Assessing Seismic Hazard and Risk Globally for an Earthquake Resilient World

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Abstract

The constant growth of world population has led to growth in conurbations prone to disasters associated with natural hazards and - as a consequence - to an increase in the overall level of societal risk. Amongst natural catastrophes, earthquakes represent about one fifth of the economic losses, and are responsible for an average of 20 thousand fatalities per year. This increasing pressure requires the development and implementation of risk reduction measures, ideally supported by reliable and technically sound risk information, such as maps, with expected hazard intensities, annualised average losses, or losses for a particular return period (or probability of exceedance). Some of the challenges to the generation of this information are due to the lack of open models, datasets and tools, as well as insufficient local capacity to create or use such resources. The recognition of this shortage of models and need to improve institutional capacity to assess the impact of earthquakes propelled the Global Earthquake Model (GEM) and its partners to develop an open seismic hazard and risk model with global coverage. In this contribution we describe the hazard, exposure and vulnerability components of this model, and the open-source tools that have been created to allow experts to reproduce the hazard and risk results, or tailor parts of the model to specific needs. We also provide a discussion regarding how the results from the global earthquake model may be used to identify global risk trends, and support the monitoring of the Sendai Framework for Disaster Risk Reduction.

The need for for a global earthquake risk model

In 10 years world population will exceed 8 billion, and by the year of 2055 we will be more than 10 billion. This growth in population has resulted in an increase in losses due to natural hazards from 14 billion USD annually to more than 140 billion USD between 1985 and 2014. Earthquakes constitute on average 20% of the annual losses, but in some years this proportion has been as high as 60% (e.g. 2010, 2011). This peril has been responsible for an average death toll of over 20 thousand people per year in the last several decades and economic losses that can reach a great fraction of a country's welfare. In Central America and the Caribbean, the earthquakes of Guatemala (1976), Nicaragua (1972), El Salvador (1986) and Haiti (2010) caused economic losses of approximately 98%, 82%, 40% and 120% of the nominal gross domestic product (GDP) of each country, respectively (Daniell et al., 2010). This impact hinders sustainable development, creation of jobs and availability of funds for poverty reduction initiatives (UNISDR, 2015). In addition to these direct consequences in the vicinity of the seismic event, business disruption of large companies can induce a negative impact at a global scale. After the Great East Japan earthquake in 2011, the electronics industry suffered systematic delays in the supply of numerous components produced by some of the affected factories, which led to a worldwide rise of prices due to stock shortage. The trend in the losses (ground-up and insured) in the last 4 decades is illustrated in Figure 1. In one quarter of the recorded years the ground-up losses exceeded 20 billion USD, and in the last 15 years the annual losses were always above 5 billion USD.

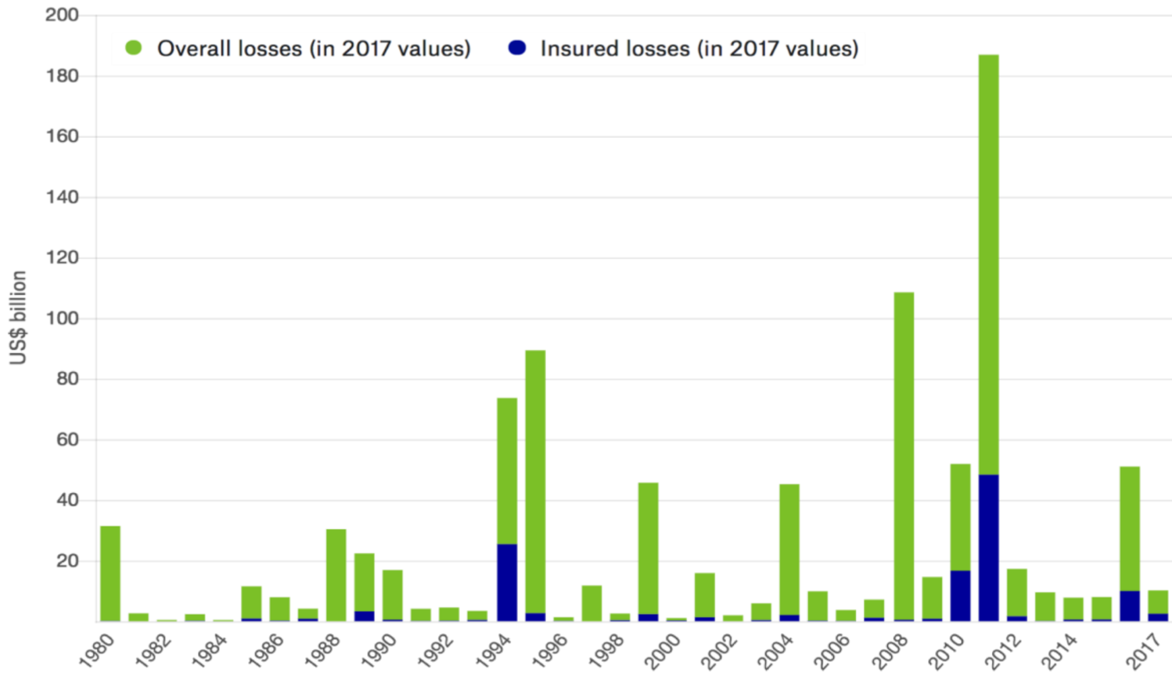

Figure 1 – Overall and insured losses between 1980 and 2013 (from MunichRe, 2018).

Altering the trend in disaster losses is only possible through the development and implementation of efficient risk reduction measures. In the last 20 years, about 12 billion EUR have been financed by large institutions (e.g. European Union, World Bank) and national governments (e.g. Japan, Australia, United States) for the implementation of risk reduction measures in regions frequently struck by natural hazards (Kellett and Caravani, 2013). Understanding the magnitude of human and economic losses from damaging events is fundamental in order to inform decision makers and disaster risk managers in the development of such measures. For example, in 2009 the Italian Government invested almost 1 billion EUR in a seismic prevention programme at the national scale. In order to distribute the funds across the different regions, a seismic risk assessment study was conducted and the funds were distributed proportionally (Dolce, 2012). Similarly, in 2002 a catastrophe insurance pool for residential buildings was created in Turkey to transfer the risk from the public sector to the international reinsurance market (Bommer et al. 2002). The establishment of this financial mechanism required an earthquake model to estimate the expected economic losses from each province. More recently, Mora et al. (2015) demonstrated how a probabilistic loss model was used to prioritize which schools should be the target of a retrofitting intervention in Colombia.

