Earthquake Impact Scale

D. J. Wald[1]; K. S. Jaiswal, A.M.ASCE[2]; K. D. Marano[3]; and D. Bausch[4]

Abstract: With the advent of the USGS prompt assessment of global earthquakes for response (PAGER) system, which rapidly assesses earthquake impacts, U.S. and international earthquake responders are reconsidering their automatic alert and activation levels and response procedures. To help facilitate rapid and appropriate earthquake response, an Earthquake Impact Scale (EIS) is proposed on the basis of two complementary criteria. On the basis of the estimated cost of damage, one is most suitable for domestic events; the other, on the basis of estimated ranges of fatalities, is generally more appropriate for global events, particularly in developing countries. Simple thresholds, derived from the systematic analysis of past earthquake impact and associated response levels, are quite effective in communicating predicted impact and response needed after an event through alerts of green (little or no impact), yellow (regional impact and response), orange (national-scale impact and response), and red (international response). Corresponding fatality thresholds for yellow, orange, and red alert levels are 1, 100, and 1,000, respectively. For damage impact, yellow, orange, and red thresholds are triggered by estimated losses reaching \$1M, \$100M, and \$1B, respectively. The rationale for a dual approach to earthquake alerting stems from the recognition that relatively high fatalities, injuries, and homelessness predominate in countries in which local building practices typically lend themselves to high collapse and casualty rates, and these impacts lend to prioritization for international response. In contrast, financial and overall societal impacts often trigger the level of response in regions or countries in which prevalent earthquake resistant construction practices greatly reduce building collapse and resulting fatalities. Any newly devised alert, whether economic- or casualty-based, should be intuitive and consistent with established lexicons and procedures. Useful alerts should also be both specific (although allowably uncertain) and actionable. In this analysis, an attempt is made at both simple and intuitive color-coded alerting criteria; yet the necessary uncertainty measures by which one can gauge the likelihood for the alert to be over- or underestimated are preserved. The essence of the proposed impact scale and alerting is that actionable loss information is now available in the immediate aftermath of significant earthquakes worldwide on the basis of quantifiable loss estimates. Utilizing EIS, PAGER's rapid loss estimates can adequately recommend alert levels and suggest appropriate response protocols, despite the uncertainties; demanding or awaiting observations or loss estimates with a high level of accuracy may increase the losses. **DOI: 10.1061/(ASCE)NH.1527-6996.0000040.**

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Introduction

Neither earthquake magnitude nor macroseismic intensity provides sufficient information to judge the overall impact of an earthquake. Whereas higher magnitude earthquakes have greater energy release and can potentially affect a much larger area, losses depend directly on the exposure and vulnerability of a population to specific levels of shaking. Earthquakes also have highly variable effects on society; the complex and variable nature of the effects for differing events can be attributed to a number of contributing factors, primarily the highly variable nature of the hazard distribution (predominantly, shaking intensity), the population exposure, the vulnerability of the built environment, and the resilience of the communities affected. Whereas these factors can now, in part, be rapidly assessed following significant earthquake disasters, communicating the impact is still hampered by the lack of an appropriate lexicon.

Currently, the USGS National Earthquake Information Center (NEIC) provides automatic alerting capabilities for all significant earthquakes around the world primarily with the Earthquake Notifications Service (ENS; Wald et al. 2008d). ENS presents fundamental improvements for USGS earthquake alerting in that users can customize their alerting levels on the basis of magnitude and location (hypocenter), time of day, and receive messages on multiple devices or electronic addresses (each with, potentially, different triggering criteria) in near real time. ENS alerts are sent to more than 145,000 subscribed users ranging from critical responders, nongovernmental organizations, governments, the media, and individuals (see Wald et al. 2008d). However, despite the benefits of ENS over earlier list-servers, the alerting criteria are currently limited to magnitude- and location-based triggers. Although well-familiarized users can take advantage of earthquake magnitude, depth, and location to make informed decisions, most users do not have enough experience or expertise to tie these parameters to population exposure and region-specific vulnerability to confidently assess the potential impact. In addition, users must either be conservative by setting a low magnitude trigger level to avoid missing significant events (and potentially get more alerts than desired),

[1]Geophysicist, National Earthquake Information Center, U.S. Geological Survey, Golden, CO 80401 (corresponding author). E-mail: wald@usgs.gov

[2]Civil Engineer, National Earthquake Information Center, U.S. Geological Survey, Golden, CO 80401.

[3]Geophysicist, National Earthquake Information Center, U.S. Geological Survey, Golden, CO 80401.

[4]Physical Scientist, FEMA, Denver, CO 80225.

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or alternatively, take the risk of missing an important event by setting to a higher threshold.

Fundamentally new content concerning the impact of each significant earthquake around the world is now produced by the Prompt Assessment of Global Earthquakes for Response (PAGER) system. PAGER results are generated automatically by the USGS NEIC within 30 min of any magnitude (M) 5.5 or larger event. PAGER rapidly assesses earthquake impacts by comparing populations exposed to estimates of shaking intensity and models of economic and fatality losses on the basis of past earthquakes in each country or region of the world.

The impact of an earthquake is controlled primarily by (1) distribution and severity of shaking; (2) population exposed at each shaking intensity level; and (3) how vulnerable that population is to building damage at each intensity level, which is dominated by the degree of seismic resistance of the local building stock. The PAGER system takes a ShakeMap as the primary hazard input; then, on the basis of a comprehensive LandScan worldwide population database (Dobson et al. 2003), computes the population exposed to each level of shaking intensity. With this approach, PAGER automatically identifies earthquakes that will be of societal importance on the basis of the total population exposed to higher intensities. Because these calculations are available well in advance of ground-truth observations or news accounts, they can play a primary alerting role for domestic and international earthquake disasters. An example of the current PAGER summary product, or onePAGER, is shown in Figure 1 for a recent destructive earthquake in Chile that killed 521 people.

The current version of PAGER can be found on the USGS earthquake event web pages, and critical users can subscribe to e-mail or text PAGER alert messages by contacting the authors. This paper describes how the USGS will be releasing a new version of PAGER in September 2010 that uses simplified loss-modeling approaches to quantify both the human and economic impact. Impacts are computed by combining shaking, exposure, and loss rates calibrated against observed fatality and economic losses from past earthquakes in each region. The public release of such near-real-time loss results necessitates creative means for portraying such sensitive content and their uncertainties.

This study proposes the utilization of the USGS PAGER system to develop and use a new earthquake impact alerting protocol, or earthquake impact scale (EIS). EIS moves beyond magnitude and hypocenter to provide a more meaningful assessment of what most critical users need to know to make response decisions, i.e., overall earthquake impact described in basic terms of estimated casualties and economic losses. Because such impact assessments can now be done in a quantifiable fashion in near real time, the potential is explored for using these quantities to initiate alert levels and response protocols. Having quantified and analyzed impacts from a large number of past earthquakes during the development and calibration of the PAGER system, this approach is simply to set thresholds consistent with the actual or inferred response levels for past earthquakes to automate assignments of response levels for future events.

As an important aside, critical users already have another option for alerting based on potential earthquake impact. The USGS ShakeCast system, short for ShakeMap Broadcast, is a freely available, postearthquake situational awareness application that automatically retrieves earthquake-shaking data from a USGS ShakeMap; it then compares intensity measures against users' facilities, sends notifications of potential damage to responsible parties, and generates facility damage maps and other web-based products for both public and private emergency managers and responders (for details see Wald et al. 2008b). ShakeCast is meant primarily for critical lifeline utility operators in areas where rapid and robust ShakeMaps are available, for example, in California. Domestically, FEMA utilizes the ShakeCast RSS feed to rapidly obtain ShakeMaps and begin production of loss estimates utilizing the HAZUS (Hazards-U.S.) application. However, ShakeCast is available globally, though with higher levels of uncertainty in the shaking estimates than for those maps constrained by numerous seismic stations (see Wald et al. 2008b, c). Although ShakeCast requires a rather high level of insight into one's facilities' vulnerabilities to take advantage of its full functionality, the EIS discussed in this study is intended for more general use with a primary focus at response and aid agencies.

It is difficult to change long-held notions of earthquake severity tied to magnitude and location. However, it is now possible to provide more informative postearthquake situational content and alerts. Both ShakeMap and PAGER depend on users' understanding of macroseismic intensity; some progress has been made standardizing and communicating intensity-based hazards and impact from inculcation through USGS products like ShakeMap and "Did You Feel It?" Communicating uncertainties (or probabilities) is another matter this study attempts to address. Rapid diffusion and acceptance of new innovations typically succeeds when the technology and appearance are not only familiar and intuitive but also require little modification to established protocols. In addition, there must also be little technical overhead to implement significant changes (e.g., Rogers 2003). Hence, an alerting scale is attempted that is both simple and intuitive. That said, the need to provide uncertainty measures associated with alerts is an area that has a poor track record in terms of public communication and consumption. Nonetheless, it is expected that with very little training, intensity-based ShakeMaps and earthquake impact alerts established on estimated fatalities and damage will become a standard operating procedure for postearthquake communication in the near future.

In what follows, existing relevant natural hazard scales and alerts are first described in the context of the desired earthquake impact scale. Next, an overview of PAGER's loss estimation methodology is provided, covering both casualty and economic loss models. The proposed earthquake impact scale (EIS) is then described in the context of uncertain loss estimates. Finally, the utility and ramifications of the EIS are discussed with examples along with an indication of the expected relative frequency of occurrence of each alert level established on historical earthquakes and their associated losses.

