COMPARITIVE ANALYSIS OF THE SEISMIC HAZARD OF CENTRAL CHINA

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ABSTRACT

Seismic hazard assessment is globally recognised as a tool in identifying levels of earthquake ground shaking within an area. However, methodologies for seismic hazard calculation are wide ranging and produce variations in results and maps.

As a case study seismic hazard and results from Gumbel's method of extremes are determined for the area of greatest intraplate seismicity in China covering the provinces of Gansu, Sichuan and Yunnan. This area is termed the North-South Seismic Zone. Devastating earthquakes in this zone include the 8.4 M_S 1920 Haiyuan earthquake causing over 220,000 deaths and the 1996 Lijiang earthquake. Most recently the 2008 Wenchuan earthquake caused over 69,000 deaths with more than 18,000 people missing.

These results and seismic hazard maps are compared with the publicly available maps of GSHAP and the national seismic hazard map of China at the level of 10% probability of exceedance in a 50 year period. The distributions of high and low hazard areas are similar and adjacent to the major thrust and strike-slip faults dominating in this area. However, results from the Gumbel method of extremes suggest that the hazard levels within certain areas are slightly different compared to the other two models. This is primarily because the Gumbel methodology is based on determining hazard from earthquakes that have already taken place whereas the other two models determine maximum hazard levels in areas which may exhibit no previous strong hazard. Additionally the Chinese national hazard map does not indicate levels of ground shaking intensity greater than IX in detail, whereas such zones are identified using the extreme value method. This work should be used to strengthen the seismic hazard analysis of this area of China.

KEYWORDS: Seismic hazard, Gumbel, GSHAP, North-South Seismic Zone China

1. INTRODUCTION

The aim of seismic hazard assessment is to determine levels of ground motion within an area of interest usually at a specific probability level or return period of occurrence. With increasing vulnerability of populations and demand in mitigating economic loss from natural disasters, the private sector has developed independent and competing seismic hazard models. Many of these simulations use advances in computer power together with established geological and seismological information of an area. However, the construction and development of these models is not always openly well known. They are almost always applied to areas of client demand. By contrast public and national seismic hazard models are for all areas of interest, often easily obtainable and the method used in their development often transparent. In most cases these methods represent seismic hazard as maps which are clear and easily understandable. This paper presents results, in the form of maps, using an alternative method of seismic hazard analysis. The differences between these new results and two publicly available seismic hazard maps are assessed and discussed.

2. NORTH-SOUTH SEISMIC ZONE (NSSZ): CHINA

The area to compare seismic outputs is selected as midwestern China. This region is the most seismically active intraplate area of China having experienced historically devastating earthquakes (Haiyuan 1920; Gulang 1927; Lijiang 1996) and most recently the site of the Wenchuan earthquake, the deadliest earthquake in the country since the Tangshan event of 1976. This region is more commonly known as the North-South Seismic Zone (NSSZ). In simple geologic terms this area is seismically active because of the resistance to the extension of the Tibetan plateau from the Tienshan mountain range to the north, the stable Ordos block to the east and Sichuan mantle uplift to the southeast (Li and Yang, 1998). This shear zone exhibits extensive strike-slip and thrust faulting. The dominant forms of faulting in the NSSZ vary in type and orientation, from northeast trending thrust faulting in the north to southeast trending strike-slip systems in the south. The NSSZ has subsequently been divided into two sections, the NSSZ North and NSSZ South. This division is based on differences in the tectonic regime and political boundaries.

2.1 NSSZ North

The NSSZ North is defined as 34-41°N 94-108°E. This contains the north-eastern extent of the Tibetan plateau and the Gobi platform. Politically it contains the province of Ningxia, a large proportion of Gansu and eastern Qinghai. Yinchuan, Lanzhou and Xining are the respective provincial capital cities and all are situated within this northern zone. It is also historically recognisable as the route of the ancient Silk Road. Dunhuang is a UNESCO site and important cultural and heritage centre. Finally the Qinghai-Tibet railway passes through this area traversing from west to east.

