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A brief overview of the past, present and future of the Global Earthquake Model (GEM) Foundation

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Abstract

The Global Earthquake Model (GEM) is an initiative that originally emerged from discussions and proposals made by the Global Science Forum of the Organization for Economic Co-operation and Development (OECD) in the early 2000's. In 2009, GEM established itself as a non-profit legal entity, the GEM Foundation, and 15 years later, it continues to operate globally with a mission to provide transparent resources for seismic hazard and risk assessment, as well as to support disaster risk reduction for a wide range of natural hazards. This paper highlights the main milestones from the past 15 years and the vision of the foundation to 2030. An overview is also provided of the status of GEM products and services, all of which are made available for the benefit of society, under a strategy that aims to assure the continued financial sustainability of the organization.

Keywords: Global Earthquake Model; OpenQuake Engine; Seismic Hazard; Seismic Risk

1. Introduction

It has been 15 years since the Global Earthquake Model (GEM) Foundation was incorporated (on 9th March 2009), and we have chosen this Special Issue of Annals of Geophysics, which is dedicated to the 25th anniversary of INGV, to present an overview of the past, present and planned future of GEM, also given the close collaboration between GEM and INGV over these years.

Today GEM has successfully reached thousands of individuals around the world, through its involvement in over 50 projects, the partnerships that have been established with over 100 public and private organizations, and the extensive training it has undertaken on data, models and software for transparent seismic hazard and risk assessment (Fig. 1). This paper documents the story that has led to these achievements, beginning with a summary of the years before the GEM Foundation was incorporated and the motivations for setting up this organization. The main phases in GEM's history are also described – i.e. GEM1, the first two working programs of GEM and the current path towards 2030. A succinct overview of the main products and services that GEM is currently maintaining for the benefit of the community is also included, and the paper wraps up with some thoughts on the main scientific and technological issues that GEM aims to tackle in the coming years.

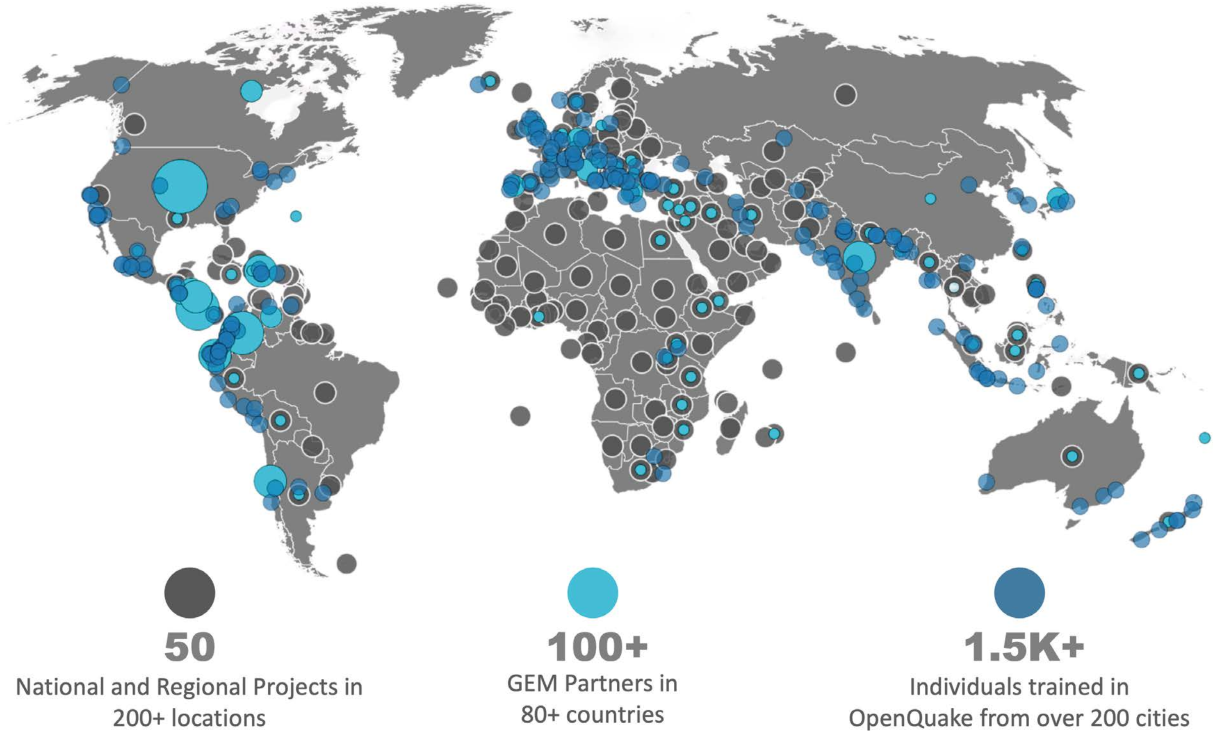

Figure 1. Overview of GEM's global reach over the past 15 years in terms of projects, partners and individuals involved in training activities.

2. The Years Leading Up to GEM

In the early 1990's, the Global Seismic Hazard Assessment Program (GSHAP) was launched by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU) (Giardini and Basham, 1993). In 1999 the first ever global seismic hazard map was released, developed through a collaborative effort involving hundreds of scientists from around the world (Giardini et al., 1999). This pioneering effort promoted a regionally coordinated approach to seismic hazard evaluation across borders and served as a demonstration program within the framework of the United Nations International Decade for Natural Disaster Reduction.

In the years following the release of the GSHAP global seismic hazard map, the lack of a venue to continue the discussions on earthquake science at the global scale was raised by the German delegation to the Organization for Economic Co-operation and Development's Global Science Forum (OECD-GSF). This led to a series of workshops and meetings being organized between 2004 and 2007, which culminated in the identification of a need to create a Global Earthquake Risk Mapping and Monitoring Program (or GEM). Four scientists played a particularly relevant role in bringing GEM to fruition during those early years: Jochen Zschau (formerly GFZ Potsdam, Retired), Ross Stein (formerly USGS, Retired), Domenico Giardini (ETH Zurich) and Anselm Smolka (formerly Munich Re, Retired). Thanks to the support of Anselm Smolka, the financial feasibility of GEM received a critical boost in 2007 after Munich Re agreed to become its first and primary private participant through a 5 M Euro contribution for a period of five years.

With the securing of this initial financial support, the focus then turned to the development of a first Business Plan, which was also drafted with the help of the acting Executive Director for GEM at the time, Kate Stillwell (formerly UC Berkeley). The vision, as set out in that Business Plan, was for GEM to be the first uniform, independent standard for calculating and communicating earthquake risk, and at the end of 5 years, it would provide a basis for comparing earthquake risks across regions and across borders. The structure of GEM was envisaged to be a public-private partnership with an administrative secretarial host that would be located in an OECD country.