Existing Natural Hazard Scales and Alerts

The need for systematic earthquake alerting protocols stems from two primary goals. First, timely response at the appropriate level requires an overall impact assessment and an objective description of its impact. Currently, no systematic way exists to rapidly qualify or quantify earthquake disasters other than difficult-to-make inferences, often inaccurate, from independent measures that include magnitude, depth, and location. Second, the development of the PAGER system, which now automatically computes population exposure and provides fatality and financial loss estimates for each earthquake, was hindered by the lack of the proper lexicon and communication tools for alerting users to the degree of such impacts. There was no simple standard for systematic comparison of past and current earthquake impacts, and thus it was difficult to indicate or ascertain what appropriate level of response would be necessary.

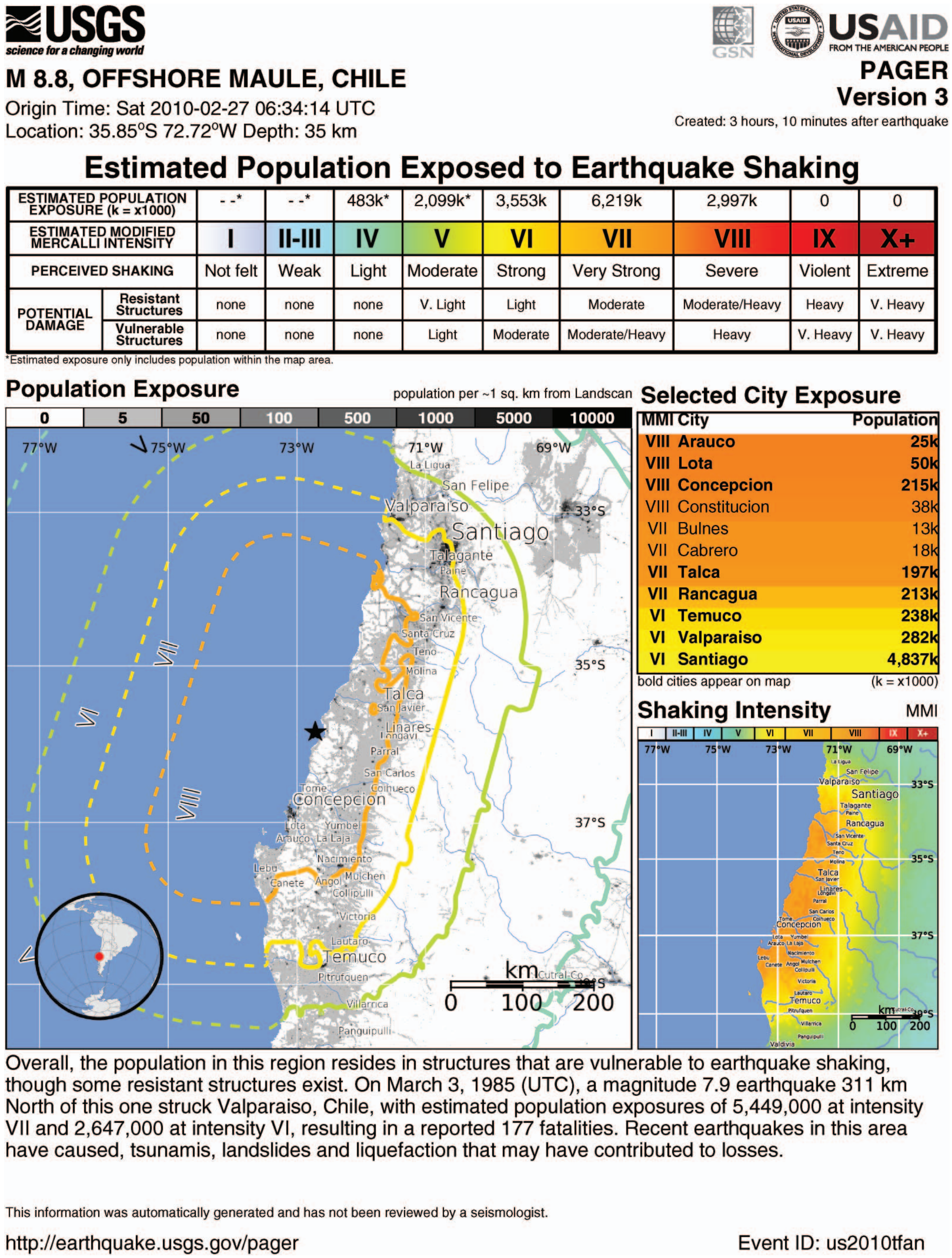

Fig. 1. (Color) Example of a PAGER "onePAGER" summary plot for the operational system of August, 2010, that provides population exposure but not loss estimates; the top intensity scale bar indicates the estimated population exposed to each intensity level; population density and contoured intensity level (lower left), selected cities with population and intensity level (upper right), and the color-coded ShakeMap intensity map (lower right)

Hazards Rather Than Impacts

Some insight is gained into the essential issues related to potential earthquake impact alerting by examination of recent improvements to existing scales for other natural hazards. Many existing hazard and societal impact scales exist, and several have become standards for alerting and for response protocols. An important limitation, however, is that although many existing scales are useful in quantifying the specific hazard, most do not address the real or potential human impact of the hazard. For example, the *Saffir-Simpson Scale* (wind speed scale from 1–5; National Weather Service 2009) has universal appeal to describe hurricane winds, but what counts for hurricane mobilization and response is the ability to assess potential impact of various wind speeds and the nature of the built environment at the actual point of landfall. Likewise, predicting the *Enhanced Fujita Scale* (NOAA 2009) level for tornado winds is useful for describing the potential for, or measuring, tornado wind speeds, yet whether a tornado hits or misses a populated area is what determines if a significant impact actually occurs. For both, hazard is divorced from impact and the impact is only assessed after postdisaster reconnaissance. The limited utility of other such hazard-based scales for describing impact is common across a range of natural hazards.

For earthquakes, currently, earth scientists commonly use two scales to measure the size of an earthquake or the severity of the shaking that it produced. These two scales are, respectively, magnitude (e.g., the Richter scale, modernized as energy or moment magnitude) and intensity [e.g., the Modified Mercalli scale (MMI; Richter 1958); or in Europe, the European Macroseismic Scale (EMS) Grünthal 1998]. Neither magnitude or intensity scales provide sufficient information to judge the overall impact of the earthquake. Although larger magnitude earthquakes have greater energy release and proximity to an earthquake source generally increases the earthquake-shaking intensity, impact depends highly on the exact nature of the shaking distribution, the exposure, and the overall vulnerability of a population (primarily, their building) to specific shaking levels.

An unintended and unfortunate byproduct of using hazard- rather than impact-based scales is the high degree of cognitive anchoring, i.e., tying the experience to the scale's event-specific value, rather than the actual impact that is experienced or witnessed in a significant disaster. For instance, with earthquakes, the general public tends to recall the magnitude of an event rather then the intensity experienced; since fewer people experience the higher intensities (in the simplest case, concentric areas of decreasing intensity cover larger and larger areas, exposing greater populations to lower and lower shaking levels), the many more people who experienced lower intensities anchor that experience against the event's magnitude. A common ramification (e.g., Celsi et al. 2005) is that people tend to underestimate personal risk because they "survived" the "big one" even though in reality they actually experienced only a moderate intensity at their location. More pertinent to this discussion, it is the authors' experience that earthquake decision-makers also have a tendency for magnitude anchoring, but with magnitude tied to impact rather than any felt experience. Most are concerned with large-magnitude events but are unfazed by moderate magnitude events. Historically, many very deadly events have occurred owing to midmagnitude 6 events (2003 Bam, Iran; M6.5; 23,000 dead), but dozens of events in this range occur each year without consequence. It is the goal of the PAGER system, combined with the EIS, to separate low and high impact events and to only alert for events with notable consequences.

One relatively new scale that crosses from hazard into impact is the National Oceanic and Atmospheric Administration's (NOAA) Northeast Snowfall Impact Scale (NESIS). NESIS, which is neither widely known nor employed, combines meteorological indices (snowfall amount) with exposed population to rank storms in one of five categories. The ranking provides an indication of a storm's potential impact on local and national transportation and the economy. Notably, the NESIS scale cannot reach higher levels without a large population exposure. Like NESIS, PAGER estimates and considers the number of people exposed to severe ground-shaking and the shaking intensity at affected cities (Wald et al. 2008a). Only when intense shaking overlaps significant vulnerable populations do disasters result. As shown later, accompanying PAGER maps of the epicentral region show the population distribution and estimated ground-shaking intensity.

Although the primary goal of PAGER is to rapidly deliver estimates of injuries, fatalities and the financial impact of an earthquake, a succinct method to portray the overall impact, and the confidence in this assessment does not exist. To that end, the essential information required is combined in the immediate postearthquake decision-making environment into color-coded alert levels accompanied by a simple but quantitative assessment of the uncertainty. Alert levels can be triggered either by the estimated number of fatalities or by the predicted financial losses, or both. In the United States, and perhaps in other countries where earthquakes only infrequently cause high numbers of casualties yet more often cause substantial financial impacts, the PAGER financial loss estimates comprise the most useful trigger for alerting purposes. For example, in 1994, the M6.7 Northridge, Calif., earthquake caused 33 fatalities and yet over $40B in losses. That earthquake casualties in the United States are rather rare despite an overall high earthquake hazard is in no small part attributable to earthquake engineering expertise and building code improvements. In the past 100 years, the United States has experienced 21 fatal earthquakes owing to shaking, but remarkably they caused only 264 deaths.

