensive data for worldwide events, and regional catalogues like NDI, BJI, MOS and DMN offer detailed information for specific seismic regions.

Table 1: Location and Magnitude of 2011 Taplejung (Sikkim) Earthquake Reported by Various Agencies/Authors

Location Agency/Author	Date			Time			Location		Depth km	Magnitude Agency/Author	Magnitude Type and Values				
	Yr	Mo	Day	Hour	Min	Sec	Lat. N	Lon. E			Type	M_w	M_L	m_b	M_S
BJI	2011	09	18	12	40	45.70	27.70	88.20	20	BJI	m_b , M_S			6.5	6.9
NDI	2011	09	18	12	40	46.90	27.85	88.06	45.9	NDI	m_b , M_L , M_w	6.9	6.6	6.7	
NEIC	2011	09	18	12	40	48.00	27.53	87.97	60	MOS	m_b , M_S			6.4	6.6
MOS	2011	09	18	12	40	48.90	27.7710	88.2060	40	IDC	m_b , M_L , M_S		5.3	5.6	6.4
IDC	2011	09	18	12	40	50.51	27.7707	88.2212	37	DMN	M_L		6.8		
DMN	2011	09	18	12	40	51.10	27.6897	88.2959	50	NEIC	m_b , M_S , M_w	6.9		6.6	6.7
GCMT	2011	09	18	12	40	59.90	27.44	88.35	46	GCMT	M_w	6.9			
ISC	2011	09	18	12	40	49.58	27.8039	88.1536	29.60	ISC	m_b , M_S			6.5	6.7

Table 2: Location and Magnitude of 2015 Gorkha Earthquake Reported by Various Agencies/Authors

Location Agency/Author	Date			Time			Location		Depth km	Magnitude Agency/Author	Magnitude Type				
	Yr	Mo	Day	Hour	Min	Sec	Lat. N	Lon. E			Type	M_w	M_L	m_b	M_S
BJI	2015	04	25	06	11	23.50	28.15	84.65	20	BJI	m_b , M_S			6.2	8.2
MOS	2015	04	25	06	11	23.60	28.194	84.726	10	MOS	M_w , m_b , M_S	7.6		6.8	7.6
IDC	2015	04	25	06	11	23.88	28.159	84.7028	0	IDC	M_L , m_b , M_S		5.0	6.0	7.8
DMN	2015	04	25	06	11	25.00	28.2172	84.7684	2	DMN	M_L		7.6		
NEIC	2015	04	25	06	11	25.95	28.2305	84.7314	8.2	NEIC	M_w , m_b , M_S	7.8		7.1	7.9
NDI	2015	04	25	06	11	27.60	28.1130	84.5840	10	NDI	M_L , m_b		6.7	7.1	
GCMT	2015	04	25	06	11	58.60	27.9100	85.3300	12	GCMT	M_w	7.9			
ISC	2015	04	25	06	11	26.63	28.1302	84.7168	13.4	ISC	M_w , m_b , M_S			6.9	7.9

We find variations in terms of date, time, origin, magnitude values of same earthquake events in these catalogues. Tables 1-2 give few example events for which various agencies reported different values. This signifies the need to determine common magnitude conversion relations applicable for Nepal region and creation of a homogenized comprehensive earthquake catalogue.

We use earthquake catalogue compiled by International Seismological Center (ISC) for a period of 1900 to 2022 for the development of new magnitude conversion relations. We extracted the catalogue for Nepal Himalaya region within 78-90 E and 25-32 N and 75-93 E and 24-34 N for comparison and validation purpose. The catalogue consists of 4700 events of $M \geq 4$, and 8,778 events of $M \geq 4$ respectively. We use mainly M_L , m_b , M_S and M_w values reported by different agencies for the determination of magnitude conversion relations.

2. Existing Magnitude conversion relations

At the global level, several empirical relationships have been developed to convert between magnitude scales such as surface wave magnitude (M_S), body wave magnitude (m_b), and moment magnitude (M_w).

Scordilis (2006) developed empirical relations for converting body-wave magnitude (m_b) and surface-wave magnitude (M_S) to moment magnitude (M_w), based on **global** dataset.

m_b to M_w :

$$M_w = 0.85 \times m_b + 1.03 \text{ for } 3.5 \leq m_b \leq 6.2 \quad \text{-----} \quad (1)$$

M_S to M_w :

$$M_w = 0.67 \times M_S + 2.07 \text{ for } 3.0 \leq M_S \leq 6.1 \quad \text{-----} \quad (2a)$$

$$M_w = 0.99 \times M_S + 0.08 \text{ for } 6.2 \leq M_S \leq 8.2 \quad \text{-----} \quad (2b)$$

The dataset used for these conversions is globally averaged and does not account for regional variations.

Ambraseys and Douglas (2004) derived relationships for the conversion of M_S to $\log M_0$ for **global level** and **Himalayan region**. Using M_0 - M_w relation by **Kanamori (1977)**, relation for M_S - M_w are determined.

Global average relations:

$$\log M_0 = 19.24 + M_S \quad \text{for } M_S < 5.3 \quad \text{-----} \quad (3a)$$

$$\log M_0 = 30.20 - \sqrt{92.45 - 11.40 \times M_S} \quad \text{for } 5.3 \leq M_S \leq 6.8 \quad \text{-----} \quad (3b)$$

$$\log M_0 = 16.14 + 1.5 \times M_S \quad \text{for } M_S > 6.8 \quad \text{-----} \quad (3c)$$

For Himalayan region:

$$\log M_0 = 19.38 + 0.93 \times M_S \quad \text{for } M_S \leq 5.94 \quad \text{-----} \quad (4a)$$

$$\log M_0 = 16.03 + 1.5 \times M_S \quad \text{for } M_S > 5.94 \quad \text{-----} \quad (4b)$$

Kanamori, 1977:

$$M_w = \frac{2}{3} \log M_0 - 10.73 \quad \text{for } M_S \leq 5.94 \quad \text{-----} \quad (5)$$

From Equations (4) and (5), we have M_S - M_w relation for Himalayan region:

$$M_w = 0.62 \times M_S + 2.2 \quad \text{for } M_S \leq 5.94 \quad \text{-----} \quad (6a)$$

$$M_w = M_S - 0.0433 \quad \text{for } M_S > 5.94 \quad \text{-----} \quad (6b)$$