At the global scale, one of the most relevant efforts to understand earthquake hazard was the Global Seismic Hazard Assessment Program (GSHAP – Giardini et al, 1999), which combined several national and regional models to produce the first global hazard map of peak ground acceleration for a return period of 475 years on rock. This map has been one of the main references to illustrate the threat posed by earthquakes globally. More recently, the United Nations International Strategy for Disaster Risk Reduction (UNISDR) supported the development of the Global Assessment Report (GAR, 2015) one of the most notable efforts at the global scale to provide uniform average annual losses for earthquakes. The exposure model developed for the GAR was derived based on a top-down approach, where national/regional population, socio-economic data and building-type information were used as proxies to estimate the spatial distribution of building counts (DeBono and Chatenoux 2015). For the hazard component, a fully probabilistic model was developed using the NEIC-USGS earthquake catalogue and hundreds of seismic sources distributed across six tectonic regions (Ordaz *et al.,* 2013). This effort employed for the first time a uniform approach for seismic hazard assessment at the global scale, resulting in sets of conventional hazard curves and earthquake scenarios. These scenarios were used to estimate annualized average losses and aggregated losses for specific return periods.

Earthquake loss models are comprised of three main components: an exposure model defining the spatial distribution, replacement cost and vulnerability class of the building stock, a suite of vulnerability/fragility functions to estimate the likelihood of damage/loss conditioned on a set of ground shaking intensity measure levels, and a probabilistic seismic hazard analysis (PSHA) model describing the probabilities of exceeding various ground shaking levels in the region. These components can be introduced in an analysis software to estimate seismic hazard and risk results. The Global Earthquake Model (GEM) has supported the development of an open-source software for such analyses, the OpenQuake-engine (Pagani et al. 2014, Silva et al. 2014). This software is capable of producing a number of relevant hazard and risk results, such as seismic hazard curves and maps, uniform hazard spectra, annualized average losses, probable maximum losses (for a set of return periods), aggregated loss exceedance curves, event loss tables and risk maps. This broad set of risk metrics can support decision-makers in the identification of regions that are prone to higher and more frequent earthquake-induced hazards and losses, to distinguish construction types that have high vulnerability, and to devise strategies for effective risk mitigation. Despite the evident importance of such results, earthquake loss models are usually only available for developed nations, and not always accessible to all stakeholders. Moreover, even when some datasets and models do exist for a particular region, the required capacity to use and customize these models might not exist, which once again impedes the use of reliable earthquake risk information in decision-making.

In order to minimize these challenges, GEM and its partners have developed an open seismic hazard and risk model capable of providing fundamental information at the national and sub-national level for the development of risk reduction measures. This article describes the different components of the global model and the open-source tools that were developed for the estimation of the results. The global model is a mosaic of individual risk models produced as part of regional programmes - for example, SARA in South America (Yepes and Silva 2017), EMCA in Central Asia (Pittore et al. 2018), SERA in Europe (Crowley et al. 2018),and SSAHARA in Africa (Poggi et al. 2017)) - or bilateral collaborations between GEM and national institutions – for example the USGS and FEMA in the United States, Natural Resources Canada (NRCan) in Canada, Geoscience Australia in Australia, and GNS Science in New Zealand. Each part of the global model was developed using (as much as possible) the same derivation methodology and the same software for the estimation of the hazard and risk results. This approach allows for a direct comparison between hazard and risk estimates between regions within the same country, or similar events between different nations. This modelling approach can also support the estimation of the different risk metrics and targets of the Sendai Framework for Disaster Risk Reduction[1].

Creating a global mosaic of hazard models

The calculation of earthquake risk requires the definition of where, how often and how severely earthquakes will strike in the future. With an earthquake hazard model and software, it is possible to compute this information and hence identify the areas where earthquakes pose a major threat. Generally, seismic hazard models refer to either a specific site or a national territory depending on the typology of the project involved, while models at continental or global scale provide a broader understanding of the spatial distribution of hazard.

The first global seismic hazard model was created within the Global Seismic Hazard Assessment Program (GSHAP) at the end of the 1990's (Giardini et al., 1999). It represented a substantial improvement in our understanding of

[1] Sendai Framework for Disaster Risk Reduction: https://www.unisdr.org/we/coordinate/sendai-framework

earthquake hazard globally and offered to many countries essential information for the design of buildings and land-use planning. GSHAP was a collective effort that involved more than a hundred scientists from dozens of countries globally and encouraged sharing of information, scientific debate and international collaboration. Because of the nature of the GSHAP project, the resulting gobal hazard model was formed by assembling various newly created continental and subcontinental models.

Almost twenty years later, GEM in collaboration with hundreds of scientists from more than 50 nations has released a completely new compilation, called the GEM earthquake hazard mosaic of earthquake hazard models created either at national or regional (i.e. continental) scale[2]. This collection of models is homogeneous in the sense that the format adopted for the description of each model conforms with the one used to describe an input earthquake hazard model for the OpenQuake-engine. However, the models in the mosaic have different origins and were developed using diverse methodologies depending on the organisations and the experts involved. Overall, the mosaic contains regional models for Europe, Middle East, Central Asia, Continental Southeast Asia, Africa, South America, Mexico, Central America and the Caribbean, Northern Asia and Pacific Islands. In the majority of cases, local scientists either led the development of the model or collaborated with GEM scientists in its preparation. At a higher resolution, a second set of models is composed of seismic hazard models developed at a national level by agencies charged with assessing earthquake hazard for their countries. This set, for example, comprises models for the Arabian Peninsula, Canada, Indonesia, Philippines, Australia, New Zealand, India, Japan and the United States. While the vast majority of models were developed either collaboratively within a GEM project or through an official development process at national level, models for a few remaining areas were developed separately by the GEM Secretariat (e.g., Russia, North Africa).

There are some notable differences between the hazard models created in the GSHAP project and the ones included in the GEM earthquake hazard mosaic. Overall, recent models are more complicated because they describe explicitly epistemic uncertainties in the seismic source and ground motion characterisation. Another major step forward has been in the improved characterization of earthquake faults and the ability to associate the locations of potential future earthquakes to active fault sources. Thus, in contrast to GSHAP, the potential occurrence of the largest

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[2] Nature article: https://www.nature.com/articles/d41586-018-07705-2

earthquakes are now associated with specific fault sources, resulting generally in more refined and accurate estimates of the most significant earthquake hazards (and associated risks).

Figure 2 shows a hazard map depicting the spatial distribution of the values of peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years. The zones showing the highest values of hazard are along the major plate boundaries, particularly on the coasts of the Pacific Ocean and within the Alpine-Himalayan deformation belt. It is worth noting that a substantial majority of the models included in the mosaic were developed using the OpenQuake-engine. The development of the OpenQuake-engine performed in parallel with the construction of the GEM earthquake hazard mosaic therefore benefited from the feedback of experts across the world and supported the widespread and parallel preparation of modern hazard models. The hazard maps were calculated following the classical probabilistic seismic hazard assessment methodologies (Cornell 1968, McGuire 2004), and the OpenQuake-engine is publicly available (including the source-code) at Github[3].

