TECHNICAL NOTE

Estimating Economic Losses from Earthquakes Using an Empirical Approach

Kishor Jaiswal,[a] M.EERI, **and David J. Wald,**[b] M.EERI

We extended the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) empirical fatality estimation methodology proposed by Jaiswal et al. (2009) to rapidly estimate economic losses after significant earthquakes worldwide. The requisite model inputs are shaking intensity estimates made by the ShakeMap system, the spatial distribution of population available from the LandScan database, modern and historic country or sub-country population and Gross Domestic Product (GDP) data, and economic loss data from Munich Re's historical earthquakes catalog. We developed a strategy to approximately scale GDP-based economic exposure for historical and recent earthquakes in order to estimate economic losses. The process consists of using a country-specific multiplicative factor to accommodate the disparity between economic exposure and the annual per capita GDP, and it has proven successful in hindcasting past losses. Although loss, population, shaking estimates, and economic data used in the calibration process are uncertain, approximate ranges of losses can be estimated for the primary purpose of gauging the overall scope of the disaster and coordinating response. The proposed methodology is both indirect and approximate and is thus best suited as a rapid loss estimation model for applications like the PAGER system. [DOI: 10.1193/1.4000104]

INTRODUCTION

Estimating realistic economic impact due to a large-scale earthquake disaster can be a daunting task. Due to the inherent complexity of estimating infrastructural and institutional impacts (in terms of direct and indirect losses), the true value of economic impact from such disasters may only be approximately known. Months or years following large earthquakes, the estimates on economic losses can still remain in flux; for example, losses for the 2010 Haiti earthquake and the 2011 Japan earthquake are only partially tallied after several months following the earthquake. Tallies of the economic impact for the 1994 Northridge, California, earthquake continued to grow for roughly a decade. Seligson and Eguchi (2005) revised the initial estimate of $44 billion in 1997 to $57 billion in 2004 mainly by adding business-interruption and casualty-related losses and by revising the insured losses. Even then, in both estimates, the assumed cost of $20 billion related to deductible, insured, and uninsured losses were highly approximate values.

[a] U.S. Geological Survey, Golden CO (contracted through Synergetics Incorporated) kjaiswal@usgs.gov
[b] U.S. Geological Survey, Golden CO

Earthquake Spectra, Volume 29, No. 1, pages 309–324, February 2013;

In the realm of post-earthquake response planning, it is necessary that the stakeholders be alerted about the potential economic disaster that may be unfolding after a large earthquake. A recent example pertains to the M5.8 23 August 2011 Virginia earthquake; the lack of obvious catastrophic losses early on was taken as an indication that losses would be rather minimal, though actual tallies a month later well exceeded $100 million (Bausch 2011, written communication), and continued to grow thereafter. Is it possible to project such losses in the immediate aftermath of such events?

The U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) program aims to inform humanitarian aid decisions in the hours or days after the earthquake before firsthand, ground-truth observations are available to assess the true scope of humanitarian needs. In order to institutionalize a globally consistent operational earthquake response procedure, impact assessments for earthquake fatalities and economic losses for both developing and developed parts of the world are needed (Wald et al. 2011).

This article describes a procedure for rapidly estimating the economic consequences in the aftermath of a large earthquake disaster. First, an estimate is made of the country- or region-specific economic loss ratio (defined here as total direct economic loss normalized by the total economic exposure), which varies as a function of shaking intensity and is calibrated against historical earthquakes losses. The economic value of all the physical assets exposed at different locations in a given area is generally not known and can be extremely difficult to compile at a regional scale, let alone at a global scale. In the absence of such a dataset, we estimate the total gross domestic product (GDP) exposed at each shaking intensity by multiplying the per-capita GDP of the country by the total population exposed at that shaking intensity level. We then scale the total GDP estimated at each intensity by an exposure adjustment multiplier to account for the disparity between wealth and/or economic assets and the annual GDP.

The economic exposure obtained using this procedure is thus a proxy for the economic value of the actual inventory (which includes buildings, infrastructure and other assets) that is exposed to the earthquake. Similarly, the economic loss estimated using this approach represents a direct loss to building and other infrastructure, and does not include economic impacts due to indirect losses. In essence, this approach bypasses the requirement of detailed building inventories, which may or may not be available for certain parts of the world.

This article illustrates the development of a country- or region-specific economic loss ratio model using economic loss data available for global earthquakes from 1980 to 2007. Further, it illustrates the economic loss estimation for a selected earthquake and demonstrates suitability of this approach within the PAGER system.

MACROECONOMIC STUDIES OF PAST EARTHQUAKES

Earthquake-induced damage and losses are an outcome of several complex and interdependent phenomena that usually happen within several seconds of strong ground shaking during an earthquake. In order to understand the causes of damage (to buildings, infrastructure, and other facilities) and the resulting losses (casualties, economic impacts), we first need to establish the physical damageability relations and mortality vulnerability at various shaking levels. Detailed damage and loss analyses thus require a number of ingredients, for example, an inventory of building and infrastructure exposure; relative vulnerability of built environment to ground shaking; an assessment of socioeconomic wealth associated with the exposed assets; and an understanding of the region's productivity, economic growth, and resiliency (Brookeshire et al. 1997, Kircher et al. 2006). Compilation of such factors at a global scale is a mammoth task in itself, and despite the availability of data for certain parts of the world, the knowledge and tools are often unavailable to perform quantitative risk and loss analyses. In addition, the availability of required data and models does not ensure useful loss estimates unless the estimates are calibrated against historical earthquake losses.