2.2 NSSZ South

The NSSZ South is defined as 21-34°N 97-105°E. This territory politically occupies Yunnan, western Sichuan, eastern Qinghai and southern Gansu provinces. Major cities in this sector include Kunming and Chengdu, the respective capital cities of Yunnan and Sichuan provinces. Lijiang in northwestern Yunnan was registered on the UNESCO World Heritage list in 1997. Within this environment lie the sources of the major rivers of the Yangtze, Pearl, Red and Mekong. Sichuan occupies a surface area of 485,000 km^2, the fifth largest of all Chinese provinces. The Himalaya Mountains rise to the west of the province. Together with the Qinling mountain range to the north these natural boundaries surround the lower elevated eastern basin region of Sichuan and the site of Chengdu, the fifth largest city of China. In total the NSSZ South covers an area similar to the combined surface area of the United Kingdom and France.

3. EXTREME VALUE SEISMIC HAZARD ANALYSIS FOR PEAK GROUND ACCELERATION (PGA) OF THE NSSZ

The analysis model adopted is entirely probabilistic and based on Gumbel's extreme value theory (Gumbel, 1958). This approach has immediate advantages. Extreme events are more likely to be reported as these primarily produce the most observable damage effects. Secondly, dependent events including foreshocks and aftershocks are likely to be removed if the extraction of extreme events is chosen from a specified time interval. Finally this method can limit the problem of incomplete earthquake catalogues in which not every earthquake is listed within the catalogue over a specific time period. Selection of an area of interest using the Gumbel method can be based on a zone-free methodology independent of any Euclidean zoning assumptions. This is unlike the traditional approach of seismic zoning in which zones are chosen based on prior seismic and tectonic knowledge (Cornell, 1968), which can be a debatable process.

Briefly, extreme values are extracted from an earthquake catalogue during predetermined time intervals (e.g.

annual) either directly, as in largest magnitudes in a set of intervals in an area, or through appropriate relationships for peak ground acceleration at a site. These extremes are then ranked, assigned a probability and a Gumbel distribution fitted to the data. A more detailed explanation of the process is given in Burton *et al.* (2003).

Local variations in seismic hazard are resolved by dividing the area into a mesh of grid points. Each grid point is at the centre of a cell. Earthquakes within each cell are used to determine parameters of the Gumbel distribution. Hazard values at specific probabilities and return periods are assigned to the cell-centre grid point for each cell analysed and these values are then mapped and contoured. Cells are designed to overlap to obtain detailed information throughout the study region.

3.1 PGA attenuation

The release of energy from an earthquake propagates seismic vibrations throughout the surrounding subsurface. The amount of energy release is quantified by the earthquake magnitude. As the seismic waves propagate outward the degree of attenuation of energy is dependent on the material of the subsurface, geometrical spreading and the focal depth of the earthquake.

3.1.1 Selection of PGA attenuation law

Many parts of the world have yet to obtain sufficient strong ground motion measurements to construct local ground motion equations as has been done for example in California, USA and Japan. Therefore for areas of the world in which there are insufficient ground motion records, the calculation of ground motion at a site is from a combination of attenuation relationships from outside the area of interest and from other theoretical considerations. The selection of the appropriate attenuation law is based on several issues including site classification, magnitude scale, source to site distance and previous experience.

The attenuation relationship used in the determination of PGA for the Global Seismic Hazard Assessment Program (GSHAP) in continental Asia (Zhang *et al.*, 1999) is for hard rock soil type from Huo and Hu (1992) (Eqn. 1).

$$\ln a = 0.1497 + 1.9088 M_s - 2.049 \ln\left[R + 0.1818 \exp(0.7072 M_s)\right] \tag{1}$$

where a is acceleration in cm s^{-2}, M_s is surface-wave magnitude, and R is shortest distance to the epicentre in kilometres. This equation is also adopted in our present analysis.

