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Foresight

State-of-the-art in Risk Mapping

Commissioned Review

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Contents

State-of-the-art in Risk Mapping

Main Report: Peter Atkinson[1], Michael J. Clark, Hugh, G. Lewis, John Bevington, Andrew Murdock and Julia Branson

Case Study 1: Mirianna E.A. Budimir, Peter M. Atkinson and Hugh G. Lewis
Case Study 2: Michael J Clark and Sally J Priest
Case Study 3: John Bevington, Hugh Lewis and Ronald T. Eguchi

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[1] University of Southampton, P.M.Atkinson@soton.ac.uk

1. Introduction

Definition

We adopt the definitions of Risk, Hazard, Vulnerability and Exposure provided by the Foresight team, referencing the Intergovernmental Panel on Climate Change (IPCC) and United Nations International Strategy for Disaster Reduction (UNISDR). In particular, Risk is defined as a function of Hazard H, Vulnerability V and Exposure E:

$$R = f(H, V, E) \qquad \text{(Equation 1)}$$

This is the definition used in most catastrophe (cat) loss models, as used extensively by the Insurance and Reinsurance (Re) industries.

Scope

Risk Mapping is taken here to encompass the geospatial expression of the outputs of risk assessment as above, and the broader sense of the mapping of its component inputs *(H, V, E)*, particularly Hazard. However, risk mapping depends heavily on models and input data sources, so these are also considered. The purpose and efficacy of mapping are also considered in scope.

Purpose

This document sets out to achieve three goals: (i) review the current best practice in natural hazard risk modelling across the three sectors of industry, government and non-governmental organisations (NGOs) and academia, (ii) identify and describe the current best practice in geospatial mapping, primarily, but not exclusively, as applied to natural hazards and risks, and (iii) identify current trends, gaps and the (primarily technological) changes that are required to fill those gaps over the next 10 years in order to position the UK for the next 40 years.

Approach

First, the document builds on an extensive review of the literature from both academic and grey sources, including publications from leading academics and commercial/service sector companies. Since the field of risk modelling and mapping is potentially extensive, the literature search was undertaken in three phases: (i) natural hazard risk mapping, (ii) cat loss modelling, (iii) specific queries around technological advances such as “crowdsourcing”, “open source”, “cloud computing” and “platforms”.

Second, a semi-structured interview survey was conducted with several notable leaders in the field of risk mapping, including representatives from industry, NGOs and academia. The questions focused on (i) characterising the activities of the respondent's organisation or department and (ii) soliciting the respondent's opinion about the state-of-the-art, future trends, gaps and requirements.

Third, the team has assembled three "Case Studies":

I. Global Hazard Risk Mapping; to compare and contrast four different approaches for global mapping, with the primary purpose of informing policy and planning.

II. Flood Mapping in the UK; to exemplify probabilistic and process model approaches to mapping, public dissemination through platforms and difficulties over public understanding of uncertainty.

III. Crowdsourcing of post-disaster damage assessment in Haiti and New Zealand; the use of satellite and aerial photo interpretation, platforms and crowdsourcing for post-disaster needs assessment.

Limitations

This Review was assembled from a targeted literature search and a limited number of interviews. Therefore, there are numerous difficulties around creating a suitable sampling frame, remaining unbiased, and reaching sufficient sample size to ensure adequate precision. The supporting Case Studies draw deliberately on the experience of the co-authoring teams, but also benefit from input from experts outside the core team to provide robustness and quality assurance.

2. Risk Modelling and Mapping

2.1 Catastrophe loss models

Cat loss modelling (Eq. 1) provides a useful framework for conceptualising the majority of risk assessment and mapping efforts (Whitaker, 2002). The following definitions are useful:

(i) Risk is conventionally the expected loss $\mathrm{E}(L)$. In recent years, however, the preferred output of cat loss models has been the probability of exceedance (EP) curve (The Review, 2008). One may distinguish between occurrence PE and aggregate (i.e., annual) PE, with occurrence PE being most relevant here. The PE curve plots the probability of exceeding a given loss $p(L > L_k)$ as a function of loss value L_k (Figure 1). This probability is readily estimated from the distribution of simulated outputs from a cat loss model.

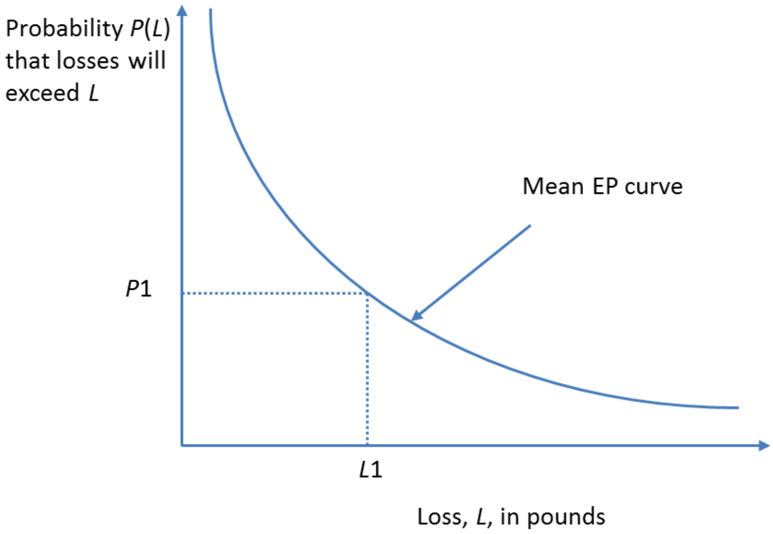

Figure 1. Schematic EP curve (based on Kunreuther, 2005).

(ii) **Hazard** is defined either (a) for multiple events by severity, location and frequency, or (b) for single events by severity, location and time. Cat loss models require as input an “event set”, that is, a set of hazard events that represent the possible hazard under current or future conditions, and that effectively sample or “cover” the space of possible events. Note that “hazard” refers to the underlying cause (e.g., earthquake) and “peril” refers to the effects (e.g., ground shaking) that result in damage (Banks, 2005). Ultimately, Equation 1 requires the peril as input. For example, for earthquakes, shaking intensity can be estimated by an exponential spatial decay from the earthquake hypocentre/epicentre. This leads to the concept of a peril footprint for each hazard event.

(iii) **Vulnerability** is defined by a transform of hazard H_m of given severity or magnitude m, into (usually) proportional loss, where proportional loss is equivalent to the loss divided by the exposure L/E. Sometimes, this transform is represented through the dual transform of (a) H_m into damage D and (b) damage into proportional loss each of which may capture non-linear relations (Woo, 2011). In simplistic models, however, vulnerability can be a single scalar value (e.g., 0.05).

(iv) **Exposure** relates to the at-risk elements, whether they are assets such as buildings (with a given financial “exposure”), people (mortality, morbidity, displacement; with its attendant costs) or disruption, for example, to business networks (which have a financial value).

Thus, Equation 1 provides an easy-to-understand framework for estimating the likely impact of catastrophe on local populations and assets. Given a hazard of severity *m*, multiplication by *V* estimates proportional loss L/E. This is then multiplied by the actual exposure *E* to estimate risk (i.e., loss). The actual procedure is far more complicated, particularly in the third (actuarial) component of cat loss models that deals with insurance structures.

The above process is repeated thousands of times for every location, or every asset, and for every event to give a distribution of losses from which the expectation and other statistics such as the EP curve can be obtained. In fact, most cat loss models will repeat this process for each of several hazards and then integrate the results statistically. The model output can then be used to create a risk map, although commonly mapping may be restricted to the hazard component.

2.2 Data inputs

The **hazard** data inputs for cat loss modelling can be provided in one of four ways (Banks, 2005):

(i) modelling historical losses based on the historical event set,

(ii) as for (i), but updating estimates of exposure and vulnerability to be more current,

(iii) simulating the hazard event set by fitting a probability distribution to historical events, drawing simulated realisations (e.g. thousands) and propagating them through Eq. 1 to estimate the loss distribution, and

(iv) as in (iii), but simulating the hazard event set informed by a plausible physical model of the process.

(iii) and (iv) have become the dominant vehicles for probabilistic cat loss modelling, with the choice depending on the hazard (Khater and Graham, 2008). For example, for earthquakes, (iii) has been prevalent while for tropical cyclones (iv) based on event sets and global circulation models (GCMs) is now the state-of-the-art. Thus, it is important to understand that whether the generating mechanism is a statistical distribution or physical process model, probabilistic cat loss modelling takes as input a simulated set of hazard events. The environmental hazards relevant to cat loss modelling are believed to be reasonably well characterised through such approaches (Chávez-López and Zolfaghari, 2010).

Vulnerability can be estimated from historical losses, from engineering design (e.g., Computer-Aided Design, CAD) specifications, or by expert opinion. Vulnerability is commonly estimated through a damage ratio approach. If vulnerability values are not provided, various approaches are available to estimate them (e.g., Papathoma-Köhle *et al*., 2011). Vulnerability data are often missing or unreliable, especially for developing world and resource-poor settings (Grossi and Kunreuther, 2004; Chávez-López and Zolfaghari, 2010). Moreover, vulnerability estimates may change as exposure increases through unplanned or poorly planned expansion of urban settlements. Thus, a large amount of uncertainty exists in vulnerability estimates which can, therefore, have a large effect on model loss estimates (Pinho, 2012) and subsequent risk maps.

Exposure can be estimated from a variety of sources including census data for population distributions and insurance data records for buildings. However, both data sources suffer from drawbacks. The census is often woefully out-of-date, especially in rapidly urbanising developing countries and does not capture diurnal variation in population concentrations. However, work on dynamic modelling of population is likely to bring great improvements over the next 5-10 years[2]. Indeed, the increase in catastrophes in recent years is largely due to an

[2] See the ESRC Population 24/7 project http://www.esrc.ac.uk/my-esrc/grants/RES-062-23-1811/read. Accessed 02 November 2012

increase in exposure and vulnerability due to rapid urbanisation in coastal areas and floodplains, rather than changes in the frequency of hazards (Windheim *et al*., 2004; Banks, 2005; Swiss Re, 2010). A long-appreciated conundrum of risk management is “risk compensation”; the fact that investment in hazard protection often raises exposure by encouraging increased investment in, and occupance of, the at-risk area as a result of lowering of the perceived risk. This means that efforts to update exposure data are critical (European Commission, 2010).

Loss data are not required directly on the right-hand side of Equation 1, but they are required for a range of purposes including (i) calibration of model parameters implicit in Equation 1 and (ii) validation of predicted Risk (which, of course, is very difficult with very long recurrence period hazards). They can also be used to inform local action in terms of response and recovery when data are acquired in near-real-time (see below).

2.3 Available models

The leaders in the field of cat loss modelling are the commercial risk modelling companies. There are three main providers: RMS, AIR Worldwide and EQEcat. The differences between the big three companies were highlighted by an inter-comparison study undertaken by the RAA/ISCM (2012). This leading reputation has been built on the relevance and skill of the models provided, the complexity of the actuarial module, and on innovation (e.g., use of process models to simulate certain hazard events such as hurricanes). As such, the models are an essential tool used widely by insurers, reinsurers and brokers (for example, Munich Re uses RMS). The dominance of the big three suggests that barriers to entry are high, but the data sources, model outputs and user applications are all evolving rapidly.

3. Hazard Modelling and Mapping

3.1 Hazard Mapping and Long-term Forecasting

Hazard mapping, including hazard zonation (i.e., the division of the land surface into areas and the ranking of these areas according to actual or potential hazard) and hazard hotspot analysis (i.e., identification of relatively high probability of loss from one or more hazards), is an important research field in its own right. The rationale for hazard mapping can vary, but is often to provide an input to risk assessment (for example, through Equation 1 or hypothetical scenario planning). Several approaches to hazard mapping may be distinguished, depending on the type of data analysed:

Hazard mapping

(i) Historical frequency analysis (y): Historical data on hazard events are analysed to provide maps of event locations and severities. This is the approach used in global hazard mapping based on simpler approaches (Case Study 1). Hazard zonation may be achieved by overlaying hazard events or peril footprints, or by smoothing the set with some spatial filter to provide a more generalised view (since historical realisations are only a sample of the full space of possibilities).

(ii) GIS overlay $(\mathbf{x})$: Multiple covariates that are believed to be correlated with the hazard are weighted using expert opinion to predict the hazard likelihood. The approach is useful where data are limited, but suffers because the weights are not calibrated to the data. Multi-criteria decision analysis (MCDA) is a popular method of eliciting the weights. A related approach involves transform of remotely sensed imagery to estimate various hazards (Joyce *et al*., 2009)

(iii) Regression $(y, \mathbf{x}, \beta)$: Historical event footprints are regressed on a covariate set to predict the “likelihood” of events at non-sampled locations (see Wardrop *et al*., 2010 for Bayesian disease mapping). The meaning of the predicted “likelihood” can vary depending on the input data, and care should be exercised in interpreting the results.

(iv) Engineering solution $(y, \mathbf{x}, \varphi)$: Mechanical relations between a possible event or its character and a set of input variables can be used to predict the likelihood of occurrence of an event or its character.

(v) Process modelling $(y, \mathbf{x}, \theta)$: Physical process models that capture the underlying mechanics of a process, albeit at an abstracted level of generalisation and space-time resolution, have the advantages of (i) capturing some process knowledge, (ii) being potentially more generalisable than site-specific statistical models, (iii) being able to propagate error to estimate output uncertainty and (iv) being applicable to data inputs other than the measured data (i.e., evaluating “what-if” scenarios). Such what-if scenarios can include exploring historical possibilities, alternative planning options and simulation under likely future conditions (e.g., climate change) (see Yang *et al*. (2011) for an agent-based approach to modelling influenza control interventions). Physical process models can be used to recreate a plausible time-series of events through computer-based simulation of thousands of runs. In hazard zonation, this approach can be used to map, for example, the '100-year return period flood’ for public consumption (Case Study 2).

In all cases, the objective is to map the spatial distribution of the hazard, most often characterised by its severity and/or frequency of occurrence.

Long-term Forecasting

(vi) Trend analysis (y): Trend fitting to a time-series of historical data or variants based on the extensive statistical field of time-series analysis (TSA) is a common approach (Adnan and Atkinson, 2011; Biggs and Atkinson, 2011). At its simplest it involves regressing some variable such as frequency against time, often linearly. The assumptions in such an approach can be dubious.

(vii) Process modelling $(y, \mathbf{x}, \theta)$: Process models (e.g., GCMs) are used routinely to make long-term forecasts. For example, RMS runs a full GCM for future time periods to forecast likely future hurricane landfalls on the Eastern US seaboard and uses these simulations in combination with event sets in its loss models.

(viii) Combination of long-term models and short-term models: one of the most commonly applied approaches to forecasting long-term future hazard (e.g., catchment flooding) is to run a present-day hazard model with its boundary conditions (e.g., rainfall and temperature) replaced with those from a long-term forecast (e.g., from a GCM scenario). Again, the linear assumptions may be unfounded.

3.2 Monitoring and Short-term Forecasting

With monitoring and forecasting, the time-line is near-event, during-event or post-event and most commonly provides probabilistic estimates in "real-time" whereas probabilistic risk mapping and hazard mapping (as defined above) are anticipatory, and map likelihood (or equivalent) either for the present or some future time. Thus, monitoring and forecasting add the following approaches to those outlined above under hazard mapping.

Monitoring

(ix) Observation in real-time (y): is used to monitor some hazard-related variable such as seismicity for Earthquakes, wind speed for tropical cyclones, and discharge for flooding (Bogue, 2012). Often sensor networks are established in situ, but may be difficult to access by decision-makers (Le Cozannet *et al*., 2008). Observation in pseudo-real-time from satellite sensors is common, but problematic because of the time taken to receive and process images. Monitoring has an obvious role in early warning systems (EWS) (see below).

(x) Damage and loss assessment (y): monitoring is also important in the response and recovery phases of an event, where variables related to damage and loss, as well as the threat of cascading hazards, may be the target. In these latter phases crowdsourcing is likely to be of great value (see Case Study 3).