Several researchers have attempted to simplify the problem of economic loss assessment using a macroeconomic-based empirical approach (Chan et al. 1998, Dunbar et al. 2002, Yong et al. 2001). In principle, these approaches consisted of developing an empirical relationship between loss/GDP and the seismic intensity, using dozens of significant historical earthquakes, for the cases of low-, mid-, and high-income countries. For example, Chan et al. (1998) divided nations according to their GDPs into categories of high income (GDP > $8,300), medium-income ($675–$8,300), and low-income (< $675) economies. The loss-GDP relations derived using these broad categories thus provided limited insight when estimating economic vulnerability of an individual country. The macro-economic based approach requires historical data on Loss/GDP ratios at each intensity unit in order to constrain these empirical relationships. Such data are rarely available for most historical earthquakes worldwide. Also, it is quite challenging to estimate Loss/GDP ratios at a local scale, due to (a) poor reporting in the literature on extent of the affected zone/damage footprint of individual earthquakes, (b) limited knowledge about local GDP of an affected region of a country, and (c) only aggregate losses available for individual earthquakes. In order to circumvent this, researchers often associate the reported losses with some "arbitrary zone" of maximum earthquake loss, which is an area within 30 km of the epicenter of an earthquake (Dunbar et al. 2002, Yong et al. 2001). This overly simplified hazard characterization may be feasible for small- to moderate-sized earthquakes with concentrated exposure limited to the epicentral area. However, for most global earthquakes the terms of earthquake losses are dictated by underlying complexities of earthquake fault type, dimension and type of earthquake rupture, site conditions (bed rock vs. soft alluvium), and the spatial distribution of exposed assets as well as their relative vulnerability to ground shaking.

A recent macroeconomic-based approach includes a global risk map for economic losses for six major natural hazards, including earthquakes, by Columbia University under the umbrella of the ProVention Consortium of the World Bank (Dilley et al. 2005). The methodology and underlying dataset were further improved in the Global Assessment Report on Disaster Risk Reduction (ISDR 2009). In order to estimate economic exposure, the study relied on raster distribution of the gross domestic product (GDP) defined in terms of a purchasing power parity (or PPP value).

Total earthquake loss from any single earthquake is not limited by GDP and it can exceed the GDP of the region or country. For example, the 6 November 1988 Burma-China earthquake caused losses on the order of 4.6 times the nominal GDP of the region (i.e., a total of $269 million of economic loss for the regional GDP of $58 million at the time of earthquake, see Table I of Chan et al. 1998); the 19 August 1992 Kyrgyzstan earthquake resulted in log(*loss*)-to-log(*GDP*) ratios of the order of 5.694 (Dunbar et al. 2002); and the 2010 Haiti earthquake losses exceeded the total nominal GDP of the country (http://www.haitispecialenvoy.org/relief-and-recovery/key-statistics/). Therefore, in order to characterize actual earthquake exposure in any given earthquake, we need to (a) find a way to apportion the total GDP of the country to the part of the country that is affected by the earthquake and (b) account for disparity between national GDP and economic value of assets that are exposed in a given area. In the following section, we describe the methodology to estimate country-specific economic loss functions and an approach to characterize economic exposure in lieu of the requirement to compile building inventory and economic exposure data worldwide.

GROSS DOMESTIC PRODUCT (GDP)

Since GDP estimates are primarily used to reflect the economic exposure in a given region, it is important to describe this term in more detail. GDP measures the total output of goods and services for final use produced by residents and non-residents, regardless of the allocation to domestic and foreign claims (World Bank 1994). The use of official exchange rates to convert national currency figures to U.S. dollars does not reflect the relative domestic purchasing powers of currencies. In order to describe the local purchasing power, the U. N. International Program (ICP) has developed measures of real GDP on an internationally comparable scale, using purchasing power parity of currencies (PPPs) instead of exchange rates as conversion factors. Thus, the PPP value is better suited for cross-border comparisons of living standards, specifically relevant to non-traded goods and services, but that is not the primary goal of the present investigation. Hence, the more general description in terms of nominal value of GDP (instead of its PPP value) is relevant and sufficient for exposure analyses needs. The GDP dataset is generally compiled by several different agencies including the World Bank, the United Nations, and the International Monetary Fund (IMF).

The Economic Statistics Branch of the United Nations Statistics Division (UNSD) maintains and annually updates the National Accounts Main Aggregates database. These data are compiled from the official data reported to UNSD through the annual National Accounts Questionnaire, supplemented by data estimates for any years and countries with incomplete or inconsistent information (http://unstats.un.org/unsd/default.htm). In the present investigation, we used the per capita nominal GDP estimates (which are simply referred as GDP) compiled by UNSD for all countries and regions since 1970. Note that the per capita GDP estimates are available at current prices (which are prices of the current reporting period, also known as nominal GDP), and thus they already account for exchange rate changes and inflation adjustments for different countries of the world (http://unstats.un.org/unsd/snaama/Introduction.asp). Historical accounts of GDP estimates were important for correlating reported economic losses from past earthquakes directly with the associated economic exposure (as measured in terms of the GDP) at the time of these events.

METHODOLOGY

We define the economic loss ratio, r, as the total direct economic loss (which includes structural, non-structural and content losses) normalized by the total economic exposure as:

$$\text{Loss Ratio } r = \frac{\text{Direct Economic Loss}}{\text{Total Economic Exposure}} \tag{1}$$

Note that the term Damage Ratio (DR) used in earthquake loss estimation studies (e.g., ATC 13 1985) is used to characterize earthquake damage to a particular structure. DR is defined as repair cost divided by replacement (or total) cost. At any given population center, we may observe single or several types of structures such as wood frame, concrete, steel frame and masonry buildings. In order to compute shaking-induced economic losses to these building types, we need to establish the ground motion-damage relationships for each structure type. Such analyses are feasible only at places where both the building stock inventory and vulnerability data for each structure type exist. In order to circumvent this, we attempt to characterize the total direct economic loss (which can be a combined assessment of losses from different structure types) using a single term r, and more importantly, not be dependent upon the arduous requirement of building stock inventory and vulnerability data.