Das et al., 2011 gave relations for global level for conversion of M_S and m_b to M_w

M_S to M_w :

For $h < 70\text{km}$

$$M_{w,HRVD} = 0.67(\pm 0.00005) \times M_S + 2.12(\pm 0.0001) \quad \text{for } 3 \leq M_S \leq 6.1 \quad \text{-----} \quad (7a)$$

$$M_{w,HRVD} = 1.06(\pm 0.00002) \times M_S + 0.38(\pm 0.0006) \quad \text{for } 6.2 \leq M_S \leq 8.4 \quad \text{-----} \quad (7b)$$

For $70\text{km} \leq h < 643\text{km}$

$$M_{w,HRVD} = 0.67(\pm 0.00004) \times M_S + 2.33(\pm 0.01) \quad \text{for } 3.3 \leq M_S \leq 7.2 \quad \text{-----} \quad (7c)$$

m_b to M_w from Inverted Standard Regression (ISR):

$$m_{b,ISC} = 0.65(\pm 0.003) \times M_{w,HRVD} + 1.65(\pm 0.02) \quad \text{for } 2.9 \leq m_{b,ISC} \leq 6.5 \quad \text{-----} \quad (8a)$$

$$M_{w,HRVD} = 1.5385 \times m_{b,ISC} - 2.5385 \quad \text{for } 2.9 \leq m_{b,ISC} \leq 6.5 \quad \text{-----} \quad (8b)$$

Das et al., 2012 used $m_{b,proxy}$ which increased correlation coefficient:

$$M_w = 1.63(\pm 0.0101) \times m_{b,proxy} - 3.194(\pm 0.281) \quad \text{-----} \quad (9a)$$

$$m_{b,proxy} = 0.724(\pm 0.03) \times m_{b,obs} + 1.455(\pm 0.16) \quad \text{-----} \quad (9b)$$

$$M_w = 1.18 \times m_{b,obs} - 0.822 \quad \text{-----} \quad (9c)$$

Thingbaijam et al., 2008 determined conversion relations for northwest India:

$$M_{w,GCMT} = 0.7042(\pm 0.0356) \times M_{S,ISC} + 1.8197(\pm 0.1896) \quad \text{for } M_{S,ISC} < 7.5 \quad \text{-----} \quad (10)$$

$$M_{w,GCMT} = 1.3691(\pm 0.211) \times m_{b,ISC} - 1.7742(\pm 1.139) \quad \text{-----} \quad (11)$$

(for $M_{w,GCMT} > 4.4$ and $m_{b,ISC} < 6.7$)

They considered M_w and M_L equivalent, i.e.,

$$M_w \approx M_L \quad \text{-----} \quad (12)$$

Kolathayar et. al., 2011 developed regression relations for Asia region $0\sim 40^\circ N$ and $60\sim 105^\circ E$, the data covered period within 250 BC – 2010 A.D.

$$M_w = 0.693(\pm 0.006) \times M_s + 1.922(\pm 0.035) \quad \text{for } 3.7 \leq M_s \leq 8.8 \quad \text{----- (13)}$$

$$M_w = 1.08(\pm 0.0152) \times m_b - 0.325(\pm 0.081) \quad \text{for } 4 < m_b \leq 7.2 \quad \text{----- (14)}$$

$$M_w = 0.815 (\pm 0.04) \times M_L + 0.767(\pm 0.174) \quad \text{for } 3.7 \leq M_L \leq 7 \quad \text{----- (15)}$$

Nath, Thingbaijam and Ghosh, 2011 determined conversion relations for $2\sim 40^\circ N$ and $55\sim 102^\circ E$. They also used proxy magnitudes for increasing the correlation coefficient.

$$M_{w,GCMT} = 0.6495 \times M_{s,ISC} + 2.163 \quad \text{for } 3.5 \leq M_{s,ISC} \leq 6.6 \quad \text{----- (16a)}$$

$$M_{w,GCMT} = 1.157 \times M_{s,ISC} - 1.179 \quad \text{for } 6.7 \leq M_{s,ISC} \leq 8.5 \quad \text{----- (16b)}$$

$$M_{w,GCMT} = 1.16 \times m_{b,ISC} - 0.663 \quad \text{for } 3.8 \leq m_{b,ISC} \leq 7.0 \quad \text{----- (17)}$$

$$M_{w,GCMT} = 0.449 \times M_{L,ISC} + 2.88 \quad \text{for } 4.6 \leq M_L \leq 6.4 \quad \text{----- (18)}$$

Storchak et al., 2012, as part of the ISC-GEM Global Instrumental Earthquake Catalogue, proposed the following magnitude conversion relations:

$$M_w = 0.67 \times M_s + 2.13 \quad \text{for } M_s \leq 6.47 \quad \text{----- (19)}$$

$$M_w = 1.10 \times M_s - 0.67 \quad \text{for } M_s > 6.47 \quad \text{----- (20)}$$

$$M_w = 1.38 \times m_b - 1.79 \quad \text{----- (21)}$$

Ader et al., 2012 gave the following relation for Nepal Himalayan region:

$$M_w = 0.84 \times M_L + 0.21 \quad \text{----- (22)}$$

Maharjan et al., 2023 used the existing magnitude conversion relations for M_s & m_b and determined few relations for M_L :

$$M_w = 1.0273(\pm 0.07) \times M_{L,NDI} + 0.0629(\pm 0.37) \quad \text{for } 3.6 \leq M_{L,NDI} \leq 6.8 \quad \text{----- (23)}$$

$$M_w = 0.6527(\pm 0.05) \times M_{L,BJI} + 1.9015(\pm 0.27) \quad \text{for } 3.8 \leq M_{L,BJI} \leq 6.8 \quad \text{----- (24)}$$

Adhikari et al. (2023):

$$M_w = 1.15 \times M_L - 1.10 \quad \text{----- (25)}$$

While global and broader-Himalaya-specific magnitude conversion relations provide a useful starting point, they have significant limitations when applied to Nepal due to regional seismotectonic differences. Therefore, developing Nepal-Himalaya-specific magnitude conversion equations based on local earthquake data is essential for improving earthquake catalogues and seismic hazard assessments.

3. Methodology

After selection and collection of appropriate earthquake catalogue for the region, the data is filtered and cleaned to ensure duplicates are removed, and poorly constrained magnitude values are excluded. The cleaned earthquake catalogues are used for developing empirical relation by regression analysis.