3.2 Gumbel 1 and extreme value forecasting for PGA in the NSSZ

The statistical model adopted in this paper to analyse computed values of PGA is the Gumbel first asymptotic distribution of extreme values. The present analysis strategy adopts a 5° square cell moving through the catalogued seismicity by 0.5° intervals. Results for the parameter set for each 5° cell are then used to calculate the arbitrary but consensually adopted statistic of the 50-year earthquake with 10% probability of being exceeded (pbe). There is a one-in-ten chance that this value will be exceeded in any 50-year period; this can be expressed equivalently as an average return period of 475 years. Figures 1a and 1b show the PGA seismic hazard map from the extreme value approach for the NSSZ North and NSSZ South zones respectively. These maps are compared with the output from the publicly available GSHAP (figures 1c and 1d) and China national map (figure 1e).
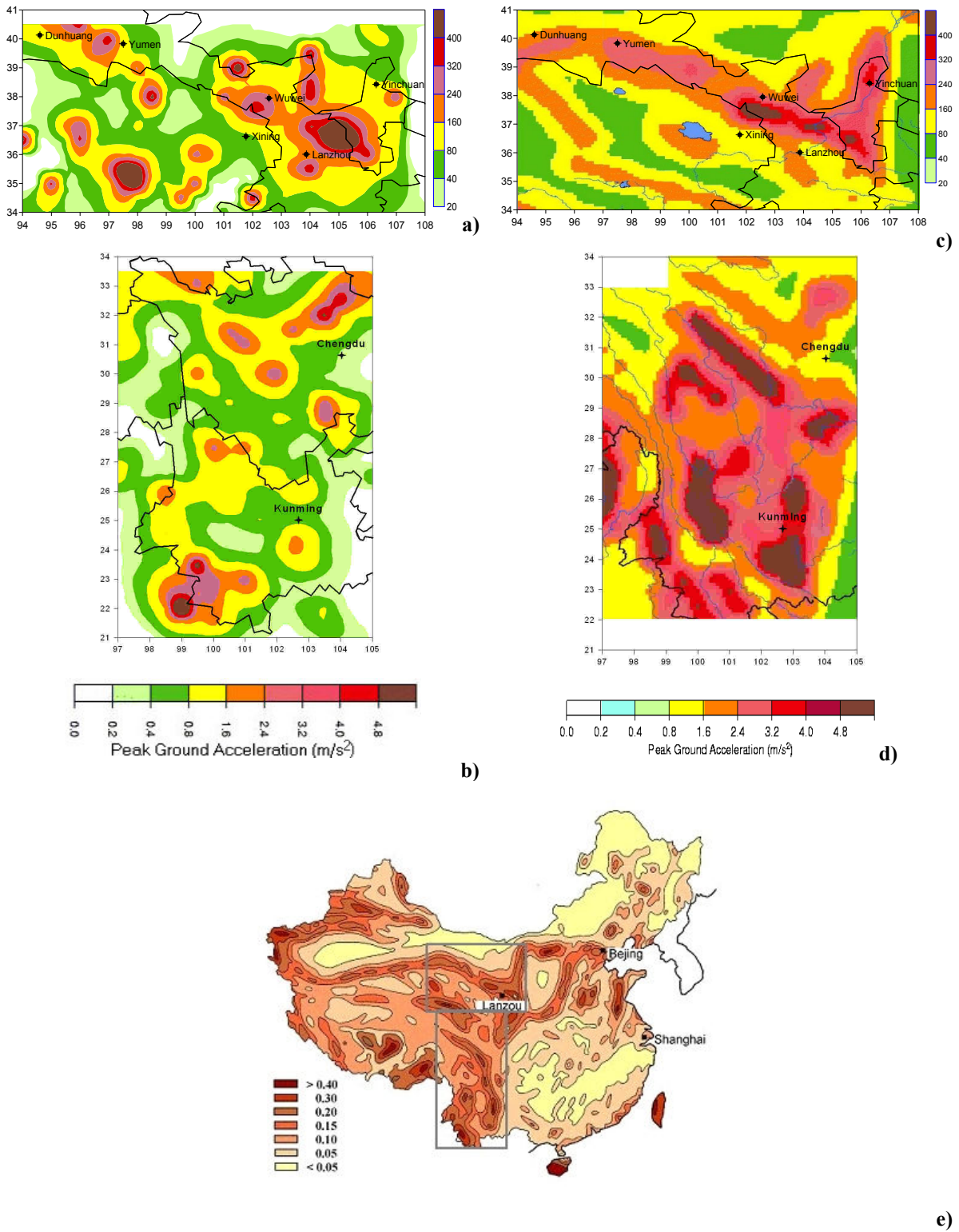
Figure 1. PGA m/s² maps with 10% chance of exceedance in 50 years for the NSSZ North (a) NSSZ South (b) using extreme value statistics compared with equivalent maps produced from GSHAP (c and d) and China national seismic hazard map (e) in terms of *g*.