Similar to DR, the loss ratio r varies with Modified Mercalli (MM) shaking intensity s. By definition, as the shaking intensity increases, the susceptibility to earthquake damage and losses increases. Similarly, the loss ratio r (defined here as ratio of total direct economic loss to total economic exposure) can assume any value between 0 and 1 at a given intensity s. These criteria, in addition to widespread historic precedence (based on earthquake damage and loss analysis in the past), we choose a two-parameter lognormal cumulative distribution function of shaking intensity s to define the loss ratio function:

$$\mathrm{r(s)} = \phi\left[\frac{1}{\beta} ln\left(\frac{s}{\theta}\right)\right] \tag{2}$$

where ϕ is the standard normal cumulative distribution function. The parameter θ represents the mean of the natural logarithm of shaking intensity s and the parameter β represents the standard deviation of $ln(s)$. In the present application, the shaking intensity s ranges from 5.0 to 9.0, where total exposure at MMI IX and above is aggregated and assigned to IX.

Unfortunately, for the last thirty years, per capita GDP estimates are unavailable at a resolution higher than the country level. Using per capita GDP at the year of an earthquake and total population subjected to a specific shaking intensity level, one can compute the total GDP exposed to the shaking intensity level at the time of earthquake. We use country-level estimates to apportion the total GDP of the country into the region's GDP under the assumption that per capita GDP estimates are uniform within a country:

$$\text{Total GDP}_{(\text{region,intensity}=s)} = \text{Per Capita GDP}_{\text{country}} \times \text{Population}_{(\text{region,intensity}=s)} \tag{3}$$

The total economic exposure at a given intensity can be computed using total GDP exposed to that intensity multiplied by the country- or region-specific exposure correction factor α as shown below

$$Eco.Exposure_{(\text{intensity}=s)} = \alpha_{\text{region}} \times \text{Total GDP}_{(\text{region,intensity})} \tag{4}$$

Note that the exposure correction factor is simply the ratio of per capita wealth to per capita GDP estimate of the country. The data on per capita wealth are directly taken from the World Bank (2006) study. This study considered several important factors including estimates of capital produced, physical capital stock, consumption, investment, natural resources and other factors in order to compute the per capita wealth in the year 2000 for 119 countries. The wealth estimate per capita is an important and useful indicator of economic well being of a region or country. Since the per capita wealth data are only available for the year 2000 (and not for other years in the past), they are assumed constant here. However, if per capita wealth data become available at higher resolution and at different time period, one could compute the exposure correction factor α_{region} specific to each region, and for each year for hindcasting historical losses. Similarly, it is also plausible to infer per capita economic exposure using other indicators, for example, household wealth data (Davies et al. 2007).

The total expected economic loss following an earthquake could be estimated by summing the product of total economic exposure and loss ratio at each shaking intensity level using the following equation

$$\mathrm{E}(L) = \sum_{\mathrm{s}} r(s) \times Eco.Exposure_{(\mathrm{intensity}=s)} \tag{5}$$

The loss ratio function $r(s)$ depends on the two free parameters, θ and β for each country or geographic region k. If we suppose that O_i is the recorded economic loss (in million U.S. Dollars, USD, taken from the Munich Re catalog) for an earthquake i, and there are N such earthquakes for that country, then we can determine the parameters of the loss ratio function in such a way that the total error ε between expected loss $E(L)$ (also termed as model estimated loss abbreviated as E_i) and recorded losses O_i is minimized using the following norm proposed by Jaiswal et al. (2009):

$$\varepsilon = ln\left[\sqrt{\frac{1}{N}\sum_{i=1}^{N}[E_i - O_i]^2}\right] + \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[ln\left(\frac{E_i}{O_i}\right)\right]^2} \tag{6}$$

The choice of the above norm is based on our limited analysis. For a given country, the catalog has many earthquakes with a lower value of economic losses and few earthquakes that have sizable value of economic losses. The goal is to search for the parameters that best hindcast the losses in bulk of these historical earthquakes, both at high and low ends of economic loss. It is plausible to use another, possibly statistically robust and efficient norm that could achieve the same purpose discussed above.

A standard iterative search technique available in MATLAB (R2007a) is used to minimize the objective function shown in Equation 6. The parameters θ and β obtained using this procedure are country- or region-specific, as described in Jaiswal and Wald (2011).

From the PAGER operational system point of view, since we do not have all the information that may be necessary to systematically quantify the total variability associated with actual economic impacts from any given earthquake, we can only use the model's predictability to hindcast past earthquake losses as a measure to infer the uncertainty that may be associated with future losses. In order to depict such uncertainty in a forward sense, we estimate the standard deviation ζ of the natural logarithm of actual or catalog-recorded loss, that is, $ln(O_i)$ given the natural logarithm of model-estimated loss $ln(E_i)$ as:

$$\zeta = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N}\left[ln(O_i) - \mu_{(ln\, O_i|ln\, E_i)}\right]^2} \tag{7}$$

The uncertainty measure ζ is assumed to be constant here between high and low losses. For simplicity, the expected value of $ln(O_i)$ given $ln(E_i)$ is assumed to be the same as model-estimated loss given by Equation 5. The sampling uncertainties and the uncertainties associated due to heteroschedasticity or due to the factors that are not fully reflected in historical earthquakes catalogs are not accounted in the present calculations. However, given the objective of the PAGER system to provide quick assessment of likely impact, we chose to disseminate earthquake losses both in terms of color-coded alert levels (selected based on median loss estimate) and in terms of associated uncertainty about the model-estimated losses obtained using Equation 7.

EMPIRICAL PARAMETERS USING JAPANESE EARTHQUAKES

In order to combine earthquake shaking, population exposure and historical earthquake loss data, we use two key datasets, namely the EXPO-CAT catalog (Allen et al. 2009; http://earthquake.usgs.gov/research/data/pager/expocat.php) and the Munich Reinsurance's NatCat Service (NatCatSERVICE 2009) database (which was made available to the PAGER team through the GEM Foundation, Italy). The EXPO-CAT dataset provides an estimate of population exposure at each shaking intensity level for historical earthquakes that occurred between 1973 and 2007 using an Atlas of ShakeMaps (Allen et al. 2008) and the LandScan population database (http://www.ornl.gov/sci/landscan/). Munich Re's database covers earthquakes between 1980 and 2007 and the economic damage data represents total direct economic losses reported for the year of an earthquake. The term 'direct economic loss' here represents the total direct losses incurred due to structural and nonstructural damage to buildings (of different occupancy types), costs associated with the structural content damage, and potential income and other losses such as temporary relocation and costs due to loss of business functionality. In contrast, the 'indirect economic loss' refers to any damage or loss that is not caused by factors that are associated with direct losses, e.g., an earthquake's impact on the regional economy, disruptions caused in earthquake zones indirectly affecting the overall business-supply chain well beyond the earthquake affected area (Brookeshire et al. 1997).