Short-term Forecasting

(xi) Machine learning (y): A class of statistical models generally referred to as "machine learning" (ML), that are data-based and non-parametric, can be used to forecast hazard event sequences over short-time-scales (Pozdnoukhov *et al*., 2009).

(xii) Process models $(y, \mathbf{x}, \theta)$: are commonly used to forecast over short-time scales (e.g., for real-time flood forecasting).

(xiii) Data assimilation $(y, \mathbf{x}, \theta)$: is commonly used to update the forecast made by a model using data on the "state" of interest from monitoring stations or other sources (e.g., Twitter; Sakaki *et al*., 2010). The linear Kalman filter is the basic approach which involves weighted integration of model- and data-based estimates based on their relative precisions; the greater the relative precision, the greater the weight in the linear sum (Neal *et al*., 2009, 2012).

Short-term forecasting based on some underlying model and data assimilation is fundamental to many EWS. The output of such systems can be the forecasted state at a given location or a map; the latter brings benefits both in terms of visualization and communication (Zerger, 2002) and, potentially, real-time risk assessment.

3.3 A note on purpose

The various approaches (or modes) identified above vary in their purpose and utility. We introduce a three-dimensional typology (Appendix 1). In particular, we distinguish four levels of purpose: policy, strategic planning, management and operational. We also distinguish between four scales of spatial extent or “levels”: global, regional, national and local. Figure 2 categorises several of the approaches given above into a matrix based on purpose and scale.

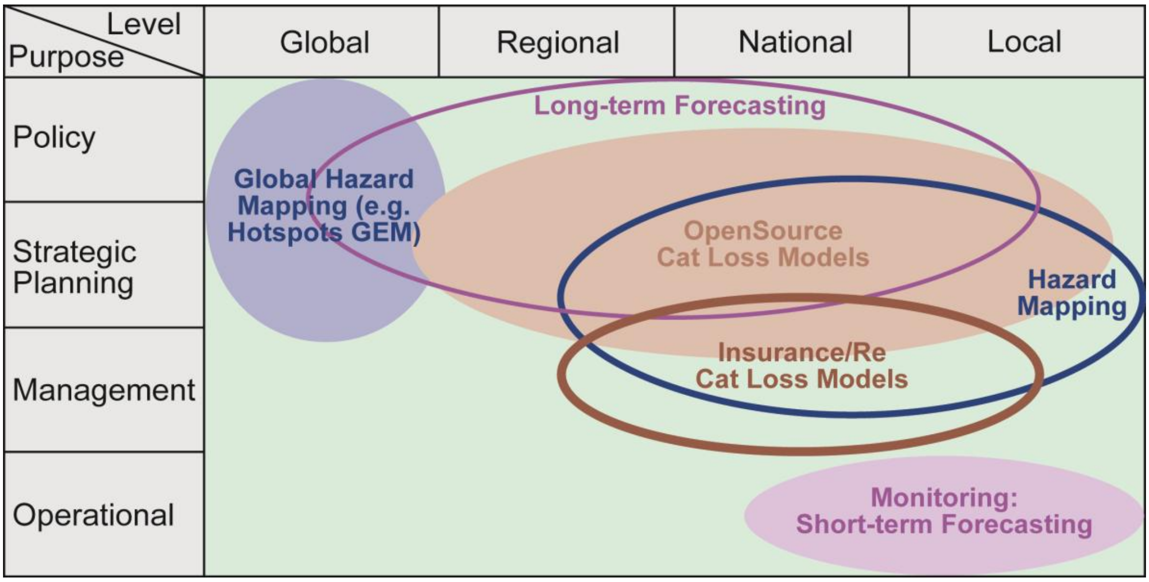

Figure 2. Matrix representation of different approaches to hazard and risk mapping

The important points to draw out from Figure 2 are:

(i) The difference in purpose between the Insurance/Re industries which target national and local risks (albeit often within a framework of global trends) and, driven by the Hyogo Framework for Action, the intention of open source platforms (e.g., the PREVIEW Global Risk Data Platform; Giuliani and Peduzzi, 2011) which target national governments and the public in relation to disaster risk reduction, building awareness and preparedness through increasing mitigation efforts, response and recovery planning and increasing resilience. It is suggested in Appendix 3 that the balance between insurance and reinsurance may shift in the future.

(ii) The difference in purpose between hazard mapping, the majority of which has been undertaken at national and sub-national levels, and global hazard and risk mapping which is a relatively new goal facilitated by platforms and open source standards (e.g., the World Bank's Hotspots map - Dilley, 2006; Lerner-Lam, 2007).

The difference between monitoring and short-term forecasting and all other goals. Monitoring and short-term forecasting are at the operational level and are relevant primarily to near-event, event and post-event timings.

4. Geospatial Mapping

Geospatial mapping of risk in the form of 2-D maps is commonly undertaken using proprietary software such as ArcGIS, a commercial desktop GIS platform. Bespoke algorithms can be added through the Python programming language (from interview).

Some fundamental considerations of any mapping endeavour are reviewed below in relation to risk mapping.

(i) **Georeferencing:** The coverage, precision and numerical resolution of georeferencing is a key driver of the quality of the resulting mapping. For example, if data are georeferenced to administrative unit only, then many assets will appear in the same unit. Moreover, there may be a risk of spatial bias.

(ii) **Data model:** the two main data models are the vector and the raster models. Vector data represent the real world as point, line or polygon objects (e.g., buildings) and raster data represent the real world as gridded images (e.g., of land use). The choice creates limits on what is possible through hazard and risk mapping. For example, in landslide hazard zonation, the choice of an object-based model requires selection of possible failure units which restricts the output (Atkinson and Massari, 1998, 2011).

(iii) **Scale of measurement 1 - spatial resolution:** A critical parameter is the spatial resolution, which is readily described for raster data (i.e., images) by the pixel size. The resolution of the data used to create output maps imposes limits on the level and purpose of those maps. This is readily exemplified by global hazard maps (Case Study 1) which generally have a “national” resolution and which, thus, have limited management and operational utility. Note that for the Insurance/Re industries, object-based mapping is most appropriate for insured assets.

(iv) **Scale of measurement 2 - extent:** The spatial extent of a map defines the level of analysis and conditions its utility and purpose.

(v) **Timing:** Hazard and risk maps represent a specific time. However, the input data are likely to represent a mixture of timings. Averaging across historical event data invokes a decision (assumption) of temporal stationarity, which may not be appropriate. Indeed, one of the greatest problems with risk maps is the lack of currency of exposure and vulnerability data. One cannot assess risk if one does not know where the present population is (including diurnal variation) and where formal and informal settlements have expanded over recent years. Note that time represents both periodicity and duration, both of which are significant in hazard management and operations.

(vi) **Visualization:** There exist various forms of static 2-D map, but these are only one of several ways to visualise hazard and risk information. Increasing attention is being placed on 3-D visualizations, including perspective views (e.g., draping on a digital elevation model), as these seem to communicate the risks much better to the general public who may not be used to an overhead view, particularly in the developing world. Publically-accessible geoportals such as Google Earth have brought such views of geospatial data to a wider audience. Moreover, dynamic displays (animations) of key information such as hazard event sets can be more powerful, if played at an appropriate speed, than a static average.

(vii) Uncertainty: All maps are “uncertain” in the sense that we can never be sure that an estimate is without error. Representing uncertainty is crucial, but challenging, as evidence suggests that the general public has difficulty in assimilating such information (see Case Study 2). Whereas the Insurance/Re industry may be attuned to probabilistic modelling, the same is unlikely to be true in the context of raising awareness and building preparedness in a national context. Moreover, the dual need to represent an estimate and its uncertainty raises challenges for visualisation. It has long been apparent that non-specialist audiences have great difficulty in handling concepts such as recurrence interval and uncertainty, and that this adversely impacts their understanding of, and response to, risk messaging – whether map-based or not.

(viii) Completeness and consistency: Maps may be incomplete (e.g., only certain parts of a domain have vulnerability or fragility curves). Moreover, they may be inconsistent (e.g., a land use map used to interpolate vulnerability to some insured houses may be inconsistent with the existing exposure map).

(ix) **Access:** A good map is of limited value if it fails to reach beneficiaries. Access is a key, but complex driver of new open source hazard and risk mapping efforts. Access includes a right to view, an infrastructure to make viewing available at an acceptable cost and time penalty, and a navigational structure that permits interested parties to view without unreasonable conceptual or effort hurdles.

(x) **Purpose:** The purpose of a map (Appendix 1) should be considered explicitly and will drive many of the above considerations. The key is that a map should be fit-for-purpose and neither more nor less, such as to balance cost-benefit. The multi-purpose utility of crowd-sourced maps means that additional detail is likely to be accrued beyond that required for any single purpose.

Explicit communication of these points on any map or dataset is important to ensure appropriate use of the dataset.

5. Future trends, gaps and requirements

5.1 Data quality

Dynamics

The dynamic nature of the human population and built environment, especially in a developing world, resource-poor context, means that risk from natural hazards grows and alters daily. We distinguish three rates of change:

(i) Slow: (e.g., changing climate over decades). There is a need to incorporate such effects into long-term forecasts (see Dlugolecki *et al*., 2009).

(ii) Moderate: (e.g., exposure and vulnerability changing annually). Since datasets are potentially out-of-date at the time of an event unfolding, there is a need to focus on currency.

(iii) Fast: (e.g., an event unfolding in real-time over days or weeks). Here, there is scope for much greater monitoring (and forecasting) before, during and after an event.

Resolution issues

Spatial resolution of available data is often coarse. For example, consider the broad utility of the global hazard and risk maps produced in Case Study 1. They may be of broad use to NGOs, but are unlikely to be of use at the national level where sub-national mapping is critical.

Crowdsourcing (below) has the potential to bridge this gap if the platform data structure established is capable of supporting detailed information upload and representation. There may be an unwillingness for public data providers to make information available at a scale greater than its precision and reliability support (see Case Study 2). In the past, access to large-scale hazard maps has been hindered by licence costs/restrictions of base mapping, but this situation is changing with the availability of platforms such as Google Maps and OpenStreetMaps. Moreover, the increasing resolution and availability of satellite sensor data as well as data from aircraft (and drones) and environmental sensor networks will help to fill this gap.

5.2 Community-based solutions

Open source communities

The open source movement has produced key organisations in a geospatial context including the Open Geospatial Consortium (OGC) which sets standards for open source sharing of geospatial data and the OSGeo organisation which advocates building bespoke toolkits from openly shared and interoperable GDAL/OGC GIS-type component algorithms. This transparency and access brings multiple advantages, not least of which is the creation of large communities of volunteers who both input to the effort (e.g., by sharing data, sharing code, correcting errors) and benefit from reduction in redundancy, access to the vast amount of information that is created, and public education (e.g., Dunbar, 2007).

The emergence of open source solutions for natural hazard risk assessment facilitated through platforms has been a relatively slower trend, building on earlier efforts to set standards including the UNDP Global Risk Identification Programme (GRIP, 2010) and surveys of approaches (see Jelenik and Wood 2007). However, in recent years several key initiatives have taken off including open-risk.org (Murnane, 2005), FEMA's RiskMAP in the USA (FEMA, 2009) and the EU Communication on a Community Approach in the EU (European Commission, 2010). These promote community-based efforts for risk mapping.

The creation of *capable* platforms is crucial in facilitating community-based efforts. Notable platforms are FEMA's HAZUS-MH which maps multi-hazard risk from hurricanes, floods and earthquakes in the USA (Schneider and Schauer, 2006; Vickery *et al*., 2006), the Global Earthquake Model (GEM), which is set to expand its portfolio of hazards beyond earthquakes, and the World Bank's OpenDRI initiative. Parallel processing and cloud computing may be key to this capability and these are discussed below.

There is a shift towards open modelling, which represents a greater transparency in the modelling approaches, but does not necessarily mean that the modules are "open source". That is, "open" refers to the modelling approach or protocol (just as the internet has a protocol), which provides a way to open up loss estimation to a wider community. However, the open approach enables these models to be used in a wider range of contexts and by a wider range of users, and enables those users to have clarity in terms of the transparency of the modelling approach.

An example is Oasis, which provides a public-private not-for-profit framework for loss modelling. GEM is also promoting open access for seismic modelling worldwide through development of hazard and risk tools and data (Pinho, 2012). However, some modules being developed for GEM are commercial. The same is true for Oasis. Such open models, platforms and frameworks have the potential to grow significantly as they represent a different market position to the world leading cat loss model companies. The market leaders are increasingly exploring transparent and open-access solutions (Shah, 2012 and from interview).

Crowdsourcing

Crowdsourcing, volunteered geographic information (VGI) or community-based survey, is potentially a “game-changer” in risk mapping (see McDougall, 2011, for three examples). It has the capability to bring huge amounts of data to bear on the same problem and outperform existing datasets, however good the model fitted to them. Crowdsourcing can be based on various incentive models (Chu *et al*., nd). Three are listed here:

(iv) Service-based (e.g., a large amount of processed data in the form of a service is provided in exchange for a small amount of data that is used to drive a processing engine)

(v) Volunteer-based (i.e., there is no service to the volunteer, but the beneficiary is a victim of or responder to a hazard event – Case Study 3 provides examples in the context of the recent Haiti and New Zealand earthquakes)

(vi) Unpurposeful (e.g., social media such as Facebook and Twitter feeds can be used as covariate data to drive an engine (e.g., Sakaki *et al*., 2010), or assembled via volunteers (e.g., Heinzelman and Waters, 2010). 10% of Twitter feeds are georeferenced and can, therefore, be mapped.

Crowdsourcing data, while benefitting from large numbers, suffer from being of low accuracy and coming from heterogeneous sources. However, ML algorithms can process such data and use the large number of estimates to reduce uncertainties to low levels. Poser and Dransch (2010) found that crowdsourcing can predict flood levels as accurately as hydraulic modelling.

An interesting example of crowdsourcing relates to the 2010 Haiti earthquake. During the Haiti event, crowdsourcing was used in a variety of applications including damage assessment from imagery (GEO-CAN - Case Study 3), search and rescue, and relief efforts: Twitter feeds were assembled and georeferenced on a map using the Ushahidi Crowdmap (http://haiti.ushahidi.com) by volunteers (Heinzelman and Waters, 2010; Starbird, 2011, 2012). Additionally, air photos were interpreted to estimate damage by a swathe of volunteers coordinated through a platform (Starbird, 2012) (Case Study 3).

The utility of crowdsourcing is likely to be greatest in (i) providing up-to-date data on exposure and vulnerability (see Bevington *et al*. (2012), for how GEM is using crowdsourcing for exposure data development and damage assessment), (ii) providing real-time data to guide early warning, response and recovery efforts, thereby building resilience. In relation to the latter, centralised planning and coordination is required to set up the system that will process such data. Note that it is claimed that crowdsourcing applications such as Twitter, Ushahidi and Sahana have not been helpful in *coordinating* response actions on the ground (Gao *et al*., 2011a, 2011b). In reality, it is likely that crowdsourced solutions will complement cat loss modelling. Some application areas will be better suited for the crowdsourced approach (especially tasks such as gathering inventory, exposure or vulnerability data to feed into cat loss models), but crowdsourcing is unlikely to replace the entire process.

5.3 Computing

Machine Learning and intelligence:

If crowdsourcing, community-based sharing via platforms and open source solutions fulfil their potential, then there is a requirement for a processing engine that can handle such vast data sets. Machine learning (ML) is a class of computer-based algorithms that focuses on data rather than model. The idea is to avoid making unnecessary assumptions about the data (typically Gaussian model, linear relations in simple statistical models). This relaxation of assumptions is made possible by large numbers of data. Thus, ML algorithms are central to the analysis of crowd-collected data. If crowdsourcing provides data in *real-time* then again, ML algorithms are valuable for performing data fusion. Given the acceleration in computer technology, future cat loss models will be hugely capable, working at fine spatial resolutions at a global level and delivering robust loss estimates in real-time, conditional on the electricity and telecommunications networks remaining viable. Sensor networks will provide much of the needed data, but a role for the "crowd" will remain.