3.3 GSHAP and China national seismic hazard maps

Launched in 1992 the Global Seismic Hazard Assessment Program (GSHAP) created a global seismic hazard map based on probabilistic seismic hazard assessments (PSHA) developed through the PSHA method of Cornell (1968) and FRISK88M computer software (McGuire, 1996). The GSHAP map of continental Asia (Zhang *et al*., 1999) depicts the PGA with 10% chance of exceedance in 50 years for a rock site classification. The attenuation relationship employed in development of the Asian GSHAP map is the Huo and Hu law above (equation 1). The ground motion seismic hazard can also be compared with the recently updated national seismic zoning map of China. This most recent update in national seismic hazard mapping was published in 2001, for a return period of 475 years, for PGA and intensity. Updating of the national seismic zoning map was in response to progress in seismic hazard assessment for nationwide projects and urban microzoning (Gao, 2003). Five institutes and 28 local seismological bureaus were involved in the project. Strong ground motion attenuation was based on strong ground records from the USA and these were modified to apply to China. In all cases the ground condition was hard rock. Our new Gumbel analysis provides an alternative PSHA technique to the GSHAP map for the area of southwest China and can be compared to the two above readily available approaches.

The Gumbel map shows that PGA is generally lower over large areas, except in active fault localities, compared to GSHAP, but otherwise the location of high and low PGA values are closely matching. In the NSSZ North the highest PGA borders southwest Ningxia province with PGA over 400 cm s^{-2} compared to more than 320 cm s^{-2} for the GSHAP map. Adjoining this area is a band of high PGA values (>160 cm s^{-2}) which trends northwest following roughly the outline of Gansu province. A subtle difference between the two maps is that the band of highest PGA values drops below 40 cm s^{-2} between Yumen and Wuwei whereas for the GSHAP map this band stretches from Dunhuang in the northwest to Lanzhou in the southeast. A parallel strip of higher PGA in the southwestern part of the zone is again more uniform within the GSHAP map, however, the Gumbel results suggest a second area of extreme PGA values of over 400 cm s^{-2} between 34.5-35.5^{o}N by 97-98°E, which exceeds the GSHAP map showing 160-240 cm s^{-2} in the same area.

The maps of PGA for the NSSZ South have similar differences. There is close agreement in the values of PGA in the northern section of this zone, to the north and west of Chengdu (including area of 2008 Wenchuan earthquake) and in southwest Yunnan with PGA > 320 cm s^{-2}. Although the arcuate line of high PGA through central Sichuan and Yunnan and close to Kunming is similar in pattern between the two models the GSHAP forecast is for PGA > 480 cm s^{-2} compared to 160-240 cm s^{-2} from extreme value analysis, for the 475 year return period.

Comparison with the national hazard map shows that again distribution of hazard is similar within both zones with values greater than Gumbel but lower than GSHAP.

4. EXTREME VALUE SEISMIC HAZARD ANALYSIS FOR MAXIMUM INTENSITY OF THE NSSZ.

Earthquake intensity is a measure of the directly observed effects of an earthquake. Intensity is measured by classifying macroseismic effects into a specific grade defined by established criteria and intensity scales. The China Intensity Scale is a twelve-degree system and corresponds approximately to the Modified Mercalli Intensity scale (Richter, 1958). It was created by Li (1954) and then rewritten by Xie (1957) to compare the scale with various intensity scales of the world, including the intensity scale of the former Soviet Union in 1952 and the Modified Mercalli Intensity Scale. The most recent update of the Chinese intensity scale was developed in 1999.

4.1 Intensity attenuation

Forecasting the seismic hazard in terms of earthquake intensity is similar to the methods used to determine

PGA. However, this process is not trivial because the forecasting of intensity requires another attenuation relationship.

4.1.1 NSSZ North intensity attenuation

The intensity attenuation relationship for the NSSZ North (Eqn. 2) is taken from Yu and Wang (2004) who determined a relation from isoseismal data of 31 earthquakes with magnitude greater than 5.0 in the northeastern Tibetan region. For the long axis of an isoseismal the intensity attenuation is

$$I = 5.774 + 1.376M_s - 4.287\log(R + 25) \quad \sigma = 0.668 \tag{2}$$

where *I* is intensity on the Chinese intensity scale, M_s is surface-wave magnitude and *R* is epicentral distance in kilometers. The publication of this relationship does not indicate the nature of the ground surface for its derivation. A hard rock sub-surface is assumed.

