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Assessment of the Relative Largest Earthquake Hazard Level in the NW Himalaya and its Adjacent Region

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A b s t r a c t

In the present study, the level of the largest earthquake hazard is assessed in 28 seismic zones of the NW Himalaya and its vicinity, which is a highly seismically active region of the world. Gumbel's third asymptotic distribution (hereafter as GIII) is adopted for the evaluation of the largest earthquake magnitudes in these seismic zones. Instead of taking in account any type of $M_{\max}$, in the present study we consider the ω value which is the largest earthquake magnitude that a region can experience according to the GIII statistics. A function of the form $\Theta(\omega, \mathrm{RP}_{6.0})$ is providing in this way a relatively largest earthquake hazard scale defined by the letter K (K index). The return periods for the ω values (earthquake magnitudes) 6 or larger ($\mathrm{RP}_{6.0}$) are also calculated. According to this index, the investigated seismic zones are classified into five groups and it is shown that seismic zones 3 (Quetta of Pakistan), 11 (Hindukush), 15 (northern Pamirs), and 23 (Kangra, Himachal Pradesh of India) correspond to a "very high" K index which is 6.

Key words: K index, GIII, ω value, return period, NW Himalaya.

1. INTRODUCTION

Earthquake hazard assessment of a region is the ultimate goal for geoscientists, which is a useful tool for the preparation of earthquake risk mitigation policies. Earthquake hazard can be defined as the probability of occurrence of future earthquakes of a specific size during a given time interval in a seismic region of the globe. Numerous qualitative as well as quantitative methods have been formulated and applied by different researchers over the years to assess the earthquake hazard in several seismic regions of the world.

The first (GI) and the third (GIII) asymptotic distributions of extreme values (Gumbel 1958) have proven a useful tool in estimating earthquake hazard in different seismic regions, globally distributed. Both Gumbel's distributions have the advantage that they do not require analysis of the whole data set used. These procedures require predetermined fix time intervals from which the largest earthquake magnitudes are selected. These arbitrary time intervals are usually based on the seismicity rate of the region under investigation. The selected time intervals are, in some cases, a good tool to exclude automatically the fore- and after-shocks which is a necessary precondition in such kind of analysis (Yegulalp and Kuo 1974, Schenkova and Karnik 1976). On the other hand, problems concerning the earthquake hazard parameters obtained through this methodology have been discussed by Knopoff and Kagan (1977). However, Båth (1973, 1975, 1983) suggested that the dependency of the method on the largest magnitudes is the principal advantage of the technique, given that the magnitudes of the largest events are more accurately determined than those of small shocks.

Particularly, the GIII distribution has another advantage of the inclusion of an upper-bound earthquake magnitude called "ω value". This upper-bound magnitude is consistent with the concept of the finite maximum stresses, which may have been accumulated in rocks during a time interval of successive earthquakes and then subsequently released when seismic events occurred. This parameter is a unique characteristic for a region and no maximum earthquake magnitudes (*e.g.*, maximum observed) in a region can exceed this upper bound magnitude. Thus, for the computation of occurrence or expectation of earthquakes with extreme magnitudes using probabilistic models, the GIII asymptotic distribution allows a proper and natural physical interpretation. The plots of frequency-magnitude distribution usually reveal a curvature shape. This curvature has been observed especially when the distribution moves near the maximum earthquakes (Page 1968, Utsu 1971, Burton 1977, Bloom and Erdmann 1980). The parameters of the GIII distribution allow for any detectable curvature to the upper bound magnitude. Both techniques of Gumbel's first and third distribution have been applied for earthquake hazard assessment by a number of researchers in different regions of the world (*e.g.*, Yegulalp and Kuo (1974) for Pacific Ocean; Makropoulos (1978) for Greece; Burton (1979) for Europe to India; Makropoulos and Burton (1985) for Pacific rim; Tsapanos and Burton (1991) for the whole world; Tsapanos (1997) for circum Pacific belt; Shanker *et al*. (2007) for Hindukush-Pamir Himalaya region; Bayrak *et al*. (2008) for Turkey; Yadav *et al*. (2012a, 2013a) for NW Himalaya; Tsapanos *et al*. (2014) for Turkey; among others).

The present paper confines itself to the evaluation of the "largest earthquake hazard level" (*K* index) for 28 predefined seismic zones in the NW Himalaya and the adjoining areas. The ω value is considered as the maximum (largest) earthquake magnitude for each one of these seismic zones and the return periods ($RP_{6.0}$) for ω values ≥ 6.0 are also assessed. The classification of the seismic zones in different groups, in terms of relative earthquake hazard level, provides an image of quantitative largest earthquake hazard in the NW Himalaya and adjacent regions.

2. SEISMOTECTONIC SETUP AND PAST SEISMIC HAZARD IN THE REGION

The study region is one of the active seismic regions in the Indian subcontinent which is bounded by latitude 25°-40°N and longitude 65°-85°E (Fig. 1). The investigated region is located at the western syntaxis of the Himalayan part of Alpide belt and its neighboring regions, which includes India, Pakistan, Afghanistan, Hindukush, Pamirs, Mangolia, and Tien-Shan. This region is one of the most seismically active continent-continent (Indian-Eurasian plates) collision type active plate margin regions of the world. Structurally, this region is controlled by large rigid lithospheric blocks of the Indian plate from the south, the Afghan block in the southwest, the Turan plate in the west, and the Tarim block in the northeast (Koulakov and Sobolev 2006, Yadav 2009, Yadav *et al*. 2012b). The region exhibits intensive folding and thrusting, which occurred in the Cenozoic and Mesozoic era (Gansser 1964). The trend of folding and faulting in the Himalayan region is of NW-SE to EW direction. The Main Himalayan Frontal Thrust (HFT) and the Hazara, Sulaiman, and Kirthar ranges highlight the collisional deformations of the Indian and Eurasian plates (Seeber and Armbruster 1981, Thingbaijam *et al*. 2009, Yadav *et al*. 2012b).

