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ORIGINAL ARTICLE

Probabilistic seismic hazard assessment for Iraq

Wathiq Abdulnaby · Tuna Onur · Rengin Gök · Ammar M. Shakir · Hanan Mahdi · Haydar Al-Shukri · Nazar M.S. Numan · Najah A. Abd · Hussein K. Chlaib · Taher H. Ameen · Ali Ramthan

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Abstract Probabilistic seismic hazard assessments (PSHA) form the basis for calculating seismic loads in most contemporary seismic provisions in building codes around the world. The current building code of Iraq, which was published in 1997, is currently undergoing a significant engineering update. This study was undertaken in order to support the building code update and to satisfy the need in Iraq for a contemporary assessment of seismic hazard in terms of spectral accelerations. Seismic source characterization largely relies on a newly compiled earthquake catalog since sufficiently detailed information is not available on active faulting in the country even though there are numerous known active faults. There is also a lack of locally recorded strong-motion data. As a result, we make use of attenuation tomography studies in the region to compare local attenuation characteristics with that in other parts of the world where ground-motion prediction equations are available for use in PSHA. For most of the country, the attenuation of 1HzLg waves indicates an attenuation rate that is slower than active tectonic regions but faster than stable continental regions. Hence, we use ground-motion prediction equations from active tectonic and stable continental regions, weighted equally. The PSHA results are presented for a 2% chance of being exceeded in 50 years and on a reference ground condition of the National Earthquake Hazards Reduction Program (NEHRP) site class B. The probability level and reference ground conditions were selected to be consistent with the update of Iraq's building code. The largest hazard, and consequently the design ground motions, is in the northern cities of Sulaymaniyah and Erbil, consistent with the fact that they are the two urban areas closest to major tectonic features to the north and east of Iraq. Additionally, the Badra–Amarah fault zone is a significant contributor to seismic hazard in the country; therefore, urban areas near it exhibit high seismic hazard.

W. Abdulnaby (✉)
Seismological Laboratory of University of Basrah (SLUB), Department of Geology, College of Sciences, University of Basrah, Basrah, Iraq
e-mail: wgabdulnaby@ualr.edu

T. Onur
Onur Seemann Consulting, Inc., Victoria, Canada

R. Gök
Lawrence Livermore National Laboratory, Livermore, USA

A. M. Shakir · N. A. Abd
University of Baghdad, Baghdad, Iraq

H. Mahdi · H. Al-Shukri
University of Arkansas at Little Rock, Little Rock, USA

N. M. Numan
American University of Kurdistan, Simele, Iraq

H. K. Chlaib
University of Sumer, Rifai, Iraq

T. H. Ameen
University of Sulaymaniyah, Sulaymaniyah, Iraq

A. Ramthan
General Directorate of Education, Thi-Qar Governorate, Nasiriyah, Iraq

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1 Introduction

When an overhaul of the building code started in Iraq, no comprehensive national probabilistic seismic hazard assessment (PSHA) studies were available in Iraq for the new building code to refer to for seismic loading. The limited number of PSHA studies that did exist were either outdated or had limited scope (e.g., Ameer et al. 2005; Schwark 2005).

Recognizing this need, in 2013, the U.S. Department of Energy through Lawrence Livermore National Laboratory (LLNL) funded a project to fill a fundamental need in Iraq for locally recorded data and for local scientists in Iraq to modernize seismic hazard studies. Three workshops, one in Erbil, Iraq, in 2014, and two smaller hands-on workshops at the University of Arkansas at Little Rock, AR, in 2015 and 2016 were organized, the latter two specifically focusing on PSHA. Following these workshops, the team worked on the PSHA model that is presented in this paper. The PSHA framework used in this project follows the traditional Cornell-McGuire approach (Cornell 1968; McGuire 1976) and has two main components: (1) seismic source characterization and (2) ground-motion characterization. The new code required seismic hazard values for communities across Iraq in terms of spectral accelerations at a 2% chance of being exceeded in 50 years.

The lack of a comprehensive national earthquake catalog in Iraq prior to this study necessitated a careful re-examination of available data and new direct calculations of moment magnitudes to improve catalog quality. In particular, we employ coda calibration technique to calculate moment magnitudes for more than 1000 Mw2.5+ events between 1989 and 2009 (Gök et al. 2016) and waveform moment tensor inversion for 65 Mw3.3+ events between 2004 and 2013 (Abdulnaby et al. 2014). These are in addition to the moment magnitudes available from other sources such as Global Centroid Moment Tensor (Global CMT) (Ekström et al. 2012) solutions. These newly calculated moment magnitudes not only provided a much more reliable estimate of event size for these particular events but they also allowed the development of more reliable magnitude conversion relations to use for older events for which digital waveform data is not available. This is especially important because Iraq lacks paleoseismic studies on known faults or reliable estimates of geologic slip rates to quantify the recurrence of earthquakes over longer periods of time.

Another big challenge in estimating seismic hazard for Iraq is the scarcity of strong-motion instrumentation and lack of publicly available strong-motion data. Prior studies in this region use ground-motion prediction equations (GMPEs) for active tectonic settings, lumping Iraq with the neighboring regions such as Turkey and Iran, where attenuation characteristics are similar to other active tectonic regions of the world. However, using a novel approach based on examination of crustal Q in the region, we were able to identify that large majority of Iraq's territory has significantly slower attenuation than Turkey or Iran, while having significantly faster attenuation than craton-like settings such as the Arabian Shield.

We describe in this paper our findings and the seismic hazard model that was developed for a national seismic hazard assessment for Iraq, including the source and ground-motion characterizations. We use the newly compiled earthquake catalog specifically developed for this study to characterize earthquake recurrence both along with fault systems and to characterize diffuse seismicity as discussed below.

2 Seismic source characterization

Iraq lies in the northeastern portion of the Arabian Plate, near the convergent tectonic boundary between the Eurasian and Arabian plates (Fig. 1). Here, in northern and eastern Iraq, the Bitlis–Zagros Fold and Thrust Belt generate intense earthquake activity, including the Mw7.3 in November 2017. The rest of Iraq is largely located on the Arabian Platform, away from major plate boundaries, and subject to less frequent seismicity. The Dead Sea fault system, a major left-lateral transform fault forming the western boundary of the Arabian Plate, is about 250 km away from the westernmost part of Iraq. Another significant tectonic feature in the region is the Makran Subduction Zone; however, the closest edge of the potential rupture zone is more than 1000 km southeast of Iraq.

Iraq is generally divided into three tectonic zones (see, for example, Numan et al. 1998; Fouad and Sissakian 2011). These divisions, from northeast to

Fig. 1 Tectonic setting of Iraq and environs (red arrows indicate plate motions in cm/year). The white square represents the study area

southwest, are as follows: (1) the Bitlis–Zagros Fold and Thrust Belt, (2) the Mesopotamian Foredeep, and (3) the Inner (stable) Arabian Platform (see, Onur et al. 2017 for more in-depth descriptions).

The Bitlis–Zagros Fold and Thrust Belt of the Alpine Orogeny (Jackson et al. 1981; Hessami and Jamali 2006) are characterized by frequent earthquake activity. In this region, many of the NE–SW trending (transverse) faults are active, such as the Lower Zab fault and the Diyala River fault, as well as the listric (longitudinal) faults that are parallel to the fold axes. The November 2017 earthquake of Mw7.3 occurred on such a listric fault in this region. According to Abdulnaby et al. (2014), much of the faulting in recent earthquakes is of strike-slip, oblique-slip, and thrust mechanism.

The Mesopotamian Foredeep is part of the Outer Arabian Platform that covers the northeast area of Iraq. It differs tectonically from the more Stable Inner Arabian Platform to the southwest. The central and southeastern part of the Mesopotamian Foredeep, called the Mesopotamian Plain, contains several buried faults that are evident through their effects on the Quaternary stratigraphy and present geomorphological landforms indicating neotectonic activity in this area (Fouad and Sissakian 2011). The Quaternary alluvial sediments of the Tigris and Euphrates River systems form a thick sedimentary sequence over the Mesopotamian Plain (Sissakian 2013). The thickness changes from 8 km (± 2 km) within the platform in the west of Iraq to 14 km (± 2 km) within the Zagros foreland in the northeast and the Mesopotamian Plain in the southeast (Numan 1997; Gök et al. 2008; Sissakian 2013).