[3] OpenQuake GitHub repository: https://github.com/gem/oq-engine/#openquake-engine

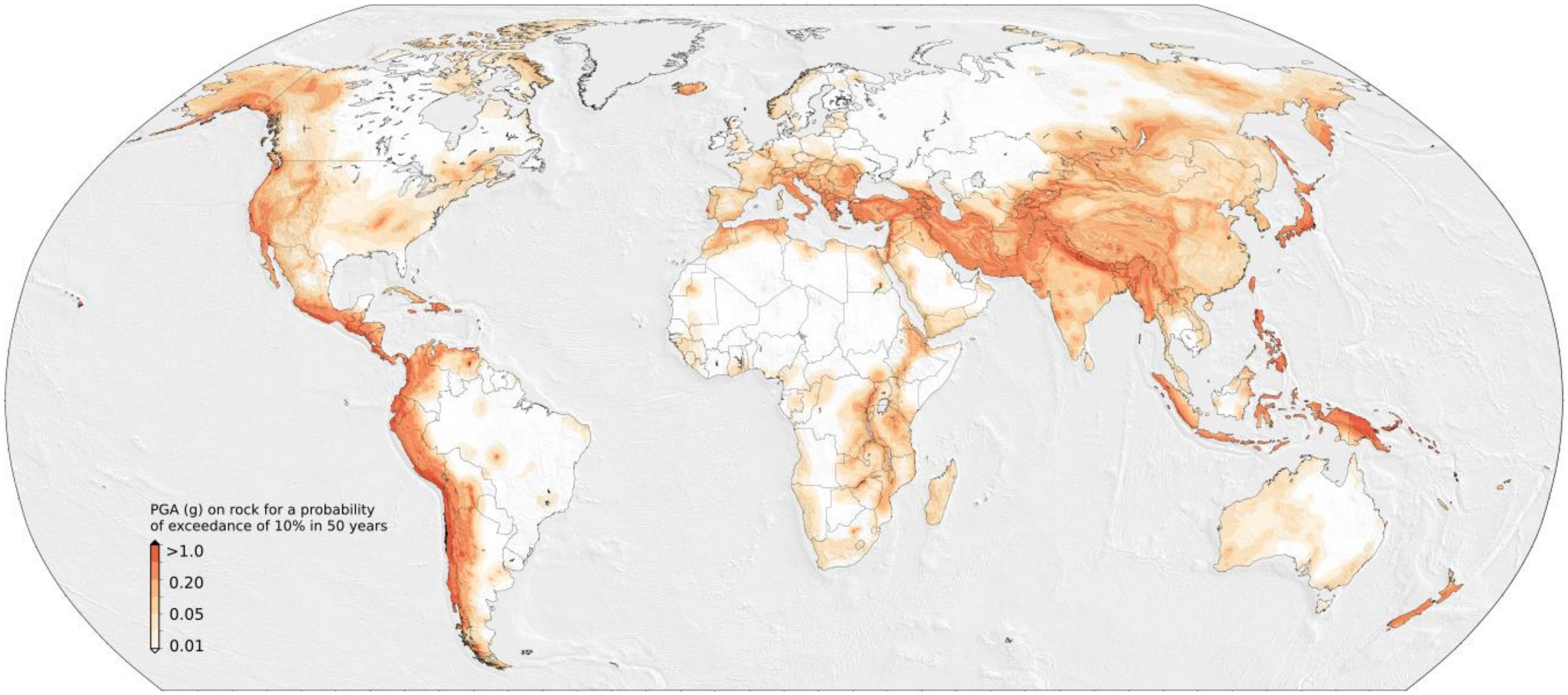

Figure 2 – GEM Global seismic hazard map in terms of the peak ground acceleration (PGA) with 10% probability of exceedance in 50 years.

Building a global exposure model

The assessment of earthquake impact requires the availability of a reliable and up-to-date exposure model. This component of the risk assessment describes the location of the assets, replacement costs, number of occupants (at different times of the day) and the vulnerability class of each asset. The development of a global exposure model is arguably one of the most difficult steps in the development of the global risk model due to the lack of data. Even when some information is available, the fact that the built environment has changed rapidly in some parts of the world (e.g. South-east Asia, Central America) makes the existing data obsolete. It is also potentially one of the most subjective components of risk analyses due to the need to complement the limited existing data with judgement from local experts.

The global risk modelling effort covers three types of building occupancies: residential, commercial and industrial. The derivation method for residential buildings differs considerably for most of the countries in comparison with the procedure required for the commercial and industrial building stock, as discussed further in the following sections.

Modelling the residential building stock

The development of the global residential exposure model relied predominantly on data from the national housing census of each country. These surveys are usually performed every 10 years at the smallest administrative level, or according to a regional division defined specifically for the purposes of the housing census (e.g. Mexico, United States, Canada). The quality of the data collected by each country, unfortunately, varies considerably. In the best-case scenario, the survey data comprises information concerning the number of buildings, type of structures (e.g. isolated houses, apartment buildings), main material of construction, material of the roofs, material of the floors, number of stories, year of construction and even the state of conservation of the building (e.g. Portugal, Costa Rica). For many nations (e.g. Algeria, Iraq, Zambia, Mali), the survey data is quite limited and only provides information on the type of dwelling and the main material of the walls (e.g. wood, brick, concrete). In these cases, it is necessary to develop a mapping scheme, which establishes a relation between the variables used by the national housing census, and the most likely vulnerability classes. The definition of these mapping schemes is performed using peer-reviewed literature, World Housing Encyclopedia (WHE) reports, and the judgment of local experts, collected using remote expert surveys or locally organized workshops. For some countries the mapping schemes had to be derived differently for different areas within a given region (urban versus rural areas), and in some cases a specific mapping scheme was also developed for a large city (e.g. Addis Ababa in Ethiopia, Panama City in Panama, Santo Domingo in Dominican Republic) or different levels of urbanization (e.g. India, Mexico). Alternative approaches were also followed in countries (e.g. Central Asia) where the housing census is either insufficient or simply not available. In these cases rapid screening activities were performed in selected locations and integrated by ancillary information derived from satellite imagery and from volunteered geoinformation (e.g. Pittore and Wieland 2012, Wieland et al. 2015).