In contrast, examination of global earthquake-shaking-related fatality data since 1900 (Allen et al. 2009b; Marano et al. 2009) shows at least 1,032 fatal earthquakes. Approximately 74% of the total shaking-related deaths were in China, Iran, Pakistan, and Turkey and approximately 80% of the total were because of just 27 earthquakes that occurred in 14 countries: China, Pakistan, Iran, Peru, Turkey, Italy, Chile, Armenia, Guatemala, India, Tajikistan, Morocco, Nicaragua, and Nepal. China alone experienced 147 fatal earthquakes since the year 1900, which in total claimed 674,745 lives including the devastating 2008 Sichuan event that caused 69,195 shaking-related deaths. Ninety-four Iranian earthquakes have claimed 172,042 lives, whereas Turkey has experienced 85 fatal earthquakes that killed more than 89,800 people. In Indonesia, 72 fatal earthquakes have killed over 13,000 people; nearly 45% of the deaths were attributed to the Yogyakarta event of May 26, 2006, which caused 5,749 deaths. Similarly, Pakistan has experienced devastating earthquakes in recent times, including the 2005 Kashmir event, which killed more than 85,000 people. Japan and Taiwan have experienced 52 and 43 fatal earthquakes, causing 8,878 and 8,018 deaths, respectively. The unfortunate, regular occurrence of such fatal earthquakes points to the need for an alert mechanism that ties casualty-based criteria to an actionable response alerting mechanism.

Internationally, both an estimate of casualties and a measure of its uncertainty are vital pieces of information necessary for most responders to assess the situation. The dimensions of the reported or estimated fatalities often trigger and set in motion the appropriate level of response. This approach stems from an intuitive, informal experience-based protocol responders employ in their decision-making, that is, recalling the nature of the response to levels of casualties from past disasters. In addition, nonfatal casualties can to some degree be related to the number of fatalities, though in a very complex and highly variable way (e.g., Coburn and Spence 2002; Peek-Asa et al. 2003; So 2009), and injury data are much fewer and more uncertain than fatality data. In general, events with high fatalities require the high levels of response to rescue entrapped victims within a short time frame, avoid nonfatal injuries from becoming fatal, provide food and shelter for survivors, and to begin the long process of recovery and rebuilding.

For both domestic and international events, fatality-based and financial impact-based alerts will be provided by the PAGER system. Some situations of both fatality and loss scales will achieve similarly low or high levels. In some cases, financial losses will trigger a higher alert than the fatality estimates, and vice versa, as previously demonstrated by the Northridge earthquake. It will be in the interest of national and international aid, response, and media personnel to determine what protocols will be most useful and suitable and under what conditions or circumstances.

Cautions from Existing Alerts

One caution on the use of newfound alerting scales comes from recent efforts at international pandemic and domestic terrorism alerts. The World Health Organization (WHO) maintains and regularly updates a 6-point scale for pandemic alerts (WHO 2009).

WHO is in the process of rethinking the criteria for calling a disease pandemic; currently, only the distribution of the outbreak is considered. Following WHO's Level-5 pandemic alert for the 2009 H1N1 flu, concern arose that because its pandemic alert scale has no mechanism to reflect the fact that a pandemic might cause mild, moderate, or severe illness and trigger varying levels of societal disruption, WHO should consider impact and exposure. Impact is controlled not only by variations in the severity of the hazard but by the vulnerability of the population exposed.

For manmade hazards (in this case, terrorism), yet another cautionary tale comes from the U.S. Department of Homeland Security (DHS) terrorism alert levels or Homeland Security Advisory System (HSAS; DHS 2009). The HSAS, often referred to as the "terror alert level," has five color-coded alert levels consisting of green (low), blue (guarded), yellow (elevated), orange (high), and red (severe). Although intended to guide protective measures when specific information is received about terrorism, it has been permanently relegated to an elevated or a high level since 2003; HSAS has never been lowered to green or blue. Additionally, it has received consistently poor marks for overall usefulness. Remarkably, administration officials couldn't agree on what color was appropriate the day the HSAS was launched (Ridge and Bloom 2009). Clearly, the system failed for several reasons including: (1) not having a specific trigger threshold; and (2) lacking specificity in any associated actions the public should take. In July, 2009, the Obama administration commissioned a task force to examine the color-coded alerts and recommend changes to or abolition of the HSAS system.

Another relevant alert scale, in this case for a combined manmade and natural hazard, is the daily air quality index (AQI) for ozone and particle pollution that is used by the states for daily air quality reporting to the general public in accordance with the Clean Air Act (U.S. EPA 1999). Again, the AQI, mapped over the entire United States, fundamentally represents the hazard (potential poor air quality) rather than risk, but importantly it provides guidance on what actions specific sensitive populations should take in a particular area. Color-coded alerts are associated to text descriptions ranging from "good" to "very unhealthy" and "hazardous" and are triggered by specific formulas that consider ozone and particulate concentrations over specified time periods.

Caveats aside from these examples, a strong need clearly exists for a better postearthquake response-alerting lexicon. A beneficial alert scale should be both *specific* and *actionable*, neither of which was accomplished by the HSAS. In this study, "specific" means quantifiable triggering measures are defined for each alert level, and "actionable" implies alert levels can be tied to particular response activities. However, "specific" does not preclude uncertainty, because uncertainty must also be quantified for justifying the potential expense or risk of the associated actions that may be taken. Likewise, detailed actions do not need to be specified by the alert scale itself; they can be provided in a general sense or historical context. The alert level should allow for a wide variety of potential recipients to develop their own specific actions for groups potentially initiating large scale personnel activities, analogous to the FEMA alert-based activation levels described in this study and in Wald and Bausch (2009).

PAGER's Earthquake Loss Estimation Methodology

A comprehensive description of the PAGER loss-modeling approaches (Wald et al. 2008a; Jaiswal et al. 2009, 2010) and the data used to derive them (Allen et al. 2008; 2009a, b; Jaiswal and Wald 2008) is provided in detail elsewhere. However, some background on the nature of the data used and the models is important for context, particularly pertaining to issues of loss estimates, their associated uncertainties, and how both will be portrayed in an earthquake-impact scale.

Data and Uncertainties

Inherent uncertainties exist in casualty and economic loss data from disasters (e.g., Coburn and Spence 2002; So 2009). Although data collection and quality seem to have improved with time, no internationally standardized methods have been established for either damage or casualty data collection (Guha-Sapir and Below 2002). The resulting available databases reflect these limitations. The uncertainties associated with casualties and economic losses share many common sources, but they have unique problems also. Often, the loss catalogs lack references to the original source of data, and it is commonplace that the same numbers are quoted in different sources, suggesting that relayed information is more the norm. To complicate matters, both casualty and economic loss values can be construed in the context of political or economical considerations. For fatality data, common sources typically include the media, aid agencies, national governments, and the United Nations (UN), but postdisaster casualty data collection is, understandably, notoriously difficult. Although disaster mortality data are considered to be more robust than economic loss data, considerable uncertainties still exist (UNISDR 2009).

The quality of casualty data has two dominant, related limitations. First, in historical reports of earthquakes casualties, a remarkable inconsistency is shown in defining, agreeing upon, and using standardized definitions of nonfatal injuries (e.g., So 2009). Therefore, whereas fatalities are somewhat more unambiguous in their definitions and applications, the terms "casualties" and "injuries" are often used very informally. This contributes significantly to the second major limitation—considerably fewer reliable casualty data are available than fatality data. Because such data form the basis for any empirical model, this study focuses primarily on empirically estimating earthquake fatalities and not lesser casualties; ongoing efforts and improved data may improve prospects of computing nonfatal injuries.

The data used in the derivation and calibration of the PAGER empirical-loss models for fatality and economic losses come from a comprehensive set of recently-developed archives, covering both hazards and losses. Our data begin with PAGER-CAT (Allen et al. 2009b), which aggregates multiple earthquake catalogs to provide accurate earthquake source information (e.g., origin, hypocenter, and magnitude) necessary to compute reliable ShakeMaps (e.g., Wald et al. 2008c). PAGER-CAT also contains available loss information (i.e., the number of dead and injured, and economic impact) comprised by aggregating multiple earthquake and disaster catalogs, including EM-DAT, USGS's Preliminary Determination of Epicenters, Utsu's catalog, and published reports (see Allen et al. 2009b; EM-DAT 2009; Utsu 2002).

Next, PAGER-CAT is used to generate an atlas of ShakeMaps (Allen et al. 2009a) that estimates the shaking distribution for more than 5,600 earthquakes (1973–2007) that had strong shaking and exposed populations. Within the atlas, almost 450 of the maps are constrained to varying degrees by instrumental ground motions, macroseismic intensity data, internet-based intensity observations, and published earthquake rupture models. Finally, PAGER methodologies are used to compute population exposures to discrete levels of shaking intensity obtained by joining atlas ShakeMaps with the LandScan global population database.

A systematically derived set of ShakeMaps combined with data on population exposure per intensity, compared with historical PAGER-CAT earthquake loss data, provides the basis for calibrating loss methodologies. The resulting database of population exposed per intensity level for 5,600 events and the resulting losses is called EXPO-CAT (Allen et al. 2009a) and forms the basis for all PAGER empirically-based loss-model calibrations.