Seismically active faults in the Mesopotamian Foredeep include the Badra–Amarah fault, which lies along the Iraq–Iran border and is considered the most seismically active fault in Iraq (Abdulnaby et al. 2016a, b), Euphrates fault (which represents the tectonic boundary between the Stable Platform and the Mesopotamian Foredeep), Hummar fault (north of Basra), Al-Refaee fault, and Kut fault.

The Inner Arabian Platform geologically constitutes a stable continental region. Although faults do exist in this zone, recent deformation is much less significant and Quaternary activity on the faults is less evident.

For most of the identified faults in the region, information that is necessary to characterize probabilistic hazard from them (complete geometry, the recurrence rate of earthquakes, and/or slip rates) is not available at the required level of detail. Hence, more research is needed before they can be used as fault sources in PSHA. It should be noted that while these sources were not characterized as individual fault sources in the PSHA, they were taken into consideration when delineating the geometry and recurrence characteristics of the area sources.

2.1 Earthquake catalog

A comprehensive earthquake catalog is a key starting point for a national PSHA for Iraq, particularly because specific faults and their activity rates cannot be explicitly included in PSHA due to lack of detailed information. For most active faults, dip angle and detailed subsurface geometry are not available. Furthermore, reliable recurrence information such as geologic slip rates or recurrence rates based on paleoseismology is lacking in Iraq. Hence, we refrain from characterizing faults as line sources and instead include them as part of the delineation of area sources in the seismic source model, which makes the quality of the earthquake catalog an essential component of the PSHA. The development of the earthquake catalog for our hazard assessment is described in detail and the catalog is provided as an electronic supplement in Onur et al. (2017). However, a brief description of the catalog is also provided in the following paragraphs.

Global earthquake catalogs miss many of the local earthquakes in our study region. For example, the International Seismological Centre (ISC-GEM) catalog (International Seismological Centre 2014; Storchak et al. 2013) has only 87 earthquakes for this region (26° N–40° N, 36° E–51° E) between the years 1900 and 2009 (inclusive) with magnitudes between 5.3 and 7.8 (including the supplement provided with the ISC-GEM catalog). In comparison, Onur et al. (2017) compilation includes 237 earthquakes over the same time period and magnitude range. The most recent regional effort for cataloging earthquakes in terms of moment magnitude (Mw) in this area is the Earthquake Model of the Middle East (EMME) project as part of the Global Earthquake Model (GEM) (Zare et al. 2014). Although EMME catalog is rich in terms of earthquakes in the northern portion of our study area (i.e., areas in Eastern Turkey), it is relatively sparse south of the 37.5° N latitude. For example, between 26° N–37.5° N latitudes and 36° E–51° E longitudes, the Zare et al. (2014) catalog includes about 1500 Mw 4.0 and larger earthquakes from the year 1900 until the end of 2006 (end of the Zare et al. 2014, catalog). By comparison, Onur et al. (2017) compilation includes roughly 3500 earthquakes for the same time period, not including contributions from the Zare et al. (2014) catalog. Onur et al. (2017) catalog also includes three additional years of earthquakes, through to the end of 2009, and includes events with magnitudes lower than 4.0, which are not included in the Zare et al. (2014) catalog.

Iraq has a long history of earthquakes. The Onur et al. (2017) catalog discusses major historical earthquakes in Iraq, describes the instrumental catalog developed with a focus on Iraq, and includes newly calculated moment magnitudes for more than 1000 earthquakes since 1989, magnitude conversions specifically developed for Iraq, and spatial distribution of completeness intervals. The catalog encompasses the region between 36° E–51° E longitudes and 26° N–40° N latitudes and includes about 16,000 events of magnitude 3.0 and larger, and about 4000 events of magnitude 4.0 and larger between the years 1900 and 2009 inclusive (Fig. 2). The geographic extent of the catalog's coverage is intended to include sources of seismicity that may cause damage inside the territory of Iraq. Roughly 90% of the earthquakes in the catalog have a depth of between 0

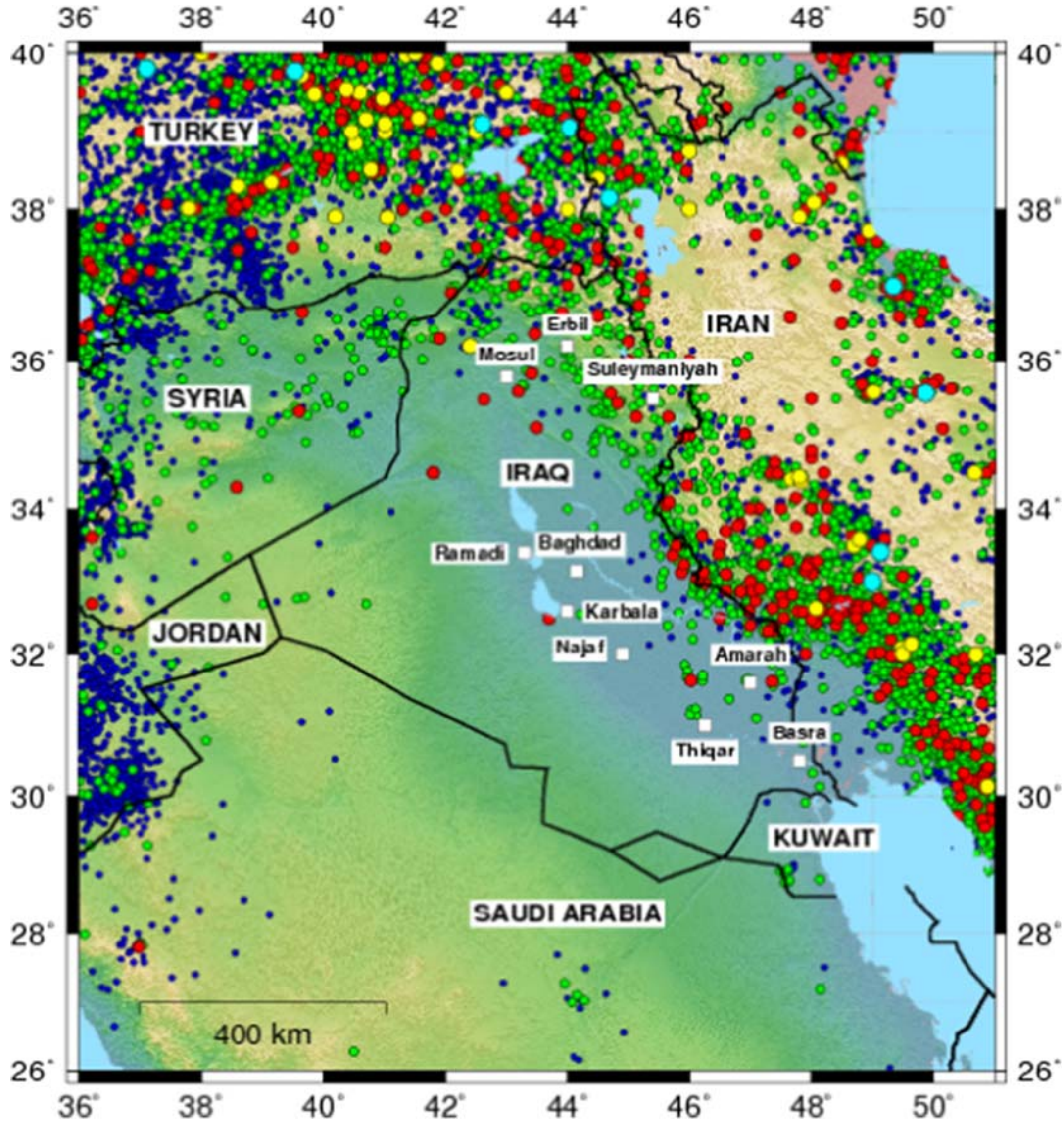


Fig. 2 Catalog of instrumental seismicity in Iraq in terms of Mw (after Onur et al. 2017). Blue Mw < 3, green Mw ≥ 3, red Mw ≥ 4, yellow Mw ≥ 5, and sky blue Mw ≥ 6

and 35 km. This indicates that the majority of earthquakes in the region exhibit shallow crustal seismic activity.