Following the presentation of the final Business Plan to the OECD-GSF in their 18th meeting in March 2008, a call was opened for bids to host the Secretariat of GEM (which led to a number of meetings with the scientific community such as that shown in Fig. 2). Given the high incidence of catastrophic natural hazards, the Government of Italy decided to become a public member of GEM and to nominate the European Centre for Training and Research in Earthquake Engineering (Eucentre Foundation, Pavia, Italy) to bid to host the GEM Secretariat, with a financial

Figure 2. Strategic planning meeting hosted by ETH Zurich in 2008, where GEM was presented to the global community of earthquake scientists and engineers.

backing of 3.5 M Euro. This bid had the full support of the INGV thanks also to the strong collaboration in the preceding years between the Eucentre and the Engineering Seismology section of INGV in Milan. In December 2008, the OECD-GSF selected Eucentre as the host institution for the GEM Secretariat, and Rui Pinho was hired as the first Secretary General. The first GEM statute was then drafted, and GEM was incorporated as a non-profit private foundation on 9th March 2009.

3. Various Phases in GEM's History

There are several papers and book chapters that have described the status of GEM at various points in its history (see e.g. Crowley et al., 2013; Keller and Schneider, 2015; Schneider et al., 2020; Schneider, 2023); in this section we summarize the main phases in GEM's history during the first 15 years from 2009 to 2024.

3.1 GEM1

Part of the initial financial contribution from Munich Re was used to launch the GEM1 pilot project that ran from January 2009 to March 2010. This project was coordinated by ETH Zurich and had the objective of developing a proof-of-concept of preliminary global hazard and risk calculations as well as the initial IT infrastructure for GEM. Several organizations from around the world were involved in the project, providing existing software, datasets, and models or reviewing the activities through the Model Advisory Group (MAG). This project laid the foundations for establishing the scientific community involved in GEM, planning the technical activities, and establishing the needs for the software required for transparent seismic hazard and risk assessment at a global scale, as documented in various technical reports[1].

3.2 Working Programme 1 (2009-2013)

The first multi-year programme defined in the GEM statute had a 5-year duration from the date of the constitution of the GEM Foundation (i.e. 2009-2013). During this phase, the GEM Secretariat directly received 5.6 M Euro from 14 public participants and 14 M Euro from 11 private participants. This funding was used to cover the costs of outreach and communication (around 1 M), regional workshops and projects (around 1.5 M), scientific development

1 https://www.globalquakemodel.org/publications?type=Report

(almost 10 M), software and IT development (around 3.5 M), governance (around 2 M) and Secretariat overheads (around 1.7 M).

The three core technical components of the first working programme (WP1) were the Global Components, Regional Programmes and the Model Facility, all of which were centrally coordinated via the GEM Secretariat, and its Executive Committee. The technical activities were all reviewed by the Scientific Board (later termed the Science Board), which was comprised of around 15 experts in IT, hazard and risk modelling; a Technical Advisory Pool was also established with 50+ experts from which smaller groups could be formed to further review and advise on the activities. Another core activity of WP1 was the engagement of the global seismic hazard and risk communities, undertaken through many outreach activities including regional workshops and annual global meetings (Fig. 3). All the above was to be overseen by the GEM Foundation, a non-profit organization governed through a public-private partnership with the following core values: transparency/openness, collaboration, credibility and public good.

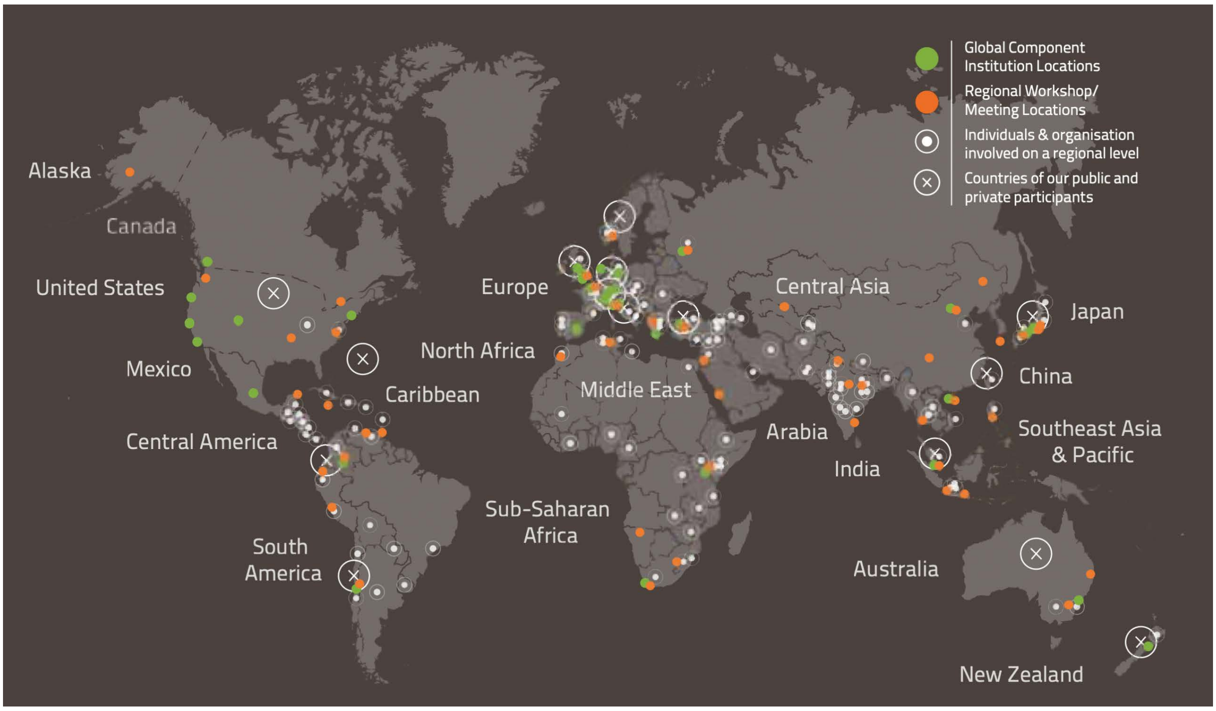

Figure 3. Status of the global community supporting and contributing to GEM at the end of the first Working Programme.

The **Global Component** projects were directly funded from the WP1 scientific budget and were carried out by international consortia that were selected after a thorough process of expert elicitation, community feedback, and peer review. During WP1, GEM funded five hazard global components projects, which each focused on developing global datasets with basic information necessary to create probabilistic seismic hazard analysis (PSHA) input models: the Global Earthquake History, the Global Instrumental Catalogue, the Global Active Fault and Seismic Source database, the Global Geodetic Strain Rate model and the Global Ground Motion Prediction Equations (Pagani et al., 2015). Five other risk global component projects were also funded: GEM Ontology and Taxonomy, Global Exposure Database, Global Vulnerability Estimation Methods, Global Earthquake Consequences Database, and Inventory Data Capture Tools. A summary of these global components is provided in Crowley et al. (2013), and the associated reports and publications can be found on the GEM website[1]. Whilst the outputs produced by some of the global component consortia may not have continued to be maintained in their original format, the majority of the activities initiated by these consortia have continued to be a priority for the GEM Foundation over the past 10 years, and many of them have evolved to new and updated products, as will be described further in Section 4.3. In addition, while not organized as a Global Component at the time, several activities were also launched in WP1 to establish the methodology for including socio-economic vulnerability within GEM's framework for integrated seismic risk assessment.

The **Regional Programmes** were externally funded projects (for a total of 5.4 M Euro) that had the objective of developing regional seismic hazard and risk models. Examples included the SHARE project funded by the European Commission that developed the European Seismic Hazard Model (ESHM13) for Europe (Giardini et al., 2013; Woessner et al., 2015) (Fig. 4), and the EMME project (Earthquake Model of the Middle East) (Erdik et al., 2012). These regional hazard models were important components of the 2018 version of GEM's global mosaic of hazard models (see Section 4.4).