A substantial recent addition to PAGER-CAT is a catalog of detailed earthquake-specific economic losses from 1980–2008 provided by Munich Reinsurance's NatCat Service in mid-2009 (Munich Re 2009), which includes events with a minimum loss of $100,000. Economic loss values are considered to be the damage in dollars at the time of the earthquake and usually include only the direct damage. Normally, economic loss in disasters is divided into (1) direct losses from destroyed or damaged assets; and (2) indirect losses pertaining to business loss and disruption, recovery, and broader economic flows; but in practice it is often impossible to know whether reported loss estimates include the latter (UNISDR 2009).

As the input data are uncertain, so are the output model results. Uncertainties in the data that are used to constrain the forward models, in addition to simplifications and assumptions in the loss estimation modeling approaches, limit the overall capabilities by the confidence in near-real-time predictions. Nonetheless, with a generalized way to portray uncertainties, and an understanding that the wide ranges of potential losses would result in radically different levels of response, our estimates are both acceptable and actionable.

Fatality Loss Estimation

For each country having a robust, fatal earthquake history, the total shaking-related deaths for each earthquake is used to develop a model of estimated deaths, which is derived by multiplying the population exposure at each shaking-intensity level (from EXPO-CAT) with a derived fatality rate to minimize the residual error between observed and estimated fatalities. The fatality rate (ν), which is a function of shaking intensity (S), can be parameterized by a two-parameter lognormal distribution function as follows:

$$\nu(S) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{S}{\theta}\right)\right] \tag{1}$$

where Φ = standard normal cumulative distribution function; S_j = discrete value of shaking intensity expressed in decimal values with 0.5 increments; and θ and β = parameters of the distribution. Let $P_i(S_j)$ denote an estimated population exposed to shaking intensity S_j for an event i. Then the expected number of fatalities E_i can be denoted as

$$E_i \approx \sum_j \nu_i(S_j).P_i(S_j) \tag{2}$$

The fatality rate depends on the two free parameters of the cumulative distribution function of lognormal distribution, θ and β. For each country or a geographic location, if there are N historical fatal earthquakes, then each event-specific fatality number is used to determine the fatality rate by reconstructing the ShakeMap for each earthquake and estimating population exposure at each interval of shaking intensity. Suppose that O_i is the number of recorded deaths for an earthquake i, then the fatality rate can be determined in such a way that the residual error (that is, the error estimate between estimated and recorded deaths) is minimized. Jaiswal et al. (2009) provide details on the norm used and the minimization approach.

To estimate the empirical fatality rate for countries with few or no fatality data, Jaiswal et al. (2009) proposed aggregation of fatal events from like-countries at a regional level through a scheme that focuses on likely indicators of comparable country vulnerability. By using this model, PAGER can estimate total event-level fatalities in future earthquakes within an average of $1/2$ to 1 order of magnitude with higher accuracy for more fatal events. The error estimated in hindcasting the total shaking deaths by using the empirical model already incorporates the total variability that comes from the uncertainty in shaking hazard for each earthquake, the uncertainty in the population exposure, and also possible errors in the number of recorded deaths in the catalog for these events. As described subsequently, the uncertainties can be used in gauging confidence in losses and associated alert levels.

An example of a country-specific model (Italy), is shown in Fig. 2. For each event, the observed and estimated values are compared and the solid green line indicates perfect agreement. The red lines indicate an order of magnitude error in the event comparison and zero values are plotted along the appropriate axis. Below these graphs are the corresponding fatality and economic loss functions of intensity. Similar analyses for other regions and countries indicate that fatality loss rates vary by more than three orders of magnitude from the lowest in California to the highest for Pakistan (see Jaiswal et al. 2009).

Financial Loss Estimation

The empirical economic loss-modeling approach is analogous to that for computing earthquake fatalities described previously and is detailed by Jaiswal et al. (2010). However, in this study, the shaking-intensity dependent loss ratio is defined as the total economic loss normalized by the total economic exposure [expressed by total gross domestic product (GDP) of the region] at the time of the earthquake. The loss ratio is parameterized by using a country-specific, two-parameter, lognormal cumulative distribution function, which, when multiplied by the economic exposure associated with each shaking-intensity level, provides an estimate of the total expected economic loss.

As with the fatality loss model, the shaking intensity and population exposure for past earthquakes (1980–2007) were provided through the EXPO-CAT database. In addition, the United Nations statistical database was referred to for determining the country-level per-capita GDP estimates since 1980, and the combined PAGER-CAT/Munich NatCat earthquake-specific economic loss data were used for historical earthquakes listed in EXPO-CAT. For the United States, three subcountry regions are used to partially account for differences in construction practices in California—the western United States (not including California), and the central and eastern United States.

The approximate regional economic exposure at each intensity level is obtained by multiplying the per-capita GDP of the region by the total population exposed at that shaking-intensity level. Estimated losses are corrected to the year of the earthquake by using country-specific GDP values. As with PAGER's fatality loss model, the two parameters for the economic loss ratio function were determined by minimizing residual error in hindcasting the country or region-specific historical economic losses.

PAGER's empirical economic loss-modeling approach appears to be robust for countries in which sufficient (three or more) damaging earthquakes have occurred since 1980 (Fig. 2). As in the empirical casualty model, grouping of countries is necessary for those with too few loss data (Jaiswal et al. 2009), but in this study relative per-capita GDP is the driving consideration rather than relative building vulnerability. That is, for dollar losses, collapse of the same structure will have varying costs that can be tied to the overall GDP of the country in which the damage occurred. More details of the financial loss calculations can be found in Jaiswal et al. (2010).

In light of the arduous requirements associated with acquiring, updating, and quality-assuring large and complex worldwide building, vulnerability, and occupancy data sets necessary for

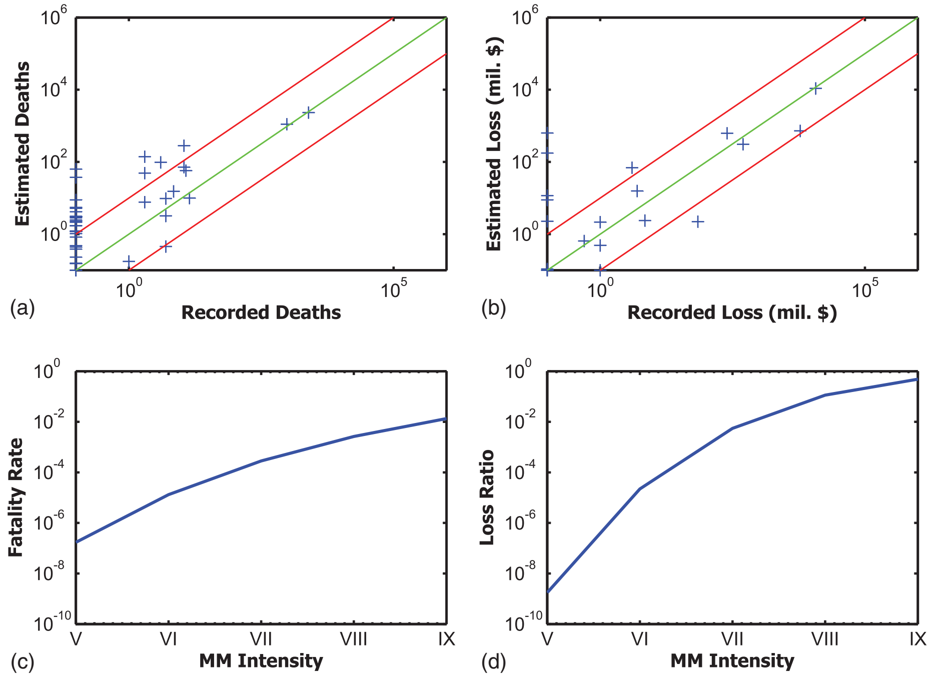

Fig. 2. (Color) Models for Italy: (a) Fatality (Jaiswal et al. 2009); (b) financial loss (Jaiswal et al. 2010); (c) the fatality; and (d) economic loss rates as a function of Modified Mercalli (MM) intensity

engineering-based loss estimation models on a global scale and the large uncertainties associated with such data sets, the empirical loss model is quite enticing. Currently, this empirical model, along with other engineering-based loss models, are used within the PAGER system for both rapid fatality and economic loss estimation, yet given these approximate global inventory data sets, the empirical model is producing the most promising results. The proposed empirical model will also provide the Global Earthquake Model (GEM; www.globalquakemodel.org) project with preliminary economic loss estimates for global applications.

Because the reported economic loss data used for calibration are uncertain (e.g., UNISDR 2009; EM-DAT 2009), financial loss estimates are also fraught with uncertainty. Hence, as for fatalities, useful but approximate loss estimates are obtained and thus logarithmic ranges in financial loss estimates are also appropriate. In addition, the probabilities of being in the primary and adjacent alert levels with the same approach described subsequently for the fatality-uncertainty calculations can be determined.

Earthquake Impact Scale

Armed with the capacity to estimate economic and fatality estimates in near real time, a method is proposed to portray this sensitive but potentially critical information. The method is described and illustrated for recent earthquakes both domestically and internationally.

Fatality-Based Alert Thresholds and Uncertainties

Internationally, in the immediate aftermath of an earthquake, the impact is first and primarily described in terms of fatalities. This fundamental measure of impact is retained, not because responding to fatalities is relevant, but because this quantitative measure is indicative of other critical impact measures demanding response, including nonfatal injuries, homelessness, damage, disruption, and overall economic impact. By setting fatality levels within logarithm-based domains (< 100, $100 < 1{,}000$, and $\geq 1{,}000$ fatalities) alert levels can be set that amount effectively to local, regional, national, and international response mobilization, respectively. These thresholds are not based on any fundamental agreement or consensus, but rather are meant to be consistent with experience at the USGS National Earthquake Information Center with views expressed by numerous disaster aid agency professionals and from historical earthquake experience.

