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PERSPECTIVES OF A GLOBAL, DYNAMIC EXPOSURE MODEL FOR GEO-RISK ASSESSMENT FROM REMOTE SENSING TO CROWD-SOURCING

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Abstract

The need for a global approach to risk assessment is increasingly apparent to the Disaster Risk Reduction (DRR) community. Different natural (e.g., earthquakes, tsunamis, tornadoes) and man-made (industrial accidents) hazards threaten every day millions of people all over the world. Yet, if the hazards can be so different, the exposed assets are mostly the same: people, buildings, and infrastructure. The challenge is thus to find innovative, efficient methodologies to collect, organize, store and communicate exposure data on a global scale, while also accounting for the inherent spatio-temporal dynamics. The aim of the paper is to assess the challenge of implementing a global exposure model for different geo-hazards at the global scale within a dynamic, scalable framework. A global exposure model able to evolve over would lay the basis for global vulnerability and risk assessment by providing reliable, standardized information on the exposed assets across a vast range of hazards.

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Introduction

Even cursory glance at the available statistics on natural disasters will highlight the geographical extent of their impact. Between 2000 and 2012, 1.2 million people were affected by disasters and an estimated US$1.7 trillion of damage were sustained worldwide1. Considering, for example, only 2012, more than 900 natural catastrophes occurred (see Fig. 1), causing significant losses and showing again that natural risk knows no border, and should be considered on a global scale. Such losses can only worsen in the future, considering that more than half of the Earth's population currently lives in cities, and by 2050 this proportion will rise to 70%. Assessing the risk arising from natural (and man-made) hazards for such increasing concentrations of people, infrastructure and assets is therefore a great challenge that calls for a strong, unified effort by researchers and decision makers.

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[1] http://www.preventionweb.net/ files/31737_20130312disaster20002012copy.pdf