Significant efforts were necessary to post-process these two datasets, especially association of earthquakes between the two catalogs (by using the magnitude, location and time of earthquake occurrence), and removing events for which damage and losses incurred primarily due to non-shaking hazards.

To illustrate the model development for an example country, we used 79 earthquakes in Japan that caused losses in excess of US$100,000 (since this is the lowest threshold of economic loss reported in the catalog) from Munich Re's catalog and mapped them with population exposure information from EXPO-CAT. Using the above methodology we obtain the parameters $\theta = 10.29$ and $\beta = 0.1$, with results shown in Figure 1. The gray line in Figure 1a

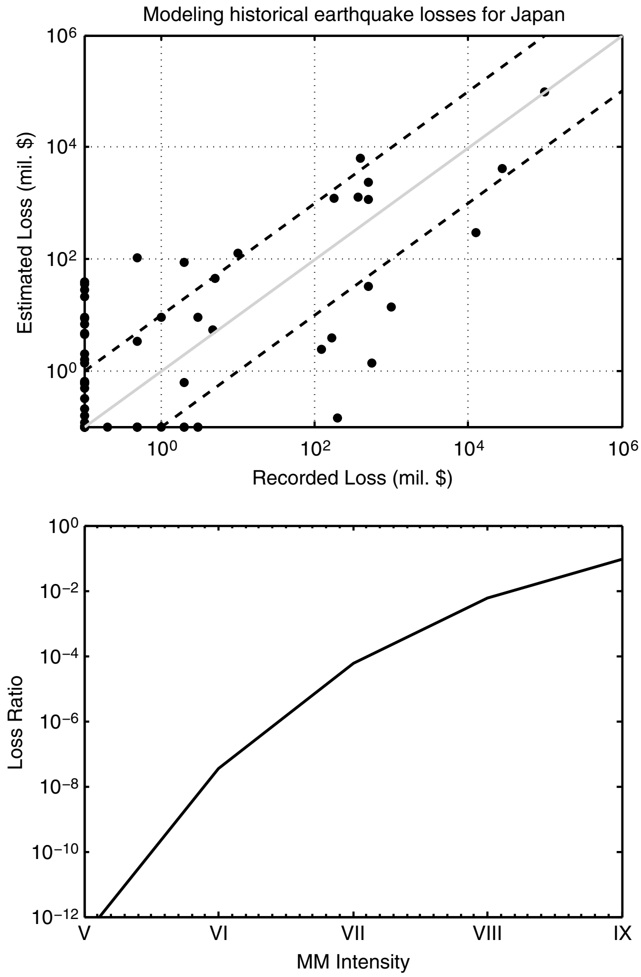


Figure 1. Diagram (a) showing estimated vs. catalog recorded economic losses for historical earthquakes in Japan obtained using (b) economic loss ratio as a function of shaking intensity ($\theta = 10.29;\ \beta = 0.1$).

shows a one-to-one match of recorded loss (from the Munich Re's catalog) and the estimated earthquake loss from the model. The two dashed lines represent one order of magnitude in estimated versus recorded loss. Figure 1b shows the loss ratio function plotted using the two parameters and equation 2. The high standard deviation $\zeta = 2.05$ as shown in Figure 1a, indicates a large spread on estimated losses from the model, especially due to earthquakes of moderate size that were reported to cause little damage. The loss ratio function defined in terms of two parameters is a cumulative lognormal distribution function of shaking intensity, and is plotted between intensity V to IX. The estimated economic loss ratio at intensity IX reaches almost 10 percent indicating significant vulnerability in terms of damage and loss for economic exposure (with $\alpha = 13.40$) at such shaking levels in Japan.

GLOBAL COVERAGE AND PAGER IMPLEMENTATION

As with the case for Japan, there are several dozen countries in the world where many damaging earthquakes have occurred during the past three decades, and where it was possible to derive a country-specific loss ratio function using historical events alone. However, in order to derive such functions for other places, we relied on additional data and inferences that would help us associate countries with similar vulnerability traits. The regionalization scheme that was originally proposed for PAGER's global fatality model (Jaiswal et al. 2009) was a good start because the scheme, besides other factors, relied heavily on building stock characterization and annual GDP data to associate countries. We considered each region (that may constitute two or more countries) where many damaging earthquakes have occurred in the past, to develop a regional loss ratio function. Even when grouping earthquakes from different countries in order to derive a regional model, the key was to hindcast the economic losses strictly based on each individual earthquake. This is achieved by considering each earthquake-specific population exposure, the GDP data, and the exposure correction factor of the country where earthquake occurred, and searching for best parameters that hindcast the reported losses in that earthquake. Again the numerical search algorithm allows solving for all the earthquakes of the region (despite that they occurred in different countries of the same region) simultaneously via minimizing the Equation 6. In this scheme, an individual country with sufficient earthquakes can be used to contribute to the regional model but still retains its own country-based loss ratio parameters. Table 1 provides economic loss model parameters for selected countries as a quick reference to the readers. Jaiswal and Wald (2011) details the process implemented in deriving regional loss ratio functions for many countries. In addition we provide an electronic database of the most recent version of the PAGER loss model parameters for all the countries of the globe that are implemented within the operational PAGER system.

Table 1. Empirical model parameters for selected countries. Interested readers are referred to Jaiswal and Wald (2011) electronic database that provides the most recent version of the model parameters used by the PAGER system.

