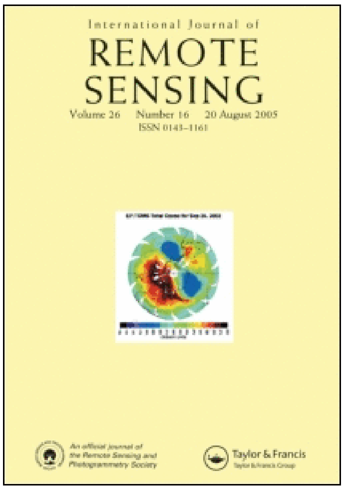

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Letter

Towards an early-warning system for global landslides triggered by rainfall and earthquake

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Drawing upon the recent advances of satellite remote-sensing technology and landslide modelling techniques, a framework is proposed to attempt an early-warning system for landslide hazards after heavy rainfall and/or earthquake, the two major triggers for landslides. This framework includes three major components: (1) a landslide susceptibility information database, including geology, elevation, topography, soil, and land-cover types; (2) a real-time space-borne precipitation estimation system (http://trmm.gsfc.nasa.gov); and (3) a near-real-time ground-shaking prediction system after earthquakes (http://earthquake.usgs.gov/eqcenter/shakemap/). The ultimate goal of this framework is to rapidly predict landslide potential after large earthquakes and/or heavy rainfall by combing the dynamic triggers with landslide susceptibility information derived from high-resolution geospatial datasets. However, the challenge for integrating these real-time systems into an operational landslide prediction network and quickly disseminating alerts around the world is tremendous. It requires continued efforts and interdisciplinary collaboration in the next 2–5 years in order to realize such a system, providing early warning for landslides around the globe in a day-to-day decision-making operation.

1. Introduction

Landslides are one of the most widespread natural hazards on Earth, responsible for thousands of deaths and billions of dollars in property damage every year. However, predicting landslide potential at a global scale is very difficult and expensive in terms of time and money. This is especially true in developing countries where expensive ground observation networks are prohibitive and in mountainous areas where access is difficult. The need to develop more effective spatial coverage of landslide susceptibility and real-time hazard warning for vulnerable countries and remote areas remains apparent and urgent (Sidle and Ochiai 2006). Drawing the recent advances of satellite remote sensing technology, this paper proposes a framework to develop an early-warning system for landslides triggered by heavy rainfall and/or earthquakes, the two major landslide triggers, around the globe. The goal of this framework is to acquire a global view of future landslide disaster alert in a real-time fashion.

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2. Framework and data

Landslides result from a combination of factors, which can be broadly classified into two categories: (1) preparatory variables that make the land surface susceptible to failure without triggering it; and (2) the triggering variables that induce mass movement, such as heavy rainfall and earthquakes. Therefore, to identify the time/space information of landslide occurrence, it is required for the proposed framework to link three major components: (1) a landslide susceptibility information database; (2) a precipitation estimation system; and (3) a ground-shaking monitoring system, as shown in figure 1. The landslide susceptibility database empirically shows part of the 'where', and the dynamic triggers primarily determines the 'when' information. The first-order control on the spatial distribution (where) of landslides is the landslide susceptibility determined by the land surface geospatial database, while the first-order control on the temporal distribution (when) of shallow landslides is the real-time estimates of rainfall and ground shakes. In use, the land-surface 'where' map is overlaid with the real-time triggers 'when' layer to identify landslide potential as a function of time and location.

2.1 *Central geospatial database: landslide susceptibility information*

A central geospatial database is needed to derive preparatory parameters for assessing the landslide susceptibility information. The basic elevation data include NASA Shuttle Radar Topography Mission (SRTM; http://www2.jpl.nasa.gov/srtm/). The global soil dataset is from Digital Soil of the World (http://www.fao.org/AG/agl/agll/dsmw.htm). The MODIS surface data provide the geographic distribution of the 17 land-cover types (Friedl *et al.* 2002). All these datasets have been downscaled or interpolated to the SRTM elemental horizontal scale of 30 m. Note