We perform the following regression analysis for developing magnitude conversion relations:

A simple and widely used approach is ordinary least squares regression, which fits a linear model of the form:

$$M_w = a \times M_L + b \text{ or} \quad \text{----- (26)}$$

$$M_w = a \times m_b + b \quad \text{----- (27)}$$

where a and b are empirical coefficients obtained through statistical regression.

One of the commonly used regression analysis methods is **Ordinary Least Squares (OLS)**. In this regression, we try to minimize the vertical distances (errors in y only) between observed points and the regression line (vertical residuals), and in the form of sum of squared vertical residuals. It takes the form of:

$$\min \sum_{i=1}^n (y_i - X_i \beta)^2 \quad \text{-----} \quad (28)$$

Where, y_i = Observed dependent variables; X_i = Predictor variables; and β = Coefficients

We perform **Orthogonal Distance Regression (ODR)** to account for errors in both variables. The regression equation takes the same form as OLS but minimizes total errors rather than just vertical deviations.

We try to minimize the **perpendicular (orthogonal) distance** from the data points to the regression line. It accounts for errors in **both X and Y**. It takes the form as:

$$\min \sum_{i=1}^n \frac{(y_i - X_i \beta)^2}{\sigma_{y_i}^2 + \|\beta\|^2 \sigma_{x_i}^2} \quad \text{-----} \quad (29)$$

or more generally, for any functions $f(x,y)=0$, it minimizes:

$$\min \sum_{i=1}^n \frac{(y_i - f(x_i))^2}{\sigma_{y_i}^2 + \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2} \quad \text{-----} \quad (30)$$

Another more general orthogonal regression is General Orthogonal Regression (GOR). This regression tries to minimize the **weighted sum of squared orthogonal distances**.

For a line $Ax+By+C=0$, it tries to minimize:

$$\min \sum_{i=1}^n \left(\frac{Ax_i + By_i + C}{\sqrt{A^2 + B^2}} \right)^2 \quad \text{-----} \quad (31)$$

This is the **square of the orthogonal distance** from each point to the line in the 2D space.

In some cases, magnitude conversion is not strictly linear, especially for large earthquakes where magnitude saturation occurs. Nonlinear regression models, such as piecewise linear models (for different magnitude ranges) can be used to better fit the data. **Specifically, for the case of M_S to M_w conversion piecewise linear models are used.**

After doing the regression analysis and finding out the regression relations, we perform the following statistical evaluation, uncertainty analysis and validation to assess the reliability or goodness-of-fit of the magnitude conversion relation:

- **Mean Absolute Error (MAE):** This measures the average of absolute differences between the predicted and observed values. This represents the average magnitude of errors. A lower MAE means the model's predictions are closer to the true values.
- **Root Mean Square Error (RMSE):** This measures how large the errors are, with more weight given to larger errors. This is the square root of the average of squared differences between predicted and actual values. Lower RMSE indicates better accuracy.
- **Coefficient of Determination (R Squared):** This indicates how well the model captures the variability in the data or how well the regression line fits the data. This ranges from 0 to 1 and higher R2 values indicate better fit.
- **Standard Deviation (sigma):** This indicates how spread out the errors are (consistency of predictions). Smaller sigma value signifies tighter clustering around the line or better fit and larger value shows more scatter or poorer fit.
- **Residuals (Observed–Predicted)** are analyzed to detect biases in the model. In a well-fitted model, the residuals should randomly distribute around zero, and show no systematic trends in residuals across magnitude ranges

The newly derived equations are compared and validated against global and regional relations (Equations 1-25) to check for consistency.

4. Earthquake Data and Regression Analysis

There are variations in different studies in compilation of earthquake data for Nepal Himalaya region. Maharjan et al., 2023 considered earthquake data within a region within 75°-93°E, and 24°-34°N. Chamlagain et al., 2020

considered the data within region 78°-90°E and 25°-33°N. Likewise, Stevens et al., 2018 considered data within 80°-89°E and 26°-31°N, Rahman and Bai considered within 79°-89°E and 26°-32°N, Thapa and Wang took data within 26°-31.7°N and 79°-90°E from 1255 to 2011. Rajaure, 2020 considered data within 75°-93°E and 24°-34°N.

In this study, earthquakes within the following two geographic area are considered for catalogue compilation and analysis: 78°-90°E and 25°-32°N (approx. 150 km from the political boundary of Nepal); and 75°-93°E and 24°-34°N (approx. 300 km in latitude and 400 km in longitude from the political boundary of Nepal). The ISC catalogues for two regions contain 8,778 and 4,700 number of events respectively that are greater than or equal to magnitude 4 during the period 1 January 1900 to 1 September 2022.

We take the following magnitude-agency pairs and data for the determination of corresponding magnitude conversion relation.

Table 3: Number of earthquakes and Agency-Magnitude Pairs used for Developing Regression Models

S. No.	Description	No. of Events for Regression	
		Region 1 (78°-90° E, 25°-32° N)	Region 2 (75°-93° E, 24°-34° N)
A.	Total No. of Events	4700	8778
B.	Period Covered	1908-2022	1905 - 2022
C.	Magnitude-Agency Pairs		
1	IDC m_b and ISC m_b	2517	4776
2	NEIC m_b and ISC m_b	1664	3059
3	NDI M_L and ISC m_b	1228	2022
4	BJI m_b and ISC m_b	918	1838
5	DMN M_L and ISC m_b	788	872
6	DMN M_L and ISC M_S	297	326
7	MOS m_b and ISC m_b	693	1385
8	GCMT M_w and ISC m_b	133	292
9	IDC m_b and GCMT M_w	99	230
10	NDI M_L and GCMT M_w	69	119
11	BJI m_b and GCMT M_w	117	265
12	DMN M_L and GCMT M_w	81	87
13	MOS m_b and GCMT M_w	133	285
14	ISC M_S and GCMT M_w	128	283

[Catalogue accessed on September 20, 2024; and Period covered: 1908 – September 1, 2022]

Regression analyses are done following Ordinary Least Squares (OLS), Orthogonal Distance Regression (ODR) and General Orthogonal Regression (GOR) methods for different combinations of data. We use python codes for running the calculations. We follow three regression methods to compare, validate and determine the most suitable regression relation.