Country	θ	β	ζ	Per capita GDP (2009 estimates)	Number of Earthquakes
Albania	9.61	0.10	1.31	$4,174	20
Australia	8.88	0.10	2.15	$48,253	18
Chile	9.73	0.10	1.14	$10,091	17
Italy	9.03	0.10	2.50	$38,640	20
Japan	10.29	0.10	2.05	$38,578	79
Nigeria	8.64	0.10	2.15	$1450	5
Trinidad and Tobago	9.65	0.11	1.73	$18,153	10
Turkey	9.46	0.10	1.74	$10,031	62
United States (without California)	11.51	0.15	1.54	$45,230	12
California	9.60	0.10	2.50	$45,230*	38

*per capita GDP for California is assumed to be the same as for the entire United States.

In the forward calculation within the PAGER system, we use the most recent GDP dataset in addition to the LandScan[1] population data to estimate earthquake losses. In our current implementation, the USGS ShakeMap system automatically triggers the PAGER system that ultimately produces earthquake impact alerts using an earthquake impact scale (EIS, Wald et al. 2011). Soon after an earthquake, there could be large uncertainties associated with many of the earthquake parameters such as location, depth, focal mechanism, source characterization or choice of ground motion prediction or the ground motion-intensity conversion equations. The PAGER loss estimate can thus vary through time between different versions as new data arrive to constrain the ShakeMap of a given earthquake. For example, within the first hour of the M9.0 11 March 2011 Tohoku, Japan earthquake, PAGER estimated a 'red alert' for economic losses using the model described in the earlier section of this article. The estimate indicated a high likelihood that the shaking-related economic impact could amount to billions of dollars. However, for the first version of PAGER, that was produced 23 minutes following this earthquake, we estimated a "yellow" alert for economic losses (indicating tens of millions of dollars of economic losses) mainly due to lower estimate (M7.9) of magnitude at that time. The earthquake magnitude was revised to M8.8 within several minutes, which resulted in the loss estimates increasing to the level of a red alert. Further, as the new data (ground motion amplitudes, felt intensities, and fault dimensions) were acquired during the days following this earthquake, newer versions of ShakeMap were produced and thus the process helped revise the PAGER loss estimates as shown in Figure 2.

Clearly, the tsunami-related losses dominated the overall damage and casualties; nonetheless, the shaking-related impact was substantial. On 24 June 2011, the Cabinet Office of Government of Japan estimated a total economic loss of US$209.8 billion[2] from tsunami and shaking-related causes, not including nuclear meltdown related issues. The World Bank study indicated that the total losses could be as much as US$235 billion[3]. Early reports suggested that the shaking-related causes could have amounted to at least US$77 billion.

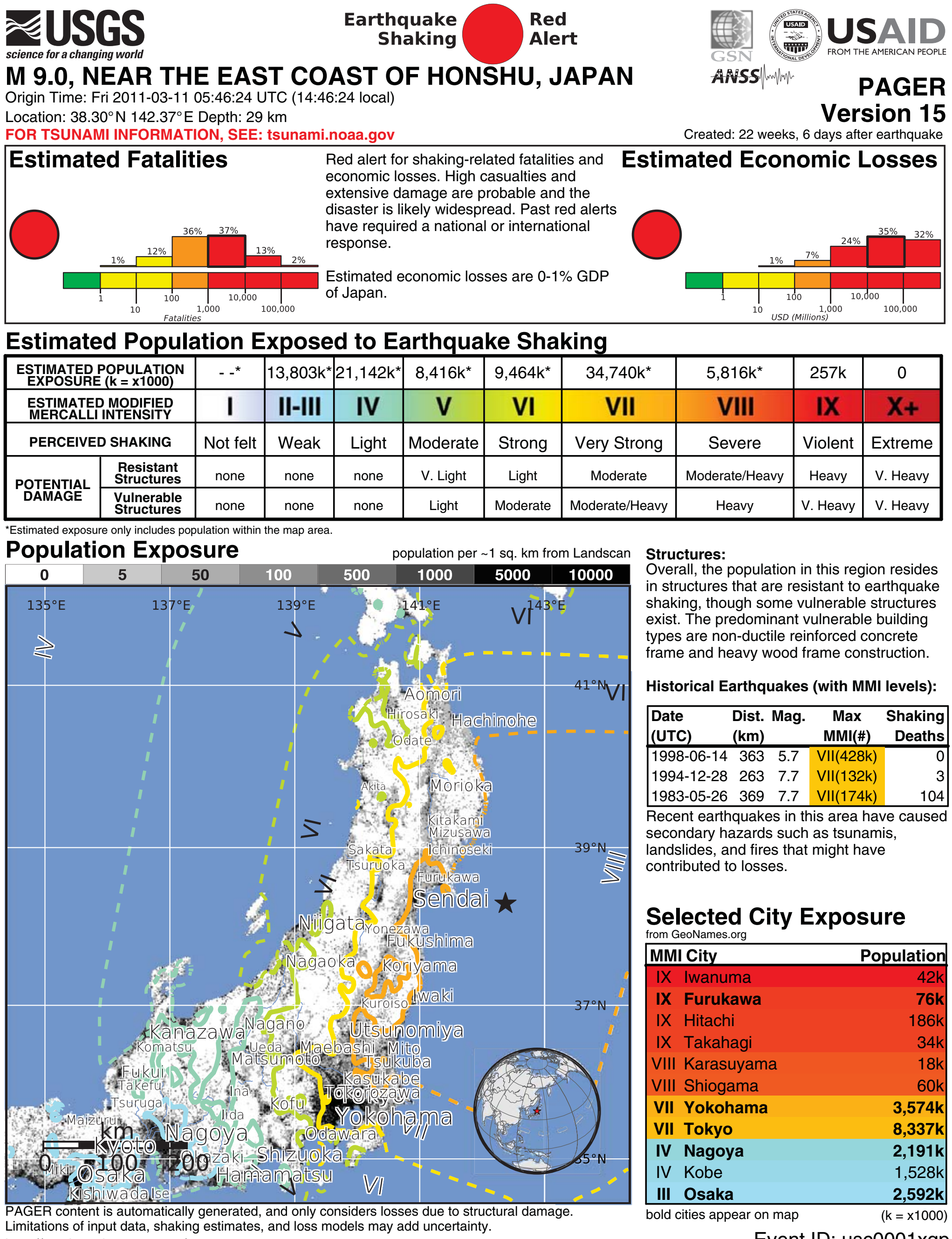
Figure 3 shows the earthquake impact alert for the M5.8 Virginia earthquake produced by the operational PAGER system indicating an orange alert for economic losses (median, i.e., 50th percentile economic loss value exceeding US$100 million). The PAGER alert indicated that there was a low likelihood of shaking related fatalities but the economic losses could be widespread, and such an earthquake could require regional level response based on historical experience.