The seismic hazard level of the region under investigation is high in terms of occurrences of larger size earthquakes during previous centuries and exceedance of peak ground acceleration (PGA) estimated through probabilistic seismic hazard assessment. Two great earthquakes (1902, Caucasus (M_S 8.6) and 1905, Kangra, India (M_S 8.6)) and several moderate to large earthquakes (Figs. 1 and 2) have occurred in the region during previous century (Gutenberg and Richter 1954, Yadav *et al*. 2012b). Several researchers

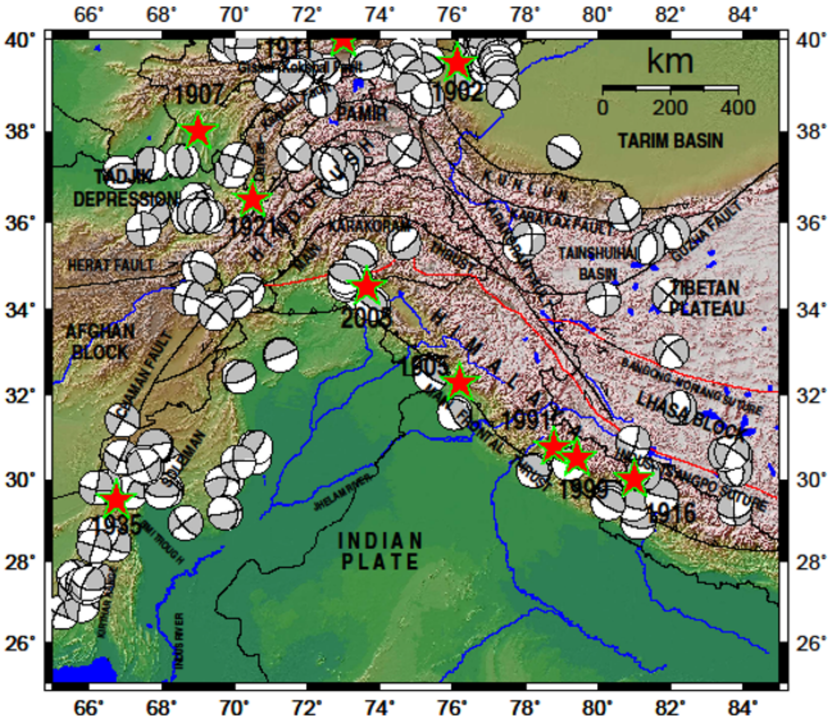

Fig. 1. Tectonic map of the NW Himalaya and adjoining regions, showing the fault and fold systems (after Koulakov and Sobolev 2006, Yadav 2009, Yadav *et al.* 2010). Focal mechanism solutions of shallow earthquakes with $M_W \geq 5.5$ obtained from Harvard GCMT catalogue during the period 1976-2010 are also shown with beach balls in the map, revealing the style of faulting in different parts of the region. Some large and damaging earthquakes are shown with stars along with year of occurrence.

(*e.g.*, Chatelain *et al*. 1980, Burtman and Molnar 1993, Fan *et al*. 1994, Lyubushin *et al*. 2010, Arora *et al*. 2012) suggested that two converging seismic regimes – northward subduction of the Indian plate beneath the Hindukush and southward subduction of the Eurasian plate below the Pamir – control the seismicity of the Hindukush–Pamir thrust zone. The western part of the Himalayan arc, consisting of the Kashmir ranges, turns to the south near Nanga Parbat to form the Hazara syntaxis (Meltzer *et al*. 2001), where the 2005 Kashmir earthquake (M_W 7.6) was nucleated. The Chaman fault zone has been associated with two major earthquakes: 1931, Mach (M_S 7.4), and 1945, Quetta (M_W 7.7). The Arabian plate is apparently being subducted northward, forming the subduction zone overlying the E-W trending Makran ranges (Quittmeyer and Jacob 1979). The seismogenic surge of the 1945

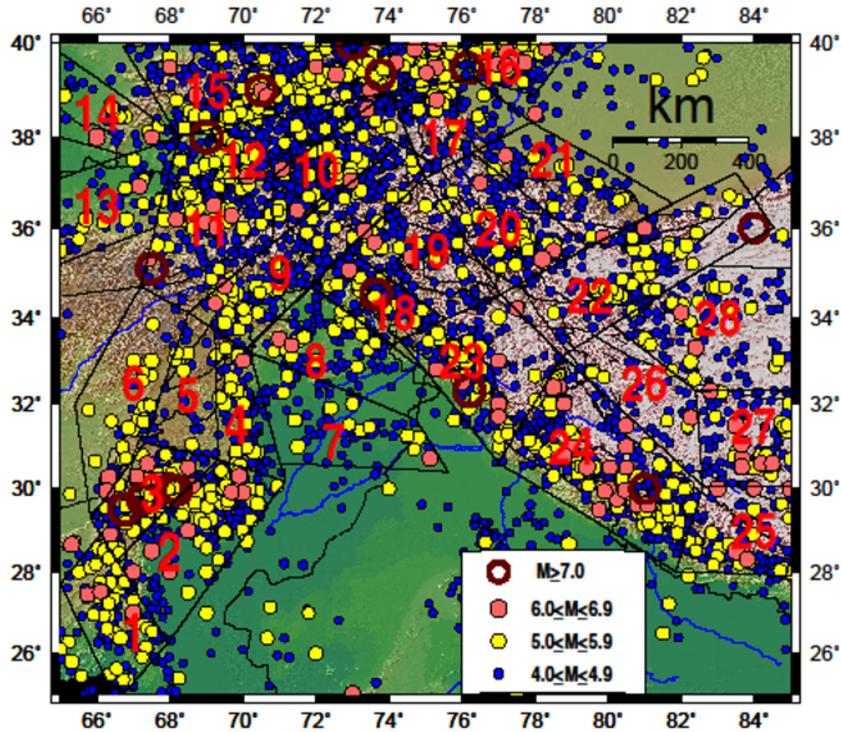

Fig. 2. Characterization of 28 possible seismic zones in the NW Himalaya and adjoining regions on the basis of seismicity, tectonics, and focal mechanism of earthquakes (after Yadav *et al.* 2012b). The epicentral distribution of independent earthquakes (main shocks) of $M_W \geq 4.0$ that occurred during the period 1900-2010 are also shown in the figure along with source zones that reveal seismic activity of each zone.