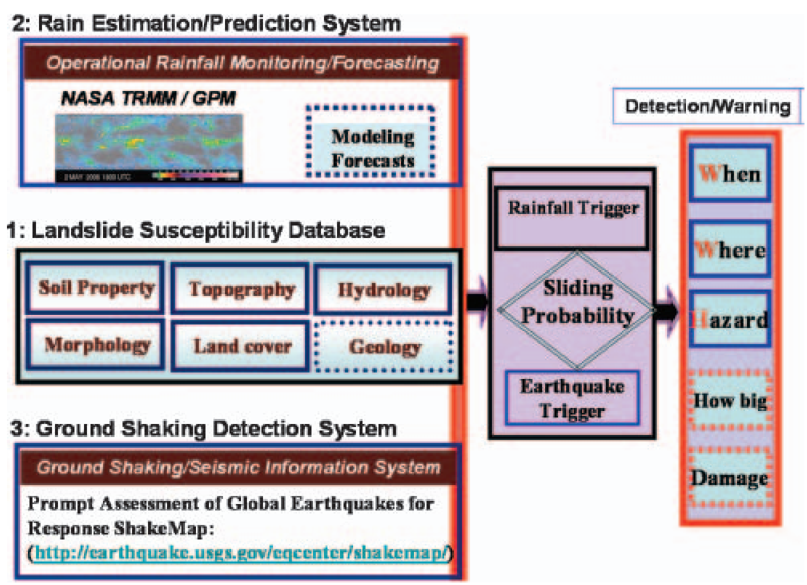

Figure 1. Conceptual framework of real-time monitoring/warning system for landslides triggered by rainfall and earthquake. Note that dash-line boxes are important components but are not covered in this study.

that more landslide controlling factors should be incorporated into this database when they become available at a global coverage and fine spatial scale, in particular, the underlying geological setting.

2.2 *Real-time space-borne rainfall estimation system*

The spatial distribution, duration, and intensity of precipitation play an important role in triggering landslides. The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) is the key dataset for the dynamic rainfall triggers in this framework. A real-time version of the TMPA product is available on the NASA site (http://trmm.gsfc.nasa.gov). Early validation shows that the TMPA is successful at reproducing the surface-observation-based histogram of precipitation at fine scale (Huffman *et al.* 2006). It is anticipated that this type of product will be continued as part of the Global Precipitation Measurement (GPM) mission (http://gpm.gsfc.nasa.gov).

2.3 *Near-real-time ground-shaking monitoring system*

Another primary trigger of landslides is earthquakes. USGS has developed a near-real-time earthquake information system (http://earthquake.usgs.gov/eqcenter/). This system is a major step forward to provide complete earthquake coverage for worldwide users. Consequently, an alarm system, PAGER (Prompt Assessment of Global Earthquakes for Response), has been developed, and a ShakeMap (http://earthquake.usgs.gov/eqcenter/shakemap/) is generated to estimate ground-shaking. It provides a range of ground-shaking levels at sites throughout the region depending on distance from the earthquake, the rock and soil conditions at sites, and variations in the propagation of seismic waves.

3. Experimental results

3.1 *Experimental prediction system for rainfall-triggered landslides*

Many efforts have been attempted to generalize one universal rainfall intensity-duration threshold for global landslides identification (Caine 1980, Clarizia *et al.* 1996, Crosta and Frattini 2001, Cannon and Gartner 2005). Recently Hong *et al.* (2006) proposed a first satellite-based rainfall intensity-duration threshold, using NASA's TRMM multi-satellite precipitation database. However, the global threshold might result in a false alert or over-detection due to its independence of local climatic and geo-morphological characteristics. Regional thresholds are defined for areas extending from a few to several thousand square kilometres. Table 1 lists the collection of rainfall intensity-duration thresholds for initiating landslides at global and regional scales.

When coupled with real-time rainfall data, rainfall intensity-duration thresholds may provide a basis for a landslide early-warning system (Liritano *et al.* 1998). Using the thresholds collected in table 1, an experimental prediction system for real-time landslide hazards was developed and updated every hour (http://trmm.gsfc.nasa.gov/publications_dir/potential_landslide.html). The global threshold is used where regional thresholds are not available. Earlier results indicate that the system does not work well for landslides triggered by rainfall in a relatively short time period, i.e. <6 h (Hong *et al.* 2007).

Table 1. Rainfall intensity-duration thresholds for initialization of landslides[a].