Table 2 provides a list of earthquakes with estimated and reported economic losses for some of the significant earthquakes of 2010–2011. There are large variations in reported economic losses for many earthquakes in the list. We used widely cited loss estimates and compared them with the PAGER estimated median economic losses obtained from the most recent version of the ShakeMap. In general, the loss estimates varied from 25% to 250% of the reported losses and are clearly within the order of magnitude loss-ranges originally desired for the PAGER rapid loss estimation system.

[1]http://www.ornl.gov/sci/landscan/

[2]http://www.reuters.com/article/2011/06/24/japan-economy-estimate-idUSL3E7HN3CM20110624

[3]http://www.latimes.com/business/la-fgw-japan-quake-world-bank-20110322,0,3799976.story


USGS
science for a changing world

Earthquake Shaking Red Alert

GSN ANSS USAID FROM THE AMERICAN PEOPLE

M 9.0, NEAR THE EAST COAST OF HONSHU, JAPAN

Origin Time: Fri 2011-03-11 05:46:24 UTC (14:46:24 local)
Location: 38.30°N 142.37°E Depth: 29 km
FOR TSUNAMI INFORMATION, SEE: tsunami.noaa.gov

PAGER Version 15
Created: 22 weeks, 6 days after earthquake

Estimated Fatalities

Red alert for shaking-related fatalities and economic losses. High casualties and extensive damage are probable and the disaster is likely widespread. Past red alerts have required a national or international response.

Estimated economic losses are 0-1% GDP of Japan.

Estimated Economic Losses

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	13,803k*	21,142k*	8,416k*	9,464k*	34,740k*	5,816k*	257k	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

Structures:
Overall, the population in this region resides in structures that are resistant to earthquake shaking, though some vulnerable structures exist. The predominant vulnerable building types are non-ductile reinforced concrete frame and heavy wood frame construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1998-06-14	363	5.7	VII(428k)	0
1994-12-28	263	7.7	VII(132k)	3
1983-05-26	369	7.7	VII(174k)	104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure
from GeoNames.org

MMI	City	Population
IX	Iwanuma	42k
IX	**Furukawa**	**76k**
IX	Hitachi	186k
IX	Takahagi	34k
VIII	Karasuyama	18k
VIII	Shiogama	60k
VII	**Yokohama**	**3,574k**
VII	**Tokyo**	**8,337k**
IV	**Nagoya**	**2,191k**
IV	Kobe	1,528k
III	**Osaka**	**2,592k**

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage.
Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

Event ID: usc0001xgp

Figure 2. An automated PAGER impact estimate showing "Red Alert" based on both fatalities, as well as the economic losses using PAGER's operational models at the time of earthquake. Note that the likelihood estimates for fatalities (shown in the bar chart above) indicated that actual fatalities could very well also lie in an "Orange Alert" level thresholds.

USGS science for a changing world

Earthquake Shaking **Orange Alert**

USAID FROM THE AMERICAN PEOPLE

GSN ANSS

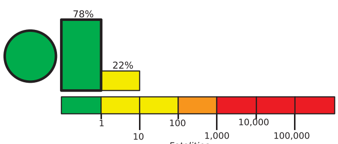
M 5.8, VIRGINIA

Origin Time: Tue 2011-08-23 17:51:04 UTC (13:51:04 local)
Location: 37.94°N 77.93°W Depth: 6 km

PAGER Version 3

Created: 2 hours, 5 minutes after earthquake

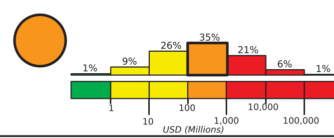
Estimated Fatalities



Orange alert level for economic losses. Significant damage is likely and the disaster is potentially widespread. Estimated economic losses are less than 1% of GDP of the United States. Past events with this alert level have required a regional or national level response.

Green alert level for shaking-related fatalities. There is a low likelihood of casualties.

Estimated Economic Losses



Estimated Population Exposed to Earthquake Shaking

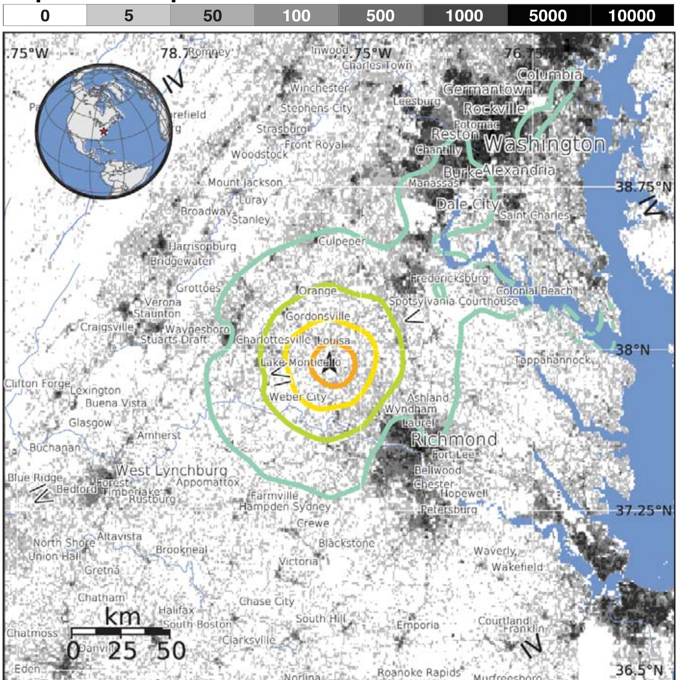
ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	19k*	9,627k*	2,285k	76k	23k	10k	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

0	5	50	100	500	1000	5000	10000



PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

Structures:
Overall, the population in this region resides in structures that are resistant to earthquake shaking, though some vulnerable structures exist.