4.1.2 NSSZ South intensity attenuation

Within China the SSB (1996) published intensity relationships for eastern and western China (Eqns. 3 and 4). Intensity isoseismals are mapped as an ellipse and the best fitting function for attenuation is obtained either from the long or short axis of the ellipse. For western China the attenuation functions are

Long axis
$$I = 5.643 + 1.538M_s - 2.109\ln(R + 25) \quad \sigma = 0.64 \tag{3}$$

Short axis
$$I = 2.941 + 1.363M_s - 1.494\ln(R + 7) \quad \sigma = 0.61 \tag{4}$$

where I is intensity (on the Chinese Intensity Scale), M_s is surface-wave magnitude, R is epicentral distance in kilometres. As a conservative estimate of intensity the long axis formula is applied in estimation of intensity within the NSSZ South.

4.2 Extreme value forecasting for intensity in the NSSZ and comparison with China intensity hazard map

For forecasting intensity the first distribution of Gumbel is applied to evaluate intensity within both areas of the NSSZ (figures 2a and 2b). The procedure is identical to the determination of PGA with the only difference being the introduction of the intensity attenuation functions. The cell size chosen is again five degrees.

The national intensity map (figure 2c) illustrates the intensity with 10% probability of exceedance in 50 years on the Chinese intensity scale. Intensity is divided into five zones ranging from less than six to equal or greater than nine. Within the NSSZ South intensity is forecast at greater than or equal to intensity VII from both models. Again it is seen that the distribution of intensity hazard is comparable between both output maps although the national map extends the area of high values through the central section of each zone whereas the extreme value maps show more localised high intensity output.

Table 1 presents PGA and intensity results from the comparative hazard maps for selected points of interest within the NSSZ including provincial capitals in midwest and southwest China.
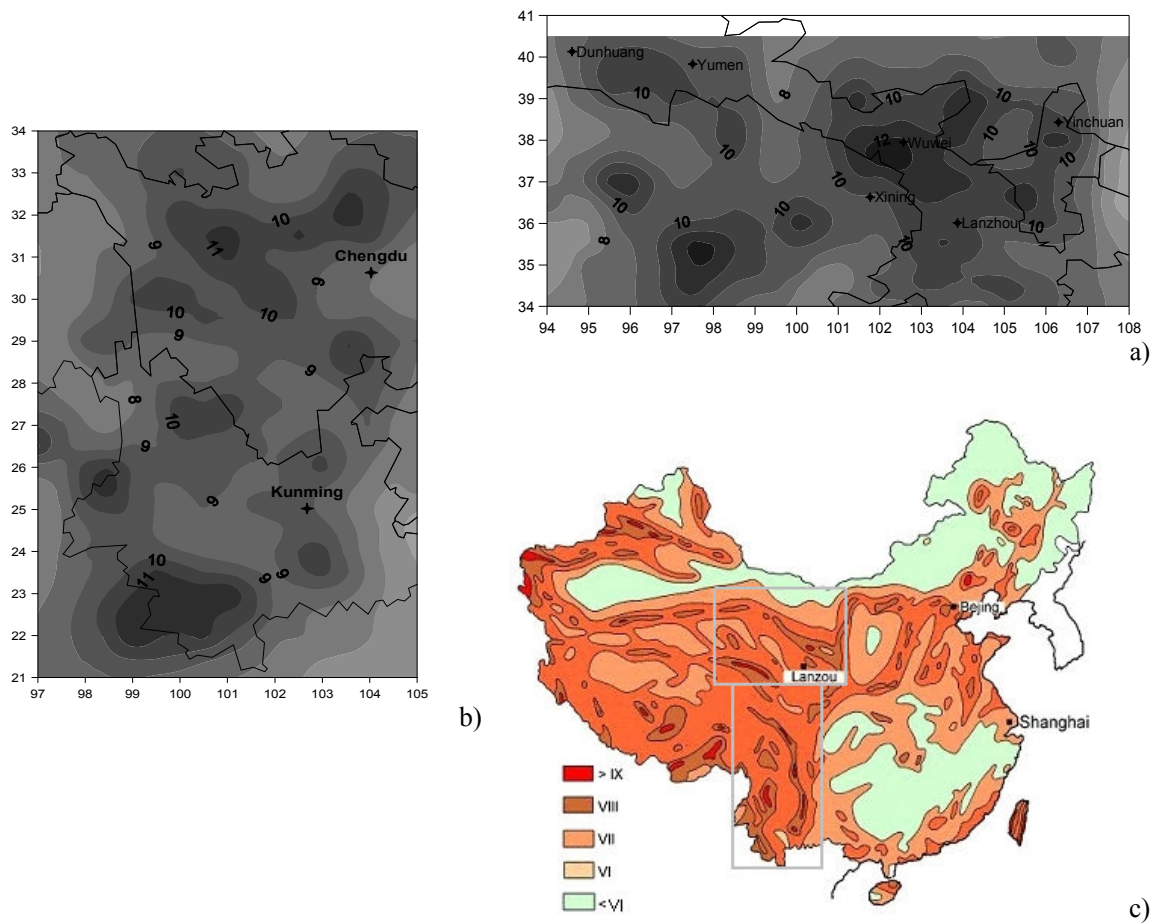
Figure 2 Intensity maps with 10% chance of exceedance in 50 years for the NSSZ North (a) NSSZ South (b) compared with China national seismic hazard map (c).