It is also worth noting that for a few countries it was not necessary to develop an exposure model based on the housing census information, due to the availability of datasets with a higher reliability that have been used in natural hazards risk analyses for many years. This applies to the United States (Jaiswal et al. 2015, FEMA P-366 2017), Canada, (covered by different versions of the HAZUS software - FEMA 2001), Australia (covered by the NEXIS dataset / Nadimpalli et al. 2007) and New Zealand. On the other end of the spectrum, there are also countries that simply have no housing information available (e.g. Democratic Republic of Congo, South Sudan), or have been heavily affected by natural hazards (e.g. hurricanes, earthquakes) after the completion of the national housing census (e.g. Haiti, Nepal). In these cases, an alternative approach had to be adopted that leveraged population datasets, satellite imagery and OpenStreetMap data.

The combination of different sources of exposure information will inevitably lead to a global exposure dataset that is not uniform in resolution, quality and vintage. Nonetheless, to the maximum extent possible, the same methodology and taxonomy (see Silva et al. 2017) was used in the generation of the exposure model of each country. An example of such an outcome is presented in Figure 3 for twelve countries located in the Middle East.

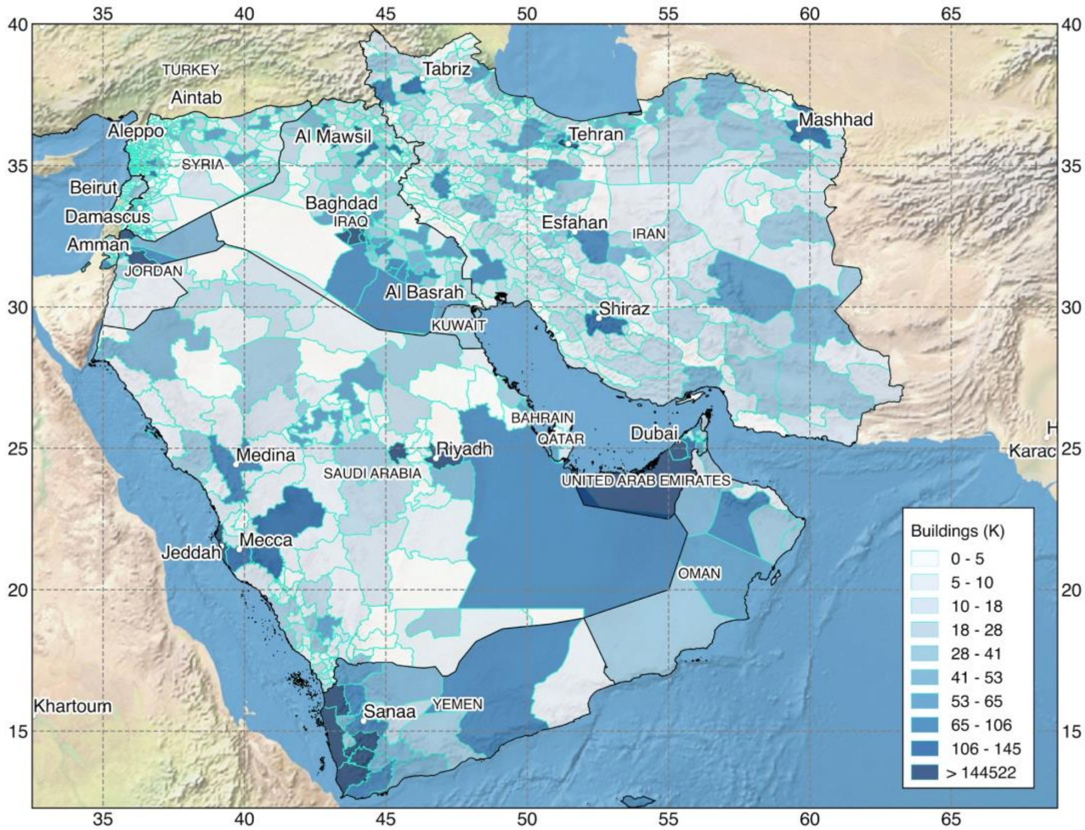

Figure 3. Distribution of the number of residential buildings at the smallest available administrative subdivision for twelve countries in the Middle East.

3.2 Industrial and commercial building stock

Exposure information regarding non-residential buildings is rarely compiled systematically at a regional or national scale, as previously presented for the residential counterpart. In the vast majority of cases, one has to rely on secondary sources of data such as economic census surveys which provide data regarding the number of employees and various other economic indicators that are related to commercial and industrial structures. The exceptions are once again the United States and Canada, where the HAZUS dataset does in fact cover detailed estimates of the commercial and industrial building stock.

The development of the exposure models for non-residential occupancy types relied on three main sources of datasets: 1) demographic data concerning the work-force across the different sectors (primary, secondary, and services) or types of businesses (e.g. agriculture, mining, manufacturing, retail, car industry, small shops); 2) data concerning the number of permits, which may also specify the date, type of business, size of the facility and number of workers; and 3) large scale datasets that identify regions according to occupancy (e.g. Corine for Europe – Sousa et al. 2017). In addition, web surveys engaging hundreds of experts to collect missing information (e.g. type of construction per sector, average area per worker) were used. The combination of these datasets allows the estimation of the average built up area or number of facilities per occupancy (at the smallest available administrative level), which is then distributed across a number of vulnerability classes. Figure 4 depicts the number of industrial and commercial facilities at the first administrative level for 7 countries in Central America.