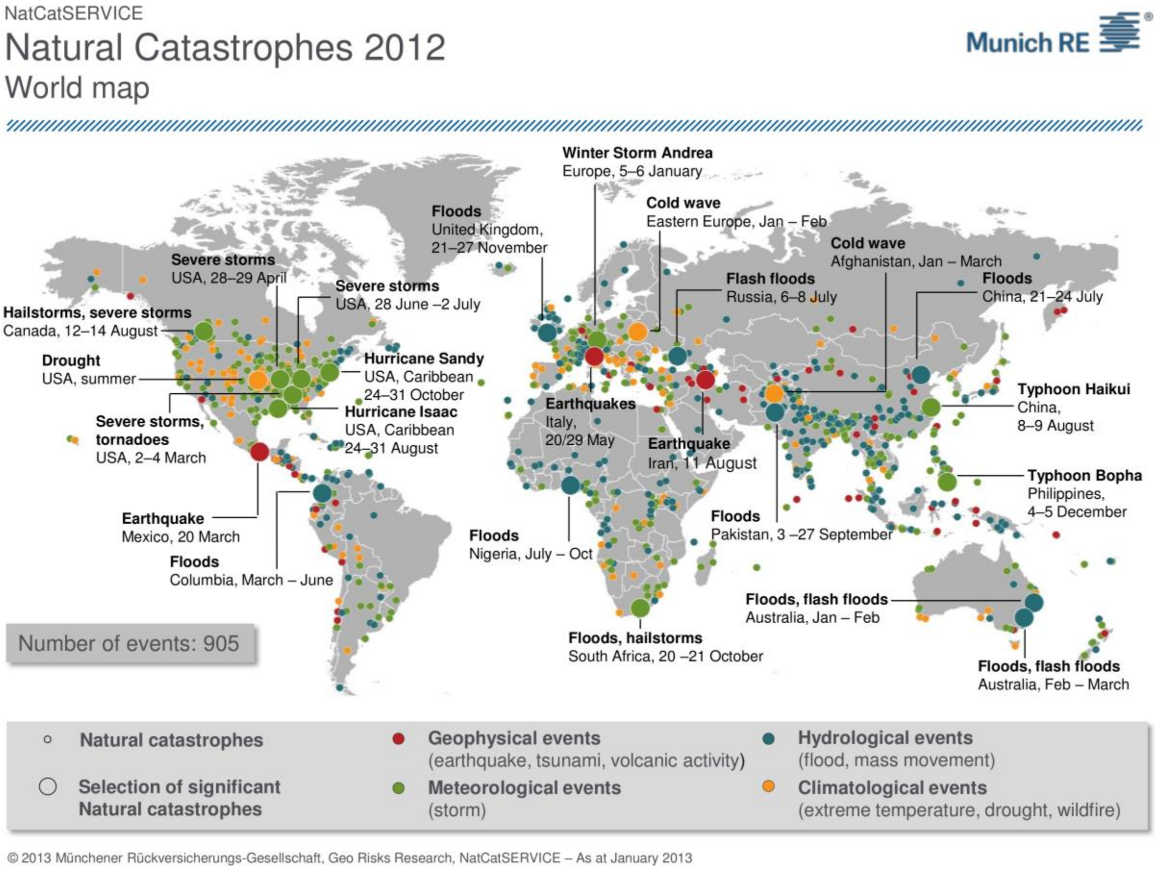

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Figure 1: Natural disastrous events that occurred in 2012 - World Map. NATCAT

A global exposure model would particularly benefit developing regions, where information about population assets and infrastructure exposed to geo-hazards is often incomplete and unreliable. Such a model would also need to capture the dynamics by which exposure evolves with time. Unplanned urbanization, urban sprawling, abrupt demographic changes and modifications in building practices can considerably alter the type and spatial distribution of exposure, in turn modifying the expected risk over a relatively short time (months, years). Following such an evolution over global scales is undoubtedly a challenge, but it would also set an important milestone in improving risk awareness and in providing policy makers and risk practitioners critical information to undertake informed and efficient risk-mitigation actions. Since keeping pace with exposure dynamics is difficult, it is important to be able to assess and communicate the reliability of the exposure data by quantifying the uncertainty and its spatial distribution.

Several international initiatives have tackled the issue of collecting and mapping geo-hazards and related risk from a global perspective. In most cases, a stronger emphasis was given to the geographical distribution of individual hazards and their estimated rate or intensity as (Alexander, 2006), (Dilley, 2005). Efforts aiming at providing useful global models have given rise to freely available, web-based databases, from Preview, started by UNEP in 1999 (UNEP, 2000), to the most recent *GAR Risk Data Platform* (GAR, 2013), each acting as a collector of the different data and models representing geophysical and meteorological risks.

Remarkably, exposure data can be considered largely hazard-independent, provided the structural and non-structural features describing the exposed assets is wide enough to satisfy the requirements of hazard-specific vulnerability models. This paper will focus on the four main tasks of describing, collecting, validating and communicating exposure data relevant for the global assessment of risk arising from geo-hazards. Geo-hazards are hereby defined as geophysical phenomenon that may lead to widespread damage, including earthquakes, tsunamis, ground movements (landslides, rock falls) and volcanism.

We hereby refer to exposure as the compilation of all elements that may be affected by one or more hazards, including lifelines (transportation, power, water, etc.), buildings, population, societal functions, the economic system, and cultural heritage. We will mainly focus on the physical components of exposure, namely building stock and infrastructure, between which no clear distinction will be applied since all are conceptually representable by a geometry and a set of attributes. Human exposure, here meaning the spatial distribution of population, will also be addressed.

Describing and storing exposure data

At the global level, it is mainly human exposure data that has been aggregated. Most countries have already developed their own national statistical classifications (NSCs). In order to achieve comparability, International statistical classifications (ISCs) are produced by international agreements among national statistics authorities in different fields. Compared to NSCs, the ISCs require approval by the United Nations Statistical Commission (UNSC) or another intergovernmental body, depending upon the subject area (Hoffmann and Chamie, 1999).

With regards to physical exposure, reliable information is often missing or incomplete and only a few examples of national exposure databases of buildings and infrastructure exist, such as in Turkey, Australia, and New Zealand. A lack of communication and standards for harmonization, however, has so far hindered the development of a global, integrated exposure model. However, between 2013 and 2014, two global exposure databases will be published, namely one within GAR13 (de Bono 2013) and the other within Global Earthquake Model[2] (GEM) (Dell'Acqua et al. 2012), providing information on population and buildings along with their structural properties on a global scale and using unifying taxonomies.