Makran (M_W 8.1) earthquake triggered a tsunami in Pakistan and Indian regions. The Himalayan Frontal Thrust belt of the Indian region has experienced three moderate to large earthquakes of M_W 6.8 and 6.5 in 1991, and 1999 at Uttarkashi and Chamoli region, respectively, and most devastating earthquake of the Kashmir Himalaya in 2005 of M_W 7.6. The study region is located in all seismic zones, V, IV, III and II on the seismic zoning map of India (Bureau of Indian Standards (BIS 2002)), with an assigned Peak Ground Acceleration (PGA) values of 0.4, 0.3, 0.2, and 0.1 g, respectively (Nath and Thingbaijam 2012).

3. EARTHQUAKE CATALOGUE USED

The earthquake hazard assessment of a region depends upon the quality of the prepared earthquake catalogue, *i.e.*, compilation, homogenization of magnitude scale, removal of dependent events (foreshocks and aftershocks), and finally completeness analysis with respect to magnitude and time. In the present study, the earthquake catalogue is adopted from Yadav *et al*. (2012b) who compiled a homogeneous and complete catalogue for the region under investigation using various historical and instrumental earthquakes catalogues. The initially compiled catalogue from different sources contains several earthquake magnitude scales, which was homogenized for moment magnitude (M_W) using different empirical relations established among body-wave magnitude (m_b), surface-wave magnitude (M_S), local magnitude (M_L), and moment magnitude (M_W). As we aforementioned, foreshocks and aftershocks are removed using a spatial and temporal windowing method developed by Uhrhammer (1986). In this technique, a scan for the entire catalogue has been performed within a defined spatial and temporal window for each given earthquake. All events (foreshocks and aftershocks) with epicenters falling within the defined two windows are removed after considering them as dependent events. The completeness of earthquakes catalogue is performed with respect to magnitude and time. The magnitude of completeness (M_C), also called threshold or cut-off magnitude, is defined as the lowest magnitude at which 100% of events in space-time volume are detected. The method of Entire Magnitude Range (EMR) (Woessner and Wiemer 2005) is used to estimate the M_C. The completeness with respect to time is also calculated using a simple graphical technique known as "visual cumulative method" given by Mulargia and Tinti (1985). A graph is constructed between the time and cumulative number of events for a particular magnitude range. Then, the completeness interval will be the number of years from the beginning of the period to the last year of occurrence in the catalogue. A full review of constructions and content of this catalogue can be obtained from Yadav *et al.* (2012b).

In the study of Yadav *et al.* (2012b) only the instrumental part of this catalogue during the period 1900-2010 with $M_W \geq 4.0$ was taken for the computation of earthquake hazard and the epicentral distribution of earthquakes is shown in Fig. 2. It is observed that most of the earthquakes of this catalogue are concentrated along the Hindukush–Pamir Himalaya region, the Himalayan frontal thrust belt and the Sulaiman–Kirthar ranges of Pakistan. The five largest earthquakes in this catalogue are: 1907 Hindukush earthquake of M_W 7.9; 1902 Caucasus earthquake of M_W 7.8 (M_S 8.6); 1905 Kangra, India earthquake of M_W 7.8 (M_S 8.6); 1935 Quetta, Pakistan earthquake of M_W 7.7; and 1911 Sarez, Pamir earthquake of M_W 7.7. The catalogue consists of 32 earthquakes having magnitude greater than M_W 7.0 and 73 earthquakes of $M_W \geq 6.5$, which suggest that the examined region is highly active.

4. THE METHODOLOGY APPLIED

The Gumbel's methodology, applied in the present study, is not a new one. But, the use of ω values of Gumbel's third asymptotic distribution (GIII) as the maximum magnitude is considered as a new approach for the scope of the present study. Since the GIII method is widely known to the seismological community, we shall give a very brief description below.

If M is the largest earthquake magnitude observed in successive equal time periods of a given area, then the probability that M is an extreme value magnitude is given by the following probability distribution function:

$$P(M) = \exp\left[-\left(\frac{\omega - M}{\omega - u}\right)^k\right] , \tag{1}$$

where ω is the upper bound to M, u is the characteristic value, and k is the shape parameter, with $P(u) = 1/e$ and $P(\omega) = 1$. If the extreme equal time span is one year, the return period RP (in years) for an earthquake magnitude M is given as:

$$T(M) = \frac{1}{\left[1 - P(M)\right]} , \tag{2}$$

where $[1 - P(M)]$ is the annual probability that an earthquake magnitude will be exceeded. If we have extreme intervals of N-year duration, then the corresponding distribution of $P_N(M)$ can be related with the one-year extreme $P_1(M)$ by the following relation:

$$P_1(M) = \sqrt[N]{P_N(M)} . \tag{3}$$

The GIII distribution gives an appropriate and natural physical interpretation with the inclusion of an upper bound magnitude (ω) that allows for the calculation of the occurrence of extreme magnitude earthquakes using a probabilistic model. The frequency-magnitude distribution often shows curvature, especially when the largest magnitudes are approached (Page 1968, Utsu 1971, Bloom and Erdmann 1980). The parameters of the GIII distribution allow both for any detectable curvature in addition to the upper bound magnitude. For curve fitting, Eq. 1 is transposed into the following form:

$$M = \omega - (\omega - u)\left[-\ln\left(P(M)\right)\right]^{\lambda} , \tag{4}$$

where $\lambda = 1/k$ and plotting M as ordinate and $[-\ln(P(M))]^{\lambda}$ as abscissa draws a straight line with ω as intercept and $-\omega(\omega - u)$ as gradient.