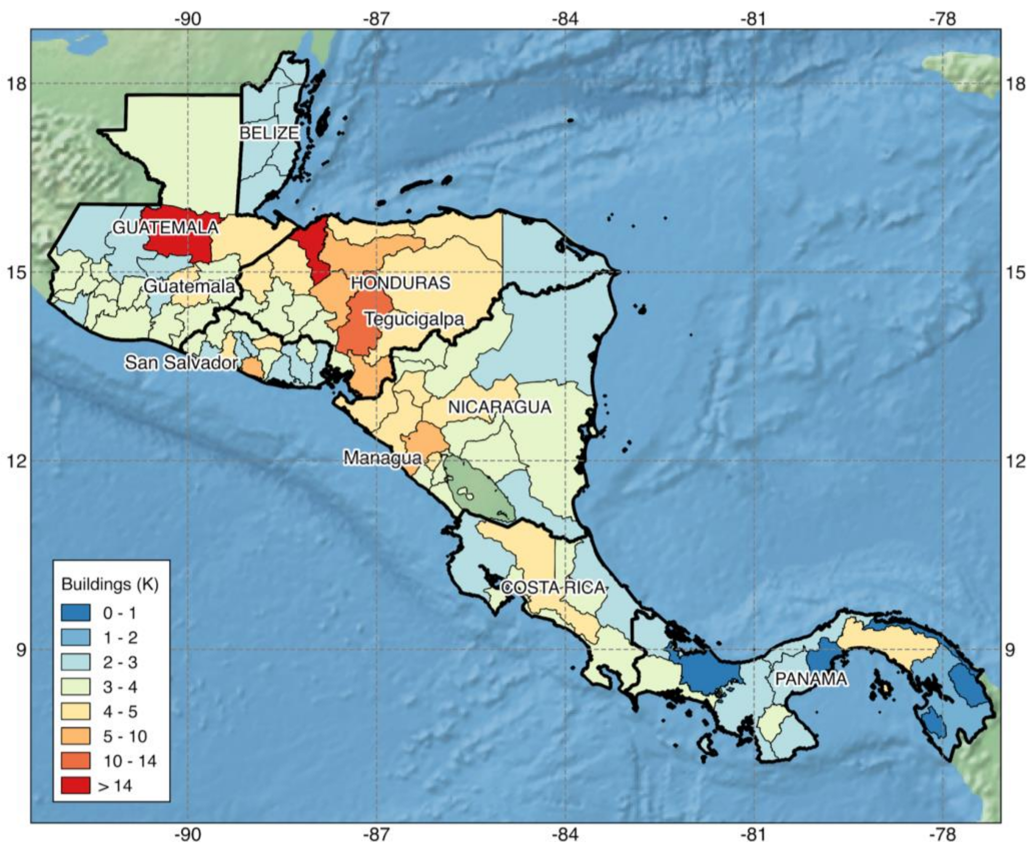

Figure 4. Distribution of the number of industrial facilities at the first administrative level for sevel countries in Central America.

It is clear that some of the administrative regions cover extensive areas (e.g. Malaysia, Indonesia), within which the seismic hazard can vary considerably. For this reason, an additional step is followed to spatially re-distribute the assets within each area, following a smaller evenly spaced grid (30x30 arcsec). In order to assess the grid points where buildings are expected to exist, a number of auxiliary datasets are considered such as nighttime lights (Elvidge et al. 2012), WorldPop (www.worldpop.org.uk) and the location of residential and tertiary roads from OpenStreetMap (www.openstreetmap.org). The evenly spaced exposure dataset can be aggregated following different approaches to illustrate the distribution of the building stock at the national, regional or global scale. The estimated number of buildings at the global scale is depicted following a hexagonal grid with 0.30x0.34 decimal degrees in Figure 5. Unsurprisingly, the resulting global exposure database indicates a large concentration of buildings in South-East Asia, western Latin America, Central and South Europe and eastern Sub-Saharan Africa. Unfortunately, as presented in Figure 1, these regions also have significant seismic hazard.

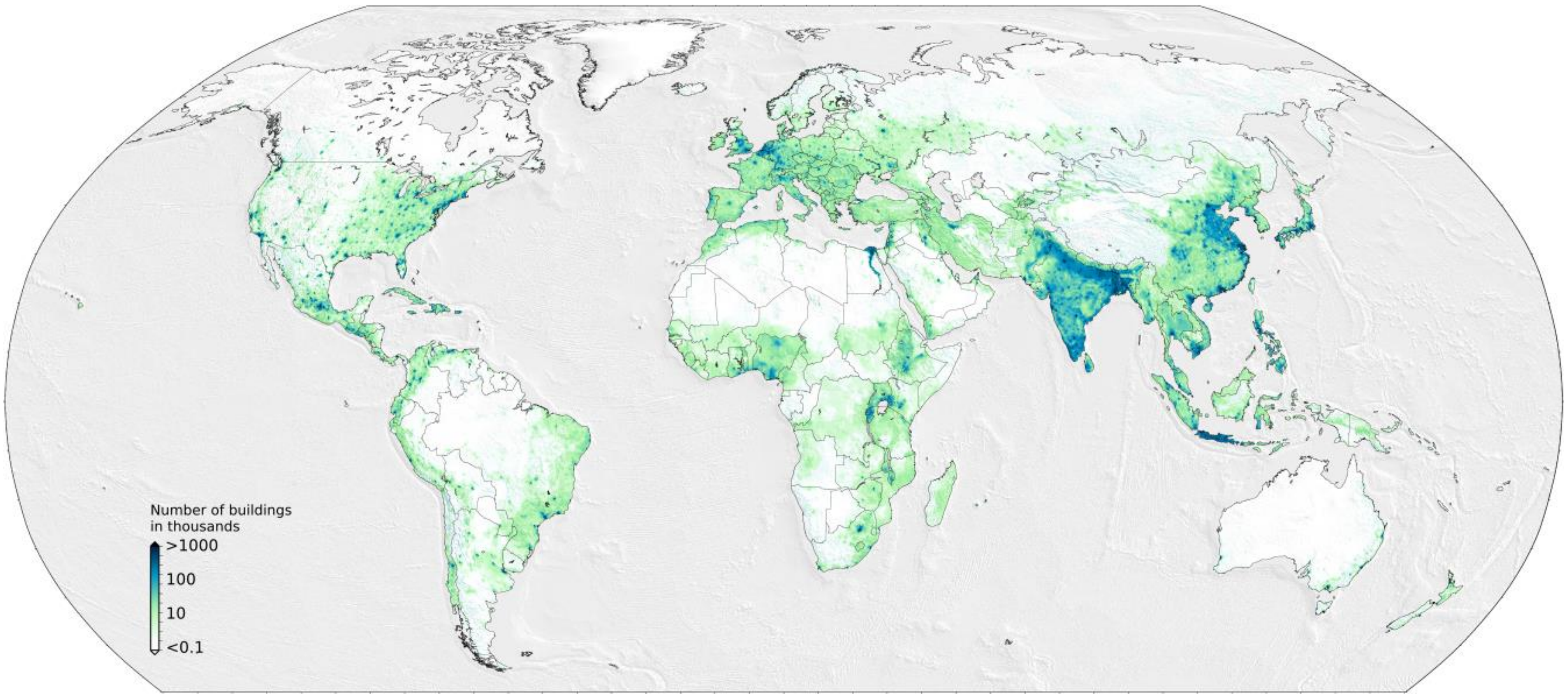

Figure 5. Global distribution of building count following a hexagonal grid with 0.30x0.34 decimal degrees.

Evaluating the seismic vulnerability of the global building stock

The vulnerability component characterizes the likelihood to suffer damage or loss given a hazard intensity. The relation between probability of loss and hazard intensity is expressed by a vulnerability model, whilst the relation between probability of damage and hazard intensity is represented by fragility functions. Despite the notable advances in regional seismic vulnerability modelling in the last three decades (e.g. HAZUS (2004) in the United states and Canada, LESSLOSS - Calvi and Pinho (2004) in Europe, SARA - Villar et al. (2017) in South America), a uniform set of vulnerability or fragility functions covering all of the building classes around the world does not currently exist. This lack of vulnerability models is particularly evident in the developing world (Yepes et al. 2016), and in other places where large earthquakes are rare. Moreover, with a few exceptions, most of the existing vulnerability functions have not been tested against damage data from previous events or have not been applied within a probabilistic framework for earthquake loss assessment (Silva et al. 2018).