Historical Earthquakes (with MMI levels):

There were no earthquakes with significant population exposure to shaking within a 400 km radius of this event.

Selected City Exposure

from GeoNames.org

MMI	City	Population
VII	**Louisa**	**2k**
VI	**Gordonsville**	**2k**
VI	Newington	21k
VI	**Orange**	**4k**
VI	**Weber City**	**1k**
VI	**Lake Monticello**	**10k**
V	Virginia Beach	425k
V	**Washington**	**552k**
IV	**Richmond**	**191k**
IV	Baltimore	611k
IV	Annapolis	36k

bold cities appear on map (k = x1000)

Event ID: us082311a

Figure 3. An automated PAGER impact estimate showing an "Orange Alert" based on the operational economic loss model at the time of earthquake. It took several weeks to quantify the actual economic impact after this earthquake, and the most recent estimate indicates that the actual loss exceeded $100 million as of 20 September 2011.

Table 2. Loss estimates produced by the PAGER system for recent worldwide earthquakes.

Earthquake	Reported Losses (in USD)	Estimated Direct Shaking-related Losses (median estimate* in USD)	Loss Fraction (Reported/ Estimated)
M7.0 January 12, 2010 Haiti earthquake	7.8 billion† (4.3 billion direct)	3.0 billion	1.43
M8.8 September 24, 2010 Chile earthquake	30 billion‡	15 billion	1.0 to 2.0
M7.0 September 3, 2010 Canterbury, New Zealand earthquake	2.2 to 2.9 billion§	2 billion	1.10 to 1.45
M6.1 February 22, 2011 Christchurch, New Zealand earthquake	16.5 to 25 billion**	37 billion	0.45 to 0.68
M9.0 March 11, 2011 Tohoku, Japan earthquake	At least 77 billion†† (direct losses due to shaking only)	31 billion	0.76 to 1.52
M6.0 June 13, 2011 Christchurch, New Zealand earthquake	4.83 billion‡‡	4.0 billion	1.21
M7.1 October 23, 2011 Eastern Turkey earthquake	500 million to 1.0 billion§§	2.0 billion	0.25 to 0.50
M5.8 August 23, 2011 Virginia, USA earthquake	200 to 300 million***	236 million	0.85 to 1.27

*Median value of shaking-related direct economic losses from most recent version of ShakeMap system
†http://www.haitispecialenvoy.org/relief-and-recovery/key-statistics/
‡http://www.aon.com/attachments/reinsurance/201012_if_annual_global_climate_cat_report.pdf
§http://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=10709579
**http://www.stuff.co.nz/business/rebuilding-christchurch/4984173/Quake-rebuild-will-eat-into-GDP
††http://www.itas.fzk.de/tatup/113/khua11a.htm
‡‡http://en.wikipedia.org/wiki/June_2011_Christchurch_earthquake
§§http://www.erra.pk/TurkeyEQ2011/FactFile.asp
***http://www.washingtonpost.com/local/region-tallies-earthquake-damage-mostly-uninsured/2011/08/24/gIQAFdxScJ_story.html

The EIS scheme allows us to not only provide useful and actionable information as quickly as possible, but also makes the user aware of inherent uncertainties associated with rapid estimation procedures like PAGER that work on a global scale.

LIMITATIONS

Regional economic exposure estimated at each intensity level using the per capita GDP, exposure correction factor and the total population exposed at that level has certain drawbacks. It is plausible that such approach may not be sufficient to represent the true physical exposure for certain areas where the actual population density and the scale of economic activities are poorly correlated with each other. Also, the assumption of uniform per capita

GDP in a given year throughout the country, as well as a stationary exposure correction factor α (due to limited available data) can add to these deficiencies. For example, we do not correct the economic exposure separately for areas of high industrial activities versus those of low economic activity. Similarly, we do not account for the high disparity of population or economic growth between urban and rural areas (compared to the natural averages that are already accounted here) in certain countries. In the future, it may be possible to improve the empirically estimated economic exposure through the inclusion of finer resolution (at ~1 sq km grid) per capita GDP dataset that were produced within the Natural Hotspot study (Dilley et al. 2005).

In addition, PAGER loss estimation is also subject to additional uncertainties or inaccuracies within the input datasets, such as the LandScan population database, shaking hazard estimates obtained from the ShakeMap system, population exposure estimates obtained from EXPO-CAT database, and estimates of per capita GDP derived for certain countries. Similar to the Jaiswal et al. (2009) fatality estimation model, the present approach does have certain deficiencies, specifically (1) it is country- or region-specific, a resolution too coarse for some countries, (2) the approach does not quantify the errors associated with reported economic losses that are available through Munich Re's historical earthquake catalog, and (3) there are uncertainties in estimating the exact population count exposed per intensity level. Any systematic uncertainty due to these factors may be included in the estimation of the uncertainty parameter ζ obtained using Equation 7; however, any unaccounted-for uncertainties within the input dataset or inaccuracies associated with the earthquake source parameters can potentially result in significant under or over-estimation of losses.

DISCUSSION AND CONCLUSIONS

The empirical economic loss-modeling approach presented in this paper is comparable to the earthquake fatality estimation model described by Jaiswal et al. (2009). However, in this study, the shaking-intensity dependent loss ratio is defined as the total direct economic loss normalized by the total economic exposure in a given area at the time of the earthquake. The earthquake specific economic exposure at each intensity level is calculated for each earthquake by multiplying the total population at a given shaking intensity by per capita GDP for the year in which the earthquake occurred and an exposure correction factor of that country.

The loss ratio as a function of shaking intensity is described by using a country-specific, two-parameter, lognormal cumulative distribution function. The loss ratio function when multiplied by the economic exposure associated with each shaking-intensity level provides an estimate of the total expected economic loss.