Table 1. Comparison of seismic hazard results for population centres within the NSSZ at 10% pbe in 50 years. Note that our intensity calculation uses the conservative long-axis of the isoseismal maps.

NSSZ-SOUTH			P.G.A (cm s^{-2})			INTENSITY	
Location	LAT	LON	Gumbel	GSHAP	China hazard map	Gumbel	China hazard map
Chengdu	104.03	30.63	61.5	160-240	150-199	VIII	VII
Kunming	102.68	25.02	121.2	320-399	200-299	IX	VIII
Lijiang	100.23	26.87	256.2	320-399	200-299	X	≥IX
NSSZ - NORTH							
Yinchuan	38.43	106.30	197.5	80-160	100-149	X	VIII
Lanzhou	36.01	103.87	208.4	160-240	150-199	X	VII
Xining	36.63	101.77	93.9	40-80	100-149	X	VII
Wuwei	37.95	102.57	237.9	240-320	200-299	XI	VIII
Yumen	39.83	97.50	182.2	80-160	150-199	IX	VII
Dunhuang	40.13	94.60	81.9	80-160	150-199	VIII	VI

5. DISCUSSION

In general even though the same attenuation law is applied the Gumbel map (figures 1a and 1b) produces values of PGA that are lower than GSHAP (figures 1c and 1d) and China national seismic hazard map (figure 1e). The explanation for this is because the GSHAP is calculated from the PSHA process of Cornell (1968) which identifies potential seismic sources and determines maximum hazard levels in areas which may exhibit no previous strong hazard. In contrast the Gumbel approach determines hazard levels from earthquake events that have already taken place and no source characterization is required. Furthermore this has the effect of showing high levels of hazard in the vicinity of previous earthquakes (associated with active faults) and much lower hazard where earthquakes have not occurred (away from faults). Despite the small numerical differences in the actual level of PGA the spatial distribution of high and low PGA hazard is very similar in all cases.   For intensity the extreme value method forecasts intensity as great as XI within the NSSZ (figure 2). A full comparison with the China national intensity map is not possible because it does not indicate intensities greater than IX in detail, simply specifying ≥IX. However, it can be seen from the maps that in general seismic hazard is high throughout the NSSZ, most recently demonstrated by the May 12th, 2008 Wenchuan earthquake.

It has been shown that there are variations in the mapped output between our extreme value approach and publicly available seismic hazard maps. The aim of all seismic hazard models is to produce a forecast on levels of ground motion. However, variations in input parameters and uncertainty in the analysis all have pronounced effects. Notwithstanding, the areas of high and low hazard from each model are broadly similar. These maps provide a general overview of earthquake hazard in an area. For further detailed work a more stringent analysis is required in combination with seismic risk assessments.

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