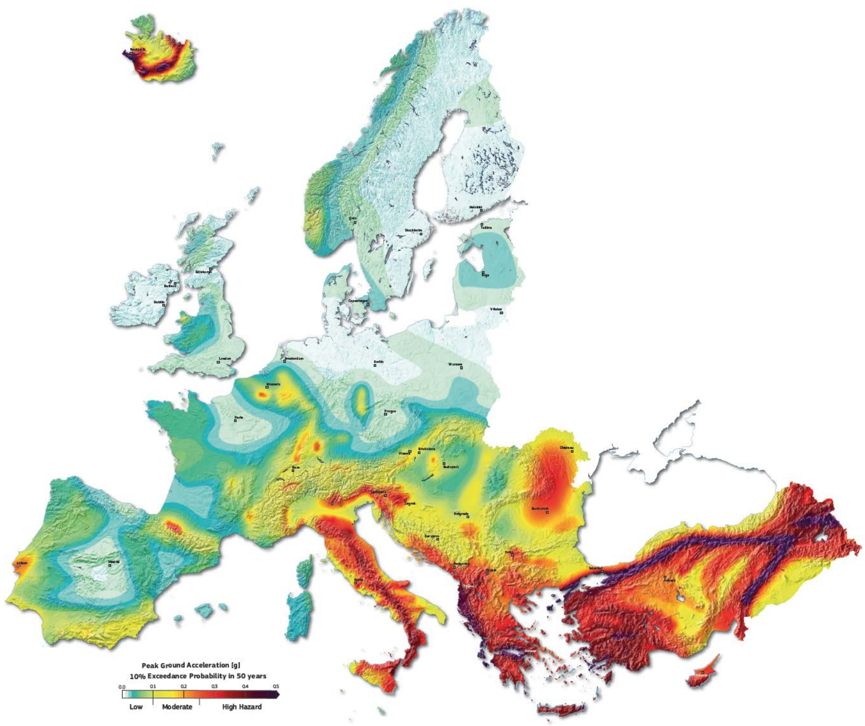

Figure 4. European Seismic Hazard Model (ESHM13) developed within the SHARE project (Giardini et al., 2013).

The **Model Facility** was a joint venture between ETH Zurich and the GEM Secretariat in Pavia, which grew out of GEM1 and that had the main aim of overseeing the initial years of development of the OpenQuake engine, the open-source software for state-of-the-art seismic hazard and risk assessment (see Section 4.2 for further details).

At the end of WP1, the global components were in their final stages of development and the activities of the Model Facility were fully transferred to the GEM Secretariat in Pavia. Some modifications to the GEM Statute were made, with the most important being the removal of the clause foreseeing the creation of an intergovernmental organization, given that it was no longer deemed to be a necessary requirement for achieving the mission of GEM. The Executive Committee was also no longer explicitly mentioned in the statute, now that the members were all employees of the GEM Secretariat. A new Secretary General was installed (Anselm Smolka, who was the GEM Governing Board Chair during WP1), and the second working programme was initiated, as described in the following section.

3.3 Working Programme 2 (2014-2018)

At the start of working programme 2 (WP2, which ran from 2014 to 2018), the GEM Secretariat expanded its IT team, and focus was placed on finalizing the OpenQuake Platform. This web-based platform was built using the GeoNode software[2], and was designed as a 'one-stop shop' for the community to access and explore all of GEM's

2 https://geonode.org/

global datasets, models, software and tools, as well as share their own contributions and discuss results with the GEM community, thanks to the interactive technology offered by the use of GeoNode. The OpenQuake platform was officially launched in January 2015.

Another key priority for the GEM Secretariat during WP2 was to begin to bring together the outputs of the global components, the ongoing regional programs and the Model Facility in order to deliver a comprehensive global assessment of seismic hazard and risk. To provide these global models of seismic hazard and risk, it was necessary to expand the scientific team working at the GEM Secretariat. During WP1 the GEM Secretariat had a few key scientific staff that had been predominantly focused on coordinating the activities being undertaken by external global and regional consortia (the Executive Committee). During WP2, instead, the Secretariat began to develop significantly more internal expertise on seismic hazard, exposure, vulnerability and risk modelling, as well as software development, such that continued improvements to the OpenQuake engine could be made to allow global calculations of hazard and risk to be run in an optimized manner.

With the increase in scientific staff and PhD students at the GEM Secretariat, there was also an augmented capacity for the organization to manage and deliver scientific projects. Thus, during this time, the number of projects involving GEM staff began to steadily increase, many of which were focused on national or regional hazard and risk assessment; these projects naturally began to form the building blocks needed for the global models[3]. The projects were also an important source of additional funding (around 3.5 M Euro) for the sustainability of the GEM Foundation, which during WP2 was not receiving the same levels of sponsorship as WP1, in particular from private organizations: during WP2, GEM received around 5.4 M Euro from 14 public participants and 5.6 M Euro from 11 private organizations.

Some important milestones that were achieved during WP2 include the recognition by the United Nations in 2016 of the GEM Foundation as a Non-Governmental Organization (NGO), operating under UN guidelines for humanitarian organizations, and the bestowal by UNDRR (formerly UNISDR) in 2018 of the Damir Čemerin Award, in recognition of GEM's leadership in supporting disaster risk reduction. During this WP there was also a change in management, with a new Secretary General (John Schneider, former WP2 GEM Governing Board Chair) taking over in April 2016.

At the end of WP2, in December 2018, the first GEM global seismic hazard and risk maps were released (see Sections 4.4 and 4.5 for more details). Three global socio-economic vulnerability maps were released shortly following the end of WP2 (see Section 4.6). With the release of these maps, the activities of the second working programme could be considered officially concluded, and thoughts turned to the next phase in GEM's story. It is interesting to note that in the original Business Plan of GEM it was stated that the "global earthquake model will take 5 years and 35 M Euro to build"; whilst it instead took closer to 10 years to reach the initial objective of a global model of relative earthquake risk based on open software and global standards, the total funding invested in achieving this goal (via sponsorships and regional projects) was however not far off the original target, at around 40 M Euro.

3.4 2019 to 2030

At the end of WP2, the GEM Statute was again revised in preparation for what would have been the next 5-year working programme. However, based on discussions of the Governing Board, it was agreed that for increased flexibility the foundation should no longer be obliged to organize its activities into fixed 5-year working programmes, but could instead proceed on a year-by-year or multi-year basis (the majority of existing sponsorships shifted to 3-year commitments, and new sponsorships have since been allowed to start at any time, rather than be tied to a fixed period). Currently, the budget and associated activities are approved by the Governing Board on an annual basis. The 2024 annual budget of the GEM Foundation is approximately 3.5 M Euro: 20 private sector sponsors provide around 1.4 M Euro, 9 public sector sponsors provide 750 k Euro, institutional projects make up around 1 M Euro and commercial projects and licenses account for approximately 350 k Euro. Furthermore, changes were made to reflect a modified vision for the GEM Foundation, where its goal to increase resilience would extend beyond earthquakes to other natural hazards[4], and the mission was updated[5].