Ontologies and taxonomies

In information science, an *ontology* represents a knowledge domain as a set of concepts, using a shared vocabulary to denote the types, properties and interrelationships of those concepts (Gruber, 1993). The univocal classification of an exhaustive set of objects defining the ontology is called a *taxonomy*. Given the complex elements composing physical exposure (for instance, the structural components of a building), a clearly defined ontology that also accounts for the functional relationships among them would contribute to overcoming possible misunderstandings amongst data collectors and analysts, especially at trans-national and global scales.

The preparation of a classification or taxonomy involves the creation of an exhaustive and structured set of mutually exclusive and well-described attributes, which can be structured hierarchically or faceted, and encoded into numeric or alphabetical codes (Hoffmann and Chamie, 1999). A taxonomy suitable for describing global exposure should be international in scope, detailed, collapsible, extensible, user friendly and applicable to different types of exposed assets and hazard types (Brzev et al., 2012b). Harmonization of information

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[2] http://www.globalquakemodel.org/

between classifications or taxonomies is of particular importance in order to be able to combine or compare data that have been collected for different populations, and over different time periods that possibly involved different data collection methods and/or spatial units. Harmonization can be achieved by applying consistent and harmonized standards and taxonomies across different data sets and by using a common ontology. Also, the establishment of look-up tables that link the categories of different taxonomies can be utilized for harmonization (Hoffmann and Chamie 1999).

Structural taxonomies

Despite national and international statistical databases that provide socio-economic or census-related exposure information, data sets and analysis tools used to specifically measure, structural – potentially hazard-dependent – aspects of exposure are often not available. Within the earthquake community, building codes have been developed in many countries in order to define guidelines and rules for the construction of buildings, including seismic resistant construction practices (e.g., National Building Code of Canada (NRC, 2010), Eurocode (Bisch et al., 2012)). The practice of designing, approving, and applying building codes, however, varies considerably between countries, with several structural taxonomies developed to classify and characterize building inventories in standardized and comparable ways.

Widely used structural taxonomies (see the review of Charleson, 2011[3]) include ATC-13 (Applied Technology Council, 1985), FEMA 154 (Karbassi and Nollet, 2007), HAZUS (FEMA, 2003), the European Macroseismic Scale 1998 (EMS-98) (Grünthal et al., 1998), PAGER-STR (Wald et al., 2008) and the World Housing Encyclopaedia (WHE)[4]. One of the advantages of FEMA 154 and EMS-98 is their simplicity, consisting of only 15 structure types. However, the disadvantage is that most of the structure type definitions are very broad and, moreover, they are region-dependent, with FEMA 154 focusing on the US building stock. HAZUS is also a US-specific taxonomy, but more detailed with 36 structural categories. The PAGER-STR taxonomy captures most key structural attributes that affect seismic performance, while being collapsible and international in scope, including structural types found outside the more developed countries. However, due to its hierarchical structure, it is difficult to extend. A recently established structural taxonomy which follows the concept of a faceted taxonomy (Broughton, 2002) is the GEM building taxonomy (Brzev et al., 2012a). A facet is an attribute

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[3] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/posts/review-of-existing-structural-taxonomies

[4] http://world-housing.net

of a building under consideration that is clearly defined, mutually exclusive, and collectively exhaustive. In comparison to traditional (hierarchical) taxonomies, where the data is organized in a tree-like structure, the hierarchy of classes in faceted taxonomies is not fixed and can be changed. Faceted taxonomies allow information to navigate along multiple paths corresponding to different arrangement of the facets and items can be described in more than one dimension.

A structural taxonomy, however, is just one of several taxonomies that together contain all relevant data about a particular exposed asset. For example, other taxonomies, such as NSCs or ISCs, need to cover issues related to general building information, non-structural elements, occupancy, population, economic values, etc. Yet a unified, comprehensive and flexible description of exposure to the authors´ best knowledge is still missing.

Spatio-temporal databases

A dynamic exposure database should be able to account for the lifespan of exposed assets and track their evolution in space and time. Earlier work in the direction of spatio-temporal database design was characterized by separate research in either the spatial (Paredaens et al., 1994) or temporal (Snodgrass, 1992) domains. Since the emerging of combined spatio-temporal databases, numerous approaches have been proposed for data modelling and reviews have categorized and compared the existing work (see, amongst others, (Abraham and Roddick 1999), (Sellis 1999), (Peuquet 2001) and (Pelekis et al. 2004)).