Comparison of statistical metrics for each method are done, and best-fit regression is identified. The magnitude conversion relations thus determined are compared and validated with the existing magnitude conversion relations.

4.1. Conversion of Local Magnitude (M_L) to Moment Magnitude (M_w)

4.1.1. Local Magnitude from DMN (DMN M_L)

The Local Magnitude (M_L), commonly known as Richter magnitude scale, is the logarithm of maximum trace amplitude of seismic waves recorded by Wood-Anderson seismographs for the earthquakes in Southern California. This magnitude scale is designed for shallow, local earthquakes (within about 600 km of the seismograph). The National Seismological Center of Department of Mines and Geology (DMN) measures earthquakes in local magnitude scale (M_L).

The DMN local magnitude M_L is estimated from the maximum amplitudes of the S_g , S_n and L_g seismic phases measured at all suitable records on the 0.3-7 Hz bandpass filtered seismic signals. The final value of M_L is the arithmetic average of all available magnitude values determined at distances greater than 95 km or 100km.

We use 87 numbers of events with $M_L - M_w$ data pairs from the ISC catalogue for conversion of M_L to M_w . We developed several regression relations for various combinations of data and by different methods of regression. After the comparison of regression metrics i.e., the Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Coefficient of Determination (R-squared), and Standard Deviation (sigma), and comparing the residual box plots, we use the following two relations for further analysis and validation with other existing magnitude conversion relations.

Model developed by ODR method in this study from data within 75-93E and 24-34N

$$M_w = 1.246 \times M_L - 1.766 \quad \text{-----} \quad (32)$$

(New_Model1_2024_ M_L - M_w)

Model developed by OLS method in this study from data within 75-93E and 24-34N

$$M_w = 0.832 \times M_L + 0.603 \quad \text{-----} \quad (33)$$

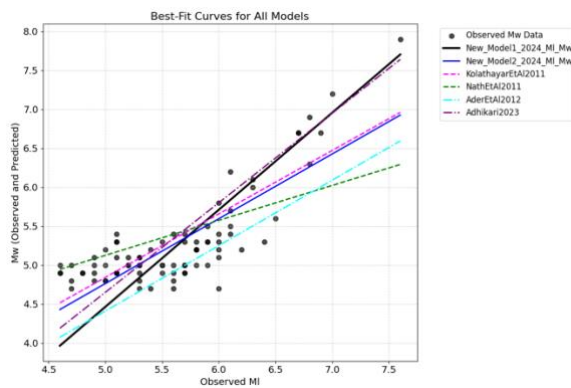
(New_Model2_2024_ M_L - M_w)

The new empirical relations are compared with the existing relations (Figure 1). Two existing relations for broader Himalayan region – Kolathayar et al., 2011 (Eq. 15) and Nath, Thingbaijam and Ghosh, 2011 (Eq. 18) and two for Nepal Himalayan region – Ader et al., 2012 (Eq. 22) and Adhikari, 2023 (Eq. 25) are used for comparison. We observed New_Model1 gives very much similar results with that by the Adhikari, 2023 relation. New_Model2 gives similar pattern with that of Ader et al. 2012 with New_Model2 giving 0.2 magnitude higher results. Kolathayar et al., 2011, Nath, Thingbaijam and Ghosh, 2011 relations are giving smaller results for magnitudes more than 5.7 and higher results for more than magnitude 5.7. The residual scatter plots (Figure 1c) show New_Model1 is giving less biased results than other existing relations.

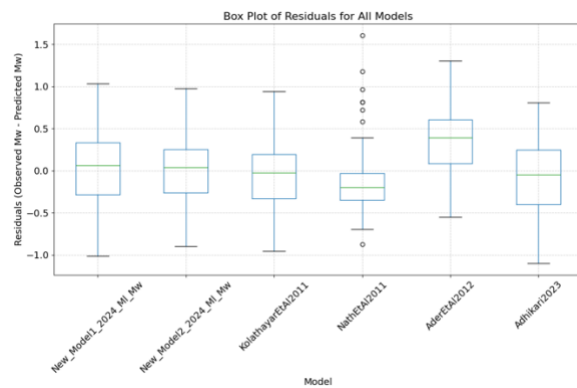
By comparing the model metrics as shown in the figures, we find the best fit model for conversion of M_L to M_w for the Nepal Himalaya Region is:

$$M_w = 1.246 \times M_L - 1.766 \quad \text{-----} \quad (34)$$

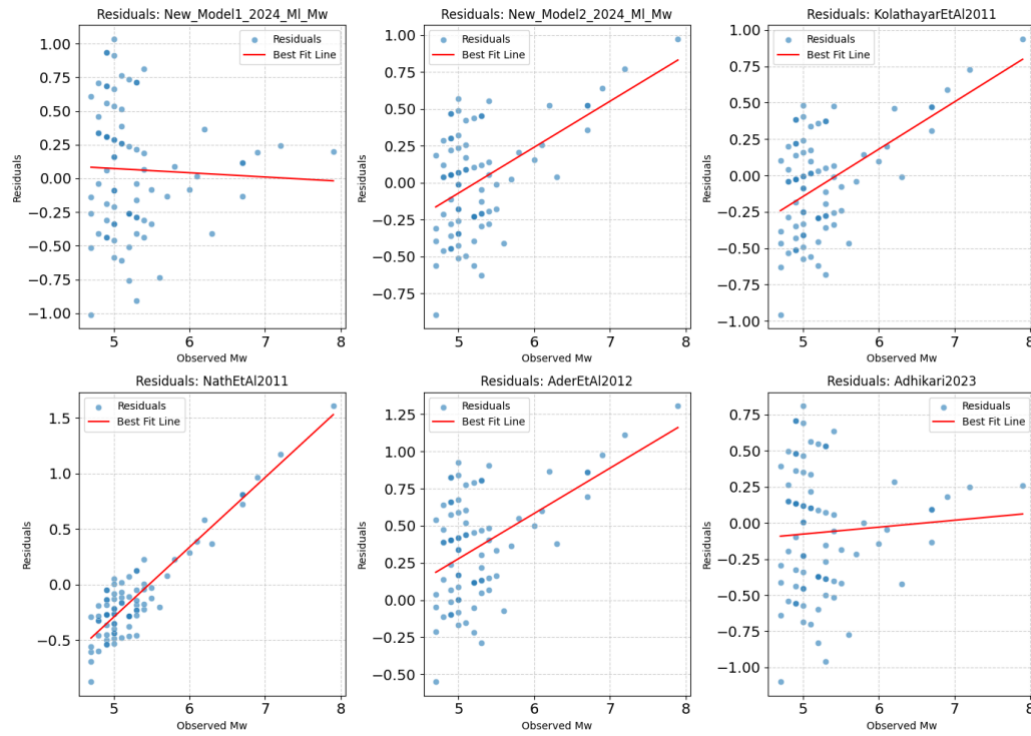
MAE = 0.39176; RMSE = 0.469723; $R^2 = 0.391702$; $\sigma = 0.465254$