3 See https://www.globalquakemodel.org/projects for an overview of key completed and ongoing projects involving the GEM Foundation

4 GEM's vision: For a world that is resilient to earthquakes and other natural hazards

5 GEM's mission: Through global partnerships, be a trusted standard in global earthquake risk modelling, a leader in the community for natural-hazards risk assessment, and a key resource for disaster risk reduction efforts worldwide.

Another change to the Statute included the modification of the Science Board to Advisory Board, and its role, which had always been to monitor, review and advise on the global scientific strategy of the GEM Foundation, was expanded in scope to include strategic support related to science, international collaboration, policy drafting and updating, individuation of users and stakeholders needs, and funding opportunities. During the first two working programmes there was a significant need for scientific direction and review of the global components, the regional programmes, the software development, and the strategy and methods used to develop the first versions of the global seismic hazard and risk models and maps. Following the conclusion of these activities, and with the organization no longer running and working towards multi-year, long-term objectives, there was felt to be less of a need to formally establish a fixed scientific body to review the activities of the foundation. Hence, at the start of this new phase in GEM's history, and after some delays caused by the global COVID-19 pandemic, a new, smaller Advisory Board was established, and this board has been supporting the GEM Foundation in looking to the future, and towards its strategic vision to 2030 (described further below). GEM Foundation is closely connected to the international scientific community, and continues to subject its methods, standards and software to peer review and community feedback. The Governing Board (GB) also regularly convenes task forces made up of GB members, associates and external advisors to review elements of its scientific program and progress. The scientific staff of the GEM Foundation continue to publish their work in scientific peer-reviewed journals (to date over 50 publications have been released by GEM Secretariat staff since 2013[6]), to disseminate their work in international conferences (e.g. at the recent 18th World Conference in Earthquake Engineering there were over 20 presentations from GEM staff and students), and to invite input and review by the community of datasets, software and tools through their open release on GEM's GitHub page[7].

During the transition from the Science Board to Advisory Board, the GEM Secretariat worked with Governing Board members and nominated experts to develop a strategic plan and roadmap to 2030[8]. GEM's overall objective to 2030 is to develop capabilities that serve the broader need for integrated risk assessment for resilience and sustainability due to globally increasing vulnerability and exposure of populations to natural hazards, including from climate change. The Advisory Board has now been installed and is currently supporting the GEM Secretariat in implementing this vision to 2030. Three core strategic objectives that are driving the next 5 years leading up to 2030 are as follows:

- **Provide**: continue to develop global standards for risk modelling for all earthquake-related hazards. GEM will maintain expertise and global leadership in earthquake hazard and risk modelling and its applications to disaster risk reduction, in particular, the continuous development and user support for GEM's flagship programmes and products: the OpenQuake Engine and the global earthquake hazard and risk models (see Section 4).
- **Support**: be a global partner to local, regional and global disaster risk reduction communities for earthquakes and other natural hazards. Driven by global drivers such as the Sendai Framework, Sustainable Development Goals, and Paris Climate Agreement, and guided by its core values, GEM will expand its organizational, technical and scientific relationships and diversify its risk products and services to engage with stakeholders in the broader disaster risk reduction community.
- **Strengthen**: GEM will invest in strengthening the capacity of developing countries and the Global South to assess their risk to earthquakes and other natural hazards through public partnerships, training and collaborative projects.

One of the first milestones in the current phase of GEM was the second release of GEM's global seismic hazard and risk maps and associated products (see Section 4.4 and 4.5), which were showcased at the first GEM Conference in Bergamo in June 2023. In August 2023 a new Secretary General was appointed by the Governing Board (Helen Crowley) and one of her first roles was to coordinate the open release of the products associated with these maps through the GEM website, GeoViewer and GitHub repositories[9]. As part of this review of the status of GEM products and services, a decision was taken to decommission the OpenQuake Platform, which had been running from 2015. The original vision of the OpenQuake Platform as a place where the community would share data and discuss their research had not materialized, with other professional networking platforms being preferred (e.g. ResearchGate,

6 https://www.globalquakemodel.org/publications?type=Peer-reviewed

7 https://www.github.com/gem

8 Available at URL: https://tinyurl.com/GEMstrategy2030

9 www.globalquakemodel.org/products; https://maps.openquake.org; www.github.com/gem

GitHub, LinkedIn, Slack), and the resources needed to maintain the underlying technology were therefore not felt to be justified. Hence, an effort was made to migrate the GEM products from the OpenQuake Platform to other webpages and technologies, leading to the current products and services offering described in the next section.

4. Global Flagship Products and Services

In this section a summary of the status of GEM's products and services is provided. To provide context to way in which GEM distributes its products and offers services, the strategy and underlying data and license policy is first outlined.

4.1 GEM's Products and Services Strategy

The key objective of GEM's Products and Services Strategy (developed in 2020)[10] is to continue to make all information freely available, with an emphasis on open access, while at the same time assuring the sustainability of the organization. Although GEM has been continuously and generously supported by public and private institutions for 15 years, the development of products and services to meet the existing and future needs of the disaster risk reduction community requires additional support and funding, which GEM has sought through engaging in more institutional projects and through more investment in commercial products and services.

GEM's products and services are released through different mechanisms depending on the product, and these can be simply categorized in three ways: 1) open software, data and models (under different open license conditions described below); 2) freely available software, data and models available for non-commercial, public good use, following a license request; 3) commercial-use products and services (i.e. subject to a license fee). It is worth underlining that GEM's products are always available freely for non-commercial, public good use, regardless of the mechanism under which they are primarily released.

Open and free distribution of data, models, and tools remains at the core of GEM's work, further enhancing their availability and accessibility. For those products that are released openly, GEM makes use of the following open licenses:

- **Open-source software**. The software license used by GEM, the GNU AGPL[11] v3, allows users to use the software for any purpose, including commercial purposes, without having to request a specific permission and without needing to become active supporters of GEM projects. The AGPL restricts (re)distribution and integration of the software – in particular it is not permitted to link AGPL software with closed-source software systems, even if this linkage is performed via a network. Users are permitted to modify AGPL software; however, users must remember to release any derived/modified versions openly under the terms of the AGPL. In essence, this means that GEM software must remain open and cannot be made into closed products without permission.
- **Open Data and Models**. The Creative Commons licenses applied to our creative contents, datasets and models, allow users to freely use and modify (by making derivative works) our products and require that the authorship of GEM Foundation is always correctly attributed and, in some cases, impose some additional restrictions on use. GEM models and datasets are distributed with either the CC BY-SA license which allows commercial use or the CC BY-NC-SA license which prohibits commercial use. Both are Share-Alike licenses; this means that the product and any modified or derived products may only be (re)distributed under the terms of the same license. In essence, this means that GEM models that are released openly must remain open and cannot be made into closed products without permission.

As a non-profit organization, any profits or income derived from commercial sales of products or services are reinvested to fund GEM's core programs (i.e. advancing capabilities in earthquake and multi-hazard risk, pioneering scientific risk assessment methods, and expanding risk and resilience applications to downstream users), with an emphasis on providing support to low/middle-income countries.