Collection and assessment

Several alternative or complementary approaches are followed to collect exposure-related data. In the following we introduce them within the context of global dynamic assessment.

Direct observation

Two principle strategies for direct observation can be distinguished: full enumeration and statistical sampling. Full enumeration refers to the detection and definition of each exposed asset within a study area. It can therefore potentially achieve high accuracies and levels of detail, but usually requires more work and involves greater investment of resources. Sampling has the advantage that only small subset areas need to be analysed in detail to estimate summary statistics for a larger area of interest, or for well-defined strata if a stratified sampling is used.

Full-enumeration

Census

Census is the elective reference for national demographic data, and the most known approach based on direct collection. Globally-monitored census data was not available until the World Population Prospects (United Nations 2012). Mostly based on full-enumeration of people and housing, national censuses have proved inefficient, relying on resource-intensive methodologies for census data collection. At the end of the first year of the 2010 census round, 2005, only an estimated 5.5% of the world's population had been enumerated. At the end of 2009, this proportion had increased to 21% and at the end of the census round in 2014, 96.3% of the world population is expected to be enumerated (based on the current census schedules)[5]. Notably, an increasing number of countries are adopting self-enumeration schemes based on web technologies.

Volunteered geographical information (VGI)

VGI is the result of the joint efforts of many individuals who voluntarily, and usually with no economic rewards, collect and submit data observed either on the ground or by using support imagery. We can further distinguish between structured and unstructured VGI. Unstructured VGI defines spontaneous, non-authoritative initiatives such as OpenStreetMap (OSM)[6], a purely bottom-up approach where the collection activity is not systematic and is left to the interest and motivation of the participants (Coleman et al., 2009). Structured VGI,

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[5]

[6] http://www.openstreetmap.org

by contrast, also builds on volunteering citizens, but has an authoritative component aimed at focusing the efforts on specific tasks and objectives (Chapman, 2012). Unstructured VGI can be regarded as a continuous, low-cost source of useful information, but consistent efforts must be foreseen for harvesting and restructuring the information, and coverage and data quality are not guaranteed. Structured VGI requires resources to coordinate the collection activity, but provides better control on the resulting data, while also entailing direct contact with the volunteers (usually part of a local community) thus helping to improve risk awareness. VGI does represent a potential opportunity for large mapping organizations as a complementary source of information for authoritative databases (Coleman et al., 2009).

Sampling

Rolling census

Census methodologies are progressively changing from full enumeration to advanced sampling and statistical modelling. By using a rolling census approach, for instance, the frequency of updates would be annual, compared with the 5/10 years of a standard enumeration (United Nations and Statistical Division, 2008). This approach involves the full-enumeration of small settlements and the continuous sampling of the most populated ones (around 10% every year). By reducing the burden of a traditional methodology, the rolling census would allow the integration of highly complex sampling and modelling techniques and a high-quality sampling frame.

Digital in-situ surveys

Digital *in-situ data capturing systems* have recently been proposed as time- and cost-effective supplements to commonly used in-situ screening techniques (FEMA 154, 2002), (Applied Technology Council (ATC), 1985). (Womble et al., 2006) introduce the VIEWS^{TM} system, a notebook-based field data collection system that integrates real-time GPS tracking with map layers and remote sensing imagery in combination with a digital video system to collect georeferenced in-situ data. The Inventory Data Capture Tools (IDCT) initiative of GEM provides with a suite of free and open-source tools to generate exposure information from remote sensing and field observations (Bevington et al., 2012). The initiative has also implemented guidelines for efficient sampling and a tool to create mapping schemes for the statistical inference of structural parameters. Wieland et al. (Wieland et al., 2012) use satellite remote sensing and in-situ omnidirectional imaging within the framework of an integrated sampling scheme to infer specific, scale-dependent information about an exposed building stock.

Remote Sensing

Remote sensing is increasingly being recognized as an important technique to derive exposure characteristics for the rapid assessment of exposure over various scales, covering large geographical areas at comparatively low costs (Adams and Huyck, 2006), (Müller et al., 2011), (Geiß and Taubenböck, 2013). Manual or automatic processing of high-resolution imagery is used for the full-enumeration of assets (buildings, roads, bridges) and their geometric characterization (footprint, shape, height). Satellite-based approaches provide information about physical exposure that can be inferred from the top view. For instance in the case of building stock, in order to provide a full-fledged description of exposure, analysis of the lateral structure and facades of buildings still needs to be carried out. Therefore, remote sensing should be efficiently combined with in-situ direct observation methods.