To minimize some of these obstacles, GEM and its partners collaborated in the development of a set of vulnerability functions for the most common building classes, using uniform and consistent derivation approaches. In this process, the most common building classes in the region were identified using peer-reviewed literature and web surveys. Then, a simplified numerical model was developed for each building class, considering the associated structural and dynamic properties. These models were tested against a large set of ground motion records, collected from databases in Japan, United States, Chile, Mexico, Europe and the Middle East. The structural response of each model against selected ground motion records was used to estimate the expected damage and loss, following a damage criterion (e.g. Villar et al. 2017). The resulting fragility functions were used directly for the estimation of damage based on the characteristics of past events, while the vulnerability functions were employed in the earthquake loss assessment at the global scale.

A similar approach has been followed for the development of fragility and vulnerability functions within the scope of regional programs in South America (Villar et al. 2017) and Europe (Crowley et al. 2018).

Assessing earthquake risk globally

The calculations for probabilistic seismic hazard were performed using the OpenQuake-engine, the open-source software for seismic hazard and risk calculations supported by GEM (Pagani et al. 2014, Silva et al. 2014b). Using the seismogenic source model for each region, the OpenQuake-engine can generate several possible realizations of seismicity conditional on a given interval of time (i.e. stochastic event sets). In this process, several sources of epistemic uncertainty can be considered using the logic-tree structure (e.g. uncertainty in estimation of maximum magnitude, seismic zonation boundaries, magnitude-frequency parameters). The number of possible branches can range from a few dozen (e.g. North and Sub-Saharan Africa – Poggi et al. 2017) to thousands (e.g. India, United States – Fields et al. 2014). Each rupture was used to generate a ground motion field considering the logic tree for ground motion prediction equations associated with each tectonic environment. Amplification or attenuation effects are accounted for through the consideration of estimates of shear wave velocity in the top 30 meters of the ground surface (Vs30), which are available globally through simplified topographic-based empirical models proposed by Wald and Allen (2007).

The ground shaking at the location of each asset is used to calculate the resulting loss ratio using the associated vulnerability function, considering the uncertainty in the distribution of the loss ratio per intensity measure level. This loss ratio is multiplied by the estimated replacement cost of the asset to obtain the final economic loss. The losses per event (across all of the stochastic event sets) can be aggregated to produce an event loss table, indicating the total loss for each generated event. The average annual loss (*AAL*) can be obtained by dividing the sum of the annualized economic losses by the total number of 1-year stochastic event sets. Additional information concerning the procedure for the calculation of the earthquake losses following the event-based approach can be found in Silva (2017).

The global risk results are presented in Figure 6 following an hexagonal grid with a spatial resolution of 0.30x0.34 decimal degrees (approximately 1000 km2 at the Ecuador). In this map, the average annual losses have been normalized by the construction cost of each country, in order to avoid an over-representation of the countries with high construction costs.

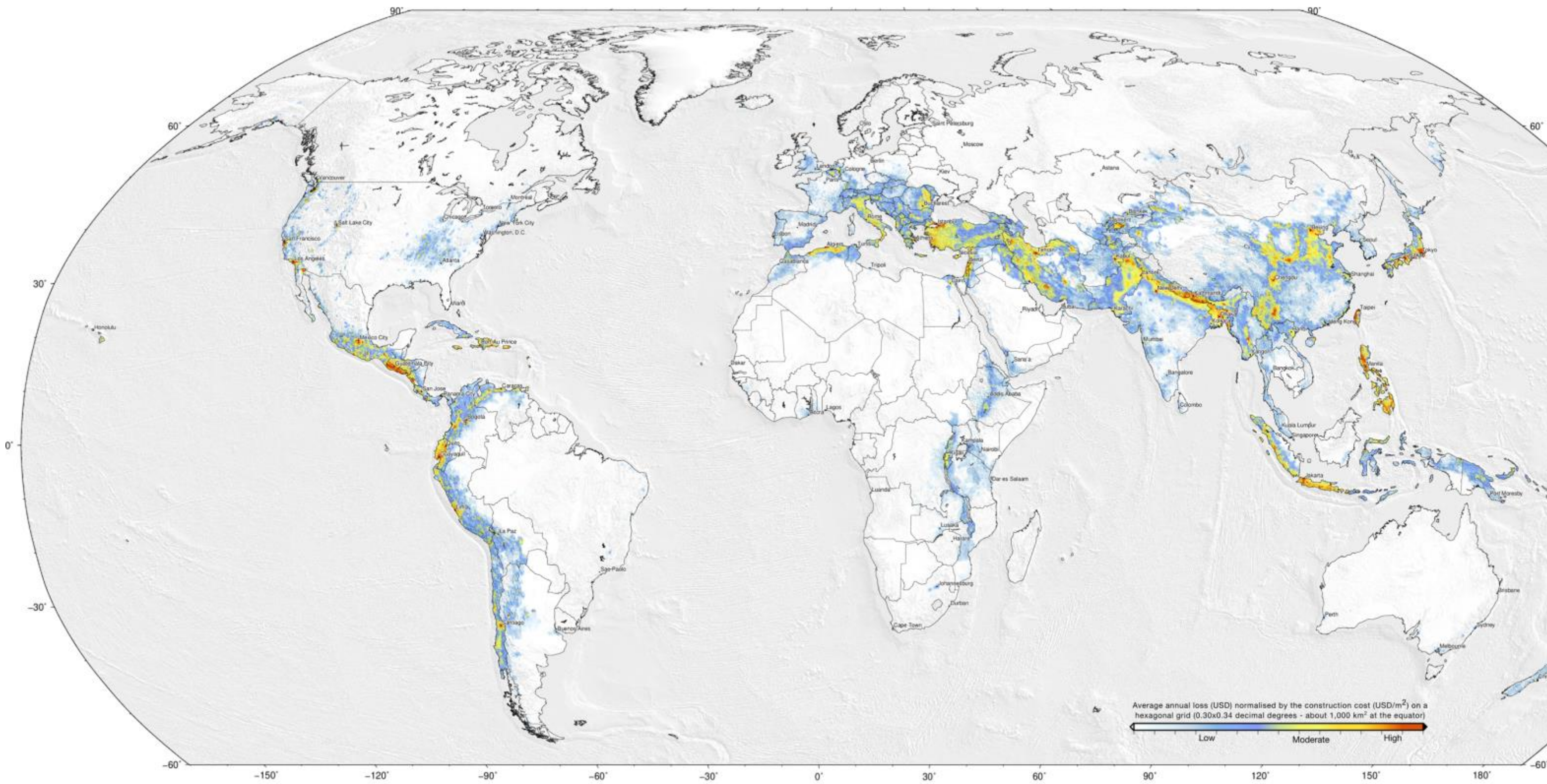

Figure 6. Global seismic risk in terms of average annual losses normalized by the average construction cost of each country, following a hexagonal grid with 0.30x0.34 decimal degrees.