10 https://www.globalquakemodel.org/products-services-public-document

11 https://www.gnu.org/licenses/agpl-3.0.html

4.2 OpenQuake Engine and Tools

As part of a review of several existing hazard and risk software applications carried out in 2009/2010 in the GEM1 project (see e.g. Danciu et al., 2010; Crowley et al., 2010), the key characteristics of the software required for a global seismic hazard and risk model were identified. Given that the requirements did not lead to an existing software that met the needs, the development of a new software (nominated the OpenQuake Engine) was initiated. As mentioned before, this was initially a core activity of the Model Facility during WP1, before being fully absorbed by the GEM Secretariat at the start of WP2.

The OpenQuake Engine[12] is an open-source software, released with a GNU AGPL software license, that provides calculation and assessment of seismic hazard, risk and decision-making tools via the data, methods and standards that are being developed by GEM and its collaborators. The v1.0 release of the OpenQuake engine was in 2013. The current Long Term Support (LTS) release (for users wanting stability) is v3.16 and the latest release (for users needing the latest features version) is v3.21 (September 2024). Each LTS release of the engine is named after a deceased scientist who has made a significant contribution to earthquake science/engineering or a related field. The main features of the OpenQuake Engine were originally documented in two key papers released in 2014: Pagani et al. (2014), which described mainly the hazard calculators, and Silva et al. (2014) which focused on the risk calculators. In the past 10 years the engine has continued to be developed with several contributions provided from scientists from all around the world[13]. The public and open release of this software has also provided significant advantages to other open-source tools. A notable example is the USGS ShakeMap code, which integrates OpenQuake libraries for its ground motion models (see Worden et al., 2020). This adoption of the OpenQuake ground motion library has enabled the implementation of a variety of ground motion models across different ShakeMap configurations. Moreover, due to the comprehensive testing and verification of this library, users can be confident in its accuracy and reliability.

From 2013 to 2024, there have been 2460 papers published citing "OpenQuake" in the development and application of seismic hazard and risk models[14]. In 2023 a significant effort was made, thanks to funding from projects including Google's Season of Docs, to overhaul the documentation of the engine, and a unified set of online documentation based on Sphinx was released[15]. An updated paper with the latest scientific features of the engine is currently under development and should be published in the next 12 months.

In addition to the OpenQuake Engine, the scientific teams at GEM have also released several tools and toolkits to support hazard and risk model developers (e.g. the Vulnerability Modeller's Toolkit: Martins et al., 2021), all of which are released through the GEM Science Tools GitHub page[16].

4.3 Global Datasets

A number of global datasets have been funded and developed over the years (mainly through the global component projects – see Section 3.2); some have continued to be maintained by GEM, whilst others have evolved into new products. In this section, we summarize the key global datasets that are currently being maintained and regularly updated by GEM and/or its partners:

- **ISC-GEM Global Instrumental Catalogue**[17]. This is the result of a special effort to adapt and substantially extend and improve currently existing bulletin data for large earthquakes (magnitude 5.5 and above, plus continental events down to magnitude 5.0). The ISC-GEM catalogue was initially co-funded by the GEM Foundation as one of its five Global Hazard Components of WP1 (described above). The catalogue Version 1 resulted from the 27-month-long project that ended in January 2013 (Storchak et al., 2013). ISC has continued to maintain and improve the catalogue with funding from several public and commercial bodies, in order to include

12 https://github.com/gem/oq-engine

13 https://github.com/gem/oq-engine/blob/master/CONTRIBUTORS.txt

14 Google scholar search on 16th September 2024

15 https://docs.openquake.org/oq-engine/manual/latest/

16 https://github.com/GEMScienceTools

17 Openly available from: http://www.isc.ac.uk/iscgem/

earthquakes (above 5.5) that occurred after 2009 and smaller earthquakes (between 5.5 and 6.3) from 1904 to 1959. Since 2018, they have worked bringing additional source parameters of early earthquakes from scientific literature, adding smaller earthquakes with Mw 5.0-5.5 in continental areas during the modern instrumental period (1964 – present) and improved magnitude determinations by identifying and addressing some reporting gaps of quality long-term seismic stations. ISC continues to provide access to the catalogue and discussions are currently ongoing regarding catalogue-related services that could be offered jointly by ISC and GEM to support its continued maintenance and improvement (also from a financial perspective).

- **Global Active Faults Database**[18]. This database has evolved from the activities initiated in the GEM Faulted Earth project (Christophersen et al., 2015), one of the five Global Hazard Components of WP1. The database is the first public, comprehensive database of active faults with worldwide coverage, based on a compilation of many regional datasets (Styron and Pagani, 2020).
- **Global Scenarios**. Given the importance of earthquake scenarios in stress-testing the various components of the probabilistic seismic hazard and risk models, GEM has invested in developing global datasets that provide information related to past earthquake scenarios. One dataset is the GEM Earthquake Scenario Database (ESD)[19], which is an evolution of the GEM Earthquake Consequences Database (GEMECD), one of the five Global Risk Components of WP1 (So, 2014). The ESD builds upon GEMECD as well as other initiatives, such as USGS's ShakeMap Atlas and AtlasCat (Marano et al., 2023), by collecting additional earthquake rupture, ground shaking and impact information, often documented spatially and with greater detail.
- **Global Exposure Model**. The original effort to develop a global model of buildings and their occupants was initiated as part of the GED4GEM project, one of the five Global Risk Components of WP1 (Gamba, 2014). In the years following the completion of this project, the GEM Secretariat invested significant efforts in data mining and harmonising datasets from public sources to produce the Global Exposure Model, a compilation of models describing the spatial distribution of residential, commercial and industrial buildings, together with their replacement value, contents, and occupants for over 200 countries in the world (Yepes-Estrada et al., 2023)[20] (Fig. 5). These exposure models classify the buildings using the GEM Building Taxonomy, another of the five Global Risk Components of WP1 (Brzev et al., 2012), which has continued to be maintained and expanded (Silva et al., 2022).

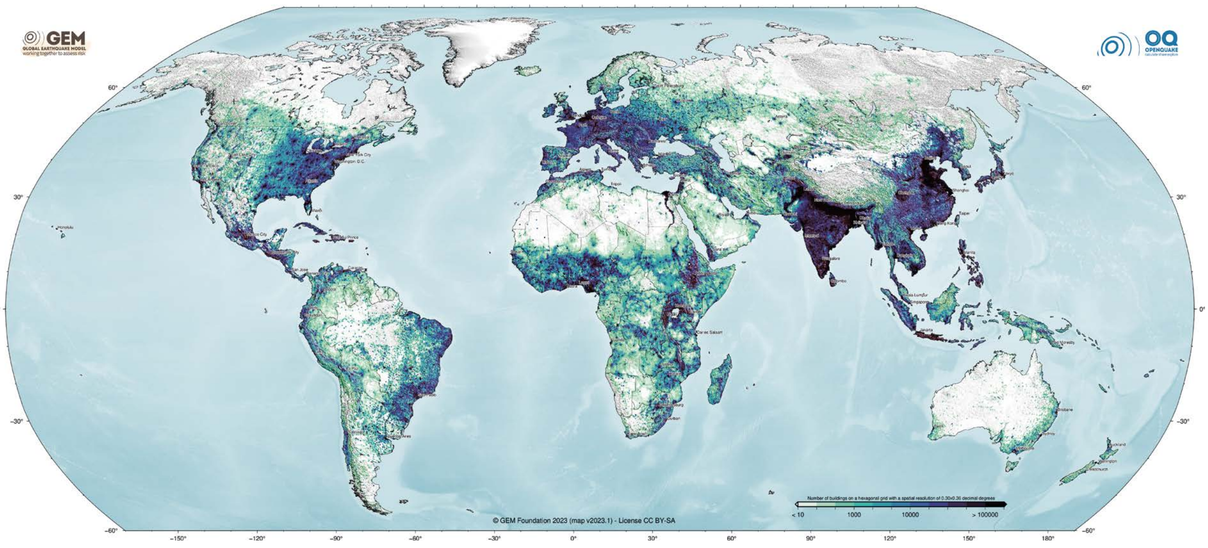

Figure 5. Number of residential, commercial and industrial buildings on an evenly-spaced grid at the global scale (Yepes-Estrada et al., 2023).