Indirect characterization of exposure

Often, the amount, spatial coverage and/or quality of the information collected on the ground are insufficient for populating global exposure databases. It is then customary to rely on several indicators, called *proxies*, to infer information on the objects of interest.

Population

A global distribution of population data, in terms of counts or density per unit area, is considered the primary source of information for exposure assessment. In particular, this approach copes well with empirical models of vulnerability, where direct estimates of loss are obtained by considering past events, and the main loss metrics account for fatalities (Jaiswal and Wald, 2010). Many global models use human exposure as a basic ingredient to define a more refined "hazard-specific exposure" (Dilley, 2005), (Peduzzi et al., 2009), (Allen et al., 2009).

Built-up mask

A further step with respect to population distribution is the spatial delineation of built-up areas. This can be considered as an intermediate description of exposure, where the characterization of the built-up environment is improved with respect to a simple population layer. Examples of global built-up area products include the Global Rural-Urban Mapping Project (GRUMPv1)[7], the Global Human Settlement Layer (GHSL) (Pesaresi and Halkia, 2012) and the Global Urban Footprint (GUF) (Esch et al., 2010).

Mobility patterns

Short-term (daily and weekly) variations in exposure refer to the temporal change in buildings' occupation due to patterns of social mobility. This temporal variability can strongly affect the quantification of human exposure in cases of natural events with rapid onsets, such as earthquakes, landslides or tsunamis. Models of building occupancy considering daily patterns have been proposed (Coburn and Spence, 1992), (Coburn, 2002), but collecting the necessary data to update such models can be very time and resource-intensive. A promising alternative approach is based on the analysis of cellular phone data provided by telephone companies (Wesolowski et al., 2013), (Lu et al., 2013).

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[7] http://sedac.ciesin.columbia.edu/data/collection/grump-v1

Multi-source integration

Due to the increasingly large variety of possible exposure information sources, the need arises for the flexible *integration of existing information* from different acquisition techniques, scales and accuracies in order to not discard available information. An example for a probabilistic integration approach is given in (Pittore and Wieland, 2013). This method is based on Bayesian networks and allows for the sound treatment of uncertainties and for the seamless merging of different data sources, including legacy data, expert judgement and data-mining based inferences.

Global databases

Global human exposure

Global models of human exposure mostly describe population data either on a regular grid or considering specific settlement coordinates or geographical boundaries. A widely used product is the Gridded Population of the World (GPWv3)[8], a gridded data set that provides a spatially disaggregated population layer constructed from national or sub-national input units of varying resolutions. The native grid cell resolution is 2.5 arc-minutes. Population estimates are provided for the years 1990, 1995, and 2000, and projected to 2005, 2010, and 2015. Other global human exposure models include LandScan (Bhaduri et al., 2007) and WorldPop[9]. These models are based on the integration of several information sources, including census and remote sensing, and are affected by a significant range of uncertainties (Potere et al., 2009), (Mondal and Tatem, 2012).

Global built-up area characterization

The GHSL is developed and maintained by the Joint Research Centre (JRC) of the European Commission. GHSL integrates several available sources about human settlements with information extracted from multi-spectral satellite images. The underlying automatic image information extraction workflow makes use of multi-resolution (0.5m-10m), multi-platform, multi-sensor (pan, multi-spectral), and multi-temporal satellite image data (Pesaresi and Halkia, 2012).

The GUF is developed by the German Aerospace Center (DLR) and is based on the analysis of Synthetic Aperture Radar (SAR) and optical satellite data. The project intends to cover the extent of the large urbanized areas of mega cities for four time slices: 1975, 1990, 2000 and 2010 (Taubenböck et al., 2012).