Earlier, Yadav *et al.* (2012a) computed the ω values in a regional scale for the 28 seismic zones in the Hindukush–Pamir Himalaya and surrounding area. For this purpose they considered data for the period 1900-2010. In the present study, an effort is made to evaluate new ω values with additional data (2011-2013), keeping the lower cut of magnitude with $M_W \geq 4.0$, but the obtained results are almost the same as those obtained by Yadav *et al.* (2012a). The average difference between the ω values estimated by Yadav *et al.* (2012a) and the ω values obtained by this new attempt is approximately –0.06, which is negligible. Therefore, we decided to use as the maximum magnitude (ω values) the results obtained in the present study for the estimation of the largest earthquake hazard level. A description of these values is listed in Table 1. In this table, it is obvious that ω values vary from 6.14 to

Table 1

The results of parameter ω (present study and Yadav *et al.* 2012a), M_{max}^{obs}, the return periods for $RP_{5.0}$ and $RP_{6.0}$ and the relative largest earthquake hazard level (K index) for 26 out of the 28 examined seismic zones in the NW Himalaya and adjacent regions

Zones	ω new (present study)	ω old (Yadav *et al.* 2012a)	Difference (ω new – ω old)	M_{max}^{obs}	$RP_{5.0}$ (in yrs)	$RP_{6.0}$ (in yrs)	K index
1	6.41	6.51	–0.10	6.3	3	62	2
2	6.99	6.90	0.09	6.7	3	24	3
3	7.73	8.44	–0.71	7.7	5	11	6
4	6.16	6.10	0.06	6.0	6	170	2
5	–	–	–	5.8	–	–	–
6	6.98	6.76	0.22	6.7	6	33	3
7	6.25	6.29	–0.04	6.2	8	387	2
8	6.46	6.58	–0.12	6.3	8	115	2
9	7.88	7.21	0.67	7.0	4	22	4
10	7.70	7.75	–0.05	7.4	2	4	5
11	8.04	7.67	0.37	7.5	2	3	6
12	8.1	8.26	–0.16	7.9	4	27	5
13	6.14	6.26	–0.12	6.1	8	302	2
14	7.22	7.00	0.22	6.9	12	61	3
15	7.92	8.15	–0.23	7.7	2	6	6
16	7.82	7.88	–0.06	7.6	4	18	5
17	6.63	6.54	0.09	6.3	3	245	2
18	7.63	8.58	–0.95	7.6	4	28	5
19	6.3	6.59	–0.29	6.3	5	89	2
20	7.05	7.13	–0.08	7.0	3	17	5
21	–	–	–	6.0	–	–	–
22	7.29	7.49	–0.20	7.1	2	14	5
23	8.12	8.03	0.09	7.8	4	18	6
24	7.71	7.86	–0.15	7.2	2	8	5
25	7.12	7.09	0.03	6.9	5	36	4
26	6.72	6.36	0.36	6.3	8	219	2
27	6.79	7.08	–0.29	6.7	4	18	5
28	6.47	6.62	–0.15	6.4	4	42	3

8.12, while the maximum observed magnitudes, M_{max}^{obs}, are between 5.8 and 7.9. The largest observed earthquake (M_{max}^{obs} = 7.9) occurred in zone 12 during the year 1907.

5. RESULTS AND DISCUSSION

In the present study, the authors emphasize their efforts to estimate the relative largest earthquake hazard level (*K* index) in 28 seismic zones of the NW Himalaya and adjoining regions using a homogenous and complete earthquake catalogue covering the time period 1900-2013. A similar approach has been introduced by Papadopoulos and Kijko (1991) for the seismic zones in the Greece and Tsapanos (2001) for the seismic regions around the circum Pacific belt. Both of the above approaches considered the maximum magnitude as the maximum regional magnitude, M_{max}^{reg}, proposed by Kijko and Sellevoll (1989, 1992). In both of the after mentioned studies (Papadopoulos and Kijko 1991, Tsapanos 2001) the relative seismic hazard level was defined by the letter *K*. We keep this symbol to our study as well.

As mentioned above, the parameter ω derived from the GIII method is used in the present work for the estimation of largest earthquake hazard level in the considered region. A first inspection of Table 1 shows that, generally, the estimated ω values and M_{max}^{obs} values do not differ significantly. This is due to the fact that the estimation of the ω parameter in most of the analyzed seismic zones is based on relatively long duration of earthquake data, which is comparable with the seismic cycle of the strongest earthquake in respective zones. The largest ω values are evaluated for the seismic zones 11, 12, and 23 with corresponding results of 8.04, 8.10, and 8.12, respectively. These seismic zones are characterized by intense seismicity during the investigated time period. We have also listed the return periods of earthquakes with $M = 5.0$ ($RP_{5.0}$) and $M = 6.0$ ($RP_{6.0}$) in Table 1. It is observed that the return periods of earthquake $M = 6.0$ make sense since this magnitude is considered to be a hazardous shock and almost all of the 28 seismic zones have experienced such earthquakes (exception observed only in zone 5 with M_{max}^{obs} = 5.8). Therefore, the return periods $RP_{6.0}$ are reliable for the further assessment of the relative earthquake hazard level. Only two of the studied seismic zones (5 and 21) show abnormal $RP_{6.0}$. We interpret this non-normality on the basis of the fact that the distribution of these zones shows a linear tendency rather than a curvature one (Fig. 3). These figures demonstrate both linear and curvature distribution (as provided by GIII) in zone 5 and 21, respectively. The χ^2 test is applied for both zones in order to examine statistically which is the dominant distribution. On the basis of χ^2 test, we