18 Openly available from: https://github.com/GEMScienceTools/gem-global-active-faults

19 Openly available from: https://github.com/gem/earthquake-scenarios

20 Openly available from: https://github.com/gem/global_exposure_model

– **Global Vulnerability Model**. The guidelines developed by one of the five Global Risk Components of WP1 on physical vulnerability development (D'Ayala et al., 2015) laid the foundations for the development of capacity, fragility and vulnerability models for thousands of building classes around the world (Martins and Silva, 2020)[21]. The initial global release of vulnerability models was based on single-degree-of-freedom systems, and these are soon to be updated based on multi-degree-of-freedom models, which will allow a better estimation of floor response and, thus, non-structural and content damage in higher-rise structures.

4.4 Global Seismic Hazard

As mentioned previously, GEM first released a global seismic hazard map (and associated poster) at the end of 2018. This map presented the spatial distribution of peak ground acceleration (PGA) with 10% probability of exceedance in 50 years on reference rock, on an ad-hoc grid with spacing between 9 and 12 km. As described in Pagani et al. (2020), the map was produced using the classical probabilistic seismic hazard assessment (PSHA) calculator of the OpenQuake Engine, together with over 30 regional, national, or sub-national seismic hazard models, which made up the global seismic hazard mosaic[22]. In the following 4 years, a number of these seismic hazard models were updated, and so in 2023 an updated map was openly released on a higher grid spacing (around 6.5 km) (Fig. 6). In addition to the PGA hazard map, hazard curves for spectral acceleration at periods of 0.2, 0.3, 0.6 and 1.0 seconds were also computed at a global scale on both reference rock and for site-specific conditions based on the USGS Global Vs30 Mosaic[23]. These hazard curves can be accessed via the ATLAS 2.0 service, described further in Section 4.7.

4.5 Global Seismic Risk

A global seismic risk map (and associated poster) was also released by GEM at the end of 2018, as described in Silva et al. (2020). This map represented the average annual loss of built-up area (of residential, industrial and commercial buildings). It was computed using the stochastic event-based risk calculator of the OpenQuake Engine. This calculator uses stochastic event sets generated from Monte Carlo simulation based on the aforementioned global mosaic of seismic hazard models, together with the Global Exposure Model and the Global Vulnerability Model (see Section 4.3). Over the following 4 years, in addition to the developments in the hazard models mentioned above, the exposure and vulnerability models continued to be developed by the GEM Secretariat through partnerships, projects and collaborations. In 2023, an updated global seismic risk map for average annual loss of built-up area was released (Fig. 7), as well as new maps for the average annual number of buildings lost, fatalities, and economic loss and a ranking of the top 15 countries or territories according to these risk metrics.

4.6 Country and Territory Seismic Risk Profiles

A popular derivative product of the global seismic risk model has been the country and territory seismic risk profiles, now hosted on GitHub[24]. Each profile summarizes key metrics of seismic risk, allowing stakeholders in risk management to get an overview of the risk in a region at-a-glance (Fig. 8 for an example). Each profile presents the following relevant information:

– Social indicators, which provide context to the region in question
– Risk indicators detailing an occupancy breakdown of exposed value and losses
– A list of the major earthquakes that have impacted the region
– Loss per region, providing a breakdown of average annual losses per administrative level 1

21 Openly available from: https://github.com/gem/global_vulnerability_model

22 For more information: https://hazard.openquake.org/gem/models/

23 Openly available from: https://earthquake.usgs.gov/data/vs30/

24 https://github.com/gem/risk-profiles

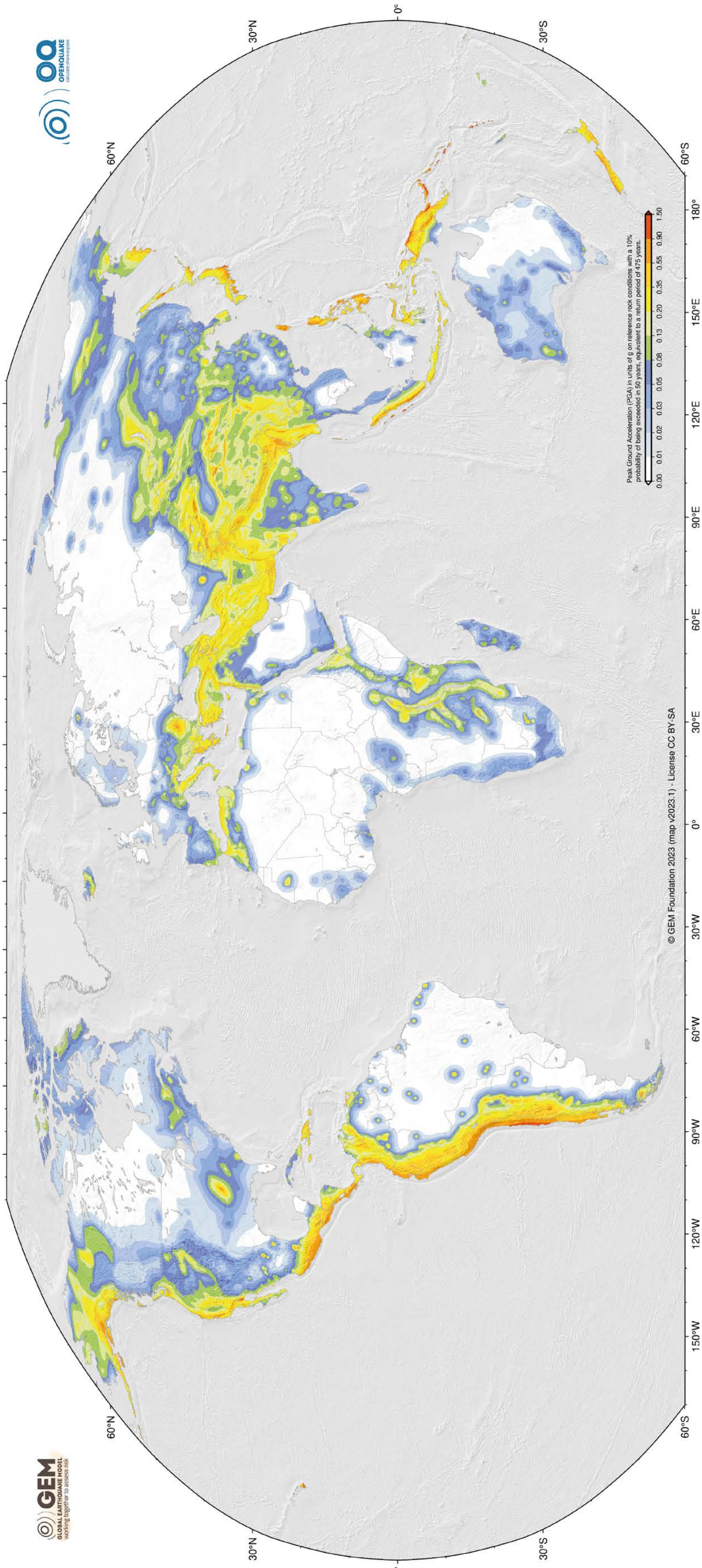

Figure 6. Global Earthquake Model (GEM) Seismic Hazard Map (version 2023.1 – June 2023), doi:https://doi.org/10.5281/zenodo.8409647.