a) Magnitude Conversion Relations



b) Residual Box Plots



c) Residual Scatter Plots

Figure 1: Comparison of New Magnitude Conversion Relation for M_L to M_w **Table 4:**Model Metrics Comparisons for M_L to M_w Conversion

Model	MAE	RMSE	R ²	Std. Dev.
New_Model1_2024_ML_Mw	0.39176	0.469723	0.391702	0.465254
New_Model2_2024_ML_Mw	0.298338	0.362904	0.636908	0.362612
KolathayarEtAl2011	0.295438	0.36576	0.631171	0.361717
NathEtAl2011	0.33173	0.430088	0.490025	0.413819
AderEtAl2012	0.415975	0.513275	0.273672	0.363139
Adhikari2023	0.363642	0.434706	0.479015	0.430022

4.1.2. Local Magnitude from NDI (NDI M_L)

NDI, India also measures earthquake events in local magnitude scale (M_L). Although both DMN and NDI measure earthquakes in local magnitude scale M_L , their magnitude values are not same. Generally, reported NDI M_L values are less by 0.2-0.8 than the reported DMN M_L values, in average NDI M_L values are 0.5 magnitude less than the DMN M_L values.

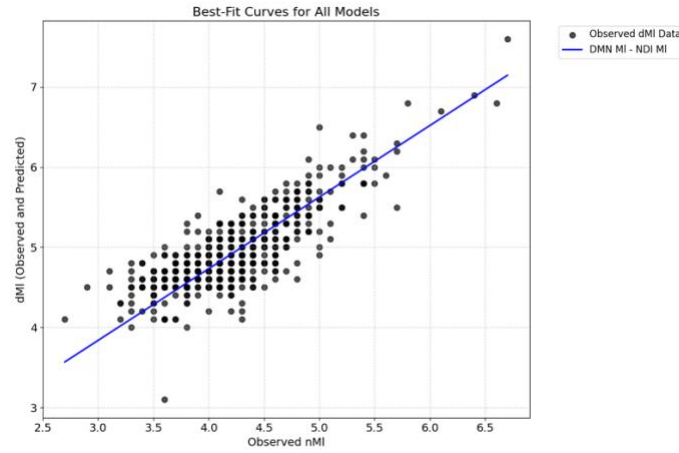


Figure 2: Comparison of DMN M_L and NDI M_L

Based on comparison of model metrics for 612 data pairs for DMN M_L and NDI M_L , the best-fit relation for the conversion of M_L (NDI) to M_L (DMN) is the one we get from the ODR Regression as below:

$$M_L(\text{DMN}) = 0.894 \times M_L(\text{NDI}) + 1.156 \pm 0.288 \quad (35)$$

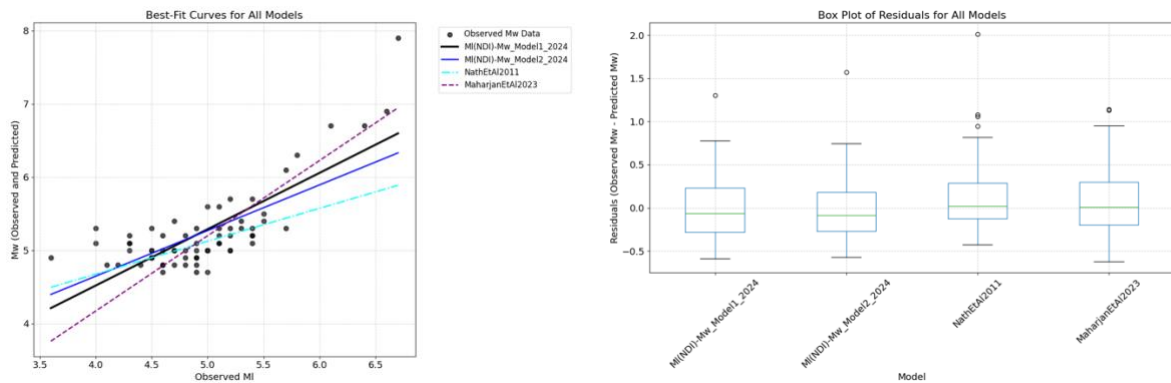
With

$$\text{MAE} = 0.2275; \text{RMSE} = 0.28818; R^2 = 0.618; \sigma = 0.28818$$

Conversion for NDI M_L to M_w

We perform regression using 69 data pairs for M_L (NDI) to M_w from data within $75^\circ\text{--}93^\circ\text{E}$ and $24^\circ\text{--}34^\circ\text{N}$, and find the following relation and compare with existing relations Nath et al., 2011 (Eq. 18) and Maharjan et al., 2023 (Eq. 23).

$$M_w = 0.769 \times M_L + 1.444 \pm 0.333 \quad (36)$$



a) Magnitude Conversion Relations

b) Residual Box Plots

Figure 3: Magnitude Conversion Relation for NDI M_L to M_w and Comparison with Other Conversions

Table 5: Model Metrics Comparisons NDI M_L to M_w Conversion

Model	MAE	RMSE	R ²	Std. Dev.
MI(NDI)-Mw_Model1_2024	0.283667	0.352621	0.593643	0.352278
MI(NDI)-Mw_Model2_2024	0.276154	0.358886	0.579076	0.358848
NathEtAl2011	0.258052	0.412287	0.444491	0.390666
MaharjanEtAl2023	0.310052	0.397214	0.484366	0.38745