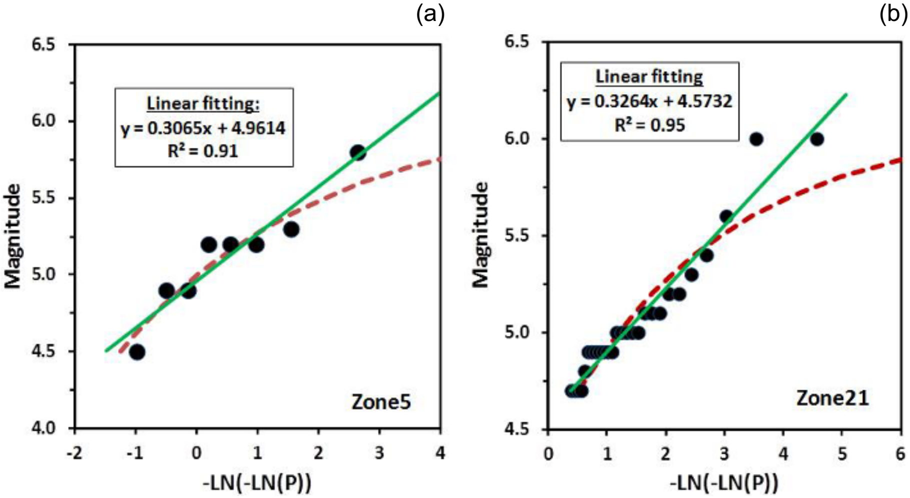

Fig. 3. Gumbel-III distribution (dash red line) and linear least square fitting (solid green line) with observed data (solid circles) for zone 5 (a) and zone 21 (b) showing that observed data set is fitted better by linear line than GIII asymptotic curve in these zones (modified after Yadav *et al*. 2012a).

observed very surprising results which show that both distributions can be accepted. For zone 5, χ^2 test for linear distribution is obtained as 0.999, while for the curvature (GIII) it is equal to 0.993. Similarly, for zone 21, χ^2 test for linear distribution is observed as 1.000 and it is 0.999 for curvature distribution. The estimated regression coefficient (R^2) for the best fit of the linear distribution is obtained as 0.91 for zone 5, while 0.95 is observed for zone 21, showing percentage linear fitting of observed data. Another evidence for linear distribution comes out from a first look on Fig. 3. The inspection of these figures shows that the curvature distribution does not fit well to the upper bound magnitude, as it was expected from the Gumbel's theory, but relents lower than the maximum observed magnitude in both zones ($M_{\max}^{\text{obs}} = 5.8$ for zone 5 and $M_{\max}^{\text{obs}} = 6.0$ for zone 21). All of the above observations make us able to conclude that the linear distribution is more proper for zones 5 and 21 than the curvature. Therefore, we excluded these two seismic zones (5 and 21) from our study.

In order to assess the relative earthquake hazard level in the considered region, we classified the 26 seismic zones under investigation in groups based on their difference in largest earthquake hazard level (*K* index). For this purpose, we follow a similar approach considered by Papadopoulos and Kijko (1991) and Tsapanos (2001). Therefore, we equally took into account the importance of ω values and $RP_{6.0}$. We considered that the *K* index is a

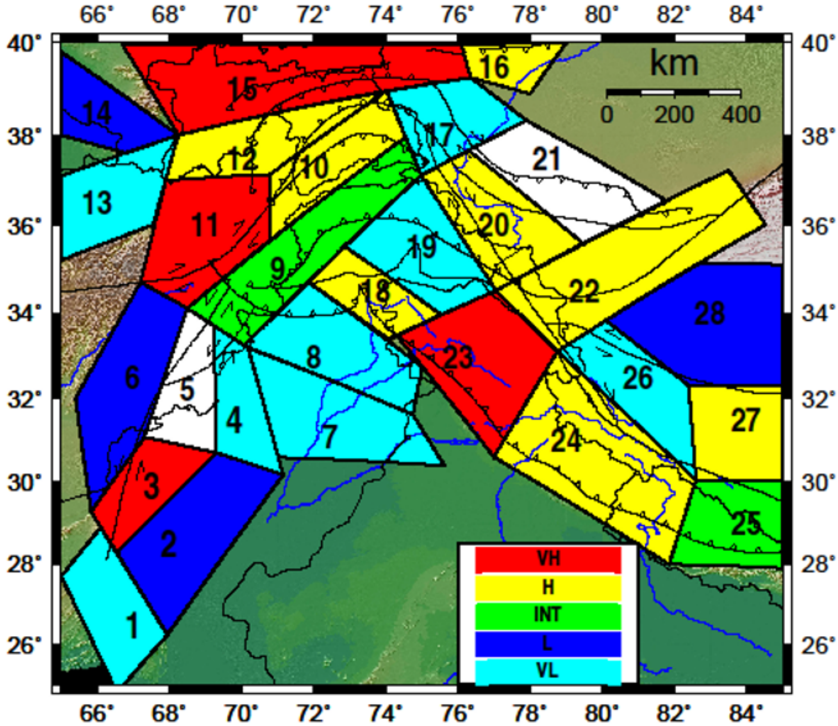

Fig. 4. Spatial distribution of relative largest earthquake hazard level (*K* index) in 26 out of the 28 seismic zones of the examined region depicting the hazard level in different zones estimated by largest earthquake magnitude expressed by ω values and return periods of *M*6.0 earthquake.