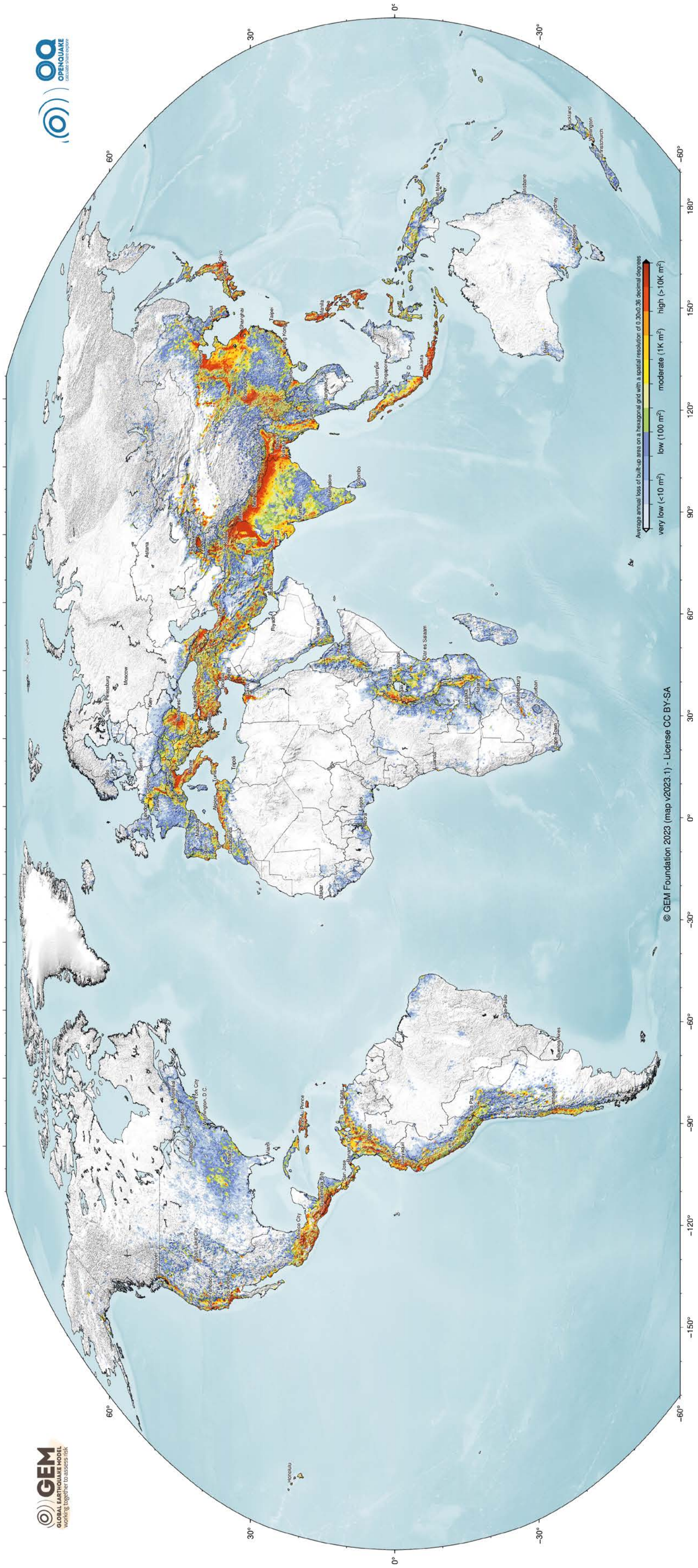

Figure 7. Global Earthquake Model (GEM) Seismic Risk Map (version 2023.1), https://doi.org/10.5281/zenodo.8409623.

- Building classes, depicting the major construction materials used in the region
- Loss curves, which provide expected losses per different return periods
- Maps depicting the geographical distribution of hazard, exposure, and losses

These profiles have also been integrated into the UNDRR's country and continent DRR profiles and resources on PreventionWeb[25] and are among the most popular products on the GEM website.

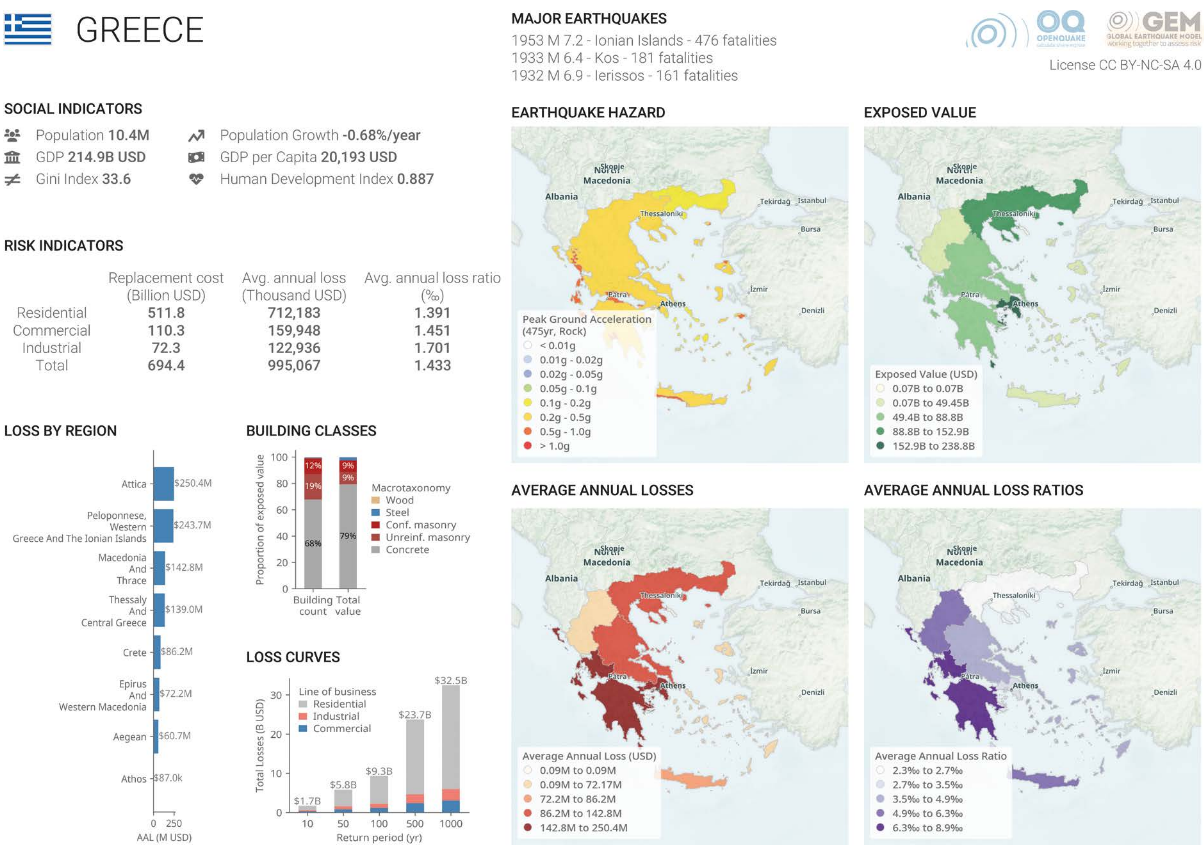

Figure 8. Example seismic risk profile for Greece.