Regions	Country	Equation	Durations	References
World	n/a	$I=14.82\times D^{-0.39}$	$0.167<D<500$	Caine (1980)
World	n/a	$I=12.45\times D^{-0.42}$	$3<D<240$	Hong *et al.* (2006)
S. America	Brazil	$I=22.4\times D^{-0.59}$	$1<D<10000$	Kanji *et al.* (2003)
N. America	Canada	$I=4.0\times D^{-0.45}$	$0.1<D<150$	Jakob and Weatherly (2003)
Central America	Puerto Rico	$I=91.46\times D^{-0.82}$	$2<D<312$	Larsen and Simon (1993)
N. America	USA/Seattle Area	$I=82.73\times D^{-1.13}$	$20<D<55$	Baum *et al.* (2005)
N. America	USA/Blue Ridge	$I=116.48\times D^{-0.63}$	$2<D<16$	Wieczorek *et al.* (2000)
N. America	USA	$I=26.51\times D^{-0.19}$	$0.5<D<12$	Jibson (1989)
Europe	Austria	$I=41.66\times D^{-0.77}$	$1<D<1000$	Moser and Hohensinn (1983)
Europe	Italy	$I=19\times D^{-0.50}$	$4<D<150$	Aleotti (2004)
Europe	Portugal	$I=84.3\times D^{-0.57}$	$0.1<D<2000$	Zezere *et al.* (2005)
Europe	Spain	$I=17.96\times D^{-0.59}$	$D>168$	Corominas *et al.* (2005)
Europe	Switzerland	$I=32\times D^{-0.70}$	$1<D<45$	Zimmermann *et al.* (1997)
Asia	Hong Kong	$I=41.83\times D^{-0.58}$	$1<D<12$	Jibson (1989)
Asia	Indonesia	$I=92.06–10.68\times D$	$2<D<24$	Jibson (1989)
Asia	Japan	$I=1.35+55\times D^{-1}$	$24<D<300$	Hong *et al.* (2005)
Asia	Philippines	$I=9.23\times D^{-0.37}$	$0.08<D<7.92$	Arboleda and Martinez (1996)
Asia	Taiwan	$I=115.47\times D^{-0.80}$	$1<D<400$	Chien-Yuan *et al.* (2005)

[a]I=rain intensity; D=rain-event duration.

3.2 *Experimental monitoring system for earthquake-triggered landslides*

Landslides triggered by ground-shaking during earthquakes have caused widespread loss of life and damage to critical infrastructure. Currently, the USGS primarily relies on the experience and intuition of the on-duty seismologists to estimate the impact of an event. To provide timely information to emergency relief organizations on the possible societal effects of earthquakes, the USGS has developed an alarm system that combines an estimate of ground-shaking with a global population database. The ground-shaking information is estimated by a ShakeMap system (http://earthquake.usgs.gov/eqcenter/shakemap/). The spectral acceleration and the peak velocity are estimated using the predictive relationship of Boore *et al.* (1997) and Joyner and Boore's (1988), respectively, and then the estimation of amplitude will be corrected based on the site soil conditions.

According to Keefer (1984), landslide analysis after an earthquake creates a unique opportunity to advance the understanding of the response of rocky slopes to seismic disturbance and subsequent rainfall. Bulmer *et al.* (2007) presented a brief description of a cost-effective motion detection technology being used in Kashmir to monitor possible landslides. Godt *et al.* (2006) reported the feasibility of rapidly estimating landslide potential after large earthquakes by combining the near-real-time estimates of ground motions, ShakeMap, with a slope stability model. Godt *et al.* (2006) presented an initial application and discussed results in the context of field and aerial observations of landslides triggered by the magnitude-7.6

earthquake of 8 October 2005 in Pakistan-administered Kashmir, which generated thousands of landslides that blocked many roads and damned rivers in the mountainous region (Schneider 2006). Godt *et al.* also argued that remote-sensing applications that map surficial materials and that estimate the near-surface moisture balance might increase the accuracy of rapid assessment of landslide occurrence following earthquakes.

4. Discussion and future work

This short letter intends to examine the possibility of developing an early-warning system for global landslides triggered by rainfall and/or earthquakes, the two major triggers for landslides. To identify the time/space information of landslide occurrence, it is required for the proposed framework to link three major components: (1) a landslide susceptibility information database; (2) a real-time satellite precipitation estimation system (http://trmm.gsfc.nasa.gov); and (3) an operational ground-shaking monitoring system (http://earthquake.usgs.gov/eqcenter/shakemap/). The basic flow and processing of information through this proposed landslide warning system after heavy rainfall and earthquakes are straightforward. Early results demonstrated the effectiveness of this system in identifying landslides. However, significant efforts must continue in order to fully realize this system. For example, the warning lead-time of landslides triggered by rainfall can be expanded by using rain forecasts (1–10 days) from numerical weather models; forecasting seismic waves is still at least several years away in seismology. Ultimately, the challenge for an integrated operational landslide prediction network and quickly disseminating alerts around the world requires wide interdisciplinary efforts and multi-agency collaboration.

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