Critically, the likelihood along with the expected range of fatalities (the range that contains the median estimate) is provided. In general, the median instead of the mean is often used to designate the central value of a lognormal random variable which associates with 50% of the total occurrence probability. PAGER uses a lognormal distribution to quantify uncertainties in its loss estimates. Given this distribution, the probability P of the actual deaths (d) being in a particular fatality range a to b is computed [Eq. (1)] by using the cumulative distribution function Φ where e is the estimated deaths and ξ is the standard deviation of normally-distributed log-residual error (logarithmic ratio of estimated death to recorded deaths)

$$P(a < d \leq b) = \Phi\left\lfloor\frac{\log(b) - \log(e)}{\xi}\right\rfloor - \Phi\left\lfloor\frac{\log(a) - \log(e)}{\xi}\right\rfloor \quad (3)$$

For alert-level purposes, a to b = logarithm-based domains that constitute the alert levels, and thus the probabilities for each alert level naturally constitute the likelihood that the actual losses are outside the alert level associated with the median loss estimate (Figs. 3 and 4). The histogram above each alert scale bar allows users to gauge the likelihood that the alert is in other loss (alert) ranges computed by varying ranges a and b. The summary figure shows population density and contoured intensity level (lower left), total population exposed per color-coded intensity level (middle), selected cities with population and intensity level (lower right), vulnerable structures and relevant historical earthquakes (middle right), and the color-coded impact scale indicated the alert level (top; expanded in Fig. 4). A link to tsunami information (top, bold red) can be added manually to the "onePAGER" if necessary.

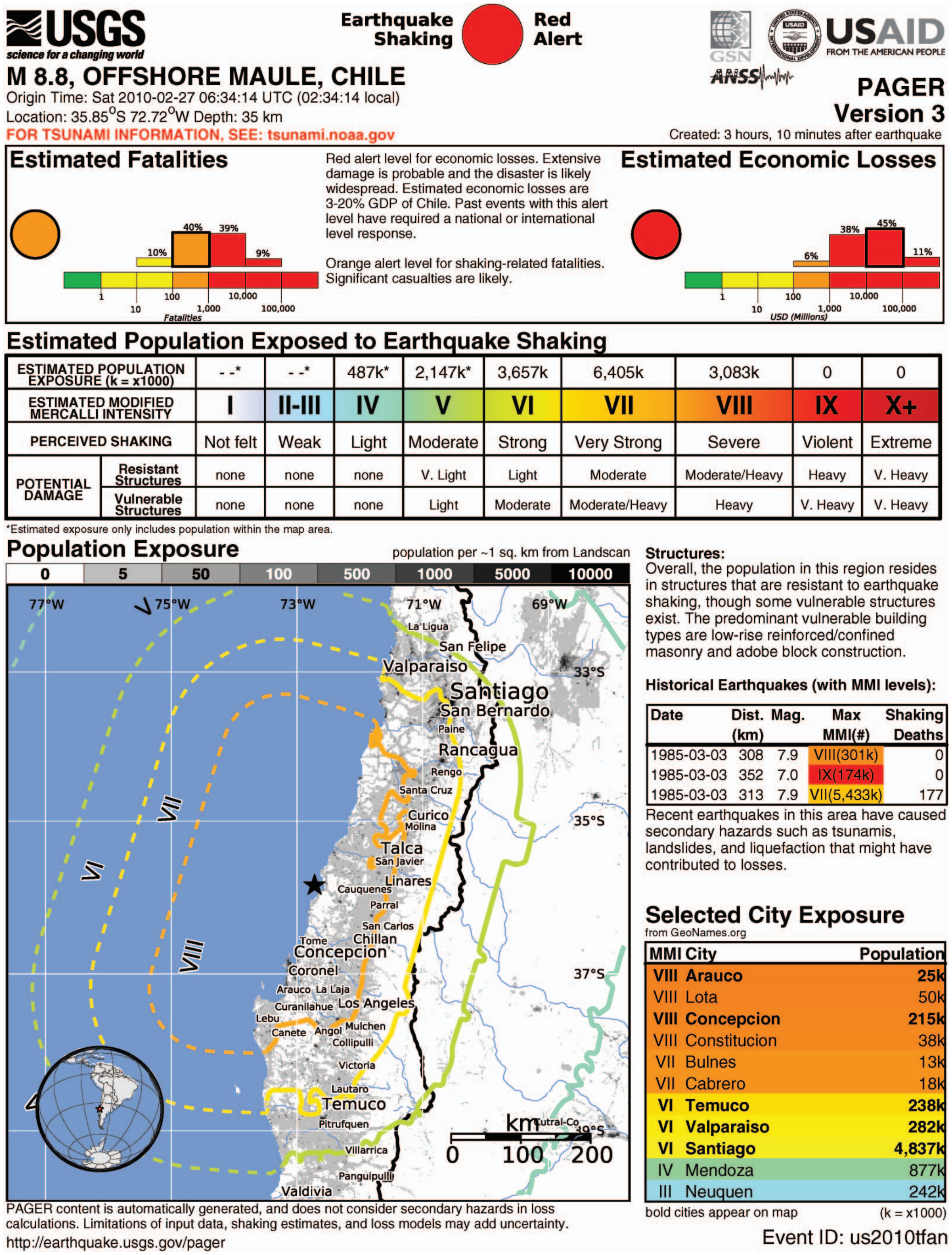

Fig. 3. (Color) Example red alert event PAGER "onePAGER" summary figure for Maule, Chile

For more details, see Jaiswal et al. (2009). In Fig. 4, the alert level is based on the median loss estimate; the uncertainty in the alert level can be gauged by the histogram and depicts the likelihood that adjacent alert levels (or loss and fatality ranges) occur. Accompanying text clarifies the nature of the alert on the basis of experience from past earthquakes.

The likelihood of alerting at an inappropriate level is greatest in the middle range of estimated losses: On the lower end of the median fatality estimates (green alert), only higher fatalities could lead to different response efforts; on the highest end (red alert), lower estimates are possible but it is unlikely that lower response efforts are requisite. In the middle range, inherent uncertainties can result in either over- or underprediction of potential response levels (orange alert). For this reason, users should be cognizant of the potential for revised alerts as further data and information become available.

The PAGER system has three parallel fatality estimate models (empirical, semiempirical, and analytical) depending on the regional data available (e.g., Porter et al. 2008; Wald et al. 2008a). For the empirical model described in this paper and currently employed for alerting, uncertainties are determined by using the model for each country to hindcast losses for past events and examining the spread of loss estimates compared with the observations. Though the empirical approach provides stable results in terms of losses, it does not allow for detailed examination of the sources of the errors. As such, reducing uncertainties will either require substantially better data (not likely) or continued efforts on the more physics-based semiempirical and analytical approaches

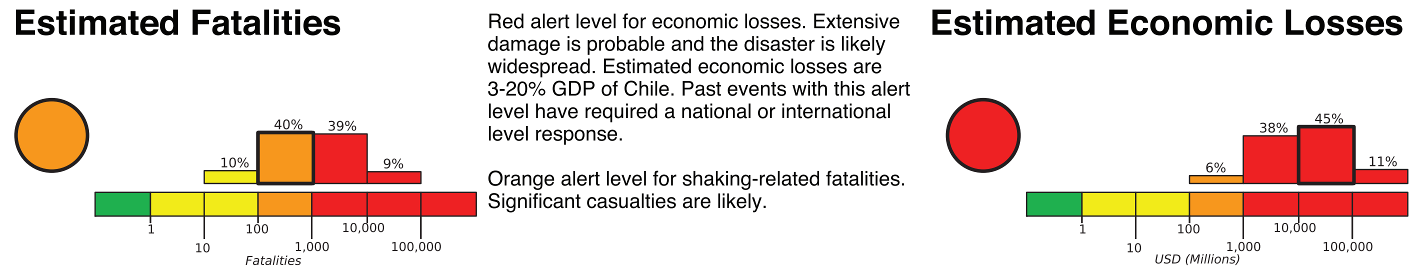

Fig. 4. (Color) Example zoom-in image of the PAGER fatality-based and financial alerts for the M8.8 Chile event of 2010 shown in Fig. 3

Table 1. Proposed Earthquake Impact Scale (EIS)

Alert level and color	Estimated fatalities	Number of global alerts per year (U.S.)	Estimated losses ($U.S.)	Number of global alerts per year (U.S.)
Red	1,000+	1.5 (0.01)	$1 billion+	1.1 (0.1)
Orange	100–999	1.5 (0.01)	$100 million–$1 billion	2.4 (0.24)
Yellow	1–99	15 (0.3)	$1 million–$100 million	13.4 (1.0)
Green	< 1	~470 (7)	< $1 million	53 (4.0)

Note: The number of each alert per year is established on a 29-year period (MunichRe NatCat Service, 1980–2008). Under the proposed EIS, during this time period, there would have been 116 green, 30 yellow, 7 orange, and 3 red domestic economically-based alerts. Green alerts rate accounts only for events with reported damage; many more will actually be reported because they are generated when ANSS or NEIC produces a ShakeMap, which is triggered at varying magnitude triggers (~M3.5 domestically; M5.5 globally). Users can configure alerts to be sent for yellow and higher to avoid nondamaging events. Domestically, an average of ten times more loss-based red alerts are issued as fatality-based red alerts, whereas globally, more fatality-based red alerts are issued than loss-based alerts. See Figs. 7 and 8 for maps of the distribution of alerts domestically (economic-loss-based) and globally (fatality-loss-based)

that allow for investigation of the relative roles of epistemic (earthquake source, shaking estimation, vulnerability functions) and aleatory (loss variability) uncertainties.