4.7 Global Socio-Economic Vulnerability

Three global socio-economic vulnerability maps were released by GEM in 2020 (Toquica and Burton, 2020; Burton et al., 2022). The first map was the Global Social Vulnerability Map, which is a composite index that was developed to measure characteristics or qualities of social systems that create the potential for loss or harm. The second map was the Global Economic Vulnerability Map, which is a composite index that was designed primarily to measure the potential for economic losses from earthquakes due to a country's macroeconomic exposure. The third map was the Recovery/Reconstruction Potential Map, which is closely aligned with the concept of disaster resilience, whereby enhancing a country's resilience to earthquakes improves its capacity to anticipate threats, to reduce its overall vulnerability, and to allow its communities to recover from adverse impacts from earthquakes when they occur. Shortly after the release of these maps there was a decision at the Governing Board level to pause the work on updating the socio-economic vulnerability databases that GEM had developed, until specific funding could be found to invest further in this field.

25 https://www.preventionweb.net/knowledge-base/continents-countries

4.8 Web services

As part of the release of the global hazard and risk maps in 2018, GEM invested in developing a web-GIS platform (so-called GeoViewer) for interactive access to the maps and some of the underlying values and data. This platform was based on a stack of open-source software including MapProxy, Django, Nginx, Leaflet, Docker, PostgreSQL and QGIS. The platform also allows for the provision of web services following the Open Geospatial Consortium (OGC) and Open Source Geospatial Foundation (OSGeo) standards (i.e. WMS, WFS, WMTS, TMS) to allow the data available in the interactive map viewers to be accessed by third-party applications in an automated manner.

The GeoViewer stack has been used by GEM collaborators and partners in various projects. Examples include the risk services of the European Facilities for Earthquake Hazard and Risk (EFEHR)[26]. These web services have allowed for the integration of some key European seismic risk maps into the EPOS ICS-C platform[27]. As part of the Integrating Resilience in Local Governance in West Bank and Gaza project, funded by the Municipal Development and Lending Fund (MDLF) via a grant from the World Bank, the Urban Planning and Disaster Risk Reduction Center (UPDRRC) of An Najah National University, used the GeoViewer to provide access to the maps that have been developed as part of the multi-hazard risk assessment[28]. The Geological Survey of Colombia has released all of its national seismic hazard model results (hazard maps, curves and disaggregation data) via its version of the GeoViewer, which was developed in collaboration with the GEM Foundation[29].

Another significant effort recently made to develop web services to access GEM data has been undertaken as part of the ATLAS 2.0 service[30], which as mentioned previously provides access to the latest set of GEM global hazard curves for various spectral ordinates on both reference rock and site-specific conditions. The GeoViewer interactive platform is available for manual download of the data, whereas an API has been developed to access the underlying database of hazard curves, allowing large-volume requests to be automated.

4.9 Software as a Service (SaaS)

In recent years, thanks to support from institutional projects (namely ASCE Earthquake Loads Overseas/AELO[31] and ARISTOTLE[32]), the GEM Foundation has strengthened its capabilities to offer the OpenQuake Engine as a service (so-called Software as a Service, or SaaS). In both aforementioned projects, a custom web-based user interface is developed to allow users to launch calculations of the engine based on user-defined inputs and access and view results. In the case of the AELO project, the objective is to compute design ground motions based on the ASCE guidelines for 500 locations in the world, using the underlying GEM hazard mosaic as the input to the calculations. For the ARISTOTLE project, the SaaS is being developed to allow the impact of an earthquake that has just occurred to be rapidly calculated, using the GEM global hazard, exposure and vulnerability models, together with additional information from partner organizations such as USGS ShakeMaps. These services are currently only available to the partners of the projects; however, the foundation is exploring the possibility of opening up these SaaS offerings to a wider range of users.

4.10 Training

An important activity that is key to GEM's mission is to provide training around the world on all of its products and services. From 2015-2023, 1036 unique individuals participated in OpenQuake training courses. More than half of these occurred in online training courses during the period 2020-2023, initiated during the COVID-19 pandemic.

26 https://maps.eu-risk.eucentre.it/

27 https://www.ics-c.epos-eu.org/

28 https://map-irlg.najah.edu/portal/home/

29 https://amenazasismica.sgc.gov.co/

30 https://atlas.globalquakemodel.org/

31 https://www.globalquakemodel.org/proj/aelo

32 https://www.globalquakemodel.org/proj/aristotle

Training activities are often incorporated into institutional projects[33] and a dedicated training website has been developed to help users get started with the OpenQuake engine[34].

5. Looking Ahead

There are several key scientific and technological topics that are a priority focus for the GEM Foundation as it works towards the next generation of GEM products and services. These include:

- Harmonization of standards for regional/national seismic hazard models – this covers a wide range of topics such as e.g., treatment of epistemic uncertainties, modelling of faults, and time-dependent hazard modelling.
- Critical infrastructure at a regional scale – this brings additional requirements related to the need to consider connectivity within and between such networks.
- Ground failure due to earthquakes (i.e. liquefaction and landslides) – there is a need to ensure that regional models based on proxy data and machine learning are also supported by the physics of these phenomena.
- Methods and processes to efficiently and dynamically update exposure models as changes occur within the urban environment – this will need to combine the use of remote sensing, crowdsourcing, machine learning with our existing engineering knowledge of the built environment.
- Assessment of damages and losses considering earthquake sequences or aftershocks, as well as damage-dependent fragility/vulnerability.
- Assessment of the embodied carbon of buildings at a global scale will allow the environmental impact due to the damage caused by earthquakes and other natural hazards to be estimated and used to encourage more sustainable methods for repair and construction.
- Standards for modelling multiple hazards and cascading effects within risk assessment.

The contributions of the global hazard and risk community in these areas will continue to be encouraged through scientific workshops and collaborative projects. Any developments that the GEM Foundation makes in these areas are transferred to products and services, and are incorporated in training activities, with the aim to transfer these best practices to scientists, researchers and engineers around the world.

Data availability statement. Data can be downloaded at the various weblinks cited herein, e.g. http://www.globalquakemodel.org/products, http://www.github.com/gem, https://github.com/GEMScienceTools, https://zenodo.org/communities/globalquakemodel.

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33 see e.g. https://www.globalquakemodel.org/proj/treq and https://www.globalquakemodel.org/proj/force

34 https://www.training.openquake.org

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