The catalog fills a gap in this region by focusing particularly on the territory of Iraq where instrumentation and earthquake reporting have been intermittent. Event details were collected from various sources and supplemented with new magnitude calculations. The pre-1964 portion of the catalog uses information from International Seismological Centre (ISC), ISC-GEM, Fahmi and Abbasi (1989), Ambraseys (2001), Zare et al. (2014), Riad and Meyers (1985), and U.S. Geological Survey (USGS) Centennial (Engdahl and Villaseñor 2002) catalogs. Post-1964, the sources included the Iraq Seismic Network (ISN) when operational, ISC, European-Mediterranean Seismological Centre (EMSC), Global Centroid Moment Tensor (Global CMT) solutions, and Ambraseys' extensive work on the cataloging of instrumental era earthquakes in the Middle East (e.g., Ambraseys 1978, 2001, 2009).

Earthquake data including date, time, location, depth, and magnitude from the different sources described above were collected and merged to form a comprehensive instrumental catalog of earthquakes for Iraq and neighboring regions. As part of the merging of catalogs, duplicate earthquakes were identified based on the location and time of the earthquake, and lower priority entries were removed from the catalog. Different prioritization schemes were applied for location and magnitude. For example, for magnitudes, direct moment magnitude (Mw) values were favored, followed by ISC body-wave magnitude (mb) assignments.

The resulting catalog was supplemented by direct moment magnitude calculations for Iraq, using coda calibration technique and moment tensor solutions (for details, see Onur et al. 2017). Regional magnitude conversion relations were developed to convert three magnitude scales that are dominant in the catalog (MD, ML, and mb) to Mw, when direct Mw calculations were unavailable (Eqs. 1a, 1b, and 1c). General orthogonal regression was used for developing the relations because it allows the uncertainty in both the dependent and independent variables to be of a similar order of magnitude (see Onur et al. 2017 for further details and comparison with other magnitude conversions).

$$\mathrm{Mw} = 1.0670 \times \mathrm{MD} + 0.1758 \; (3.0 < \mathrm{MD} < 5.0) \tag{1a}$$

$$\mathrm{Mw} = 0.7441 \times \mathrm{ML} + 1.1470 \; (3.0 < \mathrm{ML} < 5.0) \tag{1b}$$

$$\mathrm{Mw} = 0.8599 \times \mathrm{mb} + 0.7278 \quad (3.0 < \mathrm{mb} < 5.5) \tag{1c}$$

Completeness intervals depend on the sensitivity and density of seismic instrumentation over time and space. Catalog completeness is essential to establish in order to reliably estimate seismic activity rates and recurrence parameters. Completeness intervals for the catalog developed for this study are derived from plots of the logarithm of cumulative rate of earthquakes against magnitude, prepared for various time periods and by noting at which magnitude the slope of the curve deviates from a straight line and the activity rates drop off. The resulting completeness intervals for the entire catalog are as follows: Mw 6.5 and above are complete since 1900, Mw 6.0 and above since 1924, Mw 4.2 and above since 1965, Mw 3.4 and above since 1995, and Mw 3.2 and above since 2006 (Table 1). However, completeness intervals are also region-dependent in Iraq, due to the variable density and history of instrumentation. Broadly, the catalog is more complete in Bitlis–Zagros region and less complete in the stable regions of Iraq. We take into account this regional variability in the calculation of recurrence parameters for the seismic source zones.

2.2 Seismic source zones

Area sources were used in PSHA to characterize seismic activity in the region. When delineating the source zones (Fig. 3), tectonics of the region, as well as the seismicity patterns, were taken into account. The area sources broadly follow the main tectonic features in the region as described below.

Zones 1, 6, and 7 characterize, in three different segments, the main axis of the Bitlis–Zagros Fold and Thrust Belt. Zones 2 and 5 form the southern edge of the Bitlis–Zagros Fold and Thrust Belt. Although they are of similar tectonic origins, zone 5 to the south has significantly more present-day activity than Zone 2 to the north. Zone 3 roughly coincides with the Mesopotamian Foredeep. Zone 4 represents the Stable Platform. Zone 8 characterizes the seismicity in and around Sinjar Uplift and zone 12 along the Palmyrides and the northernmost section of the Euphrates fault system. Zone 9 captures the intense seismic activity in Eastern Turkey. Zones 10 and 11 represent the relatively low seismic activity to the northeast of Zagros Fold and Thrust Belt. The detail level for the geographic characterization of the source zones is generally lower for zones that are relatively distant from Iraq (e.g., zones 9, 10, 11, and 12).

Maximum magnitudes were assigned to each source zone based on various considerations such as maximum historical earthquake inside the zone (maximum magnitude cannot be lower than the magnitude of the largest observed earthquake), length of known faults within

Table 1 Catalog completeness intervals

Magnitude range	Completeness intervals (years)
Mw ≥ 3.2	Since 2006
Mw ≥ 3.4	Since 1995
Mw ≥ 4.2	Since 1965
Mw ≥ 6.0	Since 1924
Mw ≥ 6.5	Since 1900