This first version of the Global Earthquake Model indicates an average annual loss of over 45 billion USD per year, which is approximately equivalent to the annual gross domestic product of countries such as Slovenia or Guatemala, and about 4 times higher than the total investment in disaster risk reduction from international organizations (e.g. Japanese International Cooperation Agency, World Bank, European Union) in the last 20 years. The top 15 countries in terms of economic losses contribute to 80% of the global average annual loss. The residential building stock contributes 64% of the total annual loss, while commercial and industrial buildings represent 22% and 14% of the losses, respectively. Japan, China (including Taiwan), the United States of America, Turkey and Italy lead the ranking, mostly due to the high economic value of the building stock in those countries, as presented in Figure 7.

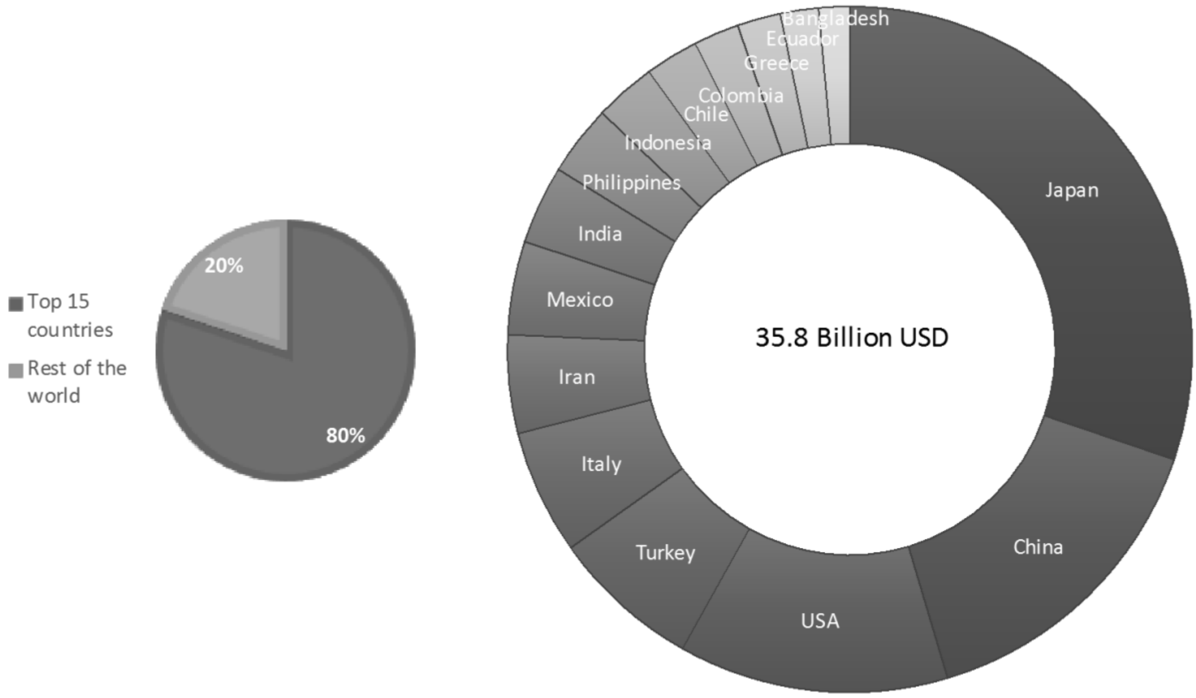

Figure 7. Top 15 countries in terms of average annual economic losses (in billion USD).

The evaluation of the earthquake risk in terms of absolute economic losses can be misleading, as poor or lesser populated countries with vulnerable structures have annual losses several orders of magnitude below nations such as Japan, United States or China. It is thus useful to normalise the average annual losses based on the total exposed value. This metric is called the average annual loss ratio and, accordingly, the top 15 countries are depicted in Figure 8. Unsurprisingly, this list is led by countries with a history of large disastrous events (e.g. 2001 M7.7 El Salvador, 2007 M8.0 Peru, 2015 M7.8 Nepal), with poor construction practices, and with high seismic hazard (see Figure 1).

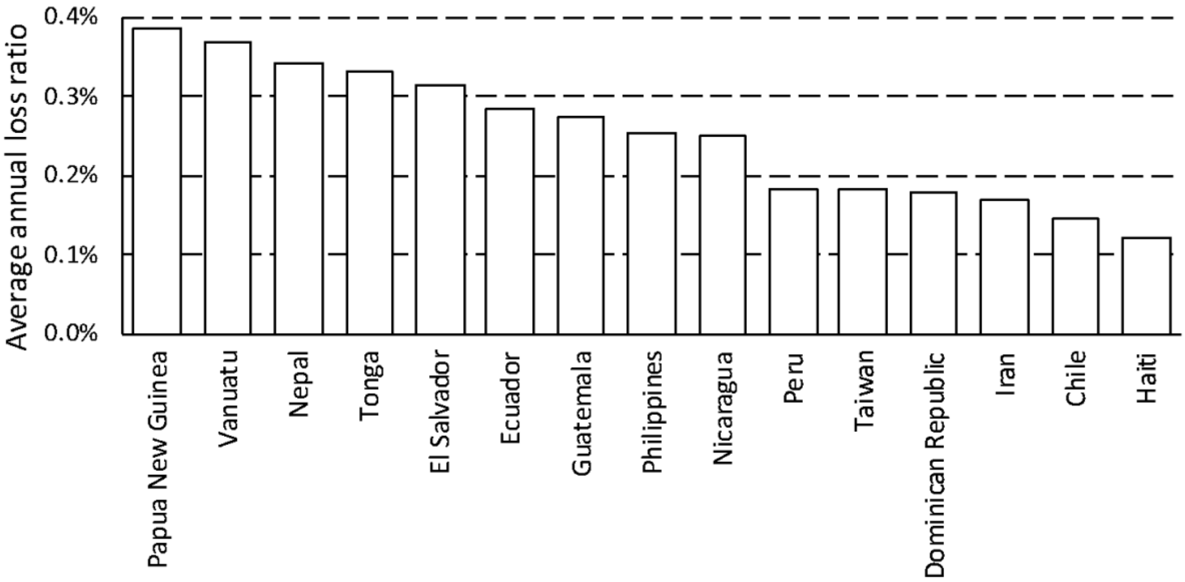

Figure 8. Top 15 countries in terms of relative average annual economic losses (i.e. normalized by the total exposed value).