Parallel processing:

One of the requirements of cat loss models is sufficient processing power to run the models. The Reinsurance industry has pointed this out as a major limitation or gap in current capability (from interview). High performance computers (HPC) with of the order of >100 nodes are required to facilitate the kind of computing envisaged above. Thus, there is a clear need for investment in HPC.

Cloud computing

Computing power can now be served up via the internet on the so-called “Cloud”, in the same way that software can be provided as a service via Google, for example. The idea is that clients can buy a service and use what they need, rather than paying for a product (e.g., 100-node HPC) that may stand idle for a large amount of time. Cloud computing, thus, brings efficiency savings. However, it also has advantages in terms of robustness to failure, and dealing with spikes in demand. It provides an alternative solution to the above HPC demand problem. There are inherent disadvantages, such as loss of control and security arising from the shift to a remote computing service, and these need to be weighed against the advantages that this architecture offers.

5.4 Modelling

Extremes

A challenge for risk modelling lies in estimating the frequency of extremes. The so-called “fat-tailed” problem arises when the probability of exceedance is under-estimated for very large events (Banks, 2005). This problem has received considerable attention in statistics and is the focus of much effort currently (Taylor, 2008). Short duration historical data are limited as a basis for fitting a skewed right distribution. Process models, are likely to fare better because they capture some process knowledge. However, ultimately all models are fitted to historical data and, thus, this remains a significant issue.

Cascading hazards

Much of the risk modelling framework (Equation 1) hinges on assumptions of independence between events. The approach is simply to run the model for a range of hazards and then to combine them to create a single EP curve. However, this approach ignores the dependence of one hazard on another. For example, a hurricane in New Orleans may be coupled with a storm surge and rainfall which may cause extensive flooding and potentially landslides or subsidence.

Moreover, amplification during “super cat” events will lead to further losses due to, for example, looting and business interruption (e.g., Iovine *et al*., 2011), and one major event may weaken the social capacity to withstand another. However, loss data tend to be bundled and attributed to the main hazard event. Thus, unfortunately historical data probably do not support such modelling.

Validation

The need for validation is a serious issue for risk modelling and mapping. The estimates of risk for larger events over the last few decades have tended to be under-estimates of the actual losses realised (Woo, 2011). It is notable that the risk outcome is a combination of the physical threat and the response not just of a fixed asset, but also of behaviour-dependent human agents who interact with the emerging physical scenario on medium and very short timescales to determine the actual impact. The psychology and sociology of risk response add greatly to the challenge of model and map validation, and there is a well-known tendency for both cognitive dissonance and an over-reliance on the efficacy of capital investment to lead to an under-estimate of real risk. The resultant under-preparation and delayed response will increase the risk impact.

Business network disruption

One of the more interesting trends to emerge recently in risk modelling has been an increasing focus on business networks and supply chains (from interview). Vulnerability estimation potentially ignores the multiple inter-dependencies in the supply chain that might arise from a first-order loss. For example, loss of a factory supplying component parts for vehicle manufacture may lead to significant losses in production time if that part cannot be sourced elsewhere. The problem deserves special attention where the supply is highly concentrated spatially. The global business risk from one factory alone may be significant. This was evident in the 2011 Thailand floods which resulted in a US$12 bn loss to the insurance industry (Swiss Re, 2012). However, Appendix 1 points out that for medium-scale events, a part of at-a-point business loss is actually transfer of business opportunity to another place or time.

5.5 Education and communication

No matter how up-to-date, complete, detailed and precise a hazard or risk mapping effort, it is only a product in itself. A hazard or risk map, crucially, needs to be delivered

as a *service*, where the needs of the customer, client or end-user are accounted for fully. Without such engagement, the “product” is unlikely to fulfil its intended purpose.

The utility of a map depends critically on the ability and willingness of the person reading the map to comprehend the information that is intended. Thus, there is a need to increase map literacy (graphicacy) or find alternative ways of presenting the information. Some examples have been given above including perspective views in 3-D, and animations. A very recent trend in geospatial mapping is “placial” GIS instead of spatial GIS. This relates to the creation of cartoon-type maps (e.g., “guide maps”, the London underground map) from formal geolocated data. The “placial” approach has the potential to better communicate to end-users and stakeholders key information on hazard and risk.

Access to information is a key issue. Where internet access is poor other means of communication must be sought. It is here that national governments must play a key role. Obstacles to progress exist, however, including the psychological barrier (individual, government) to accepting that a highly unlikely risk will happen one day. The number of people living in South America at risk of a severe earthquake is enormous. The emphasis must be on convincing national governments to invest in disaster risk reduction. The means to achieve such investment should be a mix of the moral case (human loss) and the business case (financial loss). Open access hazard and risk modelling and mapping can help with this goal: if information is made freely available, governments will feel increasing pressure to act.

6. The future of risk modelling and mapping

Section 5 provides some information on possible trends in key factors that pertain to risk modelling and mapping. This section attempts to bring together the various strands and paint a picture of the possible future evolution of risk modelling and mapping from a specific business viewpoint and, in particular, the key risk modelling companies such as RMS, EQEcat and AIR Worldwide. The question is how will such companies fare in a changing environment in the future? The attempt at providing an answer here is necessarily rudimentary and speculative, but it is hoped that by focusing on a specific business sector, some wider insights are provided about risk mapping more generally.

6.1 What business are we in?

Risk modelling companies are in the business of estimating risk (e.g., the expected loss or probability of exceedance curve) for primarily an insurance/Re client base. However, risk modelling companies also are in the business of providing reassurance and confidence to Insurance/Re companies, their clients and the wider stakeholder community. Such confidence is vital to the markets. The models, however, need to be independent of a particular client base. Outcomes that benefit insurers may be less advantageous to reinsurers, and *vice versa*, but the model is client-neutral.

6.2 SWOT analysis

Table 1 details a simple characterisation of the strengths, weaknesses, opportunities and threats for a typical cat loss modelling company. The analysis describes the business from the inside.

Table 1. Rudimentary SWOT for a hypothetical large cat loss modelling company

S-Strengths	W-Weaknesses
Market position Competitive advantages (complicated model, numerical simulation component, vulnerability curves, insurance structures) Key insurance/Re client base Size (needed to tackle the whole) Lock in due to complexity Ability to meet standards Credibility	Cat loss modelling does not have to be complicated (just fit for purpose) Vulnerability data are highly uncertain Hazard data are uncertain (e.g., downscaling) Exposure data lack “currency” Massive uncertainties in certain model parameters Changes from time-to-time in model parameters expose the uncertainty Poor understanding of loss amplification
O-Opportunities	**T-Threats**
Expansion of business into developing world Partnering with open source organisations (e.g., Oasis) Possibility of opening up models and data components (may require a different business model) Training	Open source models Open Data Portals Crowdsourcing Insurance/Re companies undertaking in-house modelling Diversification of insurers’ portfolios

6.3 Temporal PESTEL analysis

Having considered the risk modelling and mapping business from the inside, we now analyse the changing environment of the business by considering a set of changing environmental (PESTEL) factors. A complete analysis of these factors is given in Table 2. Here, we describe a series of possible future changes through the next 5, 10, 25 and 50 year periods.

6.3.1 Five years (2017)

Within five years, the Global Earthquake Model (GEM) will be online and a move to a multi-hazard GEM style open platform(s) will occur. The Oasis plug-and-play environment will be online. University and small company models will be accessible to the global community. The GEM commercial model will undergo testing and validation. The Oasis and RMS/AIR platforms will be launched and within five years app-store style cat loss modelling will emerge.

Table 2. Environmental PESTEL analysis for a hypothetical large cat loss modelling company

	5 years 10 years 25 years 50 years
Political	● Emphasis on DRR in developing world from NGOs ● Emphasis on DRR in developing world from developed world ● Emphasis on DRR from local communities ● Pressure of the crowd on global NGOs e.g., World Bank ● Increasing pressure on the individual
Economic	● Mortality risk cannot be transferred and must remain a national govt concern ● Rising living standards in developing world ● Higher expectations r.e. DRR and insurance for residual risk ● Increasing demand for insurance in developing world ● Asset pricing reflects risk directly (e.g., mortgage)
Social	● Population continues to increase, increasing exposure ● Urbanisation continues, increasing exposure ● Property-level risk mitigation increases ● Education increases and emerges as a key factor r.e. DRR ● Education of national govts ● Increased use of risk-reilient engineering and

	construction ● Education of local communities by govts for DRR ● Goodwill continues to increase public volunteering of data, models, effort etc. ● Academic "hazard" communities are drawn into risk modelling
Technological	● Increasing capability of platforms ● Increasing use of Open Data ● Resolution increases through: ● national, to ● sub-national, to ● 1 km and ● individual asset ● Increasing development of open source models ● Increasing opportunities for crowd sourcing ● currency of data improves through crowd sourcing
Environmental (primarily the hazard)	● Disasters continue to increase in frequency and severity due primarily to social changes ● Power-law distribution and non-stationary expectation through time mean that: ● some significant events will occur in the period, increasing emphasis on DRR ● unexpectedly high frequencies will occur, increasing emphasis on DRR ● Potential for super-cat disruptive events ● Increases in disasters will be attributed to climate change incorrectly
Legal	● Changing acceptance of who is deemed responsible ● Shift towards the state in terms of DRR ● Shift towards the individual in terms of residual risk ● Increasing resolution of individual residual (post-DRR) risk ● Focus on World Bank to

	cover uninsurable

The monolithic structure of commercial cat loss models as black boxes will start to be broken down into components. Commercial cat loss modelling companies will offer other services through their platforms.

6.3.2 Ten years (2022)

Within ten years, we will see the diversification of insurance risk to emerging markets (e.g., Brazil, India, China) (see Lloyd's 2025 plan). In the established Western markets more generally, there will be substantial shifts of risk responsibility from the insurer and government levels to the individual level (see Appendices 1 and 2). Risk modelling and mapping will move towards a more exposure-driven view of risk and away from traditional modelled areas and perils. This will be enabled by more complete and accurate exposure data for underwritten risks. There will be a commercial move to view risk from an engineering perspective including more sophisticated models or niche perils, applications and/or territories (e.g., SeismiCat).

In the meantime, lessons will be learned from high impact disasters that will have taken place. Market movement will occur due to large loss of life experienced in catastrophes (e.g., potentially in Istanbul, Padang, Ho Chi Minh City).

Training in a variety of aspects of cat loss modelling and DRR will emerge as requirements for governments of emerging nations and the need for education of the public in order to promote DRR will have a high emphasis. This emphasis will be driven by, and facilitated by, openness and sharing of modelling platforms and Open Data as well as crowdsourcing which for many datasets will drive up the resolution and quality of the data used beyond that available from commercial sources.

Within 10 years, crowdsourcing is likely to become the mainstream for a range of purposes including exposure development (including the use of students, smartphones etc.), damage assessment (see Case Study 3), and harnessing of the global expert community (including DRR experts, structural engineers, climatologists, seismologists).

Risk modelling companies will be challenged by the open source and Open Data environments and will seek to retain competitive advantage through various possible means including the quality of data retained (e.g., engineering solutions, although this may be outcompeted by the crowd), the scale of multi-component modelling required (although again, this is likely to be solved through platforms), through expert knowledge and critically through the client base which requires standards and confidence. The companies will also partner in open source platforms (e.g., already the case with Oasis) in order to improve corporate social responsibility in relation to DRR and control from the inside (although, in fact, increasing awareness of risk in developing nations is a key target for insurance companies and, thus, modelling companies also). Ultimately, the business model may need to change drastically if the crowd cannot be beaten, and if competitive advantage reduces to knowledge then training is likely to be a new and significant emphasis.

6.3.3 Twenty five years (2037)

Within the next twenty five years open platforms for estimation of risk will be the norm and used globally. The UN will make resolutions on DRR and national governmental responsibility to protect citizens.

The historic deterministic scenario base will have increased, but the increasing scale and frequency of disaster impacts is likely to shock even the more informed public revealing under-estimates of risk and requiring re-calibration of models and approaches. Such disasters may ensure a continuous supply of goodwill which will be utilised effectively through crowdsourcing platforms. Interestingly, platforms for model and data sharing will allow the academic community, which has traditionally focused on hazard, but less so on risk, to be drawn into efforts to model and map risk, providing component models and routines into platforms enabled through open source standards to rival and probably outcompete those in commercial packages.

The next 25 years will see an increase in the density and coverage of environmental sensor networks (e.g., stream gauges, seismic monitors, tsunami warning systems) for informing risk estimates, as an integral part of EWS and for monitoring during events. Automated meteorological feeds of data will allow assessment of emerging and cascading disaster events (e.g., hurricanes, slow-onset floods, aftershock risk) combined with real exposure to estimate risk in real-time, thus, blurring the distinction between (i) risk modelling and mapping and (ii) real-time monitoring and forecasting. Processing of social media feeds will facilitate social impact assessment and physical impact assessment. Increasingly sophisticated mapping of diurnal patterns of population distributions will have a significant effect on disaster risk assessment.

Changes in technology (power, platforms, cloud, crowd) will inevitably outpace changes in the political and socio-economic environments and drive significant changes in behaviour (for a more detailed perspective on technological change see Appendix 2). The prime outcome of technological changes will be to focus the spotlight on risk in ever increasing detail, with risk maps of individual assets being publicly available to local communities. It is this highly resolved exposure and risk that will drive the most significant changes in both DRR and the commercial risk modelling business. Politically, aided by NGOs, detailed data will heap pressure on national governments to improve disaster mitigation and reduce vulnerability (e.g., through strict adherence to building codes and retrofitting). This is especially the case in relation to mortality risk which cannot be transferred. In markets such as the UK, which have become habituated to universal and, thus, regionally cross-subsidised risk insurance (notably for flooding), it will also create an uneasy pressure on individuals in high risk zones who will no longer benefit from insurance paid by those not significantly at risk and who are, therefore, in danger of being uninsurable (Appendix 3). The enormous, and still growing, populations in high risk mega-cities will potentially be left high and dry, exposed and vulnerable with neither their national governments, nor (even informed) individuals able to take action to reduce their exposure/vulnerability and/or insure for residual potential losses due to high insurance costs. Significant parts of the world may be uninsurable. The question then is who should take responsibility?

6.3.3 Fifty years (2062)

Fifty years is sufficient time to expect significant uplift in scientific understanding of the physical processes underlying hazards and perils, as well as global atmospheric and oceanic cycling. These advances will have knock-on effects as they are assimilated into risk modelling and mapping approaches. Fifty years will see significant changes in sea-level and stronger climate-driven events such as hurricanes (cyclones, typhoons), tornadoes and El Niño/La Niña-related flooding. Populations are likely to be significantly concentrated in urban areas and cities in high risk coastal floodplains and other hazard zones. The global community may have been driven by past failures to find solutions to sharing the risk related to spatial concentrations of massive exposure and vulnerability.

Further insights into possible future changes are provided in Appendix 2 (in relation to technological change) and Appendix 3 (in relation to flood mapping in the UK). Appendix 3 can be read as foresight following on from Case Study 2.

7. Recommendations

Based on this report, several recommendations are made below for the consideration of the UK government.

1. Support open source, open data and community-based efforts as these are likely to
    a. lead to more detailed and accurate mapping (e.g., of exposure and risk) and
    b. will bring about positive changes in attitude and behaviour in national governments and local communities in relation to DRR.
2. Connect to the innovation in the academic and business communities, especially by supporting existing and new platforms.
3. Invest in development of machine learning-based engines for combining heterogeneous data sources, in addition to physical-based modelling efforts.
4. In relation to the developing world:
    a. Focus on exposure data, improving currency and resolution (e.g., through remote sensing of settlement, crowdsourcing, diurnal population mapping and monitoring).
    b. Focus on improving vulnerability estimates (e.g., through land use mapping, crowdsourcing) and development of vulnerability functions for regions with low cat model presence.
    c. Improve education and communication, for example, based on 3-D perspective views, placial maps and other means.
5. Examine the UK's supply chains as risk is connected globally.