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[8] http://sedac.ciesin.columbia.edu/data/collection/gpw-v3

[9] http://www.worldpop.org.uk/

Global description of building stock

The Prompt Assessment of Global Earthquakes for Response (PAGER[10]) (Wald et al. 2008), the Global Exposure Database for GAR 2013 (GED-13) and the Global Exposure Database for GEM (GED4GEM) are examples of global exposure databases that specifically include physical exposure information. GED-13 (De Bono, 2013) aims to create an open global building and population inventory suitable mainly for earthquake and cyclones probabilistic risk modelling using the CAPRA platform (Cardona et al., 2012). It employs building type classifications for different size categories of settlements as developed by the World Agency of Planetary Monitoring & Earthquake Risk Reduction (WAPMERR[11]) (Wyss et al., 2013). The GED4GEM[12] (Dell'Acqua et al., 2012) project aims to create an open homogenized database of the global building stock and population distribution, containing spatial, structural, and occupancy-related information at different scales as input to the GEM risk platform OpenQuake (Crowley et al., 2011) using building type classifications following the GEM taxonomy. A multi-scale database structure is followed that contains information on buildings and populations from the country scale down to the per-building scale. The initial version of GED4GEM will contain aggregate information on population, built area and reconstruction costs of residential and non-residential buildings at 1km resolution. Detailed datasets on single buildings will be integrated for a selected number of areas and will increase over time.

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[10] http://earthquake.usgs.gov/earthquakes/pager/

[11] http://wapmerr.org/

[12] http://www.nexus.globalquakemodel.org/ged4gem/posts

Validation

The aim of validation is to assess the quality of the information collected, integrated or modelled (buildings inventory, population distribution, land-use/land-cover or infrastructure atlas, for instance). Validation provides (often non-technical) end-users with some degree of assurance that the products meet the planned standards, and describe the expected accuracy even when no specific standards were set (Broglia et al., 2010). Two essential requisites for validation are:

1. it must be producer-independent,
2. it must be considered a (potentially continuous) process, based on specific methods delivering reproducible results.

Validation of exposure models should always be considered in order to account for the different uncertainties in the subsequent vulnerability and risk assessment phases. Unfortunately, validation of exposure data is often overlooked and its contribution to the overall risk analysis is consequently underestimated.

Sources and time dependency of uncertainty

Validation must account for different types of uncertainties. For the sake of simplicity, we mention here three measures of information quality: positional accuracy, attribute accuracy (thematic for categorical data) and completeness (Gahegan and Ehlers. 2000). The positional and thematic accuracies can be related to the accuracy of the measurement devices (e.g.. GPS), to observer bias (for instance. the interpretation of a human-collector) or be dependent upon the data processing. Completeness also can be affected by the employed sampling methodologies or by a lack of resources for proper data collection.

Uncertainties change over time as new data are made available, datasets evolve, or as the exposure itself changes. These intertwined dynamics are difficult to capture, especially over a global scale, where abrupt spatio-temporal changes in the quality and availability of the data require constant harmonization, hence calling, for instance, for repeated sampling.

Considering geographical scales and multiple sources

Many global databases related to exposure are based on a mixture of global and local efforts. Validation should therefore follow a multi-scale strategy. Two complementary approaches, namely quality control and statistical accuracy assessment, can be considered, each providing different information (contextual and qualitative versus statistical). Classical accuracy assessment, based on a sample of reference data, gives a quantitative figure of the information accuracy, while wall-to-wall quality control provides more exhaustive information on the nature of errors, their location and their relationship with the spatial pattern. A good example is provided by the validation of the Global Land-cover 2000 Map (Strahler et al., 2006), (Mayaux et al., 2006). Considering the GAR13 (de Bono, 2013) (Wyss et al. 2013), and the GED4GEM (Dell'Acqua et al., 2012), for most information sources, accuracy is not provided, and often the estimates are based on disaggregation of population figures, adding additional uncertainty. In both cases, no validation methodology is explicitly mentioned, although for the GAR13 database, a preliminary assessment of the expected quality based on expert judgement is given on a country-scale basis (Wyss et al.).