As loss estimates are refined to be a combination of their appropriately-weighted median values, the alert level uncertainties will also be combined. The combined loss models approach is anticipated to reduce some of the uncertainties associated with the fatality estimates, but the alert scale thresholds will remain the same and can be used independent of the loss estimation approach.

Economic Loss-Based Alert Thresholds and Uncertainties

In the United States, earthquake response management tends to be triggered by the observed or expected extent of damage to communities and infrastructure. Initially, on the local level, emergency response personnel and professionals act independently on prescripted protocols to actual emergencies. In the case of earthquake disasters, Presidential Disaster Declarations are triggered by estimated overall economic losses provided by the Federal Emergency Management Agency (FEMA) by using their HAZUS-MH (FEMA 2006) analysis software. However, FEMA, along with other response agencies and organizations, is now considering moving beyond magnitude and location-based triggers alone to automatic response activation based on PAGER's near-real-time estimates of intensity and population exposure and damage.

FEMA needs to make rapid decisions on what activation levels are implemented for the National and Region Response Coordination Centers (NRCC and RRCC). Significant, forward-looking, response planning following the Post-Katrina Emergency Reform Act of 2006 (PKEMRA) entails developing and activating prescripted mission assignments and specific earthquake-response actions depending on the initial activation level. FEMA has three response activation levels: Type I (catastrophic impacts), Type II (significant impacts), and Type III (considerable damage) for rapidly activating resources. FEMA territories consist of 10 Regions and 3 Divisions (east, central, and west). Type I initiates response from resources in the two closest divisions; Type II activates response of all resources in the respective division; and Type III triggers resources in the respective region. Activation levels need to be appropriate for different geographic regions because overall earthquake vulnerabilities and response capabilities vary from one region to another. FEMA's response activities should also include predetermined executions to address the first several hours of a major earthquake to expedite assistance.

Recommended alert levels were recently developed by using loss estimates by the PAGER system along with direct dollar-loss thresholds consistent with FEMA's activation levels (Jaiswal et al. 2010). Analysis of recent and past earthquakes over the past four decades indicates that alert levels set against overall financial impacts of those events may provide relatively robust criteria for setting the FEMA activation levels. By using the EXPO-CAT database in the same manner as with the global fatality model and comparing damage data with actual or estimated damage and activation levels implied or implemented for these events, yellow, orange, and red thresholds were assigned that are triggered by estimated economic losses reaching $1M, $100M, and $1B, respectively (Table 1).

In the central and eastern United States where actual loss data from recent earthquakes are limited, small, recent events have been supplemented with ShakeMap scenarios, PAGER exposure estimates, and HAZUS loss estimates to determine the appropriate activation levels. As shown in Table 1, PAGER yellow, orange, and red alerts correspond to FEMA's Type III, II, and I alerts, respectively.

Earthquake Impact Scale Examples

Fig. 3 provides an example of the PAGER "onePAGER" summary and EIS for the M8.8 Chile earthquake of February 27, 2010. Fig. 4 is an enlargement of the EIS on Fig. 3, indicating both the fatality-based (left) and economic-based (right) alerts and their likelihoods. The wording is alert-level dependent (see Figs. 3–6) and is meant to provide a rough gauge of the losses, the likely geographic extent of the impact, and the typical level of response, all based on the historical event database (Allen et al. 2009b). The selected alert level contains the median loss estimate and therefore has the highest likelihood; the uncertainty in the alert level can be gauged by the histogram, depicting the probability that actual losses could be in adjacent alert levels (or loss and fatality ranges). The percentages in the histogram may not sum to 100% because percentages lower than 4% are omitted. Figs. 5 and 6 show population density and contoured intensity level (lower left), total population exposed per color-coded intensity level (middle), selected cities with population and intensity level (lower right), vulnerable structures and relevant historical earthquakes (middle right), and the color-coded impact scale indicated the alert level (top).

News reports for the February 27, 2010, Chile earthquake estimated 521 fatalities and financial losses of approximately $30 billion (Associated Press 2010). PAGER estimates with a global ShakeMap (GSM; Wald et al. 2008a) loosely constrained by reported intensities, resulted in a red earthquake-shaking summary alert on the basis of an orange alert level for fatalities and a red alert level for economic losses and is illustrated in Figs. 3 and 4. The PAGER loss results at the time of the event were not distributed because they were in testing phase, but the results are encouraging.

Fig. 5 provides a second example, that of the devastating M7.9, May 12, 2008, Sichuan, China, event. Fatalities reported for this event reached nearly 88,000 (including those reported as missing), and the economic impact was reported to exceed $86 billion

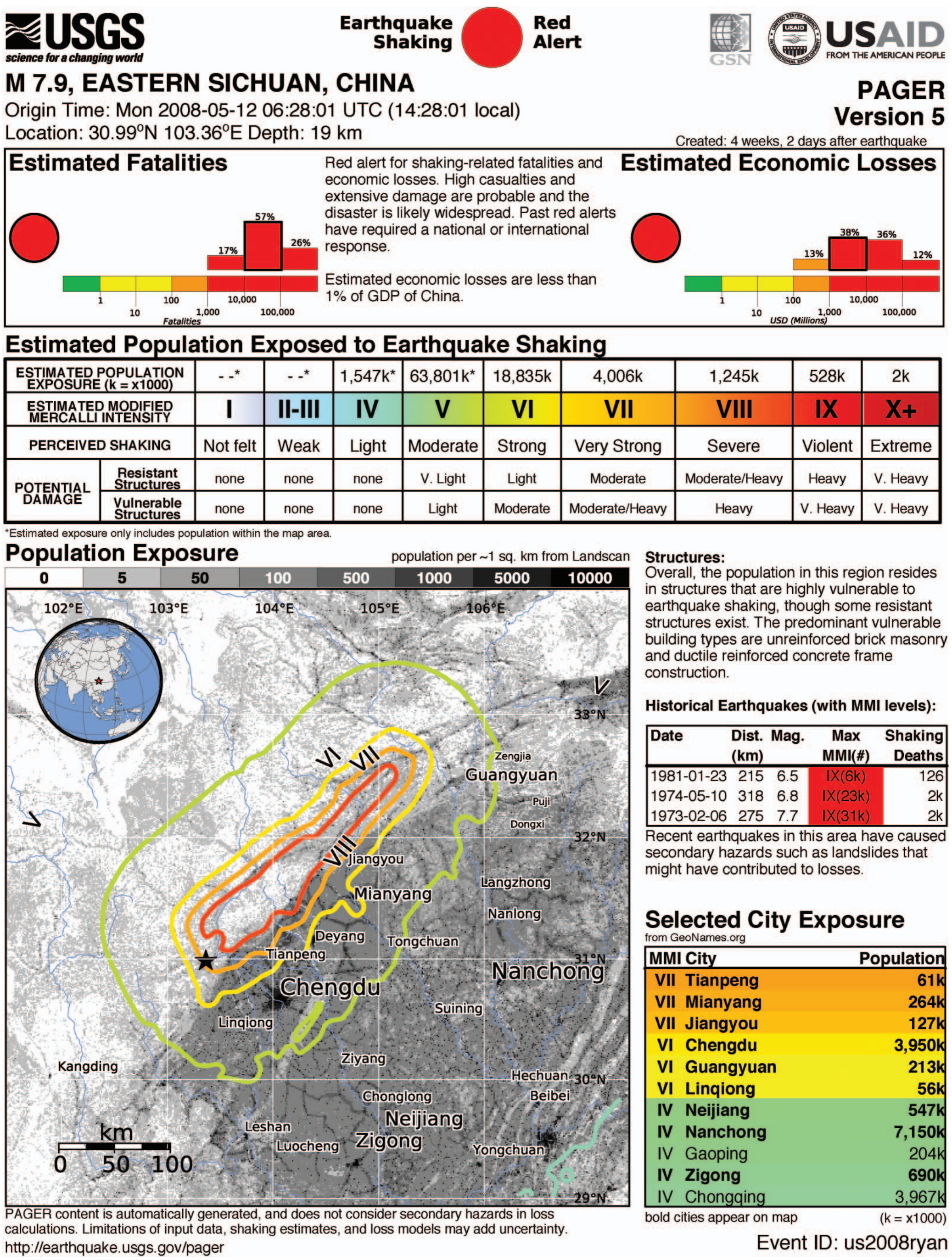

Fig. 5. (Color) Example red alert event PAGER "onePAGER" summary figure for Sichuan, China

(USGS 2008). Estimated loss results shown in Fig. 5 were limited to fatality estimates at the time of the event; the economic model was developed later in 2009 but is included in the figure for illustrative purposes.

An example of a lower-impact earthquake is provided in Fig. 6 for a moderate-sized, M6.0 domestic earthquake that occurred in Nevada on February 21, 2008. This event reached a yellow alert level for economic losses and a green alert for fatalities. Direct economic losses were reported to be approximately $9 million and with no fatalities and consistent with estimated losses. Although this event does not indicate the chance of fatalities, estimating fatalities at lower fatality levels is notoriously difficult (see Jaiswal et al. 2009) because a single collapse or incident can result in fatalities. Hence, over the course of several similar events, some fatalities are likely to occur.