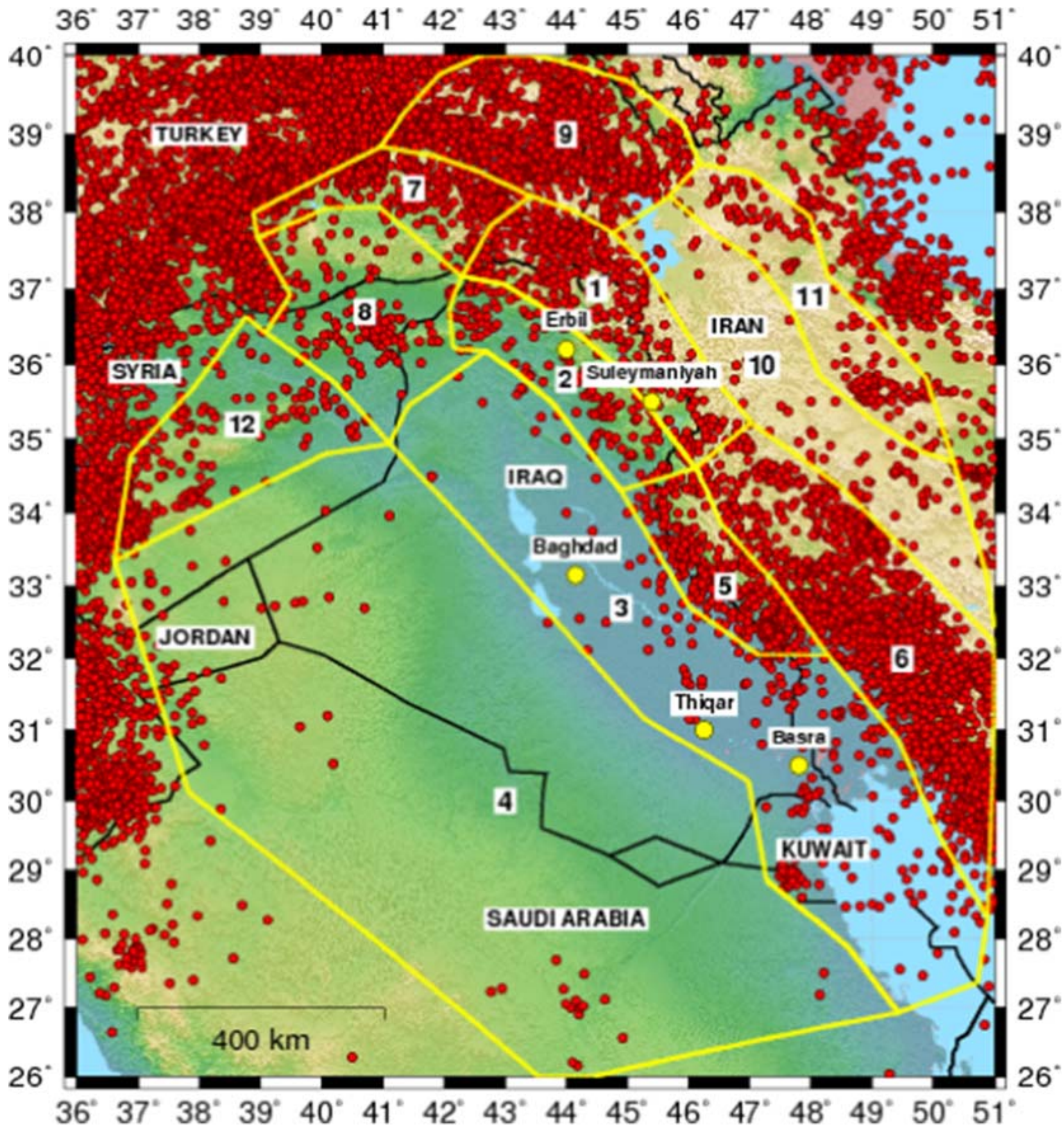


Fig. 3 Delineation of seismic source zones in Iraq and adjacent areas

each zone, potential for segmentation and possibility of multiple-segment ruptures, and other relevant tectonic information (faulting mechanism, kinematics of the fault, etc.). For the sources characterizing the multiple segments of the Bitlis–Zagros Fold and Thrust Belt, the lengths of the segments were used as a guiding consideration as well. The geometry and length of the faults were taken into account using Wells and Coppersmith (1994) magnitude scaling relations between rupture length/area and magnitude.

The choice of maximum magnitude often depends on whether an active fault is characterized as a linear source. If yes, the maximum magnitude assigned to the surrounding area source can be lowered, if no other major fault features are available inside the source zone. In our case, while some known active faults exist in the region, the information necessary to characterize them as linear sources is not available. Therefore, we assign relatively large maximum magnitudes to the area sources that are accommodating for known active fault features.

The uncertainty in the maximum magnitudes was captured by assigning the central maximum magnitude estimate weight of 50%, and the lower and higher maximum magnitude estimates 25% weight each. Generally, no zone was assigned a central maximum magnitude lower than Mw 7.4. This is in light of recent events around the world where earthquakes of Mw higher than 7 have happened in parts of the world with relatively low levels of seismic activity.

For each of the sources,

Gutenberg–Richter recurrence parameters (*a*- and *b*-values) were calculated using the maximum likelihood estimation based on the earthquake catalog developed for this project (Table 2; Fig. 4). Truncated Gutenberg–Richter relations were used for the hazard analyses with a minimum magnitude of 4.4 for all sources and maximum magnitudes varying by source (Table 2).

Generally, the *b*-value is between 0.80 and 1.22, except for source zone 4 (Stable Shelf). This zone has low activity rates and a relatively large *b*-value (1.57). This could be due to the small number of earthquakes (and of small magnitudes) in this zone; however, the fit appears fairly stable (sigma = 0.07).

Uncertainties in source parameters listed in Table 2 are accounted for in a logic tree framework (Fig. 5). In addition, uncertainty in depth of the shallow crustal seismicity is accounted for by assigning 50% weight to 10-km source depth, 25% to 15-km source depth, and 25% to 5-km source weight (Fig. 5).

3 Ground-motion characterization

The choice of ground-motion prediction equations (GMPEs) used in PSHA to characterize strong ground motion is dependent on the tectonic setting of the study area and availability of strong-motion data. In order of the decreasing amount of data, the options are to (1) empirically derive region-specific GMPEs, (2) choose regionally or globally derived GMPEs based on comparisons and/or calibrations against locally recorded strong-motion data, and (3) choose regionally or globally derived GMPEs based on the local attenuation characteristics.

Unfortunately, Iraq currently lacks a national strong-motion network and consequently strong-motion data recorded in the territory of Iraq is very difficult. Sparse strong-motion instrumentation is reportedly in place in some dams and possibly other facilities; however, the exact status of instrumentation is unknown and data from these installations is not publicly available. Recently, as part of the broader instrumentation effort in collaboration with LLNL, two strong-motion instruments were installed in Iraq: one in Sulaymaniyah and one in Basra, and others are in planning phases. As data becomes available from these instruments, a more robust strong-motion characterization in Iraq will emerge.

Since there are no strong-motion data to utilize for options (1) and (2) described above, ground-motion characterization for this PSHA study uses globally derived GMPEs. Global GMPEs broadly fall into one of the following tectonic groupings: (a) active tectonic regions with shallow crustal seismicity, (b) stable continental regions, and (c) subduction zones. Iraq largely lies in a stable continental region, but most of its earthquake activity occurs in active tectonic regions bordering with Turkey and Iran. In general, ground-motion

Table 2 Recurrence parameters for source zones

Source zone no.	Source zone name	M_{max} (lower, central, upper)	G-R *b*-value, standard deviation	G-R *a*-value, standard deviation
1	Bitlis–Zagros Thrust A	7.6, 7.8, 8.0	1.1316, 0.06	5.4698, 3.63
2	Unstable Shelf A	7.4, 7.6, 7.8	1.1996, 0.14	5.3674, 4.24
3	Unstable Shelf B	7.2, 7.6, 7.8	1.2236, 0.12	5.4069, 2.65
4	Stable Shelf	7.2, 7.4, 7.6	1.5743, 0.07	5.9980, 3.22
5	Zagros	7.6, 7.8, 7.9	1.0439, 0.20	5.0625, 5.20
6	Southern Zagros	7.8, 8.0, 8.1	1.0719, 0.09	5.7632, 4.65
7	Bitlis–Zagros Thrust B	7.6, 7.8, 8.0	1.0779, 0.10	4.9800, 2.53
8	Sinjar Uplift	7.2, 7.6, 7.8	1.2143, 0.12	5.4451, 4.28
9	Eastern Turkey	7.8, 7.9, 8.0	0.9696, 0.03	4.9833, 3.52
10	Northeast of Zagros	7.4, 7.6, 7.8	0.7987, 0.08	3.1741, 1.84
11	Iran Intermediate	7.6, 7.8, 7.9	0.8324, 0.05	3.6274, 2.51
12	Palmyrides	7.6, 7.8, 7.9	1.2239, 0.17	4.6681, 3.92