function of ω values and $RP_{6.0}$ and denoted as the term $\Theta(\omega, RP_{6.0})$. This parameter (Θ) increases with ω values and decreases with the values of return periods $RP_{6.0}$. Then, we constructed the following groups: $\omega \leq 6.9$, $7.0 \leq \omega \leq 7.9$, and $\omega \geq 8.0$, and defined them as 2, 4, and 6, respectively. We follow the same procedure for $RP_{6.0}$ (in years) and constructed three groups of this parameter as $RP_{6.0} \leq 20$, $21 \leq RP_{6.0} \leq 50$, and $RP_{6.0} \geq 51$ for the corresponding numbers of 6, 4 and 2, respectively. The arithmetic mean of these two parameters, *i.e.*, $K = 1/2\ [\Theta(\omega) + \Theta(RP_{6.0})]$ expresses the adopted *K* index of a seismic zone. The *K* index has values equal to 2, 3, 4, 5, and 6 and characterizes five groups of *K*, which are: very low = 2, low = 3, intermediate = 4, high = 5, and very high = 6. Table 1 (last column) demonstrates the *K* index for each of the studied zones. Figure 4 illustrates the spatial distribution of *K* index in the 26 seismic zones (5 and 21 are excluded) of the NW Himalaya and adjacent area, which were defined by Yadav *et al.* (2012b).

A detail inspection of Fig. 4 shows that four seismic zones (3 − Quetta of Pakistan region, 11 − Hindukush, 15 − northern Pamirs, and 23 − Kangra, Himachal Pradesh of India) are corresponding with the "very high" K index of 6. These seismic zones are characterized by intense seismic activity in the past and Yadav *et al.* (2012a, b) also evaluated the largest earthquake magnitudes, of more than 8.0, in these zones either by GIII or Kijko–Sellevoll methods. Next "high" K index of 5 is observed in seismic zones 10, 12, 16, 18, 20, 22, 24, and 27 in tectonic regimes of the Hindukush seismic Belt, Caucasus, Kunlun fault, Kashmir, Uttarkashi–Chamoli region, and part of Tibet. These regions are seismically active and have experienced several moderate to large earthquakes in their history. Only two seismic zones (9 − southern Hindukush belt, and 25 − Nepal Himalaya) show intermediate K index having a value of 4 which corresponds with moderate size earthquakes in the past. The low K index of value 3 is observed in four seismic zones: 2, 6, 14, and 28, while very low K index of value 2 is observed in seismic zones: 1, 4, 7, 8, 13, 17, 19, and 26. These regions are associated with the low seismic activity regions of the Pakistan, Afghanistan, Karakoram fault, and parts of the Tibetan Plateau. It is interesting to note that about one half of the studied seismic zones are associated with low and very low K index, while about the other half of the studied seismic zones are corresponding to high and very high K index. Yadav *et al.* (2010, 2012a, b; 2013a, b; 2015) also investigated earthquake hazard using different statistical techniques in the same seismic zones of the studied region and observed similar level of hazard in these seismic zones, revealing the seismic characteristics of the region. A good correspondence is also observed with spatial maps prepared by Khattri *et al.* (1984), Bhatia *et al.* (1999), Lyubushin and Parvez (2010), and Nath and Thingbaijam (2012) for peak ground accelerations (PGA) in the examined region.

6. CONCLUSIONS

The parameter ω deduced from GIII method in the present study is a characteristic parameter for any seismic zone. According to our knowledge, this quantity has never been evaluated before for such kind of study in the examined region. Hitherto, only the maximum regional magnitude (M_{max}) has been applied in such kind of studies (Papadopoulos and Kijko 1991, Tsapanos 2001).

For the purpose of this study, we used the relative largest earthquake hazard level (K index) which can be computed as a function of the form of $\Theta(\omega, RP_{6.0})$. The arithmetic mean of two parameters (ω and $RP_{6.0}$) is used as a criterion to classify the seismic zones of the NW Himalaya and surrounding regions defined by Yadav *et al.* (2012b) in five groups. The considered values of K index are 2, 3, 4, 5, and 6, by which the seismic zones are ranked as “very high”, “high”, “intermediate”, “low”, and “very low” level of K index. From the spatial map (Fig. 4) of these indexes, it is revealed that four of the seismic zones (3 − Quetta of Pakistan region, 11 − Hindukush, 15 − northern Pamirs, and 23 − Kangra, Himachal Pradesh of India) have very high K index of 6, while eight of them show high K of 5. It is observed that seismic zone 12, in which the largest observed earthquake (M_{max}^{obs} = 7.9) occurred, shows high K index and not very high as it was expected. On the other hand, zone 23 shows very high K index while it has experienced a great earthquake of M_W = 7.8 (M_S 8.6) in 1905. The spatial distribution of K index among these seismic zones is very useful for scientific purposes along with the designation of priority seismic zones for earthquake resistant design.

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References

Arora, B.R., V.K. Gahalaut, and N. Kumar (2012), Structural control on along-strike variation in the seismicity of the northwest Himalaya, *J. Asian Earth Sci.* **57**, 15-24, DOI: 10.1016/j.jseaes.2012.06.001.

Båth, M. (1973), *Introduction to Seismology*, Springer, Basel, 395 pp.

Båth, M. (1975), Seismicity of Tanzania region, *Tectonophysics* **27**, 4, 353-379, DOI: 10.1016/0040-1951(75)90004-9.

Båth, M. (1983), Earthquake frequency and energy in Greece, *Tectonophysics* **95**, 3-4, 233-252, DOI: 10.1016/0040-1951(83)90070-7.

Bayrak, Y., S. Öztürk, H. Çinar, G.Ch. Koravos, and T.M. Tsapanos (2008), Regional variation of the ω-upper bound magnitude of GIII distribution in and around Turkey: tectonic implications for earthquake hazards, *Pure Appl. Geophys.* **165**, 7, 1367-1390, DOI: 10.1007/s00024-008-0359-z.