Validation of exposure data from VGI

In the recent literature, several studies have addressed the completeness of OpenStreetMap (OSM) by comparing it with other reference data sets (Haklay, 2010), (Zielstra and Zipf, 2010), (Girres and Touya, 2010), (Hecht et al., 2013). It is concluded that OSM is fairly accurate, but far from being a vital replacement for professional acquired data sets, mainly due to quality issues related to areas located far away from city centres. These empirical studies indicate that the level of completeness in OSM at the regional scale is still low (for example, it is less than 30% in two selected regions in Germany) and shows a considerable spatial variation (Hecht et al., 2013), although improving as more users join the community. This leads to the complete coverage of the studied areas in Germany, assuming current rates, being achieved in around 9 years. However, as expected, urban areas are generally better mapped than their rural counterparts. The mentioned studies mainly focused on completeness analysis, and partly on positional accuracy. Thematic accuracy has not been analysed in detail, mostly due to the reduced amount of thematic information in OSM concerning building stock and other features of interest for exposure modelling.

Crowd-sourced collection vs. crowd-sourced validation

Validation can be carried out either by comparison, using reference data, or using ground-truth data collected with adequate sampling strategies. The latter is usually resource-intensive when applied to global-scale exposure models, however, at regional and global scales, reference data is often scarce and of low quality. The Volunteered Geo-Information (VGI) paradigm can therefore also be used for validation, that is, to rely on distributed, not-authoritative approaches to collecting local ground-truth (Fritz et al., 2009).

Communication

In addressing the communication of physical exposure, we focus on the visualization and the dissemination phase. Visualization in this context refers to creating and displaying maps depicting the geographical distribution of exposure. Mapping a population´s geographical distribution represents one of the first visualizations of exposure information at the global scale. Such maps can greatly improve decision makers´ understanding of the subsequent vulnerability when they are compared with the extent of existing geo-hazards.

Mapping global (exposure) uncertainty

Regardless of the complexity or quality of the information contained in exposure database, decision makers often base their choices on a few visual representations (including cartography, thematic and chorophlet maps) which cannot capture all facets of available knowledge, nor the lack of it. Mapping should thus be used to also communicate the uncertainty affecting available exposure data to help practitioners make informed and efficient decisions in the pre-event risk-mitigation stage as well as in critical situations. Several studies (Harrower, 2003), (MacEachren et al., 2005), (Shi, 2008) have explored different approaches towards the visualization of uncertain geographical information. In general, the mentioned studies acknowledged the usefulness of portraying uncertainty for decision-making purposes, while cautioning on the end-user "learning curve" associated with depicting uncertainty on maps.

Considering exposure-databases on a global scale, a particular effort should be made in finding optimal ways to capture and communicate uncertainties in a dynamic fashion (accounting for the spatio-temporal evolution of uncertainty). In particular, thematic accuracy, completeness, and data vintage should be carefully depicted, in consideration of the heterogeneity of sources and the fragmentation of the geographic coverage.

Sharing (open) data

Dissemination of (global) exposure data is the key to empowering different end-users and communities and allowing improved risk evaluation. Most global exposure databases covering population and other physical assets are already or will soon be available (e.g., GRUMP, LANDSCAN for population, GAR13, GED4GEM for buildings), although not all will follow an open data sharing policy. In some cases, the data have to be bought (LANDSCAN) or availability could be restrained, depending on the specific aggregation level. The level and amount of information disclosed will vary between countries, and on the specific type of information. If these issues are reasonable, clear standard guidelines should be agreed upon to minimize the amount of restricted data. Authoritative sources are expected to exert a stronger control on the availability of high resolution exposure data (e.g., building by building data) in comparison with non-authoritative ones. Even in cases of volunteered geographical information, it would be possible to collect and share to the whole community detailed and useful exposure information, while still restricting the dissemination of more sensitive data (Chapman, 2012). Such dissemination efforts should not only consider the data, but also the necessary metadata (source, vintage, accuracy, coverage). With the rise of Web2.0 applications, sharing object-oriented metadata would complement the provision of useful datasets with a sound quality assessment and hence ensure the long-term sustainability of exposure information (Shi, 2008).