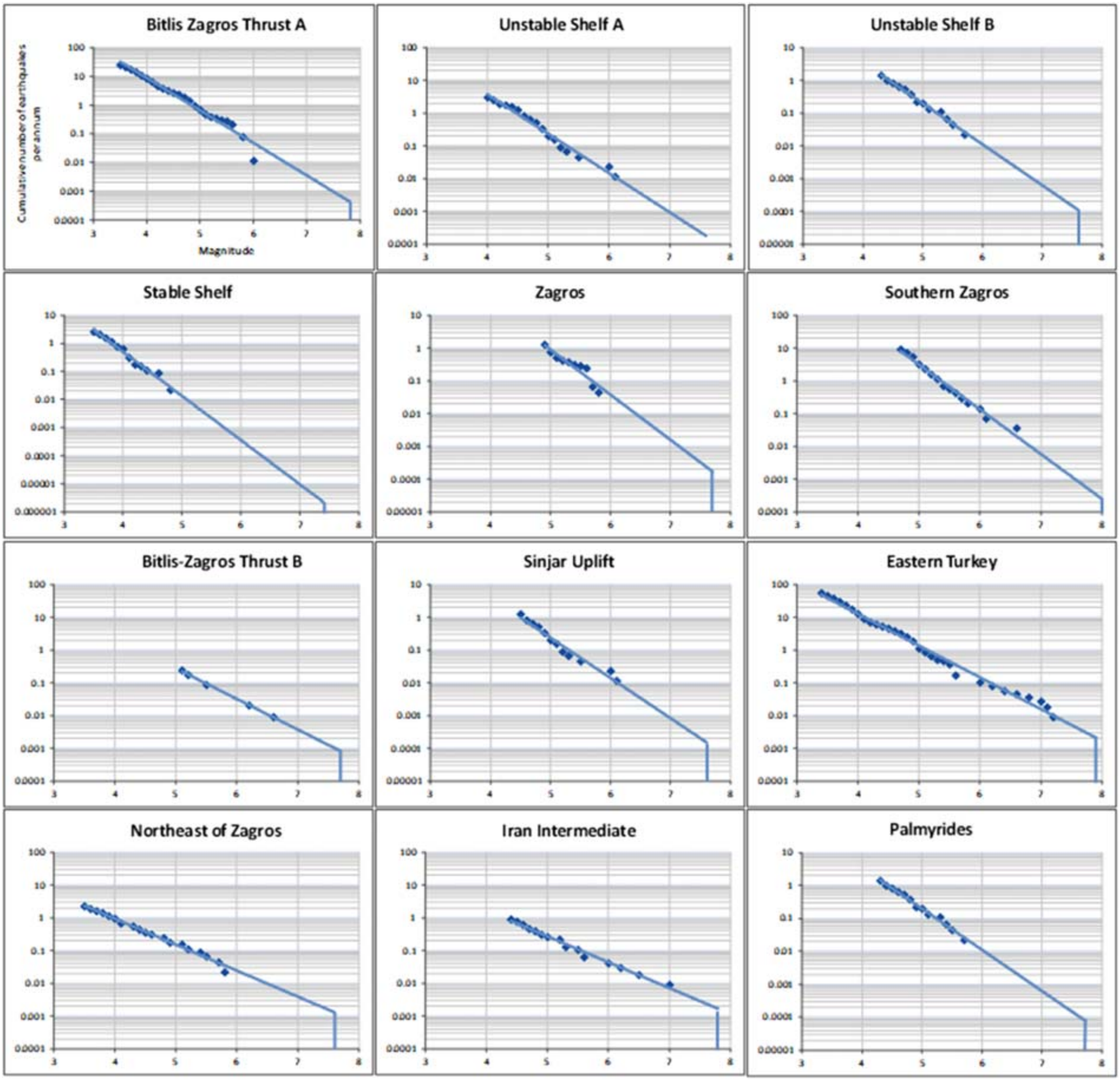


Fig. 4 A cumulative number of earthquakes per annum plotted against magnitude for two example source zones; these are the Bitlis–Zagros Thrust A and the Unstable Shelf A

attenuation is faster in active tectonic regions compared with that in stable continental regions.

As guidance for the selection of the GMPEs in the absence of locally recorded strong-motion recordings, we examine the attenuation characteristics of the region through other means. Al-Damegh et al. (2004) and Pasyanos et al. (2009) studied Sn and Lg attenuation in the Middle East. Their analyses show that even the "active" parts of Iraq have slower attenuation compared with areas such as California and parts of Turkey, where much of the data for global and regional GMPEs for active tectonic regions come from. This effect was also observed by Kale et al. (2015) when comparing attenuation in Iran (slower) to Turkey (faster).

Using the same 1 Hz Lg attenuation studies (e.g., Pasyanos et al. 2009), we find that the "stable" parts of Iraq have faster attenuation than stable craton regions. In fact, all of Iraq exhibits fairly similar attenuation characteristics (Lg Q 300~600), somewhere between "active tectonic regions" (Lg Q 150~250) and "stable craton"

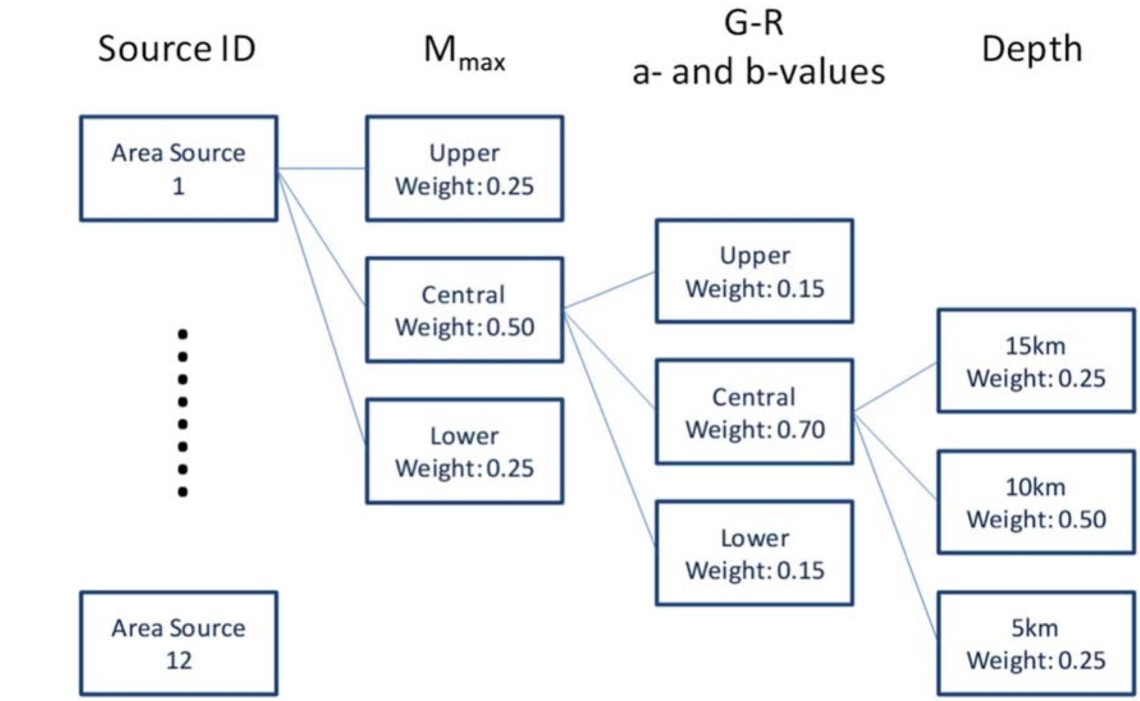


Fig. 5 The logic tree used for source characterization

(Lg Q~1000 or higher). Therefore, we weigh attenuation relations from active tectonic regions against stable continental regions, in a logic tree approach, for this project.

Four GMPEs from Next Generation Attenuation (NGA) West-2 project (active tectonic regions) and two GMPEs from NGA East project (stable continental

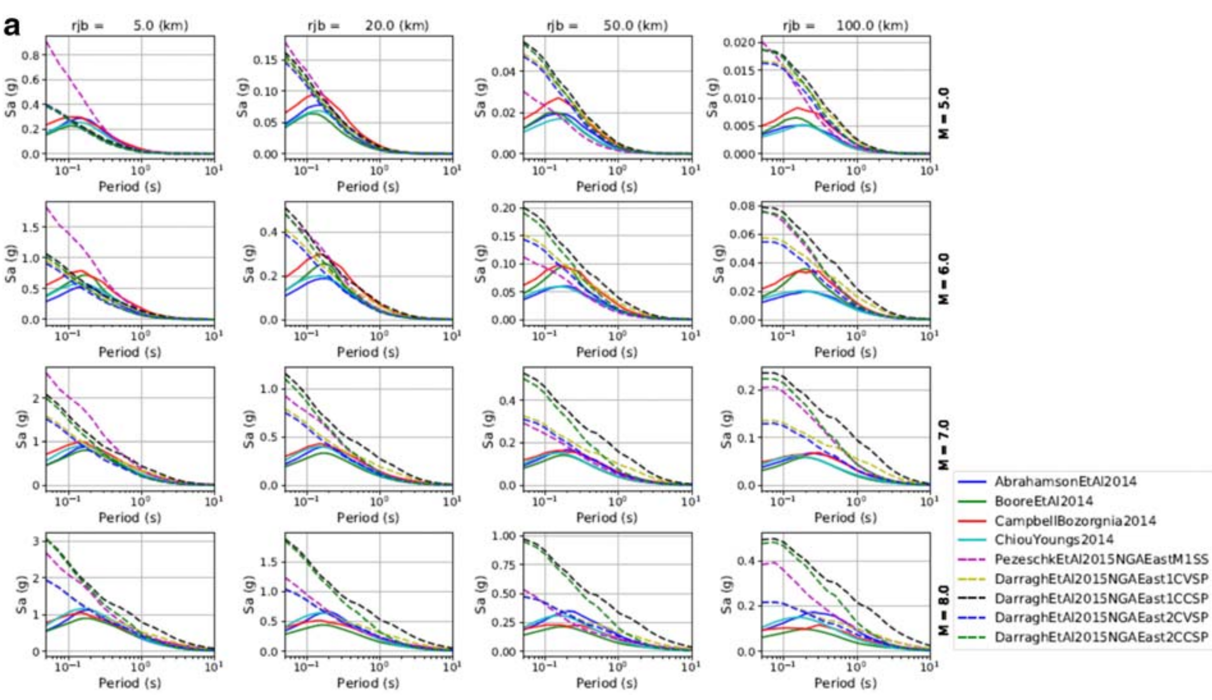


Fig. 6 **a** Trellis plot comparing the GMPEs used in the hazard assessment. **b** The logic tree used for ground-motion characterization