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APPENDIX 1. TYPOLOGY OF APPROACHES TO RISK MAPPING

Note that any particular hazard map will be characterised by attributes of mode, scale and category:

THE CORE FUNCTIONAL TYPES OF RISK MAPS

The starting point is a simple four-fold classification based on the basic functional inputs (mapping modes) from which the map has been derived:

Mode 1	Historical record	Stationary snapshot. By definition, indicates past conditions.
Mode 2	Covariate explanation	Basic GIS overlay and spatial regression approaches.
Mode 3	Process model	Single variable or multivariate. Current, prospective or retrospective states.
Mode 4	Real-time monitoring	Real time and quasi-real time. Event-based.

These mode distinctions are gradations rather than crisp boundaries, and there are substantial overlaps and ambiguities (for example, monitoring often feeds into modelling). Conventionally, risk maps would have tended to represent one or other of these modes. Increasingly, data fusion (automated or manual) is providing multi-modal maps (e.g. historic base map with modelled or monitored overlays).

MAP AND DATA SCALE/COVERAGE (MAP LEVEL)

Maps can be produced at any scale, but there is a strong convention to represent scale (or, more strictly, coverage) as a four-fold classification. In common parlance, the map level is usually referred to as scale (local scale, national scale etc.).

Level 1	Global	Self-evident: global = global.
Level 2	Regional	Often used for the highest-level subdivision of the globe, but also as a surrogate for other key characteristics such as economic/development level. Continents are often used, and the UN has adopted “standard” high level regions with each nation allocated to one region.
Level 3	National	Given the likely purposes for creating risk maps, national coverage is likely to be extremely significant. However, whereas the global and major region levels have somewhat similar scale and areal coverage, at national level these are hardly linked at all given the enormous differences in the size of different countries.
Level 4	Local	For operational purposes, local risk maps are often invaluable. There is no conventional definition or practice to define the absolute size of a local area, and therefore no link between local level and map scale. Boundaries may be political, natural or arbitrary.

MAP PURPOSE/FUNCTION

Maps are (or should be) strongly characterised by their purpose/function: single-function maps are likely to be more tightly specified in terms of data sources and cartographic characteristics than multi-purpose maps. There is no standard functional typology, but it remains useful and important to carry this functional aspect in mind when classifying maps. One structure that is implicit rather than explicit is:

Category 1	Policy	The purpose is high-level lobbying and policy informing. More likely to be Level 1-2-3 than Level 4. Impact more important than resolution. Informing as a basis for formal policy and informal attitude. May well take the form of scenario analysis. Long-term rather than near-term.
Category	Strategic	A basis for long-term action, but in the planning

2	planning	rather than response context. To some extent likely to focus on hazard zoning and hotspot analysis rather than detailed characteristics. Causation may be significant. In most cases Level 2-3, but for mega-hazards there is increasing use at Level 1.
Category 3	Management	Basis for conventional hazard management. Needs a high-level of hazard characterisation (intensity, behaviour) as well as a good level of spatial delimitation. Used to build awareness and preparedness. Most likely to be Level 3-4, but not exclusively. All modes.
Category 4	Operational	A basis for near-time and real-time tasks. Main use is in hazard warning and response. Most likely to be Level 4 and Mode 3-4, but not exclusively.

Clearly, there are significant overlaps between these categories, but the core definitions are robust.

APPENDIX 2. TECHNOLOGY FUTURES

Given the rapid rate at which technology may change over the next 50 years, we offer some deeper insights here into the likely and possible nature of such changes in technology in relation to risk modelling and mapping. Technological progress in the next 50 years will serve to mitigate and reduce much of the risk due to natural (and other) hazards and provide the means for increased resilience.

Kurzweil's "Law of Accelerating Returns" suggests that the rate of technological progress – and, indirectly, scientific progress – will increase at an exponential rate (Kurzweil, 1999) and lead to a "technological singularity" where progress would occur almost instantly. Even if we take a more pessimistic view, our understanding of the natural hazards that lead to disasters, our ability to predict these events and our ability to respond and recover will certainly be enhanced from our present-day levels. Kurzweil's Law can be seen as an extension of "Moore's Law"(Moore, 1965), which suggested originally that the number of transistors that can be placed on an integrated circuit would double every two years. Moore's Law has remained valid since its conception, with some small adjustment to the rate of growth, and has been used to describe different capabilities of electronic devices and many problems addressed using computers.

In the context of risk mapping, risk reduction and disaster response, four technology areas are important: computing (including hardware, software and algorithms), communications, sensors and manufacturing.

Rapid-prototyping and manufacture – for example using 3D printing technology – will enable some of the practical resources required to enable the disaster response to be created on-site and on-demand. In particular, Unmanned Aerial Vehicles (UAVs), which are already in use for image and video collection within disaster zones (Adams and Friedland, 2011), could be manufactured in this way within the next five years (Marks, 2011). Autonomous vehicles (including UAVs) that make use of novel computing technology could be providing rapid disaster response capabilities within 25 to 50 years.

With respect to computer hardware, advancements in the last decade include faster processors, increased memory capacity, parallelisation, hybrid and cloud computing. In the future, Moore's Law will likely be sustained and advancements continue through the development of optical, quantum and DNA computing. In the context of computer software and algorithms, Kurzweil opined that machine intelligence will surpass human intelligence and enable the technological singularity within a few decades (Kurzweil, 2001). Again, even following a less optimistic point of view, machine intelligence will result in decision-support systems for disaster response in five years and, in conjunction with developments in communication and sensors, autonomous systems for disaster management and monitoring within 10 to 20 years (e.g. see the Autonomous Learning Agents for Decentralised Data and Information Networks (ALADDIN) project, http://www.ecs.soton.ac.uk/research/projects/aladdin). That is not to say that human intelligence will not be important. Education will need to stay abreast of these technological changes and the next generation will likely be a generation of computer programmers (see Burns, 2012). Given the current proliferation of small, programmable, Internet-enabled devices and the rapid growth of applications (“apps”) for these devices, we can anticipate that risk mapping models – providing highly localised or even personal maps – could exist in the near-future on these devices. Sensors currently embedded on mobile phones (e.g. cameras, accelerometers, positioning) will become more advanced (e.g. the number of pixels on a CCD array also follows Moore’s Law) will enable large networks of people to provide real-time or near-time data, distributed processing following established crowdsourced solutions (e.g. SETI@Home) and receive real-time mapping and risk information in return.

As communication devices and their geo-location improve, it is tempting to assume that crowd-sourced real-time risk messaging will also improve in amount and quality. This, of course, depends on equal and coincident enhancement both in the bandwidth needed to transmit the signal (despite outage due to facility damage in the worst-affected areas) and in the capability of the services receiving, processing and targeting the resultant information. It would be naïve to expect these enhancements to be automatic or in phase, and there will remain a tendency for services to fail where and when they are needed most. However, if this source of information is demonstrated to be of significant value then these deficiencies could be substantially reduced.

Smart sensors with wireless communication capability (Chong and Kumar, 2003) will become ubiquitous within the built and natural environment (on the ground, in the air and in water) in the next five to 10 years and disposable sensors will likely be deployed, on-demand to fulfil particular disaster management needs in the following decades. At the same time, proposed military, disposable satellite systems able to provide timely, high-resolution imagery of an extended area on the globe (DARPA, 2012) will emerge within the civilian sector within 25 to 50 years to complement UAV and autonomous vehicle capabilities for disaster management and response. These sensors will close a capability gap with respect to inventory, exposure and vulnerability data allowing real-time updates to risk maps and enabling emergency management decisions and rapid response.

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APPENDIX 3. FLOOD FUTURES

BACKGROUND

The trouble with the future is that it is even more complex than the present and the past, so inevitably we understand it less. It is so inter-connected that even a simple speculation (and this is all it is, despite being based on demonstrable underlying trends) inevitably follows many divergent paths: anything less risks a still less complete and unconvincing scenario. However, future paths will involve the following components:

- Hazard will increase – primarily driven by externalities such as climate change, deforestation and urbanisation, exacerbated by deforestation, urbanisation etc., but also through the emergence of new hazards, such as diseases.
- At-risk population will increase – the global population continues to increase, with more people living in urban zones and with greater (over-) reliance on defences.
- At-risk assets will increase – the rising affluence, increasing dependence on technology, over-reliance on defences and the inadequacy of defences will ensure the increase exposure and vulnerability of high-value and critical assets.
- Risk will increase - mainly impacting population in the developing world and assets in the developed world.

In spite of the predicted increase in risk, there are counter-intuitive aspects of the risk with respect to property, assets, business. These aspects are explored below in a case study focused on flood risk.

CASE STUDY: FLOODING

Much of the damage cost of a flood transforms into alternative business opportunities (sales of replacement goods together with reconstruction/refurbishment contracts). Much of the lost business cost is transferred (someone, somewhere else picks up the business) or delayed (the business is picked up later). With a small or medium event, the damage “hit” is thus carried more by the individual (or individual business) but felt less severely by the overall society/economy. Catastrophic hits can, however, destabilise the economy and society, and repeated hits can be multiplicative rather than just additive. So the issue is not just whether risk will rise in the future, but how that total risk will be distributed between events of different frequencies and magnitudes.

The non-transferable cost of flooding is in mortality and morbidity (including stress). Beyond question, quality of life suffers hugely, and globally the prospect is not good in terms of future flood impact.

IMPLICATIONS FOR THE FUTURE

A speculative scenario would run thus: the technology (hardware, software, crowd and cloud) for **monitoring floods** and monitoring the drivers of floods (precipitation, antecedent conditions, weather, climate, El Niño, whatever) will improve substantially – though doubtless within the strict constraints of diminishing returns.

The systems for flood modelling and overall probability estimation will likewise improve greatly, both in concept and data richness, quality and timeliness. Flood probabilities (contributing to an insurance concept of flood risk) will be much better estimated – downscaled, detailed and less uncertain. Ironically, this will define the risk so precisely that it will make at-risk people and property much less insurable at a feasible cost, so individual flood insurance could well drive itself out of business , though some variant of reinsurance pitched at aggregate risk for corporate or government clients may well prosper correspondingly. The insurance industry is currently a mega-player in flood risk mapping, so this will have huge implications.

Despite this, it is likely that uncertainties will still cloud **local individual-event forecasting** so greatly that timescales of detailed and accurate warning will remain in the hours rather than days or weeks – though more general predicted “alerts” or “flood status” designations (both of which feed maps) will doubtless improve. Science specialists may dispute this, rightly or wrongly.

Governments are likely to be increasingly disinclined to hold onto or pick up the cost of **flood risk mitigation or avoidance** (including flood protection) because they will probably judge that the risks are increasing faster than any economically-feasible approach to protection (the current wave of economic “austerity” in many countries reinforces this, but the trend was already clear). Many governments have always intervened mainly in post-disaster relief and made little attempt at protection; others (as in the UK) have fought valiantly for disaster prevention but now have less appetite for it (in policy, strategy, willingness and ability to respond effectively).

If this is indeed the case, the UK could well see a **massive shift in flood risk responsibility** away from insurers (which are a very British obsession in this domain) and government towards the individual. This means a move towards individual property protection and resilience (two very different things) at individual cost (though doubtless absorbed through the mortgage system and eventually lost as a background cost like ground rent). The Environment Agency focus on flood warning, on “what’s in your backyard” (see Case Study 2) and on advice concerning the scope for individual mitigation activities is symptomatic of this refocusing on the individual. Flood risk maps are thus targeted at the individual as much as at the specialist, and increasing interest emerges in using individual inputs (crowd sourcing) to flood monitoring.

A further implication is that hazard risk protection could then take its place alongside other individual-level safety and health campaigns as part of public pressure for individuals to conform to the new risk-bearing regime. All the experience of past campaigns is that very many individuals will shut their minds to this risk and ignore the advice (cognitive dissonance). Nevertheless, we must be prepared to find that government is no more willing to fund individual property flood protection than it is to fund individual property crime prevention. Individual-level risk maps and current status maps will, however, increase greatly in importance as the focus shifts away from state public protection.

In the UK, the most critical implication of the retreat of insurers from many at-risk properties could be the necessity to reformulate the mortgage industry to absorb the risk – and doubtless to pass it on in terms of aggregate reinsurance. This is a massively challenging task, and could well bring a renewed focus on aggregate risk maps. It should also fuel an irresistible demand for flood-resilient building codes, the absence of which greatly increases the cost of flood risk. If these codes were to be regionalised by risk (an entirely logical approach, but politically highly contentious because of the differential impact on local property construction or reconstruction costs), then again there would be great pressure on the Environment Agency to continue improving flood probability modelling and risk mapping.

As always, the current spotlight seems to be directed at technical capability (hardware, software, systems, concepts) but the real uncertainties and the really difficult risk management challenges remain essentially political, economic, social and attitudinal. This is where risk mapping should be primarily directed.

Authors: Mirianna E.A. Budimir[1], Peter M. Atkinson[1] and Hugh G. Lewis[2]

CASE STUDY: Global Multiple Hazard and Risk mapping

Case Study Overview

Natural hazards occur globally and cause significant economic and human losses each year. The UNDP report (2004) estimated that 75% of the world's population lived in areas affected by earthquakes, cyclones, floods or drought between 1980 and 2000. Hazard assessment research has typically been confined to single hazard types rather than a multi-hazard approach, although it is common for a location to be at risk of several hazard types. Global multiple hazard and risk mapping can, therefore, be used to determine areas of high risk. State-of-the-art global multiple hazard and risk maps available include Munich Re's World Map of Natural Hazards, the UNDP's Disaster Risk Index (DRI), the World Bank's Hotspots report and the UNU-EHS's World Risk Index (WRI).

A framework for estimating risk can be understood by the equation:

$$Risk = f(Hazard \ast Exposure \ast Vulnerability)$$

Where *Hazard* is the frequency, severity or probability of an event occurring; *Exposure* represents the at risk elements (such as financial or people); and *Vulnerability* is the degree of loss given that a hazard of a particular magnitude occurs.

Global Hazard and Risk Map Characteristics

World Map of Natural Hazards

Munich Re's World Map of Natural Hazards charts occurrences of earthquakes and volcanic eruptions, windstorms, floods, marine hazards and the effect of El Niño and anthropogenic climate change.

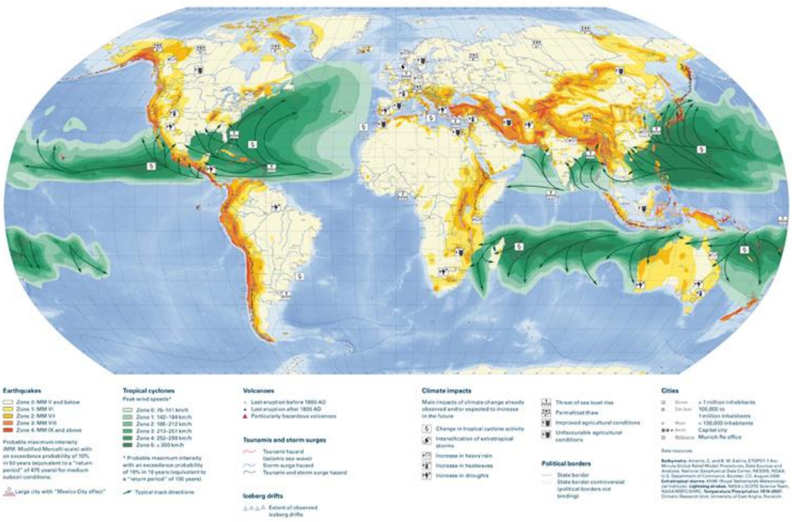

Figure 1: World Map of Natural Hazards (Munich Reinsurance).

[1] University of Southampton, Faculty of Social and Human Sciences. [2] University of Southampton, Faculty of Engineering and the Environment

The Munich Re World Map of Natural Hazards shows the historical locations of multiple natural hazards on a global scale, thus, providing a general idea of hazard distribution and concentration. However, the risk from natural hazards is not conveyed in this map as vulnerability and exposure are not included in the calculation. The Disaster Risk Index, Hotspots project and World Risk Index extend further the World Map of Natural Hazards.