4.2. Conversion of Body Wave Magnitude (m_b) to Moment Magnitude (M_w)

4.2.1. Conversion of m_b (ISC) to M_w (GCMT)

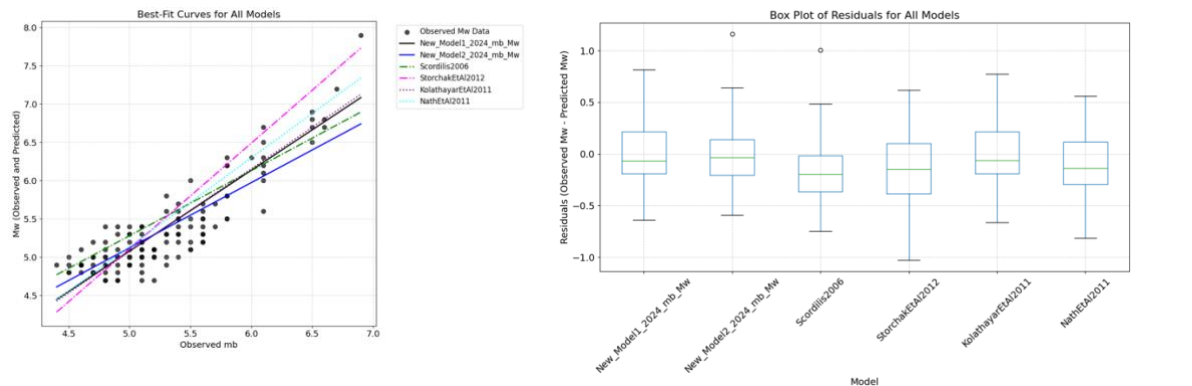
The body wave magnitude (m_b) is the most commonly used magnitude scale and most recording stations measure m_b for particularly tele-seismic events. The body wave magnitude (m_b) is a measure of earthquake size calculated from the amplitude of P-waves (primary or compressional waves) recorded by seismographs. It is typically measured at periods of about 1 second and is most effective for deep and distant earthquakes (usually at distances greater than 20° from the epicenter). In ISC catalogue, most events are reported in m_b .

For Nepal Himalaya Region, from the ISC Catalogue 292 number of data pairs of m_b and M_w are used for regression, and we find the following relations:

New models:

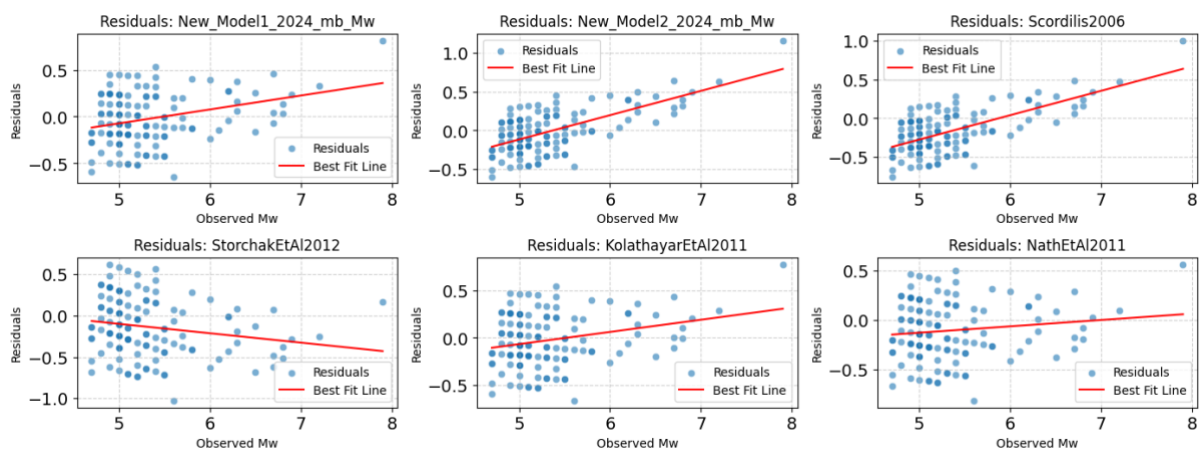
Model Name	Regression Relation
New_Model1_2024_ m_b - M_w	$M_w = 1.055 \times m_b - 0.195$ ----- (37)
New_Model2_2024_ m_b - M_w	$M_w = 0.852 \times m_b + 0.862$ ----- (38)

We then compare the results obtained from the new model with the results obtained from existing models - with Scordilis 2006 (Eq. 1), Kolathayar et al., 2011 (Eq. 14), Nath et al., 2011 (Eq.17), and Storchak et al. 2012 (Eq. 21). The model metrics are comparable with the existing models, Kolathayar et al., 2011 gives consistent results with the new model.



a) Magnitude Conversion Relations

b) Residual Box Plots



c) Residual Scatter Plots

Figure 4: Magnitude Conversion Relation for ISC m_b to M_w and Comparison with Other Conversions

Table 6: Model Metrics Comparisons for $m_b - M_W$ Conversion

Model	MAE	RMSE	R ²	Std. Dev.
SNS1_mb_Mw_oq_model	0.225729	0.274921	0.774152	0.274009
SNS2_mb_Mw_ols_model_1	0.219546	0.277385	0.770085	0.277181
Scordilis2006	0.266767	0.324384	0.685574	0.277418
StorchakEtAl2012	0.31	0.373169	0.583889	0.346558
KolathayarEtAl2011	0.228519	0.277542	0.769825	0.276503
NathEtAl2011	0.255331	0.307691	0.717104	0.288425

New_Model1 gives similar results with that of Kolathayar et al., 2011; whereas New_Model2 is giving smallest results among all the models. Storchak et al., 2012 is giving highest results for higher magnitude values. The residual scatter plot shows less biasness by the New_Model1, whereas all other relations are giving higher biasness. Therefore, the final relation for $m_b - M_W$ conversion is:

$$M_w = 1.055 \times m_b - 0.195 \quad \text{-----} \quad (39)$$

MAE = 0.217; RMSE = 0.2682; $R^2 = 0.6995$; $\sigma = 0.268$

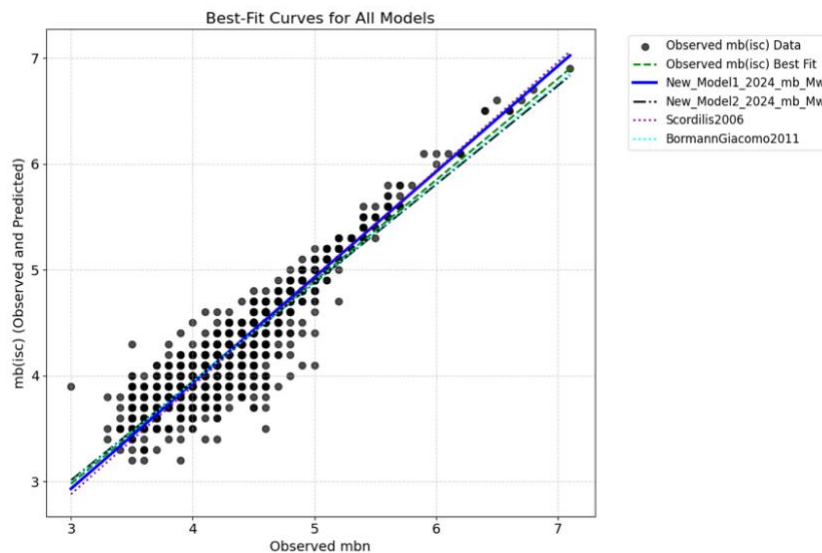
4.2.2. m_b from NEIC and ISC

We do the regression for 1664 data pairs by three methods of regression with different combinations of data: all data together, data split into training and test data.

From various regression models, we observe that m_b given by ISC and NEIC are practically equal. The best-fit model after comparing the model metrics for Nepal-Himalaya region is:

$$m_b(ISC) = 0.998 \times m_b(NEIC) - 0.062 \pm 0.191 \quad \text{-----} \quad (40)$$

MAE = 0.138445; RMSE = 0.191753; $R^2 = 0.849135$; $\sigma = 0.191471$

**Figure 5:** Comparison of NEIC m_b and ISC m_b

Scordilis (2006) has also shown the mb magnitudes given by ISC and NEIC are practically equivalent and given the relation:

$$m_b(ISC) = 1.02 (\pm 0.003) \times m_b(NEIC) - 0.18 (\pm 0.011) \quad \text{-----} \quad (41)$$

for $2.5 \leq m_b(NEIC) \leq 7.3$ with $R^2 = 0.99$, $\sigma = 0.20$, $n = 215$

4.2.3. Body wave magnitudes from other agencies

Other agencies mainly, BJI, MOS and IDC have also reported body wave magnitudes (m_b) for the Nepal-Himalaya region and considered their data for the compilation of earthquake catalogues. Therefore, m_b given by these agencies are also compared, and following relations are determined. The model metrics are also determined and found to be reasonable.

Agency and data pairs	Conversion Relation	MAE	RMSE	R^2	Std. Dev. (σ)
BJI (n=265)	$M_w = 1.087 \times m_b(BJI) - 0.164 \pm 0.266$ ----- (42)	0.215115	0.287007	0.7542	0.286993
MOS (n=285)	$M_w = 1.018 \times m_b(MOS) - 0.161 \pm 0.256$ ----- (43)	0.207809	0.26579	0.788906	0.264851
IDC (n=230)	$M_w = 1.148 \times m_b(IDC) - 0.201 \pm 0.284$ ----- (44)	0.243356	0.308499	0.698074	0.306751

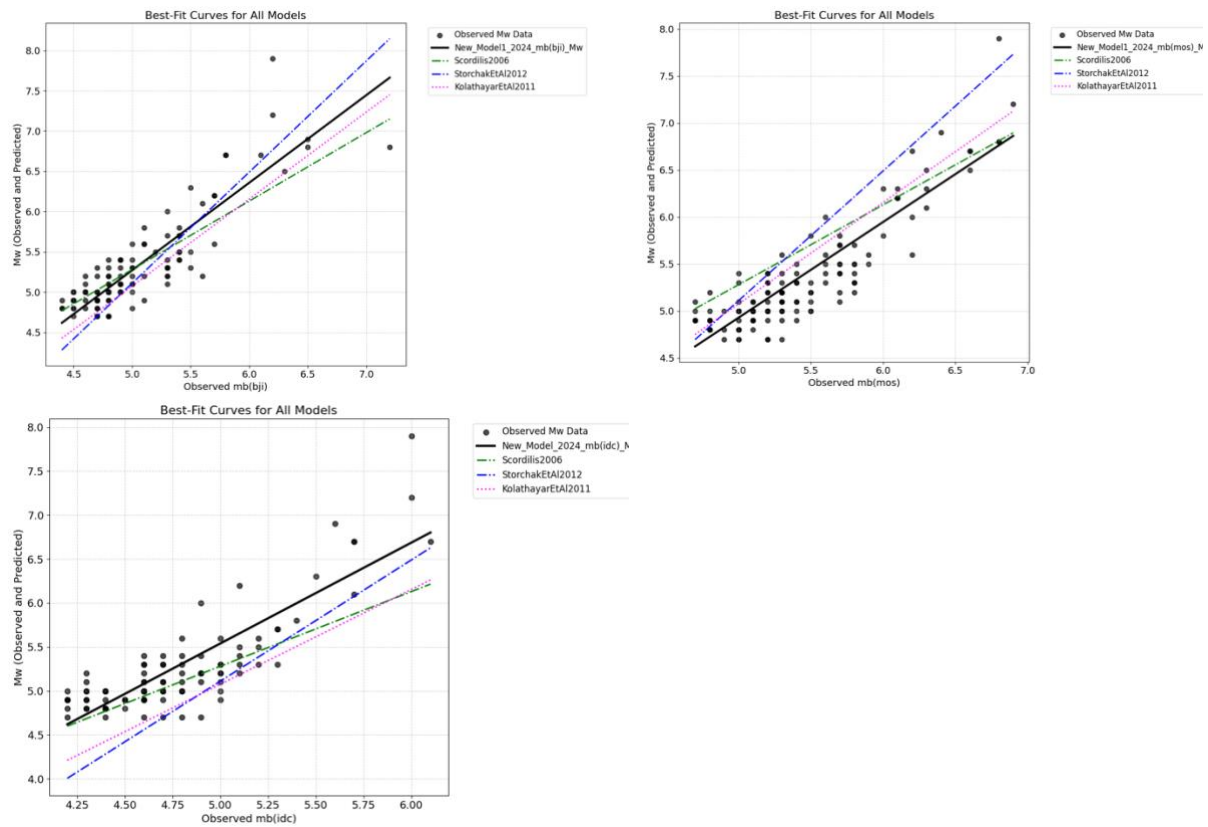


Figure 6: Magnitude Conversion Relations for BJI, MOS, IDC m_b to M_w

There are some variations in the coefficients of the new relations for other magnitude agencies. The magnitude relations developed for $m_b(ISC)$ (Equation 39) can be considered reasonable for all other magnitude agencies for Nepal-Himalaya region.