Conclusions

In this paper we addressed the challenges of collecting, describing, validating and communicating exposure data (people, buildings, infrastructure) within a multi-scale, global and dynamic framework. Data-sources, methodologies and experiences deemed significant were reported and discussed within the broader framework of Disaster Risk Reduction (DRR). Although not exhaustive, this review allows us to point out several items that need to be considered in future initiatives:

Description

- An important benefit of global datasets is the collection and harmonization of locally-collected information. The use of standard (or widely accepted) and flexible descriptions of the exposed assets is strongly advocated. A wider use of taxonomies to classify exposed assets and ontologies to describe functions and interrelations within different exposure domains (buildings, infrastructures) is therefore required.
- Several (sometimes competing) taxonomies have been suggested and are increasingly being used with good results. A unified, comprehensive and flexible description of physical exposure (largely hazard-independent) should be pursued with the widest agreement, in order to overcome cultural and linguistic barriers.
- Further efforts should be devoted to exploring the potential of semantic web and related resources to create dynamic "dictionaries" able to transcode between different evolving ontologies, in particular to make use of data collected through unstructured crowd-sourcing.

Collection

- Local/regional data collection, and in particular censuses, directly or indirectly dominate current global estimates of exposure. In the last decade, most countries have adopted modern and more efficient methodologies for census implementation, therefore making it a very powerful tool for collecting data related to risk-mitigation. It is important to foster the further evolution of such methods, for instance, by including in the household surveys a more detailed description of dwellings.
- Institutional organizations will always have a large role in supporting and coordinating global estimates, and proposing widely accepted standards. Data collection efforts should nevertheless be integrated by the strong involvement of local communities.

- Remote sensing techniques have proved useful for the preliminary assessment of exposure over wide areas. Further efforts should focus on providing simple and effective methodologies and tools to properly exploit the full potential of remote sensing and to combine it with complementary in-situ data collection.

- Particular attention should be devoted to considering authoritative versus non-authoritative data collection methodologies. The authoritative approach gives better results at local scales, but often pose harmonization problems at cross-border / global scales. Moreover, institutional efforts focusing on the collection of exposure data are missing in many (mostly developing) countries.

- Data obtained through unstructured volunteered geographical data collection (e.g., OSM) have proved useful as complementary information sources. Being still very sparse, this data cannot substitute authoritative databases in data-rich countries, but can efficiently integrate other sources in developing countries, especially in urban areas.

- Structured volunteered geographical data collection (e.g., Humanitarian OpenStreetMap (H.O.T.)[13]) represents a promising trade-off between the authoritative and non-authoritative paradigms. It combines the advantages of in-situ, community-based collection activities with higher information quality standards and allows for a more efficient allocation of the efforts by volunteers, in line with end-user requirements.

Validation

- Validation should be always considered and tailored to the specific data collection methodologies, including being properly spaced over time to capture the evolution of the exposed environment and of the data quality.

Communication

- With the increasing levels of complexity of global exposure models (from population distribution to detailed characterization of building stock), the visual mapping of exposed assets should be carefully addressed. In particular, the visualization of spatial, temporal and thematic accuracies should always be accounted for.

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[13] http://hot.openstreetmap.org/

- As the use of mapping services and collaborative platforms spreads, communication and collection of exposure data will be increasingly intertwined. Careful communication of the geographical coverage, uncertainty and vintage of data would improve participatory actions. Simple GIS-based tools would further enhance participatory planning, while favouring "learning by doing" capacity building.
- Openly sharing reliable exposure data at the global scale would allow a better estimation of vulnerability with respect to different geo-hazards, thus contributing to raising the level of awareness of the public and institutions.

Road-map towards global-exposure

Several recommendations can be further distilled from the conclusions, and are provided to sketch a road-map towards the effective implementation of global, dynamic exposure databases:

- A stronger collaborative effort between the world´s disaster risk reduction institutions is advocated to implement a unified exposure taxonomy, largely independent on the particular hazard. A global exposure taxonomy should be open, flexible, and built upon shared standards and complemented by a comprehensive ontology.
- Rapid, large-scale data collection based on remote sensing should be fully exploited and whenever possible be integrated with in-situ information, employing multi-source and scale data sampling methodologies.
- Authoritative and non-authoritative sources should be integrated while ensuring quality standards and compliance with disaster risk reduction purposes. In this context, it becomes important to harvest data from crowd-sourced information (incidental data) and exploit structured VGI to augment authoritative sources and involve communities and experts, especially in data-poor countries.
- Exposure-collection should be regarded as a continuous process that is constantly evolving over space and time.
- Data and (statistical) models must coexist in a statistically sound framework in order to overcome the infeasibility of having a complete and fully enumerated global dynamic exposure database.
- Validation and quality assessment should be carefully assessed throughout the collection-description-dissemination process.

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