Disaster Risk Index

The Disaster Risk Index (DRI) is a measure of relative and absolute mortality risk levels from earthquakes, tropical cyclones and floods at the national level based on data from 1980 to 2000. This measure uses disaster data from CRED (EM-DAT) to assess the risk from hazards in each country. An analysis of drought was included in the DRI in the latest 2009 study.

Hazard	Description	Data source
Cyclones	The population exposed to cyclones was estimated from historical data.	Carbon Dioxide Information Analysis (CDIAC) of the US government.
Earthquakes	Hypocentre records from 1965-2004 with magnitude ≥5.5 on the Richter scale were used to generate circular buffers of Modified Mercalli Intensity (IMM) to model population exposure.	Council of the National Seismic System's (CNSS)
Floods	Historical watershed data were used in the HYDRO1k Elevation Derivation Database to model approximate estimates of flooded area.	EM-DAT, Centre for Research on the Epidemiology of Disasters (CRED)
Drought	Meteorological drought was defined as a sustained period (three months or more) in which monthly precipitation at a given location is significantly below the long-term average (in this model, more than 23 years), at 2.5°resolution.	Columbia University, International Research Institute for Climate Prediction (IRI), and US National Centres for Environmental Prediction (NCEP), Climate Prediction Centre.

Table 1: Hazard data sources and description of how physical exposure was calculated in the DRI.

The DRI calculates mortality risk as a function of physical exposure (a function of hazard frequency and population exposure) and vulnerability. Physical exposure for the DRI is measured by the number of people located in areas where hazardous events occur combined with the frequency of hazard events (i.e. the average number of people exposed to hazards in a given year). Vulnerability is quantified using indicators based on a selection of five socio-economic and environmental variables: GDP purchasing power parity per capita, modified percentage of arable land, percentage of urban growth, percentage of country forest coverage, and transformed value of the percentage of the country dedicated to crop land.

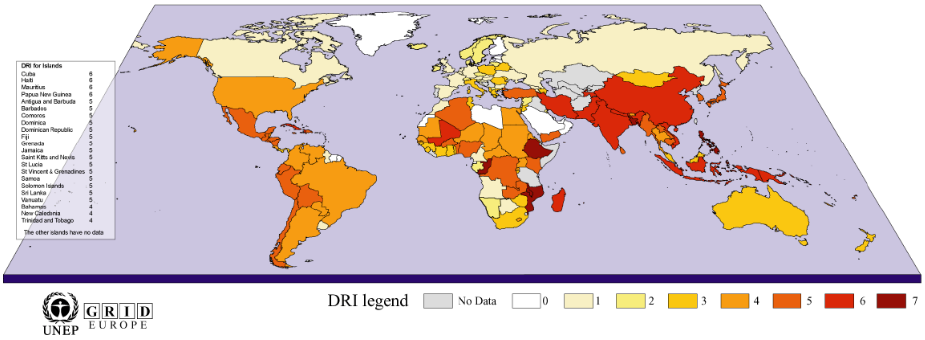

Figure 2: The Disaster Risk Index map (Peduzzi *et al,* 2009).

The predicted mortality values from droughts, floods, tropical cyclones and earthquakes are summed to give a value of multiple hazard risk. The DRI is computed per country based on absolute (fatalities per year) and relative (fatalities as a percentage of the total country population) multiple risk figures. The logarithms of the two variables are normalised to a 0-1 scale using the following thresholds: 0.5-500 killed per year and 0.1-10 killed per million per year. The two normalised variables are then averaged and classified based on an equal-interval classification scheme to create a multi-hazard risk map, with an index of risk from 0-7.

Hotspots Report

The Hotspots report assesses the relative risk of mortality and economic losses for six hazards: earthquakes, volcanoes, landslides, floods, droughts and cyclones. Hazard distribution maps are available to examine the relative exposure to natural hazards. Multi-hazard distribution maps can be used to help decision makers previously focused on single hazards realise that there may be multiple hazards affecting their region. The Hotspots program was the first study to calculate risk worldwide at a sub-national scale, rather than at country-level. The ISDR Global Assessment Reports from 2009 and 2011 also contain global risks assessments with sub-national scale resolution (see http://www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/GAR-2011/GAR2011_Report_Chapter2.pdf).

Hazard	Description	Data resolution	Data source
Cyclones	Wind-speed exceedance frequency data 1980-2000.	30”	UNEP/GRID-Geneva Pre-View
Drought	Weighted Anomaly of Standardized Precipitation (50% below normal precipitation for a 3-month period) 1980-2000.	2.5°	IRI Climate Data Library
Flood	Large event count from 1985-2003*.	1°	Dartmouth Flood Observatory World Atlas of Large Flood Events
Earthquakes	10% in 50 year ground acceleration exceedance probability (expected pga > 2 m/s2).	Sampled at 1’	Global Seismic Hazard Assessment Program (GSHAP)
	Large event count (>4.5 Richter magnitude) for 1976-2002.	Sampled at 2.5’	Advanced National Seismic System (ANSS/USGS) Earthquake Catalog
Volcanoes	Event count (does not include ash plume) 1979-2000.	Sampled at 2.5’	UNEP/GRID-Geneva and NGDC
Landslides	Index of landslide and snow avalanche hazard.	30”	Norwegian Geotechnical Institute

Table 2: Summary of data sources for each hazard in the Hotspots Map; * indicates missing data for 1989, 1992, 1996, and 1997; quality of spatial data for 1990-91 and 1993-95 limited.

Risk levels for the Hotspots project were calculated as a function of a measure of hazard degree, population or economic exposure, and vulnerability. The hazard exposure is calculated as a function of the number of people in the cell and the “degree of hazardousness.” The latter is different for each hazard. For earthquakes, for example, the degree of hazardousness is the probability of exceeding a particular peak ground acceleration in each grid cell location. For droughts it is the frequency of a drought of given severity (6 months at less than half the median rainfall for the season) over a 21 year period. For landslides it is the probability of occurrence. To calculate risk, each exposure value is weighted by a vulnerability coefficient. These coefficients were calculated from EM-DAT data (mortality or economic losses).

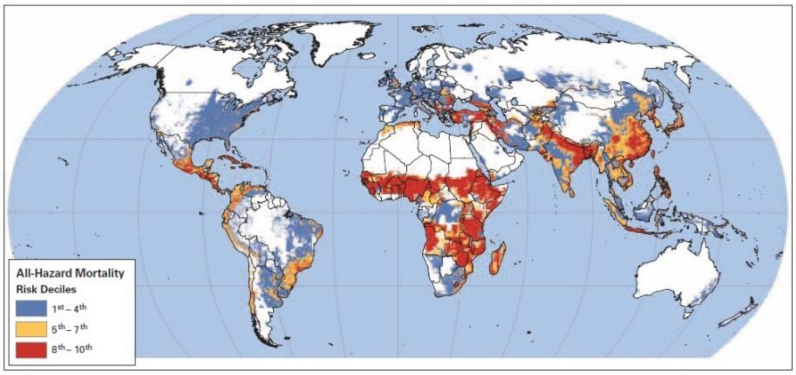

Figure 3: Global distribution of disaster mortality risk hotspots for all hazards (Dilley *et al,* 2005).

Each vulnerability coefficient is a "loss rate" or average loss per event, for groups of countries grouped by region and sub-grouped by country wealth class.

The risk values calculated for each hazard were summed for all six hazards per cell. A mortality-weighted multi-hazard disaster risk hotspot index is, therefore, calculated as the sum of the adjusted single-hazard mortalities (scaled into deciles) in the grid cell across the six hazard types. The global distribution is then divided again into deciles 1-10 for an index of multi-hazard risk globally. The top three deciles are considered as relatively significant multiple hazard risk. This data can also be represented based on the number of hazards affecting each cell. The top three deciles of multiple hazard risk are categorised by the number of hazards each grid cell is exposed to.

World Risk Index

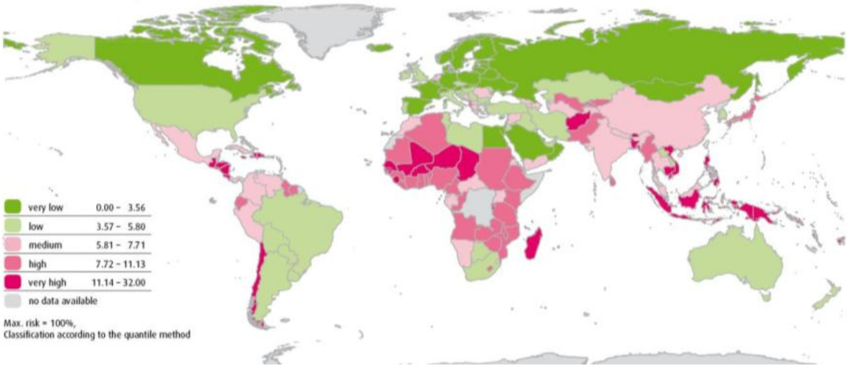

Figure 4: World Risk Index (Bundnis Entwicklung Hilft, 2011).

The World Risk Index (WRI) indicates the probability that a country or region will be affected by a disaster. This includes floods, storms, earthquakes, droughts and sea-level rise. The index consists of exposure to natural hazards (the number of people exposed to a natural hazard in a year per country) and vulnerability. Vulnerability is comprised of susceptibility as a function of public infrastructure, housing conditions, nutrition and the general economic framework; coping capacities as a function of governance, disaster preparedness and early warning, medical services, social and economic security; and adaptive capacities to future natural events and climate change.

Hazard	Description	Data source
Earthquakes	Physical exposure calculated by the number of persons per spatial unit of space ($1km^2$) who are exposed to the hazard on average per year per country.	Global Risk Data Platform PREVIEW of the United Nations Environment Program (UNEP)
Storms		
Floods		
Drought		
Sea-level rise	Potential exposure to one meter sea-level rise based on CReSIS data compared with global population data.	University of Kansas, Centre for Remote Sensing of Ice Sheets (CReSIS); and Columbia University, Centre for International Earth Science Information Network

Table 3: Hazard data sources and description of how physical exposure was calculated in the WRI.

Whereas the DRI and Hotspots report examine risk from a quantitative perspective, the WRI approaches risk from a more holistic perspective. The different factors which determine vulnerability are the main focus of this project and are useful for understanding the context and underlying causes of people's vulnerability. This information is important for disaster preparation and in terms of supplying aid and research efforts.

Comparison of Risk Methodology

The risk calculation for the **DRI** can be represented by the equation:

$$R_{DRI} = H_{fr} \times Exp_{pop1} \times Vul_{DRI}$$

Where R_{DRI} is the number of expected human impacts (fatalities per year), H_{fr} is the frequency of a given hazard (events per year), Exp_{pop1} is the exposed population living in a given at risk area (exposed population per event), and Vul_{DRI} is the vulnerability depending on socio-politico-economical context (non-dimensional number between 0-1).

The risk calculation for the **Hotspots** report can be represented by the equation:

$$R_{Hotspots} = H_{dcg} \times Exp_{pop2} + Vul_{H}$$

Where $R_{Hotspots}$ is relative mortality risk or economic loss risk, H_{deg} is the degree of hazard measure (such as frequency or probability of occurrence), Exp_{pop2} is the exposed population or GDP, and Vul_H is the vulnerability coefficient from historical losses (average loss per event) grouped by region and country wealth-class.

The risk calculation for the **WRI** is given by:

$$R_{WRI} = PhysExp_{pop} \times Vul_{WRI}$$

Where R_{WRI} is the probable risk of a country being affected by a disaster, $PhysExp_{pop}$ is the number of people exposed to each hazard per year (incorporating the hazard and exposure factors in the risk equation) and Vul_{WRI} is a function of susceptibility, coping capacities and adaptive capacities, each contributing 33% to vulnerability.

Objectives

The purpose of global hazard and risk mapping is the development of global disaster risk assessment through the use of global data sets in which the spatial distributions of hazards, elements at risk, and vulnerability factors, rather than national statistics which are recorded differently for each country, are the primary independent variables. Global hazard and risk maps can be used to determine spatial patterns, and to identify high risk areas.

Stakeholders

The above global hazard and risk assessments were typically carried out between global organisations and universities, with the exception of the Munich Re World Map of Natural Hazards. Munich Re's Geoscience Research Group published its first World Map of Natural Hazards in 1978, revising it in 1988 and 1998. The DRI was developed by UNEP/GRID-Europe in 2004 and republished in 2009 to include drought. It was mandated by the United Nations Development Programme (UNDP), Bureau for Crisis Reduction and Recovery. The Hotspots project was instigated by the World Bank and Columbia University and published in 2004. The WRI was developed on behalf of the Bündnis Entwicklung Hilft by the United Nations University Institute for Environment and Human Security in Germany and published in 2011.

Review of Hazard Map Impact

The maps are an important resource for resource-poor governments to make decisions about strategic planning of exposure and planning mitigation measures and to increase preparedness and resilience. The World Map of Natural Hazards is also used in Munich Re's NATHAN (Natural Hazards Assessment Network) Risk Suite to calculate insurance risk.

The Hotspots report is widely cited in the academic literature and used as a reference for further study into high risk areas, as is the DRI. The WRI was published in late 2011, so the impact of the project is difficult to establish. However, due to its unique perspective on vulnerability factors in relation to risk, it could be useful in targeting funding and aid towards underlying causes of vulnerability which lead to higher risk and loss rates as a result of natural disasters.

Evaluation

The Hotspots report produces a global risk assessment for multiple hazards at sub-national resolution as the other global maps reviewed here calculate risk at national-resolution. Sub-national scale mapping is useful for determining locations and patterns of high risk within countries.

Each of the global hazard and risk maps are useful as a reference for further studies in natural hazard risk by identifying the high risk areas. They have initiated research into areas previously unknown to be at risk and also more detailed studies of areas known to be at risk.

The choice of hazards and measurement type is also subjective. The DRI and WRI include earthquakes, tropical cyclones, floods and drought. The first three hazards were included because they account for 94% of casualties reported from 1980-2006 in the EM-DAT database. The WRI also includes sea-level rise. However, the Hotspots report also includes volcanoes and landslides, and the World Map of Natural Hazards covers earthquakes and volcanic eruptions, windstorms, floods, marine hazards and the effect of El Niño and anthropogenic climate change. The measurement used to quantify the hazard in the risk equation also varies between and within each global risk map. Frequency and probability are most often used. As each measurement of risk is scaled to create a risk index, this may not pose a problem as relative risk is still conveyed.

Although the DRI, Hotspots report and WRI all calculate global risk from hazards, each calculates risk using different methods. The choice of vulnerability parameters is subjective; the DRI uses population, the Hotspots reports uses population and GDP, and the WRI uses factors of susceptibility, coping capacity and adaptive capacities. Each map, therefore, either progresses from the previous representation by including more hazard types and improving the resolution of risk patterns, or shows risk from a different perspective.

There are implicit assumptions in all of the global risk maps that risk sources are independent, leading to the neglect of possible interactions of risk. A thorough multi-hazard approach cannot be based solely on superposition of distinct single hazard maps, because hazards acting in the natural system are not just the sum of its components, but are a net of interacting parts and as such need to be examined in a more complex approach.

Constraints/Challenges

Problems associated with multi-risk mapping are mostly related to issues of data availability, quality and accuracy. For multi-hazard analysis, often there are not enough data available at sufficient levels to be comparable for all specific hazards. Difficulties arise in finding or creating data sets of uniform quality for multiple hazards due to the differences in hazards and in methods of recording hazard data. Problems often arise in obtaining complete spatial and temporal records for hazards and risk factors. Due to missing data, the WRI could be computed for only 173 countries.

Although the DRI and WRI are global maps, they represent risk only at the national scale. Therefore, any patterns of risk at a sub-national level are unrepresented, which is unrealistic as hazard processes do not follow arbitrary boundaries. The calculation will mask any sub-national hotspots; for example, it is not obvious whether a country has medium risk throughout the country, or whether there are high risk hotspots within the country, with the remaining area at low risk. The Hotspots report represents risk at sub-national resolution, but the data used to compile the map are at different spatial resolutions; the hazard data are per country, whereas the GDP and global population data represented are on a 2.5' x 2.5' latitude-longitude grid.