For each event, the summary EIS level, shown atop the onePAGER figure, is taken as the greater of the fatality and economic models. Domestically, economic losses tend to result in higher alert levels than fatality alert levels (see Table 1); in the most vulnerable countries, China, for example, fatality alerts tend to be higher than economic loss thresholds; in Indonesia, a country with moderate-to-high vulnerability (Jaiswal et al. 2009), economic and fatality-based alerts are usually comparable.

Discussion

It is critical for users to be aware of the likely frequency of potential alerts when signing up for notifications. Too infrequent alerts result

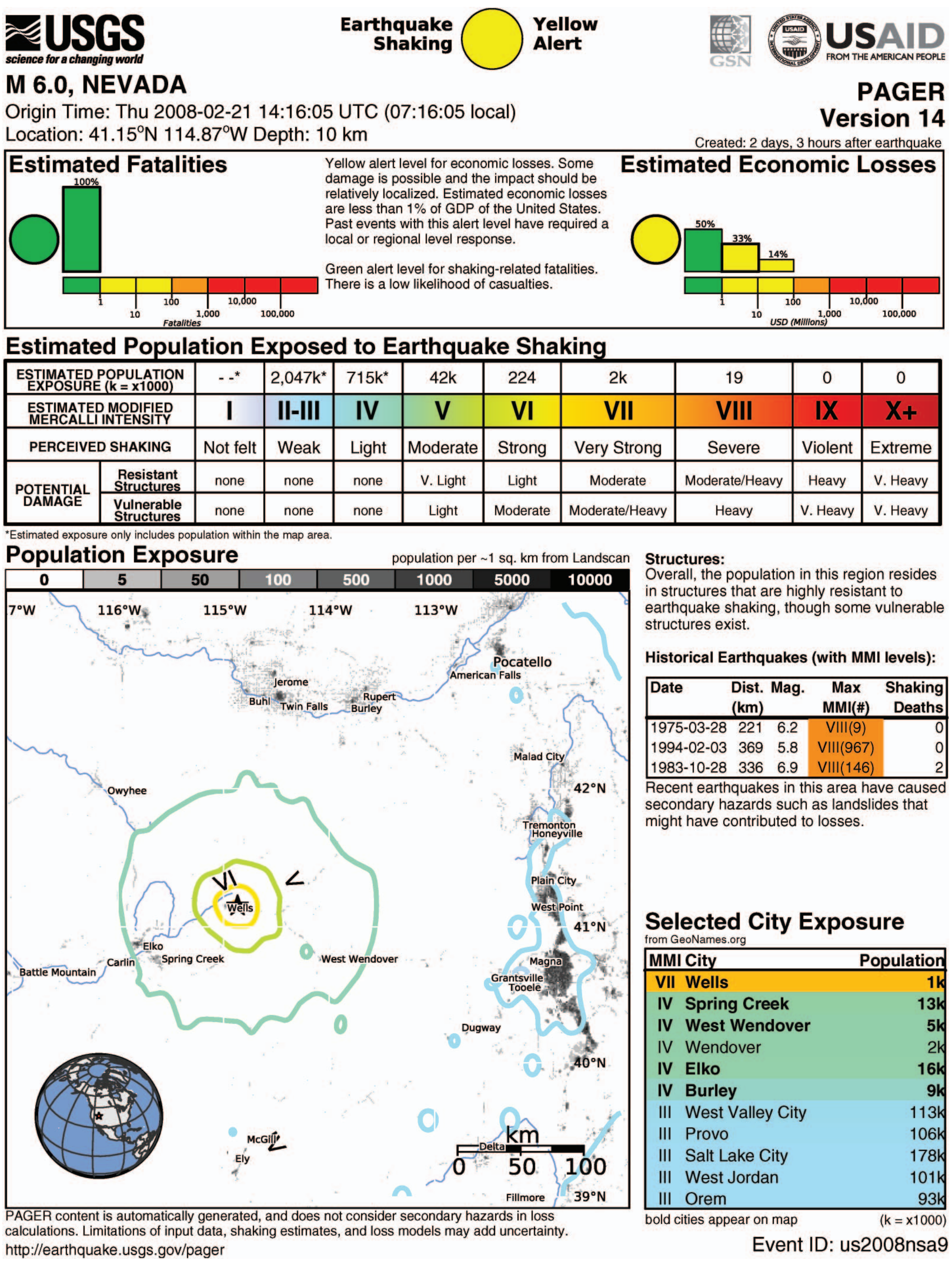

Fig. 6. (Color) Example yellow alert event PAGER "onePAGER" summary figure for Nevada

in the lack of familiarity with the information content; conversely, too frequent alerts tend to be more easily ignored. How often might each alert threshold be reached? From 1970 to mid-2008, the years that comprise PAGER-CAT catalog (Allen et al. 2009b) and given the fatality-based alerting protocol suggested in this paper for global earthquakes, there would have been approximately 17,792 green, 568 yellow, 52 orange, and 49 red alerts. Red alerts were comprised of 36 events with greater than 1,000 fatalities and 13 events with greater than 10,000. Over that time period there were approximately 15 yellow, 1–2 orange, and 1–2 red alerts per year (Table 1).

Fig. 7 is a global map of the spatial distribution of events and the fatality-based alerts that would have been produced over the past 35 years. The spatial distribution reflects contributions from relative hazard, population exposure, and building vulnerability. Domestically, the fatality-based alerting levels are, as expected, much less frequent. Hence, domestic alerting based on economic impact is more suitable for response. The legend in Fig. 7 provides the fatality threshold for color-coded alert level. The past 38 years would have seen approximately 17,792 green (not shown in figure), 568 yellow, 52 orange, and 49 red alerts (approximately 15 yellow, 1–2 orange, and 1–2 red alerts per year).

For economically-based alerts, Fig. 8 depicts the spatial distribution of domestic events and their associated alert levels that would have been reached since 1980, the date from which our economic loss data are of relatively consistent quality. Given the limited total number of data, this does not necessarily reflect future losses but the pattern is reflective of the hazards in general. Since 1980, the reported losses would have been associated with approximately 116 green, 30 yellow, 7 orange, and 3 red alerts or approximately 1 yellow per year; 1 orange per 4 years, and 1 red alert per 10 years. The legend in Fig. 8 provides the trigger threshold in millions of dollars for the color-coded alert level. Green alerts are under-representative of total numbers because only events that have $100,000 or more in losses were considered; no lower limit to is given for green alerts, so effectively any earthquake without losses could be considered a green alert level

This discussion has focused on alerts established on the estimates of fatalities associated with shaking damage, primarily building collapse. Marano et al. (2009) separate out the main secondary causes of fatalities for earthquakes over approximately the past 40 years and find that although shaking-related deaths dominate overall, specific events can have a significant proportion of fatalities caused by secondary effects (specifically, landslide, fire, and tsunami). Because these tend to cluster geospatially, event-specific qualitative messages are added that are associated with our PAGER summaries to alert users to the potential for such secondary impacts. The loss of life caused by secondary effects is not yet included in the PAGER loss estimation models quantitatively. However, the qualitative statements PAGER automatically provides have proven useful for several important cases including the 2008 Sichuan, China, earthquake in which nearly 1/4 of the fatalities were attributed to landslides. In the future, well-constrained, probabilistic estimates of losses owing to secondary causes can be readily included in this framework for the determination of the appropriate alert levels.

The EIS is meant to be applicable independent of the source of loss information. Currently, the PAGER empirical loss estimates are employed for events worldwide because comprehensive building, vulnerability, demographic, and fatality-rate data needed for more comprehensive approaches are still being improved (Jaiswal and Wald 2008). As the PAGER data and models evolve and confidence in their application is gained, the semianalytical or analytically-derived casualty and economic loss values can simply replace or be weighted against the empirical model estimates used in this study. Any model is required to provide the likelihood of losses in the ranges required by the proposed scale, but beyond that, the EIS is otherwise generally applicable. In fact, even if the loss values were observed rather than estimated, this scale is still applicable; under such conditions uncertainty ranges are still pertinent and should depict the inherent uncertainties associated with the observed loss estimates. In this sense, the EIS can be beneficial not only for triggering alerts but also for quantitative comparative analyses.