Earthquake loss estimation is a challenging problem. In the realm of rapid economic loss estimation within the PAGER system, the purpose is to produce both actionable and acceptable economic loss estimates that can help its users determine appropriate levels of response in the initial hours of an earthquake disaster. While detailed inventory-based earthquake loss estimation models exist, at least domestically (e.g., FEMA's HAZUS program or commercial insurance industry models), PAGER's goal is to serve to the global earthquake disaster needs. Empirically derived loss estimation models, though enticing, are subject to some drawbacks. These models can be developed only at places where sufficient historical earthquake damage and loss data exist, or where sound inferences are possible by virtue of supplementary information related to seismic vulnerability. Thus, this model is not intended to challenge or replace detailed inventory-based loss estimation models with simpler empirically derived ones. Fatality and economic loss based alerts produced in such a way by the PAGER system help identify the relevant and significant shocks, from the thousands of earthquakes that are recorded every year by the USGS National Earthquake Information Center.

ACKNOWLEDGMENTS

Munich Reinsurance's NatCat Service provided the economic loss data for earthquakes that occurred between 1980 and 2008. Other online data sources include the United Nations Statistical Service (UNSD), and the World Bank. David Perkins, Margaret Hopper, Nico Luco, and Jill McCarthy of USGS are thanked for their reviews. The GEMVEM project funded by the GEM Foundation provided partial support for this research work. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

REFERENCES

Allen, T. I., Wald, D. J., Hotovec, A. J., Lin, K., Earle, P. S., and Marano, K. D., 2008. *An Atlas of ShakeMaps for Selected Global Earthquakes*, U.S. Geological Survey Open-File Report 2008-1236, 47 pp.

Allen, T. I., Wald, D. J., Earle, P. S., Marano, K. D., Hotovec, A. J., Lin, K., and Hearne, M., 2009. An atlas of ShakeMaps and population exposure catalog for earthquake loss modeling, *Bull. Earthq. Eng.* **7**, DOI: 10.1007/s10518-009-9120-y.

Applied Technology Council (ATC), 1985. *Earthquake Damage Evaluation Data for California*, Applied Technology Council, Redwood City, California.

Bausch, D., 2011. Written communication.

Brookeshire, D. S., Chag, S. E., Cochrane, H., Olson, R. A., Rose, A., and Steenson, J., 1997. Direct and indirect economic losses from earthquake damage, *Earthquake Spectra* **13**, 683–701.

Chan, L. S., Chen, Y., Chen, Q. F., Liu, J., Dong, W., and Shah, H., 1998. Assessment of global loss based on macroeconomic indicators, *Natural Hazards* **17**, 269–283.

Chen, Y., Chen, Q. F., and Chen, L., 2001. Vulnerability analysis in earthquake loss estimate, *Natural Hazards* **23**, 349–364.

Davies, J. B., Sandstrom, S., Shorrocks, A., and Wolff, E. N., 2007. *The World Distribution of Household Wealth*, UNU-WIDER Research Paper, World Institute for Development Economic Research (UNU-WIDER).

Dilley, M., Chen, R. S., Deichmann, U., Lerner-Lam, A. L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Bradfield, L., and Yetman, G., 2005. *Natural Disaster Hotspots: A Global Risk Analysis, Synthesis Report*, http://sedac.ciesin.columbia.edu/hazards/hotspots/synthesisreport.pdf (accessed 3 May 2010).

Dunbar, P., Bilham, R., and Laituri, M., 2002. Earthquake loss estimation for India based on macroeconomic indicators, in *Risk Science and Sustainability: Science for Reduction of Risk and Sustainable Development of Society* (T. Beer, and A. Ismail-Zadeh, Eds.), Kluwer Academic Publishers, Dordrecht, 163–180.

Federal Emergency Management Agency (FEMA), 2006. *HAZUS-MH MR2 Technical Manual*. Washington, D.C., http://www.fema.gov/plan/prevent/hazus/hz_manuals.shtm (accessed 22 August 2008).

International Strategy for Disaster Reduction (ISDR), 2009. *Global Assessment Report on Disaster Risk Reduction*, United Nations, Geneva, Switzerland.

Jaiswal, K., Wald, D. J., and Hearne, M., 2009. *Estimating Casualties for Large Earthquakes Worldwide Using an Empirical Approach*, USGS Open File Report, OF 2009-1136, 83 pp. (http://pubs.usgs.gov/of/2009/1136/).

Jaiswal, K., and Wald, D. J., 2011. *Rapid estimation of the economic consequences of global earthquakes*, USGS Open File Report, OF 2011-1116, pp 47. (http://pubs.usgs.gov/of/2011/1116/).

Kircher, C., Seligson, H., Bouabid, J., and Morrow, G., 2006. When the Big One Strikes Again-Estimated Losses due to a repeat of the 1906 San Francisco earthquake. *Earthquake Spectra* **22(S2)**, S297–S339.

NatCatSERVICE, 2008. *Natural Catastrophes Worldwide 1980–2008*, Münchener Rückversicherungs-Gesellschaft, Geo Risks Research (data made available through GEM Foundation, Pavia Italy).

Seligson, H. A., and Eguchi, R. T., 2005. The true cost of earthquake disasters: an updated tabulation of losses for the 1994 Northridge earthquake, *Proceedings, International Symposium on Earthquake Engineering Commemorating the Tenth Anniversary of the 1995 Kobe Earthquake Int. Symp. Earthq. Eng. 2005*, Kobe, Japan, 13–16 January, 6 pp.

Wald, D. J., Jaiswal, K. S., Marano, K., and Bausch, D., 2011. An earthquake impact scale, *Natural Hazards Review* **12**, 125–139.

World Bank, 1994. *World Development Report 1994: Infrastructure for Development*, Oxford University Press, Inc., New York, 264 pp.

World Bank, 2006. *Where Is the Wealth of Nations?: Measuring Capital for the 21st Century*, World Bank, Washington, D.C., 188 pp.

(Received 7 November 2011; accepted 2 May 2012)