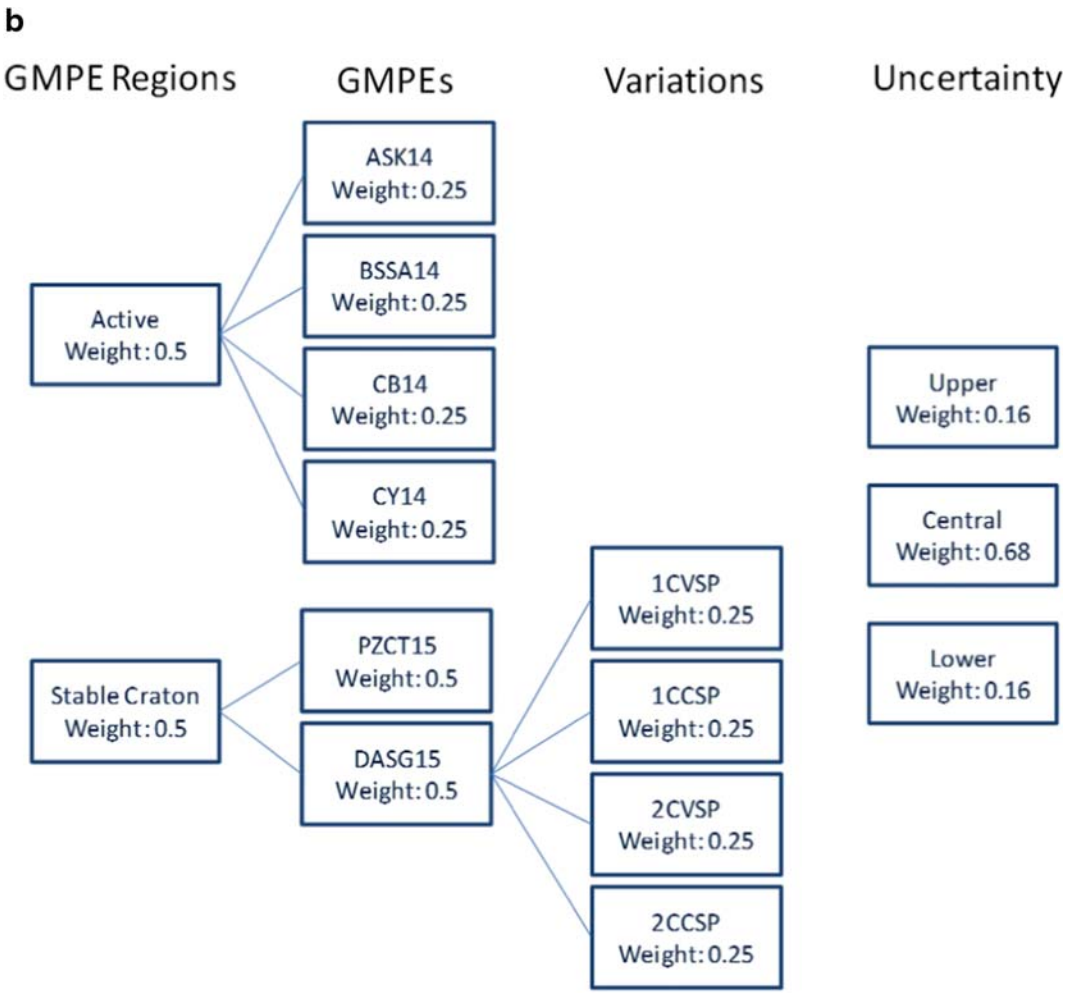


Fig. 6 (continued)

regions), one of which with four variations, were used in this project (Fig. 6a) through a logic tree approach (Fig. 6b). NGA West-2 GMPEs that were used are as follows: Abrahamson et al. (2014), referred to as ASK14 in the rest of the paper; Boore et al. (2014), BSSA14; Campbell and Bozorgnia (2014), CB14; and Chiou and Youngs (2014), CY14. The NGA East GMPEs that were used are as follows: Pezeshk et al. (2015)–PZCT15 and Darragh et al. (2015)–DASG15 with the following variations: single-corner variable stress parameter (1CVSP), single-corner constant stress parameter (1CCSP), double-corner variable stress parameter (2CVSP), and double-corner constant stress parameter (2CCSP).

Ground motions from all GMPEs were computed for site class B site condition since the draft update of the building code of Iraq uses site class B as the reference site. Site classification is based on the National Earthquake Hazard Reduction Program (NEHRP) site classes (BSSC 2001), which uses the average shear-wave velocity of the top 30 m of the site for the classification of ground conditions.

Once strong-motion data becomes available from recently installed instruments, a more informed update can be made to the ground-motion characterization. Recorded strong-motion data may also reveal the need for new GMPEs for regions like Iraq, where the attenuation appears to be not as fast as California or Turkey, and not as slow as stable craton. A region-specific ground-motion modeling study, also accounting for the thick sedimentary deposits in the Mesopotamian Plain, would be invaluable for future PSHA studies in Iraq.