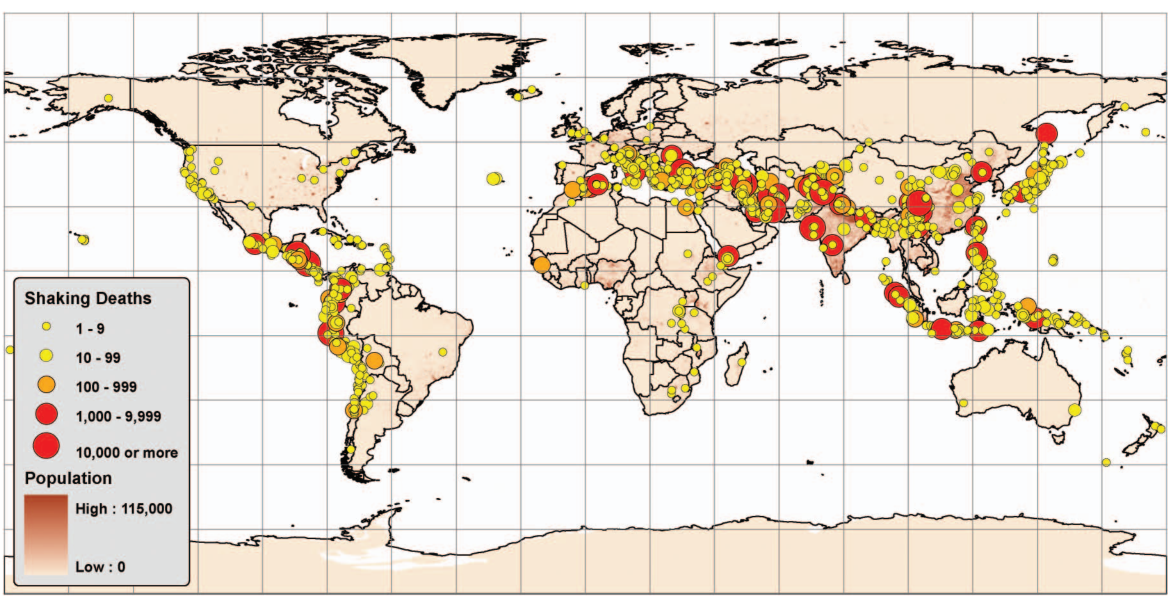

Fig. 7. (Color) Map of fatality-based alert levels that would be triggered given the observed fatalities for events in the PAGER-CAT v2008_06.1 (Allen et al. 2009a) during 1970 through mid-2008

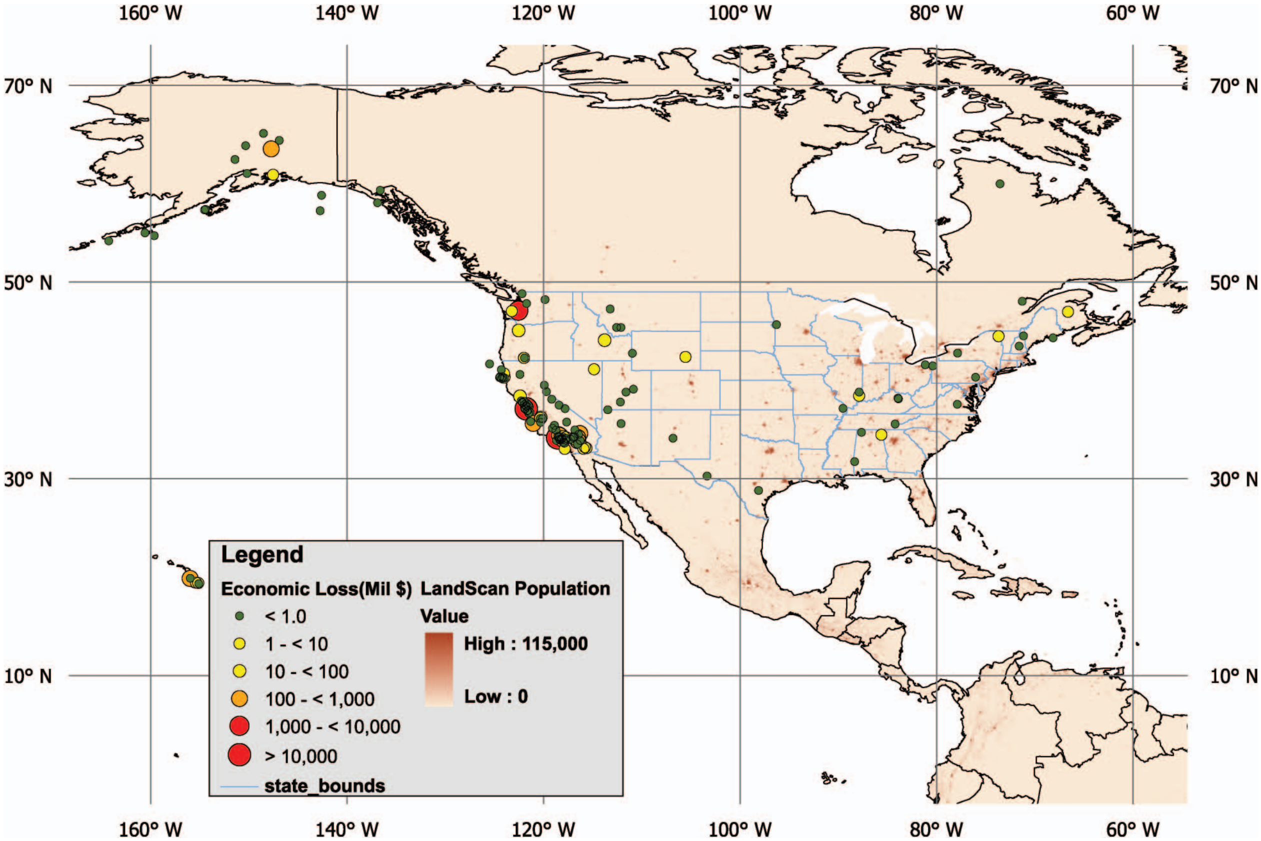

Fig. 8. (Color) Map of economic-based alert levels that would be triggered given the observed or estimated damage for events in the combined PAGER-CAT/Munich NatCat

Estimating the spatial distribution of damage and casualties would be the next level of benefit from a rapid alerting system. If feasible, such information could warrant more specific actions aimed at likely areas of impact concentrations, but because the loss models are statistically-based, there is always a trade-off between increased spatial resolution and increased uncertainty for specific impacts at more refined locations. Some confidence has been gained in the process of producing PAGER loss results internally over the past two years. Notably, very few occurrences were seen in which the alert level changed in the immediate aftermath of earthquakes that initially resulted in orange and red alerts. At lower alert levels, revisions to earthquake source information (magnitude and depth, in particular) can lead to revisions in the alert level, particularly from green to yellow and from yellow to orange. Experience to date leads to the expectation that alert levels will rarely change if initially green or red, but will change nearly 25% of the time if the initial level is yellow (to green or orange) or orange (to yellow or red). This limited number of re-alerts is encouraging, and in fact, such statistics overemphasize the difference because when initial alerts changed, they were just as likely to be in the adjacent alert levels to start, an observation easy to note from the users' perspective.

As an automated, near-real-time system, PAGER updates will be provided in the first several hours of any significant earthquake. It is necessary for users to be aware of these changes and to recognize that initial results may depend heavily on uncertain earthquake source information produced by the NEIC earthquake response personnel and systems. In addition, users should check the USGS PAGER web pages to assure that they are considering the latest rendition of the PAGER results and maps (which are version number controlled) in the course of any decision-making or response-planning.

Conclusion

An Earthquake Impact Scale (EIS) is proposed on the basis of two separate criteria, fatalities and economic loss. The proposed earthquake impact scale components are (1) log divisions of financial loss and fatalities; (2) calibration against past earthquake loss data; (3) a simplified depiction of alert-level uncertainty; (4) intuitive green, yellow, orange, and red color assignments; and (5) a summary alert color or level to pick if the financial and fatality calculations yield different levels. Although developed under the auspices of the USGS PAGER project, EIS does not depend on any specific approach to produce estimates of fatalities and economic losses. However, any model should quantify uncertainties for direct adoption of the EIS.

For domestic (U.S.) events, the estimated direct cost of damage tends to drive the overall response because fatalities have been relatively low, at least historically, for events that have nonetheless had very significant financial losses. Hence, although emergency response is critical, at the Federal level, the overall response needs are more typically tied to sheltering and housing, insurance claims, community and business continuity, and overall recovery. Internationally, at least in countries with highly vulnerable building stock, estimated fatalities drive the alert level.

PAGER-based intensity/exposure calculations, and therefore the fatality and financial loss estimate alerting, can be computed within a few tens of minutes of an earthquake in the United States (often much faster) and thus provide the initial basis for response management. Indeed, this impact scale was in part motivated by evolving sophistication at FEMA in prescribing postdisaster protocols and understanding the hazards and impact levels that would trigger each response level. Other domestic agencies and organizations will also benefit from these alerting protocols.

Internationally, alert levels were set on the basis of PAGER's median estimate of fatalities. By using a log scale of fatalities and choosing subjective thresholds, alert levels are set associated with yellow (< 100 fatalities), orange ($100 \leq$ and $< 1{,}000$ fatalities), and red ($\geq 1{,}000$ fatalities) alerts to be at ranges of fatalities—and commensurate societal impacts—appropriate for what is deemed to be regional, countrywide, and international level responses, respectively. The median fatality estimate is not indicated to avoid drawing attention to highly uncertain values, and rather only implicitly indicate the median value by showing the highest likelihood range for the fatality estimates. The formal uncertainty is given in the loss estimates by providing the likelihood of the actual value of fatalities or dollar losses being within adjacent ranges and thus adjacent alert levels.

Economic- and fatality-based alerts are combined to determine a summary impact alert by assigning the alert to the higher of the two levels. In some cases, they may be equal. However, individual users are encouraged to concentrate on the appropriate alert associated with their activities. A tendency may exist to correlate fatalities with economic losses to determine a cost-per-fatality, but this would be a false relationship. Naturally, countries with high earthquake-resistant building construction standards will have a higher ratio of dollars to deaths and vice versa, but the dominant factor driving the economic losses relate to higher GDP and cost per structure. In addition, countries in which economic losses dominate the data, dollar losses are more rigorously accounted because buildings tend to be insured and the occurrence of damage or collapse draws attention to continued construction deficiencies. That said, these statistics do belie the fact that mitigation of lost lives can be less expensive on a per-capita basis in highly vulnerable countries than in countries in which mitigation efforts have already been taken. In addition to providing a basis for postearthquake alerting for more rapid response, the loss data presented should be considered as a call to action in regions in which red alerts are repeated over the short time frame analyzed.

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