4.3. Conversion of Surface Magnitude (M_S) to Moment Magnitude (M_w)

The surface wave magnitude (M_S) measures an earthquake's size based on the amplitude of surface waves (Rayleigh waves) with a period of about 20 seconds. This scale measures earthquake size for moderate-to-large events, commonly for magnitudes between ~ 5.0 and 8.5 , and works best for shallow earthquakes (depth < 50 km).

M_S relies on long-period surface waves, making it useful for distant earthquakes. M_S saturates for very large earthquakes ($M > 8.5$). For giant earthquakes (e.g., 2004 Sumatra), moment magnitude (M_w) is preferred. Many pre-1970 earthquakes were recorded using M_S (before M_w became standard).

Scordilis (2006) is the most commonly used magnitude conversion relations to convert between M_S to M_w . The relations follow two-segment piecewise linear relations for conversion of M_S to M_w . Two-segment regression improves accuracy by allowing different slopes below and above a breakpoint (~ 6.1 M_S). We follow similar approach for determination of Nepal-Himalaya region specific magnitude conversion relation for M_S .

We developed regression relation from 128 data pairs of ISC catalogue following the ODR method and compared with Scordilis 2006.

The new model is:

$$M_w = 0.570 \times M_S + 2.53 \pm 0.112 \quad \text{for } M_S \leq 6.1 \quad \text{-----} \quad (45)$$

$$M_w = 1.025 \times M_S - 0.245 \pm 0.191 \quad \text{for } M_S > 6.1 \quad \text{-----} \quad (46)$$

The comparison with existing model shows these new models gives comparable results with the existing models – Ambraseys and Douglas, 2004 (Eq. 6a, 6b), Scordilis 2006 (Eq. 2a, 2b) and Nath et al., 2011 (Eq. 16a, 16b).

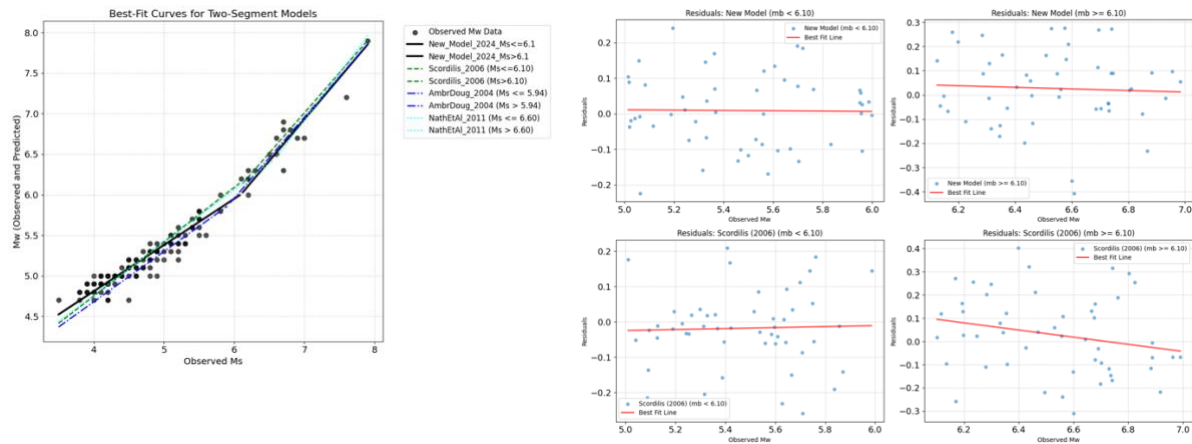


Figure 7: Magnitude Conversion Relations for ISC M_S to M_w

Table 7: Model Metrics Comparison for M_S - M_w Conversion

Model	Segment	MAE	RMSE	R ²	Std. Dev.
New_Model_2024	Overall	0.094438	0.123166	0.955541	0.122704
Scordilis_2006	Overall	0.109664	0.143349	0.939776	0.141322
AmbrDoug_2004	Overall	0.126832	0.151049	0.933132	0.133347
NathEtAl_2011	Overall	0.107984	0.138742	0.943585	0.138197

5. Discussion and Conclusions

We used ISC catalogue for the region 75°-93°E and 24°-34°N that covers the period 1905 to 2022 for determination of new magnitude conversion relations for Nepal Himalaya Region. The catalogue consists of 8778 events of magnitude 4 and more for which 292 events with M_w values. We determine magnitude conversion relations for local magnitude (M_L), body wave magnitude (m_b) and surface wave magnitude (M_S) to moment magnitude (M_w). Conversion relations for local magnitudes reported by DMN and NDI; body wave magnitudes (m_b) reported by ISC, NEIC, BJI, MOS and IDC; and surface wave magnitude (M_S) reported by ISC are determined. Local magnitudes (M_L) of DMN and NDI differ to each other by 0.3-0.8 and body wave magnitudes of ISC and NEIC are approximately equivalent.

The new magnitude conversion relations determined in the study are compared and validated with existing magnitude conversion relations at global level and regional level. Statistical metrics - mean absolute error (MAE), root mean square error (RMSE) coefficient of determination (R-square), standard deviation (sigma), residual box plot and residual scatter plot are used for model comparisons. Orthogonal Distance Regression (ODR), General Orthogonal Regression (GOR) and Ordinary Least Square (OLS) methods of regression are used for development of conversion relations. We used our own python codes as well as existing python code from Openquake for the regression calculations.

The comparison and validation showed regressions using ODR methods and Openquake python code gave best-fit results, and these relations are used for further analysis.

Generally consistent results are obtained with new magnitude conversion relations. There are significant variations among the results obtained from existing global magnitude conversion relations. Our results are closer to the results obtained from regional conversion relations.

We used the new magnitude conversion relations for compilation of comprehensive earthquake catalogue for Nepal Himalaya Region which is used for determination of seismic hazard parameters i.e., magnitude frequency relations.

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