The results from this global seismic risk model were also compared with the estimates provided by other initiatives, in particular the previously described Global Assessment Report (GAR 2015). The latter risk estimates provide average annualized losses and loss exceedance curves for six building occupancies (DeBono and Chatenoux 2015, GAR 2015). A comparison between the aggregated *AAL* covering the residential, commercial and industrial building stocks from GAR and GEM is presented in Figure 9.

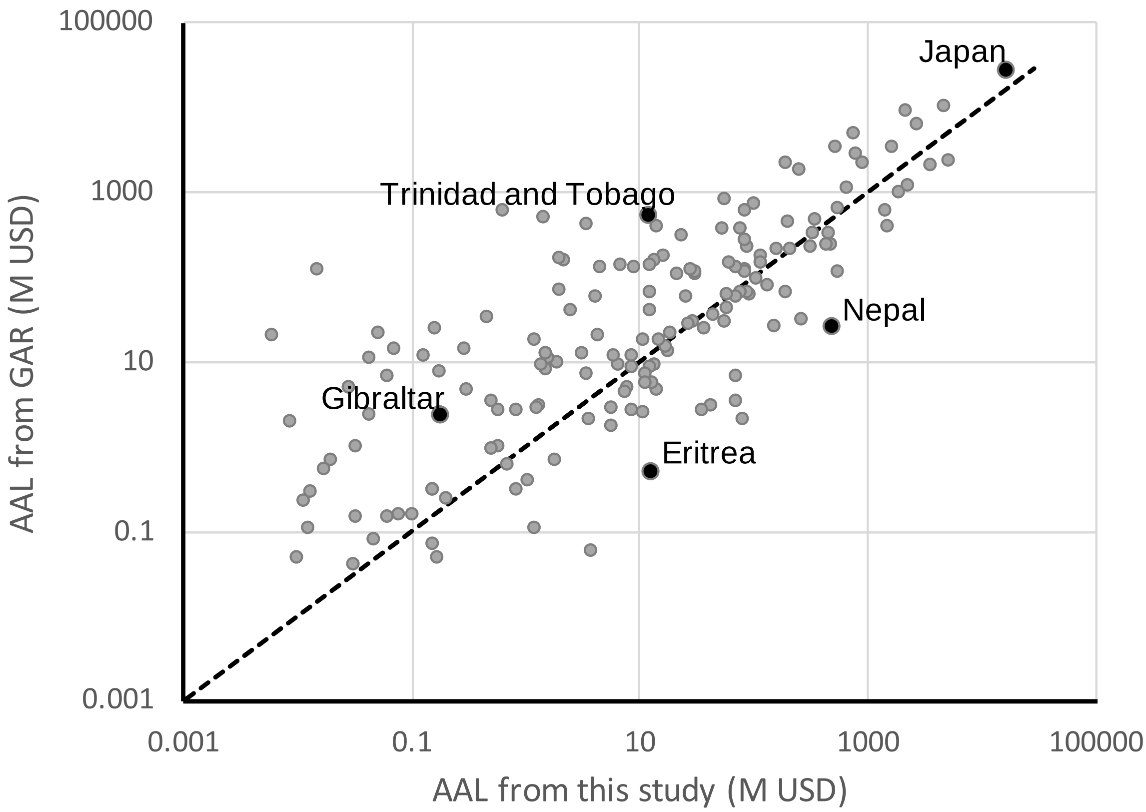

Figure 9. Comparison between the AAL provided by GAR and GEM.

Although there is an evident agreement in the trend of the risk estimates from both studies, the results from GEM are on average below the ones presented by GAR by approximately a factor of 2. Globally, GAR indicates an average annual loss due to ground shaking of about 100B USD, while in this study a value of approximately 45B USD was obtained. The identification of the causes for these discrepancies is a rather complex process, since as described in the preceding sections, the methodology to develop the main components (seismic hazard, exposure and vulnerability) of GAR was considerably different from the methodology adopted by GEM and its partners.

Final remarks

The Global Earthquake Model results from nearly a decade of work by more than 100 collaborators worldwide and represents a major step forward in earthquake hazard and risk assessment compiled with global coverage. The Global Earthquake Model is in fact a mosaic of models developed at regional to national scales. Most of the models were developed using the open source hazard and risk analysis software, OpenQuake; the remainder were translated into OpenQuake in order to allow researchers from around the world to compare and contrast assumptions and methods within a common analysis platform. This collaborative process also results in hazard and risk models that are more likely to be accepted, trusted and used by risk managers, planners and risk reduction practitioners.

The Global Earthquake Model will initially be made available under an open license CC BY-NC-SA[4] which lets others modify and build upon the work for non-commercial applications, as long as credit is given and new creations are licensed under identical terms. The global risk map identifies areas of high seismic risk at present, but the underlying earthquake risk model has also been designed so that others may update it with new hazard, vulnerability and exposure information. In so doing, trends in future risk may be identified, and cost-effective solutions may be developed to mitigate and reduce earthquake risk globally.

The application of uniform datasets, methodologies, and tools for the assessment of the seismic hazard and risk allows a just and unbiased comparison of the risk between countries, or regions within a particular nation. For example, depicts the top 15 countries in terms of average annual economic losses. Such comparison is helpful to understand the relative risk between different countries. Additional results regarding the global seismic hazard and risk results can be explored at https://www.globalquakemodel.org/gem.

The global earthquake model has been developed for application to a wide range of decision making applications, including: insurance and risk financing for international companies and reinsurance companies with globally distributed portolios; international disaster response planning by the UN and INGOs; and risk monitoring for the Sendai Framework for Disaster Risk Reduction. The regional to national hazard and risk models can form the bases for many government risk reduction actions, including: improvement or review of seismic building regulations; post-disaster contingency risk financing such as through catastrophe bonds or insurance pools; prioritization of exposed populations, buildings and infrastructure, or geographic areas where further work should be done to mitigate or reduce risk. The Global Earthquake Model provides one of the most complete and transparent assessment of earthquake risk created to date on a global scale. It is an open and freely available resource for risk assessment experts, disaster risk management practitioners and the public to use in order to better understand, commit to and reduce earthquake risk globally. The completion of the Global earthquake model fulfills a major commitment of the sponsors and partners of the GEM Foundation toward its vision for a world resilient to

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[4] https://creativecommons.org/licenses/by-sa/4.0/

earthquakes. To that end, GEM, as a global community of researchers and risk management practitioners, is committed to its application, maintenance and continuous improvement.

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