Bhatia, S.C., M.R. Kumar, and H.K. Gupta (1999), A probabilistic seismic hazard map of India and adjoining regions, *Ann. Geophys.* **42**, 6, 1153-1164, DOI: 10.4401/ag-3777.

BIS (2002), Indian standard criteria for earthquake resistant design of structures. Part 1 – General provisions and buildings, IS 1893-2002, Bureau of Indian Standards, New Delhi, India.

Bloom, E.D., and R.C. Erdmann (1980), The observation of a universal shape regularity in earthquake frequency-magnitude distributions, *Bull. Seismol. Soc. Am.* **70**, 1, 349-362.

Burtman, V.S., and P. Molnar (1993), Geological and geophysical evidence of deep subduction of continental crust beneath the Pamir, *Geol. Soc. Am., Sp. Paper* **281**, 1-76, DOI: 10.1130/SPE281-p1.

Burton, P.W. (1977), The application of extreme value statistics to seismic hazard assessment in the European area. **In:** *Proc. Symp. Analysis of Seismicity and on Seismic Risk, 17-22 October 1977, Liblice, Czech Republic*, Vol. 1722, Academia, Prague, 323-334.

Burton, P.W. (1979), Seismic risk in southern Europe through to India examined using Gumbel's third distribution of extreme values, *Geophys. J. Int.* **59**, 2, 249-280, DOI: 10.1111/j.1365-246X.1979.tb06766.x.

Chatelain, J.L., S.W. Roecker, D. Hatzfeld, and P. Molnar (1980), Microearthquake seismicity and fault plane solutions in the Hindu Kush Region and their tectonic implications, *J. Geophys. Res.* **85**, B3, 1365-1387, DOI: 10.1029/JB085iB03p01365.

Fan, G., J.F. Ni, and T.C. Wallace (1994), Active tectonics of the Pamirs and Karakorum, *J. Geophys. Res.* **99**, B4, 7131-7160, DOI: 10.1029/93JB02970.

Gansser, A. (1964), *Geology of the Himalayas*, Interscience Publ., London, 289 pp.

Gumbel, E.J. (1958), *Statistics of Extremes*, Columbia University Press, New York, 375 pp.

Gutenberg, B., and C.F. Richter (1954), *Seismicity of the Earth and Associated Phenomena*, Princeton University Press, Princeton, 310 pp.

Khattri, K.N., A.M. Rogers, D.M. Perkins, and S.T. Algermissen (1984), A seismic hazard map of India and adjacent areas, *Tectonophysics* **108**, 1-2, 93-134, DOI: 10.1016/0040-1951(84)90156-2.

Kijko, A., and M.A. Sellevoll (1989), Estimation of earthquake hazard parameters from incomplete data files. Part I: Utilization of extreme and complete catalogs with different threshold magnitudes, *Bull. Seismol. Soc. Am.* **79**, 3, 645-654.

Kijko, A., and M.A. Sellevoll (1992), Estimation of earthquake hazard parameters from incomplete data files. Part II: Incorporation of magnitude heterogeneity, *Bull. Seismol. Soc. Am.* **82**, 1, 120-134.

Knopoff, L., and Y. Kagan (1977), Analysis of the theory of extremes as applied to earthquake problems, *J. Geophys. Res.* **82**, 36, 5647-5657, DOI: 10.1029/JB082i036p05647.

Koulakov, I., and S.V. Sobolev (2006), A tomographic image of Indian lithosphere break-off beneath the Pamir–Hindukush region, *Geophys. J. Int.* **164**, 2, 425-440, DOI: 10.1111/j.1365-246X.2005.02841.x.

Lyubushin, A.A., and I.A. Parvez (2010), Map of seismic hazard of India using Bayesian approach, *Nat. Hazards* **55**, 2, 543-556, DOI: 10.1007/s11069-010-9546-1.

Lyubushin, A.A., B.R. Arora, and N. Kumar (2010), Investigation of seismicity in western Himalaya, *Russ. J. Geophys. Res*. **11**, 1, 27-34.

Makropoulos, K.C. (1978), The statistics of large earthquake magnitude and an evaluation of Greek seismicity, Ph.D. Thesis, University of Edinburgh, Edinburgh, UK, 193 pp.

Makropoulos, K.C., and P.W. Burton (1985), Seismic hazard in Greece: I. Magnitude recurrence, *Tectonophysics* **117**, 3-4, 205-257, DOI: 10.1016/0040-1951(85)90273-2.

Meltzer, A., G. Sarker, B. Beaudoin, L. Seeber, and J. Armbruster (2001), Seismic characterization of an active metamorphic massif, Nanga Parbat, Pakistan Himalaya, *Geology* **29**, 7, 651-654, DOI: 10.1130/0091-7613(2001)029 <0651:SCOAAM>2.0.CO;2.

Mulargia, F., and S. Tinti (1985), Seismic sample areas defined from incomplete catalogues: An application to the Italian territory, *Phys. Earth Planet. In.* **40**, 4, 273-300, DOI: 10.1016/0031-9201(85)90038-X.

Nath, S.K., and K.K.S. Thingbaijam (2012), Probabilistic seismic hazard assessment of India*, Seismol. Res. Lett.* **83**, 1, 135-149, DOI: 10.1785/gssrl.83.1.135.

Page, R. (1968), Aftershocks and microaftershocks of the great Alaska earthquake of 1964, *Bull. Seismol. Soc. Am.* **58**, 3, 1131-1168.

Papadopoulos, G.A., and A. Kijko (1991), Maximum likelihood estimation of earthquake hazard parameters in the Aegean area from mixed data, *Tectonophysics* **185**, 3-4, 277-294, DOI: 10.1016/0040-1951(91)90449-3.

Quittmeyer, R.C., and K.H. Jacob (1979), Historical and modern seismicity of Pakistan, Afghanistan, northwestern India, and southeastern Iran*, Bull. Seismol. Soc. Am.* **69**, 3, 773-823.