Hazardous events are difficult to compare because they differ in their nature, intensity, measurements, return periods and the effects they may have on the exposed elements. Developing an overall scheme to compare or calculate total hazard risk is, therefore, subjective due to the requirement to choose vulnerability coefficients.

Lessons Learned

Global multi-hazard risk assessment is needed to provide insights into disaster-risk patterns in order to improve disaster preparedness and the prevention of losses. Although national-resolution maps such as the DRI and WRI are simpler to produce than the Hotspots report given data constraints, they mask patterns within countries.

Potential future areas of research could update or improve the initial data sets used (e.g., through probabilistic hazard mapping, or including more hazards such as wildfires, tornadoes, tsunamis etc.). Also, future studies should concentrate on investigating areas of high risk from single or multiple hazards in more detail.

Multi-hazard risk assessment should also take into consideration the interaction between multiple hazards affecting an area. Natural hazards act in a natural system and as such are complex and affect each other. The cascading effects of natural hazards and their impact on resultant risk is an important area of research which has received little attention to date.

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Authors: Michael J Clark[3] and Sally J Priest[4]

CASE STUDY: Flood Hazard Mapping in the Environment Agency

Case Study Overview

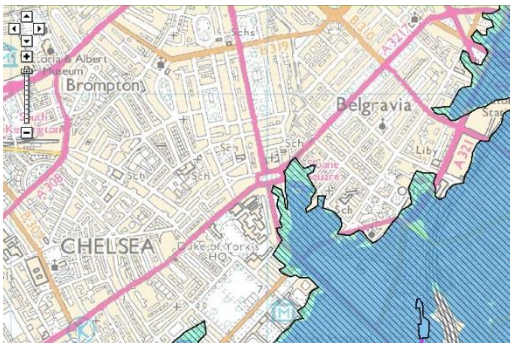

Figure 1: 2012 version of the EA flood map

Despite more than a century of hazard management attempts in the developed world, loss of life from natural hazards has declined but property damage by hazards has not. One reason for this is that hazard information (including hazard mapping) has improved more rapidly than the communication and use of that information. This conundrum can be demonstrated through the specific example of a web site managed by the Environment Agency (England and Wales) with the express purpose of reducing flood risk to life and property by managing awareness and consequent behaviour.

Figure 2: 2008 version of EA flood map

The usage and effectiveness of the Environment Agency (EA) flood map (part of the Agency's *What's in your backyard?* environmental data service) have been reviewed several times (Priest, Clark and Colclough, 2008), and as a consequence the impact of the maps has increased steadily. This evolution of approach provides a valuable case study of the issues underlying hazard map design and presentation. The 2012 version of the map (Figure 1) is larger, clearer, better annotated and very much more intuitive in terms of web interaction and navigation than that of 2008 (Figure 2) - but it retains some of the fundamental underlying design concepts which enshrine a particular view of hazard mapping.

Three long-established issues emerge in any attempt to understand the changes of EA hazard mapping style and effectiveness – the link between information and behaviour, the public

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[3] University of Southampton, Geography and Environment (GeoData Institute)

[4] Middlesex University, Flood Hazard Research Centre

understanding of science and the cognitive processing of mapped information. First, the earlier version of the map has been assessed in detail in the context of the ***links between information and action***. Science-driven information services and products (including maps) are often based on a crude assumption that quality information triggers rational decisions and actions. In reality, the linkage (if one exists at all) is much more complex, with presumptions, prior knowledge and attitudes all mediating between information and decision (intent), which in turn has complex links with actual behaviour and its sustainability. In terms of hazard mapping, the clear implication is that map design and the context within which the map is presented (including web navigational tasks, map interactivity and required understanding such as an awareness of probability and uncertainty) will have a significant impact on map user attitudes and thus on intent and behaviour.

Second, many attempts have been made to evaluate ***public understanding of science*** and environmental issues and suggest reasons why there is often a gulf between scientific and lay understanding of environmental problems such as flooding (Hargreaves, Lewis and Spears, 2003; Phillimore and Moffatt, 2004). This problem is confounded by the fact that “public understanding of science” interacts with perceptions of deeply complex concepts such as probability and uncertainty, and is strongly influenced by styles and contexts of textual and graphic (mapping) communication (Faulkner and Ball, 2007). All of these aspects combine to constrain awareness, which in turn is mediated by attitude before it can influence behaviour (decision and action), so it is no surprise that public information (including hazard mapping) and public response are difficult to link!

Third, the EA flood maps have been evaluated in the context of the psychology of learning (Priest, Clark and Colclough, 2008), notably in terms of **cognitive load theory** (Mayer and Moreno, 2003). This considers aspects of a web site experience that mediate between the map user and the “message”, which can suggest improvements in map presentation. The assimilation of new information requires cognitive processing, for which the user has a finite capacity. If the cognitive demands of a hazard map and associated web site exceed the user’s cognitive capacity, then cognitive

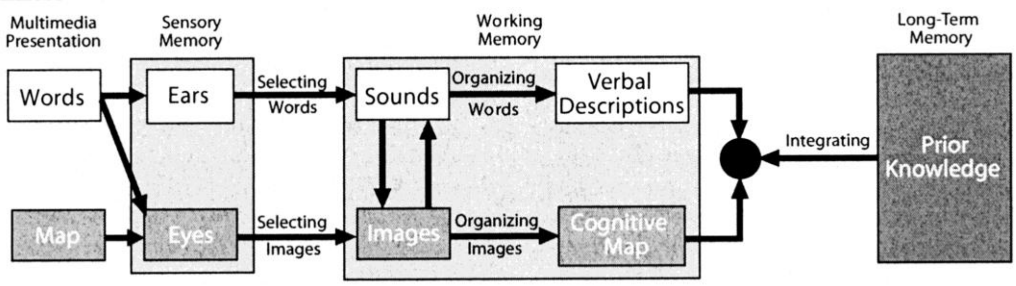

Figure 3: A cognitive model of map reading (Bunch and Lloyd, 2006)

overload takes place, information assimilation is impaired and attitudes may become negative. Paradoxically, a modest cognitive load placed on the web-site user (for example, through map interactivity) actually enhances sustained learning, but more generally a heavy cognitive load created by web-site navigational structure, content or presentation can be a barrier between the user and the intended message about flood hazard. Bunch and Lloyd (2006) regard maps as both efficient visual stores of information and powerful representations of relationships between information (Figure 3). Since part of the cognitive load carried by a user assimilating new information is to build relationships, this makes the map a potential tool for reducing the threat of cognitive overload with its related reduction in learning. This is a useful basis for assessing the EA flood map and web site in terms of its impact on user awareness and response behaviour (or propensity to act).

EA Hazard Map

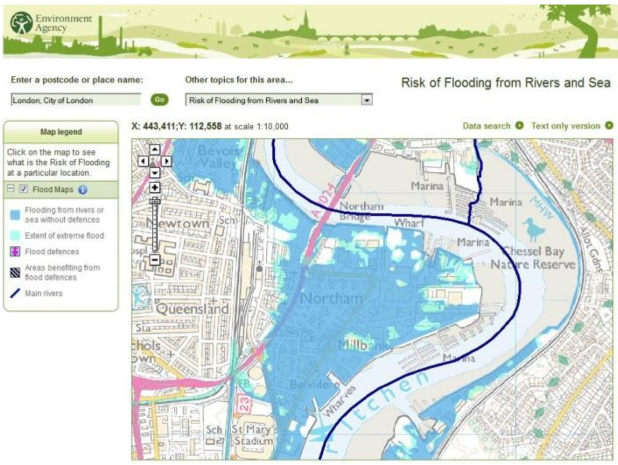

Figure 4: The EA flood map, 2012

The EA flood zone map is designed to alert the public, but also planners and flood managers in England and Wales, to the overall spatial distribution of flood risk derived from historic data and modelling. It is intended to inform public response by triggering more appropriate flood awareness and personal response planning, but is categorically not a flood warning device and the maps do not carry real-time or predicted information. Nevertheless, at times of raised flood alert, the site may be visited by a million people a day, and thus has massive potential as a response support source.

The map (with its associated information pages on the Environment Agency web site) provides an information resource with three attributes: substantive content (facts, explanation, advice), presentation (cartographic and textual style) and access (the user interface). Each of these attributes influences the communication (informing) process, and thus interacts with the hazard map user’s flood awareness, attitudes and response behaviour. The EA maps have been evolutionary. The first public version, known as the Indicative Floodplain Map, was first released on the Agency’s website in December 2000. These maps had themselves developed from a rather basic representation (hence the title “indicative) of whether an area had been demonstrated to be at risk from inland and/or coastal flooding, to one where the risk was represented more comprehensively and reliably. By 2007 the EA presented flood hazard through two different hazard maps: the indicative flood map layer and the National Flood Risk Assessment (NaFRA) dataset.

The **indicative flood data** were presented as a two-toned blue mapped layer. This information has undergone a number of improvements since its launch in 1999, and where possible detailed topographic surveys had been combined with river flow information (sea level and wave data in the case of coastal flooding). To produce the 1 in 100 and 1 in 1000 year outlines, the model J-FLOW (a 2D Diffusion wave model) was used to input into the flood hydrograph for each 1km section and generate flood outlines for the inflow point of the hydrograph, which were then combined to produce the overall envelope of flooding (Bradbrook *et al*., 2005). This flood layer also presented information about where flood defences are situated and the areas that were protected from these flood defences, though information coverage was incomplete and thus undermined user confidence.

National flood risk assessment (NaFRA) data were added in the EA flood map 2004 re-launch as additional information on the flood map, accessed by a user selecting a *Learn more* option. The RASP (Risk Assessment for Strategic Planning) method developed by HR Wallingford provided a more specific likelihood of risk taking account of flood defences. The flood map's extreme (the 1 in 1000 year) floodplain were divided into 100 x 100m cells and 37 different flood scenarios (from floods that might occur each year to extreme flooding) were then applied to each cell to calculate whether its centre would flood under each scenario. The likelihood of flooding was allocated to three risk categories – LOW (annual flood probability 0.5% or <1 in 200 or less), MODERATE (annual probability 1.3% or 1 in 200 to 1 in 75 or less, but greater than 0.5% or 1 in 200) or SIGNIFICANT (annual probability >1.3% per cent or 1 in 75). This enabled a comparison of relative risks within each of these catchments, rather than a detailed, local assessment of the risk at a specific location. Despite its assumptions and uncertainties, the NaFRA approach was nationally consistent and provided all users with a more refined estimation of their flood risk.

Because of the differences between these two sources, the outcomes often varied – sometimes significantly. This perceived "confusion" irritated many users and led in some cases to the development of negative attitudes to the information, particularly given the relatively low-quality cartography employed. If the EA service was to provide equal access to all potential users (or, at least, to all web-literate users), then it needed to minimise the map-reading challenge. This reinforces the importance of acknowledging the very wide range of information backgrounds of those who access web-based hazard maps. In practice, the users' learning efficiency could be significantly increased by the simple expedient of presenting the map through a familiar mapping platform (Google Maps or Ordnance Survey), which would enable users to draw much more effectively on their prior map knowledge. This has now been achieved, and the current version of the map is larger, coloured, more detailed, much more familiar in terms of function and navigation, better provisioned with zoom and pan capability and based on a single map which combines flood extent and role of flood defences.

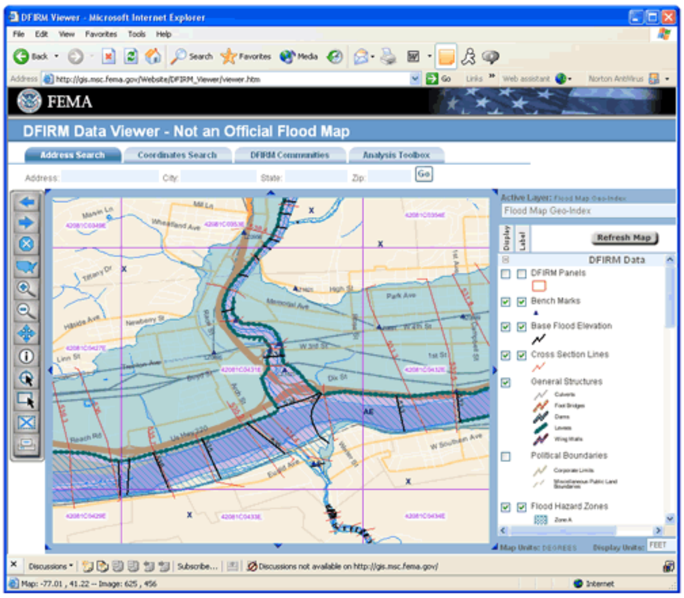

Figure 5: FEMA Flood Insurance Rate Map

During the 1970s, the US Federal Emergency Management Agency (FEMA) started to produce Flood Insurance Rate Maps (FIRMs: see Figure 5) which showed areas liable to flooding, including the 100-year base flood elevation, Special Flood Hazard Areas (SFHA), flood insurance risk zones and areas subject to inundation by the 500-year flood. These are now based on historical, meteorological, hydrological and hydraulic data, together with open-space conditions, flood-control works and development. The flood maps are designed for both professional and public users, and their aim is formally and unambiguously stated as being to identify the location of a specific property in relation to the Special Flood Hazard Areas, to identify the base (100-year) flood at a particular site and to identify the magnitude of flood hazard in a specific area. Maps are large, detailed and property-level, and users are tutored on-line to make a risk assessment using them. This is dramatically different to the generalised and caution-bound aims of the systems operating across the British Isles, but closely in tune with what many users appear to want of such a service.

Recent EA Mapping

During the last the last three years the EA flood map has continued to evolve, demonstrating how improved data together with maturing ideas about designing hazard maps for maximum impact can underpin major gains in effectiveness and efficiency. In effect the maps still embody two separate layers with the indicative flood map (with defences marked but not accounted for in the modelling) and the NaFRA data beneath. However, the NaFRA data are now being updated directly by the EA at a more local scale which brings greater access to local knowledge and also potentially reduces the time taken to update, with an opportunity to focus on the places where data quality is poor or flood issues are particularly complex.

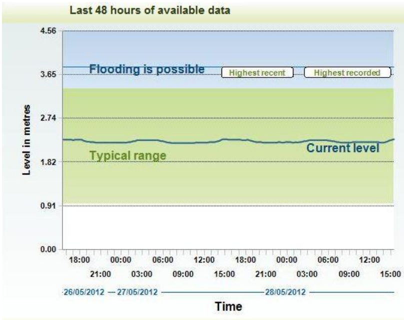

Figure 6: River levels

But this is now just a start! The information service is now much richer – and at the same time much more challenging to website visitors who are seeking a simple answer to what they think is a simple question. River and sea-level data are now provided to help "people who live in flood warning areas make better informed decisions, allowing them to decide what actions to take as water levels change", a demanding task though this is an impressive quasi-real time level display (Figure 6). Areas at risk from reservoir flooding are mapped, together with a complex disclaimer about the low absolute probabilities and excluded reservoirs. Another map presents information on flood and coastal risk management schemes that have been funded for implementation in the current financial year. Informal comments have suggested that the EA is planning to supplement this basic statement with an interactive resource on planned or proposed defence works, including information on funding. Above all, what is apparent is that in practice the concept of the "hazard map" is being increasingly widely interpreted and the combined cognitive load of these many strands will start to become a challenge, particularly when information from several maps has to be brought together to make an informed decision.

In this context, it is relevant that a Risk Regulations map is also under development in order to comply with the EU floods directive which may add depth and velocity as well as information about the confidence in the flood likelihood information. Whether this will be available online to the public is not yet clear. There are currently two national maps for surface water flooding: Areas Susceptible to Surface Water Flooding and the Flood Map for Surface Water. As local authorities also have their own maps, there is now a move towards developing one "agreed" map for each area combining the best of these maps and other local mapping. It is not only in the context of cognitive overload that some non-professional hazard map users will feel that we are now moving from an information deficit to information surplus.