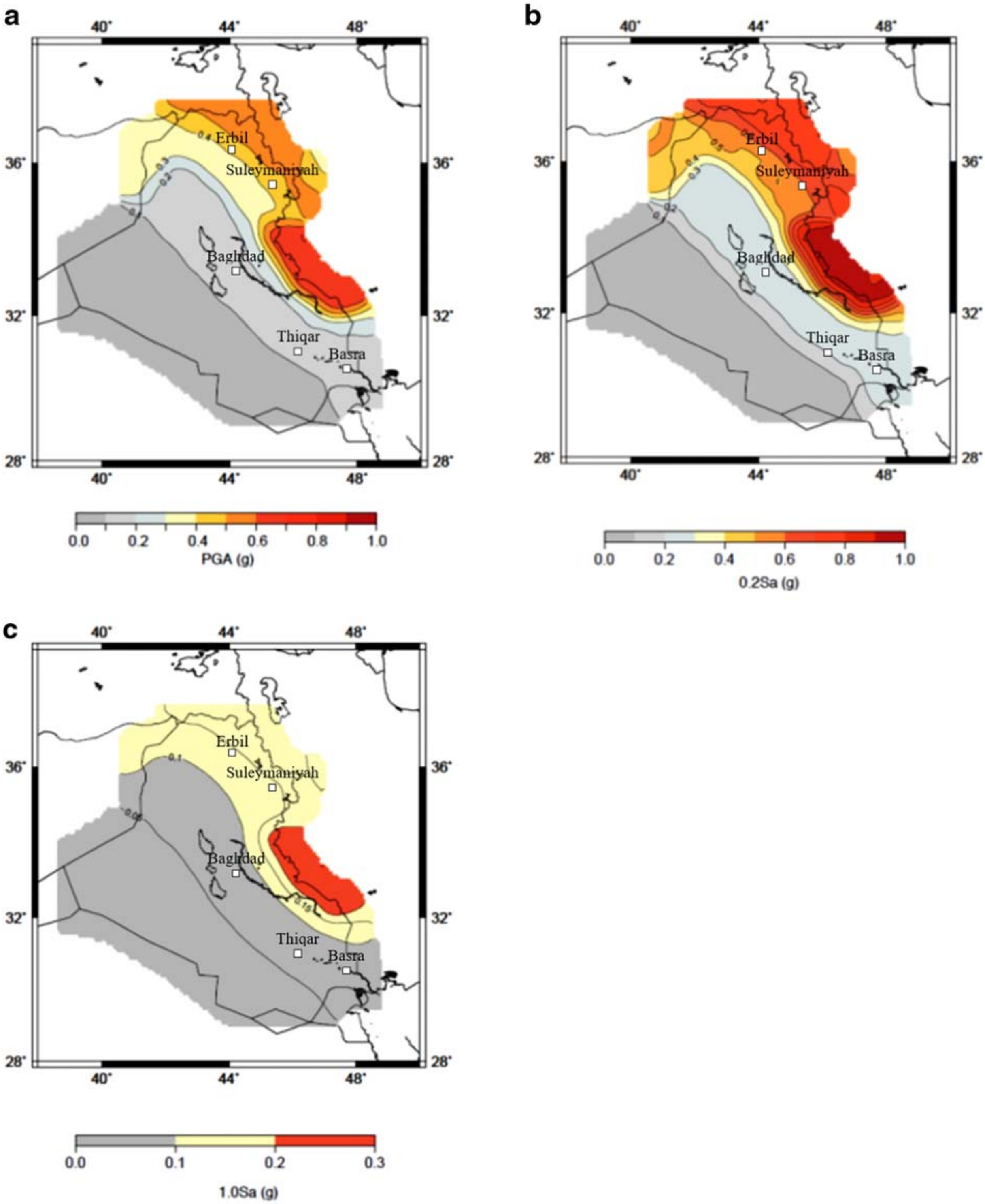
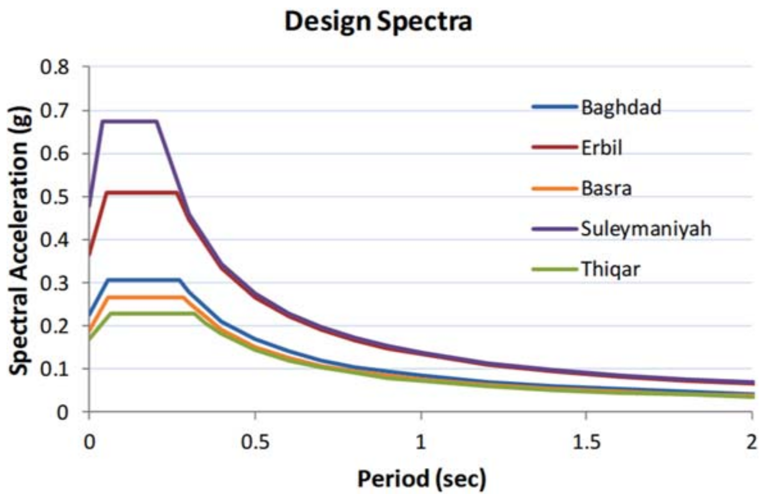


Fig. 7 Probabilistic seismic hazard in Iraq with a 2% chance of exceedance in 50 years on site class B in terms of **a** PGA, **b** spectral acceleration at 0.2 s, **c** spectral acceleration at 1.0 s

Fig. 8 Design spectra for selected cities in Iraq



4 Model implementation and results

Various free and open-source PSHA software are available to implement the source and ground-motion characterizations and run probabilistic analyses, such as OpenQuake (Pagani et al. 2014), OpenSHA (Field et al. 2003), and EqHaz (Assatourians and Atkinson 2013). EqHaz was used for this study due to its ease in the implementation, as this project had a significant training component.

The ground motions were calculated for a 2% chance of being exceeded in 50 years, or a return period of 2475, as required by the building code. Results are presented in hazard maps of PGA, and spectral accelerations at periods of 0.2 s and 1.0 s (Fig. 7).

Design spectra for selected cities, as constructed according to the provisions in the draft building code of Iraq, are plotted in Fig. 8.

In addition, mean hazard curves for spectral acceleration at 0.2 s for Baghdad, along with median, 16th percentile, and 84th percentile curves are presented in Fig. 9.

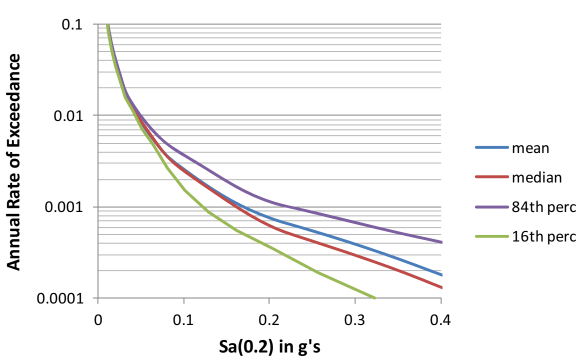


Fig. 9 Hazard curves (spectral acceleration at 0.2 s) for Baghdad

5 Sensitivity analyses and comparison of results

Sensitivity analyses indicated that the largest contributor to uncertainties in the hazard model with the biggest impact on the hazard results is the selection of GMPEs. The hazard dropped significantly if we used only the suite of GMPEs that represent "active tectonic regions" (NGA West 2). Conversely, using only the "stable continental region," GMPEs (NGA East) significantly increased the hazard. Table 3 demonstrates the sensitivity of the 2%-in-50-year PGA in select cities to the selection of GMPEs.

Additional analyses indicated that the short period response, SA(0.2 s) was significantly less sensitive than PGA, and the long period response, SA(1.0 s) was slightly more sensitive than PGA. The sensitivity also varied spatially, reflecting the differences in the hazard across the country.

The high sensitivity of results to the selection of GMPEs highlights the acute need for recorded strong motions in Iraq. As more strong-motion instruments get installed in the country, the understanding of the nature of strong-motion attenuation as well as robustness of hazard assessments will significantly improve.

The hazard study presented here is specifically focused on Iraq, but as a comparison, we examine the differences between our results and a recent regional study undertaken by the EMME project (Giardini et al. 2018, Şeşetyan et al. 2018, Erdik et al. 2012). The

Table 3 Sensitivity of 2%-in-50-year PGA to the selection of GMPEs for select cities in Iraq

2%-in-50-year PGA (cm/s^2)	Active tectonic region GMPEs	Stable continental region GMPEs	Mean PGA
Baghdad	129	311	220
Erbil	199	517	358
Basra	109	259	184
Suleymaniyah	280	655	468
Thiqar	105	224	165

EMME project spans the area between Turkey in the west, and Afghanistan and Pakistan in the east, and partially includes Iraq in the southwestern periphery of its project region. EMME Project uses an active fault compilation for the broader region, including some areas bordering north and east of Iraq, though none of the major active faults modeled in EMME is entirely within the territory of Iraq. This is consistent with our finding that there is an acute lack of reliable geologic slip rates or paleoseismological studies for active faults in Iraq. In the areas bordering northeastern Iraq, despite the different approaches to seismic hazard assessment by EMME (use of specific active faults) and our study (use of area sources to capture a uniform region of active faulting), our results (PGA ~ 0.5 g with a probability of exceedance of 2% in 50 years for NERHP site class B) generally agree with results from the EMME study (PGA of 0.4 g~0.5 s). However, EMME study tends to concentrate high hazard in the immediate vicinity of the faults that are modeled, whereas our results tend to have wider bands of higher hazard around the active fault regions. Given that a Mw7.3 earthquake occurred in November 2017 to the northeast of Iraq on a previously unknown fault within the Bitlis–Zagros fold and thrust belt, we feel that our zone approach to characterizing seismicity from active faults within this region works reasonably well. As we go further southwest deeper into the territory of Iraq, our results tend to be somewhat higher than the EMME study. This is likely due to the differences in the GMPEs selected.

6 The Mw7.3 earthquake in November 2017

As this manuscript was being prepared, a major earthquake of Mw7.3 occurred near the border between Iraq and Iran on 12 November 2017, providing an opportunity to check some aspects of the PSHA model. The earthquake was a result of thrust faulting in one of the unidentified faults within the fault system of Zagros Fold and Thrust Belt. Its mechanism is consistent with the convergence of the Arabian Plate with the Eurasian Plate along the Zagros Fold and Thrust Belt (Fig. 10).