Schenkova, Z., and V. Karnik (1976), Application of the largest values theory to Balkan earthquakes. **In:** *Proc. Sem. Seismic Zoning Maps, UNESCO, 27 October – 4 November 1975, Skopje, Yugoslavia*, Vol. 1, 193-205.

Seeber, L., and J.G. Armbruster (1981), Great detachment earthquakes along the Himalayan arc and long-term forecasting. **In:** D.W. Simpson and P.G. Richards (eds.), *Earthquake Prediction – An International Review*, Maurice Ewing Series, Vol. 4, Am. Geophys. Union, Washington, 259-277, DOI: 10.1029/ME004p0259.

Shanker, D., R.B.S. Yadav, and H.N. Singh (2007), On the seismic risk in the Hindukush–Pamir–Himalaya and their vicinity, *Curr. Sci.* **92**, 11, 1625-1630.

Thingbaijam, K.K.S., P. Chingtham, and S.K. Nath (2009), Seismicity in the North-West Frontier Province at the Indian-Eurasian plate convergence, *Seismol. Res. Lett.* **80**, 4, 599-608, DOI: 10.1785/gssrl.80.4.599.

Tsapanos, T.M. (1997), Regional variation of the ω values in the circum-Pacific belt*, Pure Appl Geophys.* **150**, 1, 113-120, DOI: 10.1007/s000240050066.

Tsapanos, T.M. (2001), Evaluation of the seismic hazard parameters for selected regions of the world: the maximum regional magnitude, *Ann. Geophys.* **44**, 1, 69-79, DOI: 10.4401/ag-3615.

Tsapanos, T.M., and P.W. Burton (1991), Seismic hazard evaluation for specific seismic regions of the world, *Tectonophysics* **194**, 1-2, 153-169, DOI: 10.1016/0040-1951(91)90278-Z.

Tsapanos, T.M., Y. Bayrak, H. Cinar, G.Ch. Koravos, E. Bayrak, E.E. Kalogirou, A.V. Tsapanou, and G.E. Vougiouka (2014), Analysis of largest earthquakes in Turkey and its vicinity by application of the Gumbel III distribution, *Acta Geophys*. **62**, 1, 59-82, DOI: 10.2478/s11600-013-0155-8.

Uhrhammer, R.A. (1986), Characteristics of northern and central California seismicity, *Earthq. Notes* **57**, 1, 21 (abstract).

Utsu, T. (1971), Aftershocks and earthquake statistics (III): Analysis of the distribution of earthquakes in magnitude, time and space with special consideration to clustering characteristics of earthquake occurrence (1), *J. Fac. Sci. Hokkaido Univ., ser. 7*, **3**, 5, 379-441.

Wessel, P., and W.H.F. Smith (1995), New version of the generic mapping tools, *EOS Trans. Am. Geophys. Union* **76**, 33, 329, DOI: 10.1029/95EO00198.

Woessner, J., and S. Wiemer (2005), Assessing the quality of earthquake catalogues: estimating the magnitude of completeness and its uncertainty, *Bull. Seismol. Soc. Am.* **95**, 2, 684-698, DOI: 10.1785/0120040007.

Yadav, R.B.S. (2009), Seismotectonic modeling of NW Himalaya: A perspective on future seismic hazard, Ph.D. Thesis, Department of Earthquake Engineering, IIT Roorkee, India, 198 pp.

Yadav, R.B.S., D. Shanker, S. Chopra, and A.P. Singh (2010), An application of regional time and magnitude predictable model for long-term earthquake prediction in the vicinity of October 8, 2005 Kashmir Himalaya earthquake, *Nat. Hazards* **54**, 3, 985-1014, DOI: 10.1007/s11069-010-9519-4.

Yadav, R.B.S., Y. Bayrak, J.N. Tripathi, S. Chopra, and E. Bayrak (2012a), Regional variation of the ω-upper bound magnitude of GIII distribution in Hindukush–Pamir Himalaya and the adjacent regions: A perspective on earthquake hazard, *Tectonophysics* **544-545**, 1-12, DOI: 10.1016/j.tecto.2012.03.015.

Yadav, R.B.S., Y. Bayrak, J.N. Tripathi, S. Chopra, A.P. Singh, and E. Bayrak (2012b), A probabilistic assessment of earthquake hazard parameters in NW Himalaya and the adjoining regions, *Pure Appl. Geophys*. **169**, 9, 1619-1639, DOI: 10.1007/s00024-011-0434-8.

Yadav, R.B.S., T.M. Tsapanos, G.Ch. Koravos, Y. Bayrak, and K.D. Devlioti (2013a), Spatial mapping of earthquake hazard parameters in the Hindukush–Pamir Himalaya and adjacent regions: Implication for future seismic hazard, *J. Asian Earth Sci*. **70-71**, 115-124, DOI: 10.1016/j.jseaes.2013.03.007.

Yadav, R.B.S., T.M. Tsapanos, Y. Bayrak, and G.Ch. Koravos (2013b), Probabilistic appraisal of earthquake hazard parameters deduced from a Bayesian approach in the northwest frontier of the Himalayas, *Pure Appl. Geophys*. **170**, 3, 283-297, DOI: 10.1007/s00024-012-0488-2.

Yadav, R.B.S., G.Ch. Koravos, T.M. Tsapanos, and G.E. Vougiouka (2015), A probabilistic estimate of most perceptible earthquake magnitudes in the NW Himalaya and adjoining regions, *Pure Appl. Geophys.* **172**, 2, 197-212, DOI: 10.1007/s00024-014-0864-1.

Yegulalp, T.M., and J.T. Kuo (1974), Statistical prediction of the occurrence of maximum magnitude earthquakes, *Bull. Seismol. Soc. Am*. **64**, 2, 393-414.

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