Nevertheless, this evolution of hazard mapping principle and practice is an excellent example of the way in which an organisation can use thorough analysis of usability not just data quality to refine its presentation of hazard information – but there is one aspect of the underlying mapping philosophy that has not yet changed so significantly. From the outset the EA set itself resolutely against providing information to assess risk at the individual property level, despite calling the service *What's in your backyard?* The map resolution is such that it is frustratingly difficult to relate the mapped hazard boundaries to individual properties. This restriction was originally vigorously defended by the EA given the quality and resolution of the flood and elevation data, the incomplete coverage and status of flood defence information, the uncertainty inherent in flood prediction – and, one assumes, the appreciation of the litigious nature of the user population given that an adverse risk assessment could negatively impact both property value and resident's peace of mind. More recently, as confidence in the data has increased and techniques have improved, a greater openness to property-level indication may be emerging. There is no right answer in setting the breakpoint between more information or less, but any discussion of this contentious issue requires reference to the US flood map, which takes a completely different approach to that used anywhere in the British Isles. It is surprising that two countries with such similar technological levels and research backgrounds should emerge with such highly contrasted strategies with respect to a flood map service. At the very least it emphasises that there is ample room for critical debate on what might be deemed to be best practice.

EA Hazard Map Users

Different audiences require different types of information regarding technical topics that impinge upon personal decisions and actions – the context within which the flood map has been designed and used. In the setting of air quality management, Lindley and Crabbe (2004) suggest a threefold audience with markedly differing information requirements: *scientists* (complexity, methodologies, accuracy/uncertainty), *policy-makers* (generalisation, link to legislation, reliability) and the *wider public* (transparency, personalisation, simplicity/reliability). This stereotyping shows some match to the respondent population for the EA flood hazard map, but there are also some clear distinctions. When surveyed, the public users of the map showed a clear commitment to the relevance of uncertainty (though not a great mastery of the concept) and a strong concern for accuracy (tested personally by comparing flood map predicted risk zones with their local knowledge). This has clear relevance to the consideration of the EA *What's in Your Back Yard* web site, which by intent and purpose is positioned as playing a one-way public informing role. The users of the EA site often have difficulty with concepts such as probability and uncertainty. Although Miller (2004) suggests that scientific literacy is increasing, it would be wise to assume that no more than 20-25% of flood-prone adults in England and Wales (potential users of the EA *What's in Your Back Yard* web site) are currently scientifically literate. Recent user surveys have suggested that it may be useful to develop specific map versions for user categories such as the public, strategic planners and emergency planners (Meyer *et al*., 2012)

The EA web site's underlying philosophy was significantly modified through an internal review process in 2007-8. This moved the site away from an open-access format which in practice provided a high level of service to only a minority of potential users, towards the notion of providing highly efficient routing of core users to core data sets. Content may be more selective, but access is more effective for core users – here defined in terms of a set of personas, three being for in-house EA users, but for public users 5 categories were recognised as representing the prioritised core users of the EA site: researchers, business users, environmentally-conscious users, at-risk users and recreational users. Clearly, the "at risk" persona closely matches the profile of many user hits on the *What's in Your Back Yard* part of the website, and thus guarantees a priority user experience (a "fast track" to the required information).

Review of Hazard Map

The impact of the EA flood hazard map has been reviewed here in terms of its influence on individual attitudes, decisions and actions with respect to flood risk which represent the ultimate measure of the effectiveness of the map as an informing mechanism. The present (2012) flood map has made a number of advances over the version running in 2007-8, the impact of which was mediated by a number of issues:

Awareness and Action: The aim of the EA *What's in your backyard?* hazard map and web site is to improve user flood risk awareness and encourage appropriate response action, but in practice the map and text are mainly directed at the former. When web-site users have reached the map and considered the supporting information they have an overall indication of their risk status – but what then? What action should they take? Users appear to remain disoriented despite the availability of supporting guidance, and this suggests that more obvious routes to response options might be needed.

Differences between the two mapped data sets: It has been noted that the *What's in your backyard?* information service initially used two different data sets to assess flood risk. While this approach was acceptable in principle, allowing the most suitable data set to be used for each task, in practice there was great scope for user confusion. The focus of the current (2012) risk presentation on a single hazard map, albeit with complex content, is indicative of a successful institutional response to this user problem

Map format: In 2007-8 there were also problems associated with the small format and poor quality (in the view of many users) of the mapping itself. In the context of cognitive load, it is easier for users to assimilate new flood risk knowledge if it is related to familiar maps and map scales. This is a powerful message, and lies behind the frustration expressed by many EA flood map users as they struggled to relate flood risk (new knowledge) to an unfamiliar low-resolution and small-scale black and white map in a small window with restricted technology to zoom and pan. Ironically, in its determination to deny users the ability to visualise high-resolution locational data (see 4 below), the EA undermined the cognitive efficiency with which those users were able to assimilate the flood risk message, as their existing map expectations applied only with great difficulty to the EA base map. Here again, the EA has responded substantively to these deficiencies in the most recent version of the flood map.

Map resolution and property-level assessment: The single greatest point of contention for users surveyed in 2007-8 (Priest, Clark and Colclough, 2008) was that their desire to obtain a detailed risk assessment for their individual property was confounded by the flood map. Other countries take a variety of positions on this issue. All the government flood hazard map services in the British Isles opted to reject property-level interpretation while the US FEMA service encouraged it. The restriction is generally justified on the grounds that the data and models used to create the flood map and risk assessment lack the precision and accuracy necessary to support property-level inference, despite the fact that the US service uses very similar data to support its property-level assessment.

Handling assumptions and disclaimers: Closely linked to the issue of property-level risk assessment is the role and placement of the disclaimer information which alerts users to the fact that the hazard map has limitations in terms of precision and certainty. When *What's in your backyard?* was first launched, users had to acknowledge the disclaimer by clicking on it before being allowed to view the map. This was a robust approach, but unpopular with some users, so future *What's in your backyard?* versions introduced an optional disclaimer that users could visit at any time, or could decide not to visit. This is another example of a clash between convenience and quality of service. Disclaimers and the presentation of probability and uncertainty are attempts to influence public interpretation of the hazard map so as to avoid misperceptions that could trigger inappropriate attitudes and behaviours. At the same time, disclaimer and assumption information is seen as serving to protect the information distributor from complaint or litigation generated by disgruntled users who feel that they have suffered by being misled.

It is widely recognised that information provision and the associated learning, awareness and behaviour change represent highly significant contributions to national flood response strategy, and that hazard mapping is a major component of this mission. Considerable success has been achieved by the Environment Agency on the basis of repeated user reviews and a willingness to learn from experience. Nevertheless, hazard mapping could benefit from a more formal and less intuitive approach to the design of the message and its mechanisms of delivery. In practice as well as in theory, models of learning are every bit as important to the Environment Agency as models of flood hydrology, and deserve the same attention, investment and respect.

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Authors: John Bevington[5a], Hugh Lewis[6] and Ronald T. Eguchi[1b]

CASE STUDY: Crowdsourcing Remote Sensing Post-disaster Damage Assessments: The Global Earth Catastrophe Assessment Network

Case Study Overview

The magnitude 7.0 Mw earthquake on 12 January 2010 led to over 200,000 deaths and left over a million people homeless in the Haitian capital, Port-au-Prince, and surrounding regions (Washington Post, 2011). In the immediate aftermath, an understanding of the true damage to the region and its effect on the Haitian people was urgently required by multilateral organisations to inform the relief effort and to direct aid to those in need. Due to the scale and magnitude of the humanitarian emergency, damage to critical infrastructure and the loss of government administration following the earthquake, an assessment using remote sensing was the only real option (Bevington *et al*., 2010).

Following an initial damage assessment of Port-au-Prince made by a core team of over 50 remote sensing scientists, a network of over 600 volunteers from 131 private and academic institutions in 23 countries participated in a larger-scale damage assessment. This network, the Global Earth Observation Catastrophe Assessment Network (GEO-CAN), made use of the existing Google Earth software tools to view and map features in the remotely sensed imagery. Lessons learned from this initial effort by GEO-CAN were used to improve the subsequent damage assessment performed by volunteers following the magnitude 6.1 Mw 2011 Christchurch, New Zealand, earthquake of 22 February 2011.

This case study focuses on the GEO-CAN effort that began in response to the 2010 Haiti earthquake and continued in the aftermath of the 2011 Christchurch earthquake. We will review the motivation for this crowdsourced solution, how the mapping task was implemented to address the constraints on the network of volunteers, the subsequent evaluation and lessons learned.

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[5] ImageCat, [a]Ashtead, Surrey, UK. jb@imagecatinc.com | [b]Long Beach, California, USA. rte@imagecatinc.com

[6] University of Southampton, School of Engineering Sciences. h.g.lewis@soton.ac.uk

Application

The Global Earth Observation Catastrophe Assessment Network (GEO-CAN) is a global network of GIS and remote sensing scientists and structural engineers that has been convened to provide a coordinated and crowdsourced damage assessment after major disaster events. It was first assembled following the 2010 Haiti earthquake. The GEO-CAN volunteer community identified over 30,000 collapsed or heavily damaged buildings that fed into a multilateral Post Disaster Needs Assessment (PDNA) report. GEO-CAN has existed as an informal network since 2010 and was initiated again following the February 2011 Christchurch earthquake.

2010 Haiti earthquake

Following the destructive Haiti earthquake there was a pressing need to identify the worst affected regions to aid response and relief activities as well as understand the financial donations required to promote recovery in Port-au-Prince and surrounding areas. Commercial satellite companies had captured imagery of Port-au-Prince the day after the main shock and data was being made widely available to the humanitarian community. The World Bank (WB), working with the Haitian government and a private company, ImageCat Inc (IC; Long Beach, CA, USA and Ashtead, Surrey, UK), instigated a remote damage assessment using these images to identify collapsed buildings. Within 48 hours of image acquisition, the first damage maps of over 5,000 buildings were delivered for an area of 133 sq. km (Bevington *et al*., 2010). The ad hoc nature of this first activation meant the tools used by the

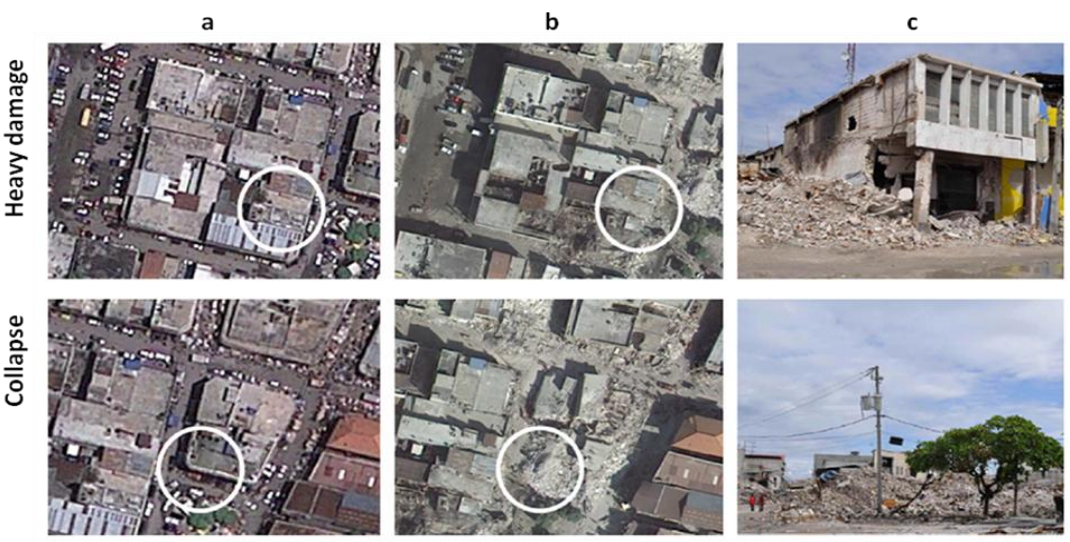

Figure 1. Examples of collapsed and heavily damaged buildings in Port-au-Prince, Haiti following the 2010 earthquake. Collapsed and heavily damaged buildings are shown across the rows, seen in (a) pre-event satellite imagery (b) post-event aerial imagery, and (c) ground-based photographs. (From Ghosh *et al*., 2011).

volunteers were basic, with the analysis of imagery in Google Earth and data management performed manually.

The second phase provided imagery with finer spatial resolution than the 50 cm acquired by the GeoEye-1 satellite sensor. An aerial reconnaissance team from Rochester Institute of Technology (RIT: NY, USA) - the WB-IC-RIT mission - captured imagery at 15 cm spatial resolution over the whole of Port-au-Prince and affected towns to the north and west (a total area of 1,025 sq. km; Bevington *et al*., 2010). Volunteer scientists, engineers and image analysts each analysed 500 × 500 metre grid cells to identify collapsed and heavily damaged buildings (Figure 1) using a short user guide to aid interpretation. GIS footprints were created for each affected building with the damage grade and user confidence level (0-100) assigned (Ghosh *et al*., 2011).

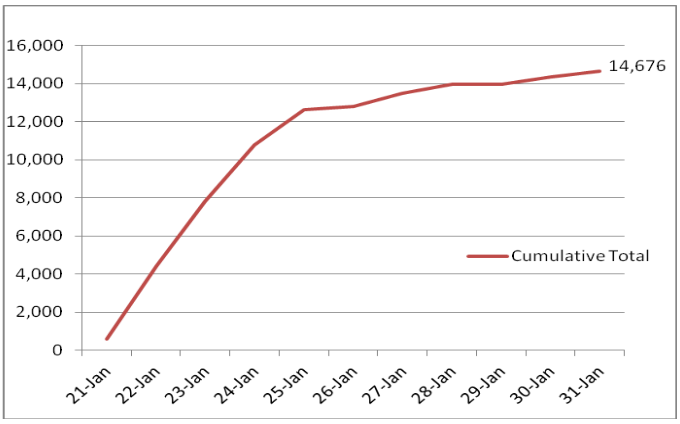

Figure 2. Cumulative number of collapsed or heavily damaged buildings in Port-au-Prince identified by GEO-CAN volunteers following the Haiti earthquake activation, 2010.

Over the space of 13 days, 14,676 buildings in Port-au-Prince were identified as damaged (Figure 2) with the total number across Haiti rising to nearly 30,000. Statistical inference using sampled ground observations and land use information was used to infer the total number of moderately and slightly damaged structures (Corbane *et al*., 2011), with the final number of buildings requiring replacement set close to 90,000 (Haitian Government, 2010). The resulting data was used in the joint Post Disaster Needs Assessment for the built environment jointly published by the Government of Haiti, World Bank, United Nations (UNOSAT) and the European Commission (Government of Haiti, 2010). The damage data, as well as aerial imagery and GPS-referenced field photographs, were also made available on the Virtual Disaster Viewer[7] (VDV) for distribution to the wider scientific community.

[7] www.virtualdisasterviewer.net

2011 (February) New Zealand earthquake

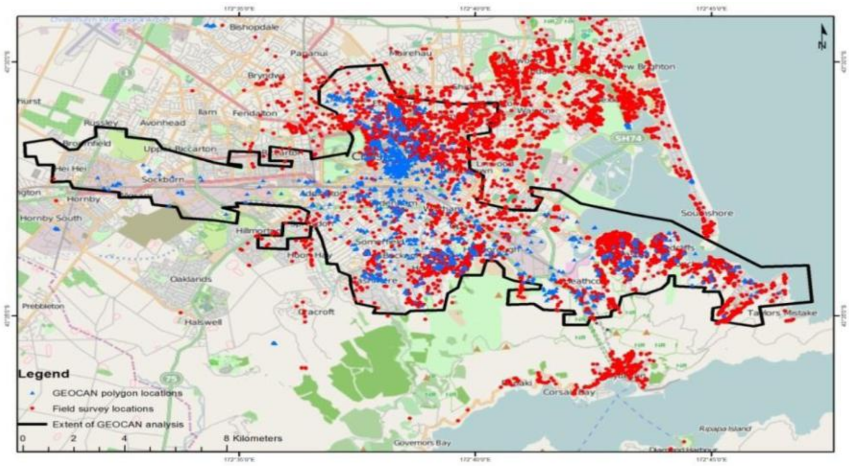

Figure 3. The extent of analysis for the February 2011 Christchurch earthquake. The area analysed by GEO-CAN is shown by the black line with the GEO-CAN digitised damage polygons in blue and field survey locations in red. (From Foulser-Piggott *et al*., 2012).