The seismic source zones in our hazard model that are in the vicinity of the fault that ruptured in this earthquake are sources 1 (Bitlis–Zagros Thrust A), 2 (Unstable Shelf A), and 5 (Zagros A). The maximum magnitudes assigned for these sources are Mw7.8, Mw7.6, and Mw7.8, respectively. The November 2017 earthquake is well within the maximum magnitude of these source zones.

The observed ground motions from this earthquake are available in the form of felt reports from both sides of the border and strong-motion recordings from the Iranian strong-motion network. The largest recorded ground motion by a station of the Iran Strong-Motion Network (ISMN) is Sarpolezahab (SPZ) station that has a peak ground acceleration (PGA) of nearly 0.7 g (Zare et al. 2017) at a distance of about 40 km. The Vs30 at the station is 619 m/s (site class C). The hazard assessment for Iraq was carried out for site class B, so the ground motions recorded need to be adjusted down accordingly, to make a comparison possible. Using the NEHRP site amplification factors, the recorded ground motion would have been around 0.5 g on site class B. The hazard maps indicate, for this area, 0.5 g–0.6 g at a 2% chance of exceedance in 50 years. Therefore, a building designed to the proposed Iraqi building code should have survived the largest recorded ground motions from this earthquake. It should be noted that the epicentral region likely experienced stronger ground shaking than the Sarpolezahab (SPZ) station.

7 Discussion and conclusions

A PSHA for Iraq was conducted to support the update of the seismic provisions in Iraq's building code. As required by the new building code, the PSHA results are presented for a 2% chance of being exceeded in 50 years and on a reference ground condition of NEHRP site class B. The highest seismic hazard is in locations near the Badra–Amarah fault in eastern Iraq, which ruptured many times in historical times causing major damage to nearby communities. Northern Iraq also has a significant seismic hazard, where the fold and thrust belt causes frequent significant earthquakes (such as the Mw7.3 earthquake on 12 November 2017). Although seismic activity is relatively rare in central and western Iraq, and these regions have lower seismic hazard than the rest of the country, a major earthquake cannot be ruled out anywhere in Iraq.

The lack of recorded strong-motion data in Iraq necessitated novel approaches to modeling ground

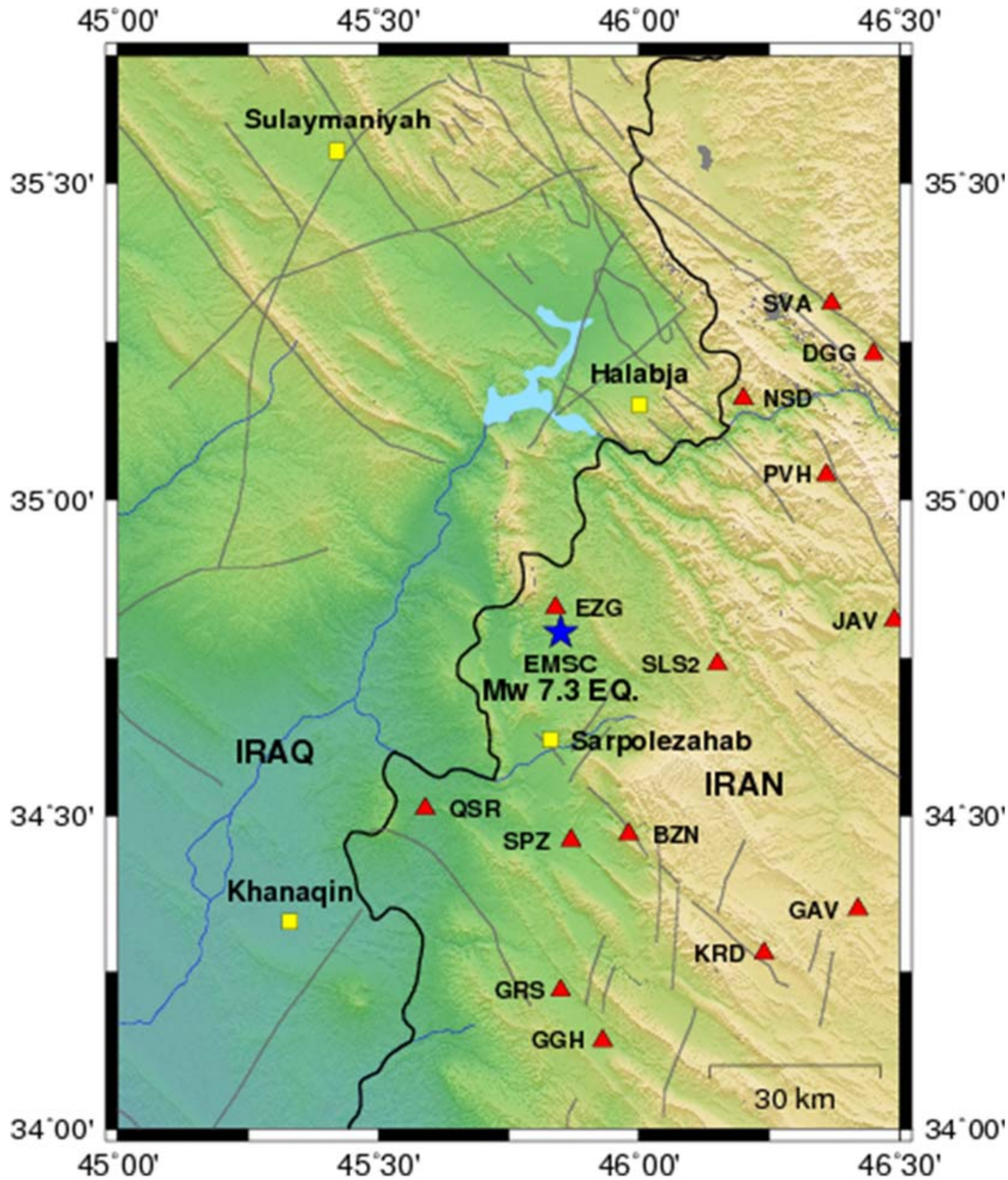


Fig. 10 The epicenter of the Mw7.3 earthquake on 12 November 2017 taken from the EMSC (blue star) and location of strong-motion stations of the Iran Strong-Motion Network (ISMN) (red triangles)

motions in this study. 1 Hz Lg Q appears to indicate that the craton in the region (Arabian Shield) has similar slow attenuation characteristics as the craton in Central/Eastern North America, and active tectonic regions (such as parts of Turkey and Iran) have fast attenuation rate, similar to California. However, attenuation in Iraq appears somewhere in the middle of these two extremes, which compelled us to equally weigh GMPEs for active tectonic regions against those for stable continental regions. There are likely other parts of the world where a binary assumption on crustal GMPEs (either “active” or “stable”) may not be appropriate. In these cases, 1 Hz Lg Q may provide a reasonable way to validate GMPE assumptions or assist in choosing suitable logic tree weights.

This study represents the most recent effort to understand seismic hazard in a region that had major gaps in seismic data and knowledge. The resulting maps are aimed to benefit not just the updated building code but also understanding and reduction of seismic risk in the region.

While this study utilized the best available data and research to date, currently, several additional studies are being undertaken by the authors to improve the PSHA described in this paper. The earthquake catalog used in this study goes until the end of 2009. An update of the catalog is underway adding six more years of seismicity. Since the Badra–Amarah fault is such a significant contributor to seismic hazard in the country, detailed tectonic studies of this fault are underway in order to allow a better characterization of this fault in future PSHA studies. Lessons learned from the Mw7.3 earthquake in November 2017 are still emerging and will be incorporated into the next version of the PSHA. Finally, since this study was conducted, two strong-motion instruments have been installed, one in Sulaymaniyah (northern Iraq) and one in Basrah (southeastern Iraq). As strong-motion data becomes available from these instruments, ground-motion prediction equations used in this study will be revised.

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