GEO-CAN was also initiated by the scientific community following the Christchurch earthquake of February 2011 (one of many severe tremors in this year). This event allowed the increased development of a data management system and the Disaster Mapper web user interface developed by Tomnod Inc (San Diego, CA, USA) (www.tomnod.com/geocan), supporting imagery collected before and after the earthquake. The data used in Christchurch included aerial and satellite imagery for identification of building damage across the city. An area of 77 sq. km detailed building damage to 1,400 buildings across the central business district (Figure 3). Additional analysis in Christchurch saw a subset of geotechnical engineers identified areas of liquefaction and lateral spreading that was prevalent in this earthquake.

Formal Drivers and Objectives

On average, almost 250 million people are affected by natural disasters each year, and this number could grow to 375 million by 2015 due, in part, to climate change (Bailey, 2009). Following natural disasters, there is an urgent need to direct search and rescue (SAR) operations, assess damage to buildings, critical infrastructure and livelihoods for managing aid and relief activities, and to identify the financial assistance required to support and promote recovery. Often, the operation of local or national government is severely compromised in the aftermath of a natural disaster and the priority is on SAR, such that the damage assessment and recovery needs are met by outside agencies. This frees up personnel on the ground, who may have limited resources, and, by prioritising areas of damage, increases the effectiveness of SAR teams and responders.

Within this context, the ability to perform this assessment remotely, through the use of satellite and aerial imagery, is a valuable asset. However, the short turn-around, the typical large-scale nature of disasters and the fine spatial detail needed to perform a reliable assessment call for large data volumes, significant computational requirements and the use of large teams of expert analysts.

Stakeholders

To date, the GEO-CAN projects have brought together a large number of stakeholders from across the world. Following the Haiti earthquake, the World Bank through the Global Facility for Disaster Risk Reduction (GFDRR), the United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme (UNOSAT) and the European Commission's Joint Research Centre (JRC) collaborated with the Haitian government (Centre National d'Information Géospatial, CNIGS), the International Development Bank and the Economic Commission for Latin America and the Caribbean to provide a rapid Post Disaster Needs Assessment (Corbane *et al*. 2011, Government of Haiti, 2010). This damage assessment was coordinated by ImageCat Inc with data provided by GeoEye Inc (Herndon, VA, USA) and Rochester Institute of Technology. The image-based analysis by GEO-CAN volunteers provided the foundation for quantification of financial needs for recovery of the built environment across the affected areas in Haiti.

The GEO-CAN Haiti volunteers came from 23 different countries, with more than 600 individuals participating from 60 universities, 18 government agencies and non-profit organisations and 53 private companies (Ghosh *et al*., 2011). The scientific study following the 22nd February 2011 Christchurch earthquake was commissioned by the Global Earthquake Model (GEM), GNS Science, New Zealand and the New Zealand Ministry of Civil Defence and Emergency Management. The team of GEO-CAN scientists were led by ImageCat and included Cambridge Architectural Research Ltd and the Earthquake Engineering Research Institute. The web platform for the analysis was developed by crowdsourcing specialists, Tomnod Inc.

Impact: Cost and Benefits

Costs of enabling GEO-CAN vary greatly depending on the extent and location of the disaster event as well as the availability of imagery datasets. In general, the costs for a GEO-CAN activation consist of:

1. The largest financial requirement is the sourcing, purchase and processing of satellite and aerial data. This can entail initiating an aerial reconnaissance mission such as the WB-IC-RIT mission that collected aerial imagery over Haiti (Ghosh *et al*., 2011). After a significant event, provision of satellite data from commercial sensors and hosting of data is often provided for humanitarian purposes, but this is not guaranteed and so the costs should be budgeted for.

2. Customising and hosting the Tomnod Disaster Mapper web-interface. This includes customisation of the user interface as well as customisation of in-built volunteer management and user profile analytical tools.

3. Incentives for volunteers (a potential future option). GEO-CAN relies on volunteers for its success. However, for frequent activations, there may be the need to provide incentives for participation. This need has not yet arisen as altruism and willingness to share expertise are widely regarded as the main drivers for participation.

Enablers and Critical Success Factors

The GEO-CAN crowdsourcing solution was integral to the success of the damage assessment performed for the Haiti earthquake as it provided the large team of expert analysts, the computational resources (the volunteers' own personal computers) and a mechanism for distributing the large data volume (through Google Earth and VDV). These factors greatly reduced the time and cost associated with mapping the damage to buildings (Figure 2).

GEO-CAN was successful because it appealed to the altruistic nature of the volunteers and their desire to feel involved and make a direct impact on the response and recovery efforts following the Haiti and Christchurch earthquakes. GEO-CAN was able to engage with this diverse set of volunteers because it made use of existing technologies and services (e.g., Google Earth, VDV), some of which were familiar to, and regularly used by, the network of volunteers. Contributions were encouraged and fears (of mislabelling damaged buildings) were assuaged by the overall quality assurance for the damage assessment provided by expert analysts and earthquake engineers. These experts were familiar with the disaster scenario and the assessment of damage to buildings, etc., from remotely-sensed imagery and the ground. Issues remaining with respect to the correct classification of building damage by volunteers were addressed, in part, by the subsequent introduction of a training programme, a dedicated Disaster Mapper developed for the Christchurch effort (Figure 4), and the use of a consensus-based approach to amalgamate volunteer inputs.

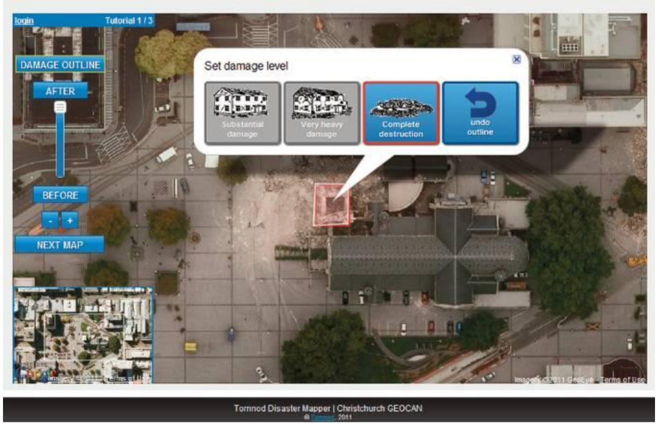

Figure 4. The Disaster Mapper developed by Tomnod Inc for the GEO-CAN analysis of the February 2011 earthquake in Christchurch, New Zealand (www.tomnod.com/geocan).

Evaluation: Failure or Success

The GEO-CAN initiative, as demonstrated in the Haiti and Christchurch events, has been successful on several levels. The following points are based on scientific evaluations of both activations (Corbane *et al*., 2011, Foulser-Piggott *et al*., 2012):

• In both earthquakes, much damage is visible in the fine spatial resolution satellite images and aerial photos analysed (50 cm and 15 cm spatial resolution). Buildings reported to be damaged in the GEO-CAN assessment are generally confirmed to be damaged in field investigations (low commission error). Damage to masonry buildings is identified most accurately of all structural types, due to the presence of debris and rubble. It was also seen that the number of correct analyses increases with user experience level.

• Conversely, significant numbers of damaged buildings are not identified in the GEO-CAN assessment (high omission error). Some types of damage regularly failed to be detected, including internal damage, soft-storey collapse and damage to timber buildings. The crowd-analytics functionality of the Tomnod Disaster Mapper shows that these types of damage were missed by analysts with all levels of remote-sensing experience.

The activation of the GEO-CAN after both disaster events led to the analysis of very large areas in a number of days (the Haiti study area was greater than 1,000 sq. km). Automated analyses over the same areas may prove faster, but are much less accurate and require much higher skill levels than using crowdsourcing as a data collection method (Clasen, 2010). The data produced by the network targets ground-based teams involved in relief activities or expert reconnaissance of damage.

GEO-CAN has allowed the latent expertise of scientists, engineers and professionals across the globe to participate and bring their knowledge to bear on disasters across the globe. It uses remote technologies and web-based interfaces to allow people to contribute to the disaster response without travelling to the site or putting strain on local resources that can be limited or incapacitated by the disaster. As GEO-CAN becomes more widespread, it will also enable the inclusion of diaspora or expatriate communities to provide valuable local knowledge that puts the damage in context.

Constraints/Challenges

Several constraints and challenges have arisen from the GEO-CAN initiatives described in this case study. One of the most striking observations is that performing damage assessments on imagery captured from a vertical perspective **will never be able to identify all types of damage.** In manual interpretation, analysts can identify by physical clues in the imagery. As such, damage to masonry buildings has the highest accuracy due to the presence of debris. There is an inherent incapacity to identify internal or non-structural damage if the exterior frame of the building is not significantly damaged. However, the GEO-CAN network can be used to target ground-based reconnaissance to areas of worst damage and also to the areas identified as non-damaged. A fusion of data sources including aerial imagery, oblique-view aerial, and ground-based data can also decrease the uncertainty in damage estimation.

As with any crowdsourcing venture, **assessing the accuracy** of distributed analytical results is the most widely raised issue. Barrington *et al*. (2011), describe several methods GEO-CAN has used to reach a consensus of opinion when the same building is surveyed by more than one analyst: visual and statistical tools are used alongside crowd-analytics drawn from the user profile to increase reliability of the analysis and to identify malicious submissions. Creation of a standard user interface with in-built user profile analytics has gone some way to improving performance in this area. GEO-CAN has spent considerable introspective time assessing the accuracy and efficacy of the data it generates (Corbane *et al*., 2011, Foulser-Piggott *et al*., 2012, Ghosh *et al*., 2011).

The **size and nature of the "crowd"** is also a major consideration. There is an ongoing debate in the community about the place in such initiatives for a public crowd over a purely scientific volunteer network and the credentials of non-expert interpretation (Welinder *et al*., 2010, Kerle and Hoffman, 2012). However, what is certain is that any volunteer community should be provided with a range of training tools and learning resources to increase performance in damage assessments.

Maintaining the social network is complex and involves significant investment. GEO-CAN's success and conversely its main vulnerability is its reliance on the participation of volunteers from the academic, public and private sectors. An incentive scheme and/or growing of the social network around the community should be the priority for this network, and could include many aspects including a mailing list, website, training, financial incentives (such as Amazon's Mechanical Turk: Amazon.com Inc 2011), targeting analysis based on professional specialism, and future feedback to members. GEO-CAN has remained an informal network to date and it is an independent entity. However, it may need to be institutionalised for many of these issues to be resolved.

Collection and serving of **appropriate imagery** is a vital consideration for the GEO-CAN. Web-interfaces such as the Tomnod Disaster Mapper (Barrington *et al*., 2012) and GEM's OpenQuake (Bevington *et al*., 2012) will allow the network to have a focal point in future disaster events. However, the network will always require financing of satellite and aerial data and will have a managerial overhead for any damage assessment activity. In the past, the World Bank and GEM (amongst others) have supported the network's activities and it is vital that funding for future events can be secured.

Data generated by GEO-CAN is freely provided to the wider community. However, feedback from users following the Haiti event showed the **lack of knowledge of end-users** on the types of data that can now be delivered following disasters. In Haiti, the use of the data outside the Post-disaster Needs Assessment report was limited, yet much can be done to alleviate this issue. The Haiti event demonstrated the potential for crowdsourced damage assessment as a new paradigm in disaster management (Bevington *et al*., 2010) and as crowdsourcing image interpretation becomes established, so communication on the use, assumptions and limitations of data with potential end-user stakeholders needs to increase. This should be done before the next disaster event for it to be a trusted data provider in any response capacity.

Recommendations/Lessons

The following lessons were learned from the GEO-CAN initiative in Haiti and Christchurch:

• Crowdsourcing can provide a mechanism for engaging and connecting with a distributed and broad community of volunteers, and for encouraging an altruistic but direct response to natural disasters, through the analysis of pre- and post-event imagery. In the future, the Facebook and Twitter communities of GEO-CAN users could be harnessed to encourage wider participation. The GEO-CAN network provided rapid inputs to difficult and evolving disaster response and recovery scenarios in two different parts of the world. In addition, by highlighting volunteer experiences and working with volunteers to address their needs and expectations, GEO-CAN identified a number of key enhancements to support the volunteer roles within the network:

a. A single entry-point for volunteer analysts and data users was developed by Tomnod Inc, to improve the user experience, the assessment process and access by emergency managers. This web-based application provided secure access for volunteers and immediate access to imagery via a graphical interface, which allowed users to draw polygons and select damage states (Figure 4).

b. Improved confidence and accuracy of damage assessment was obtained by assigning several volunteers to the same image, such that damage assessment was built by consensus. In addition, work to include user-specific information in the consensus calculation is ongoing. For example, a greater weighting may be given to users from the professional earthquake or image analysis community or to users performing well on previous assessments.

c. A training programme was created, including a short training video and test. The training provides detailed guidance on the image artefacts that are associated with building damage, the damage scales used to classify such damage and how to indicate confidence in an assessment. Future work in this area will involve the development of pre-event inventory data and the assignment of volunteers to particular building types, use of data collected on the ground to inform the training, and the provision of information on construction practices that are sensitive to the cultural and regional context.

• Damage assessments using remotely sensed imagery will remain uncertain; not all instances or types of damage can be identified. Much damage is visible from a manual assessment of satellite images or aerial photos with a spatial resolution of 1 metre or less and buildings reported to be damaged based on the GEO-CAN assessment were generally confirmed to be damaged in field investigations (12% commission error for Christchurch). The commission errors were made by analysts at all levels of experience using both satellite and aerial imagery but the number of correct identifications increased with analyst experience level. Significant numbers of damaged buildings were not identified in the GEO-CAN assessment (omission error was 54% for Christchurch) and some types of damage regularly failed to be detected. GEO-CAN have identified a number of measures to reduce the uncertainty in future damage assessments:

a. Pre-event building inventory information will allow analysis to be targeted based on structural type or occupancy and assign these to users with relevant expertise. A sister initiative, GEM's Inventory Data Capture Tools component, is using crowdsourcing as one method for contributing to building inventory knowledge globally (Bevington *et al*., 2012). Involving diaspora communities of the affected country to provide local contextual information will appeal to their sense of altruism and remove some uncertainties from the image interpretation.

b. Reliable, crowd-derived consensus can be used as examples to train machine learning algorithms that can provide an additional machine input or prompt.

c. Algorithms and approaches should be explored that are able to infer non-visible damage based on the extent of damage that can be seen.

d. Users should be asked to identify non-damaged buildings in addition to damaged buildings.

e. Field validation studies should be performed as early as possible, covering a good sample of the different areas, building types, and estimated damage grades.

f. Statistical outputs should be generated that can be scaled to observational data

Data Sources and Further Information

The data and figures herein were provided by founders of GEO-CAN, ImageCat Inc. Content and opinion comes from the experience of the authors: **Dr. John Bevington** is a Director of ImageCat, co-founder of GEO-CAN and was central to the coordination of the network in Haiti and New Zealand. **Dr. Hugh Lewis** was a participant in the Haiti GEO-CAN deployment and is Senior Lecturer in Aerospace Engineering, with a PhD in remote sensing from the University of Southampton. **Ronald T. Eguchi** is President and CEO of ImageCat and has over 30 years of experience in risk analysis and risk management studies, authoring over 250 publications. He was Principal Investigator on both the Haiti and Christchurch GEO-CAN activations and has been Chair of numerous governmental, technical and academic advisory boards on disaster risk management.

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