Rainfall Warning for Sediment Related Disasters in Sierra Madre Oriental, Mexico

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Sediment related disasters represent a major hazard in the Mexican territory. Throughout its history, the state of Nuevo Leon in Mexico, have been suffered by major tropical storms, hurricanes and heavy rainfall episodes that led to several sediment related disasters causing many damages and loss of human lives in the area. The objectives of this study are to analyze the rainfall conditions during hurricane events and heavy rainfall episodes to establish critical rainfall for warning in Nuevo Leon state. This study shows that maximum intensity that triggered sediment related disaster during a heavy rainfall episode was of 167 mm/day and during hurricane event was 171 mm/day. The minimum intensity in where a sediment related disaster was observed in case of heavy rainfall was 68.2 mm/day and during hurricane 85.4 mm/day. In this area the rainfall warning and sediment related disaster mitigation should be implemented.

Key words: Sediment related disaster, rainfall warning, hurricane

1. INTRODUCTION

Sediment related disasters are defined as the phenomena that cause direct or indirect damage to the lives and properties of people, inconveniences to the life of people, and/or the deterioration of the environment, through a large-scale movement of soil and rock [*Ministry of Land, Infrastructure and Transport of Japan*, 2004].

The influence of rainfall on landslides differs substantially depending upon landslide dimensions, kinematics, material involved, etc. Shallow failures are usually triggered by short intense storms [*Campbell*, 1975; *Lumb*, 1975; *Brand et al*., 1984; *Cancelli and Nova*, 1985; *Cannon and Ellen*, 1985; *Wieczorek*, 1987; *Guzzetti et al*., 1992; *Polloni et al*., 1992; *Morgan et al*., 1997; *Crosta*, 1998; *Corominas and Moya*, 1999; *Flentje et al*., 2000; *Paronuzzi et al*., 2002] while most deep-seated landslides are affected by long-term variation of annual rainfall which has to last several years [*Bonnard and Noverraz*, 2001]. For landslides such as rockfalls, no precise correlation with rainfall can be surmised, as they appear more sensitive towards other factors such as chemical-mechanical weathering of the rock mass and temperature fluctuation across the freezing point [*Sandersen et al.*, 1996]: only late spring and summer rockfalls can be related with rainfall. For example, a large fall occurred, after some days of intense precipitation, in the Brembana Valley (Italian Central Alps) at the beginning of May 2002, killing three persons [*Aleotti, 2004*].

In Mexico, the consequences of rainfall-induced sediment related disasters in areas where meteorological events such as cyclones, hurricanes or typhoons are recurrent are devastating. The worst episode inside the Mexican territory, took place in La Paz on 1st October of 1976 as a result of a geotechnical failure; flash-floods and mudflows were generated by the collapse of a six-meter dike produced by the intense precipitation of Hurricane Liza, this event involved at least 1,000 causalities. Given the lack of rain gauges, based on indirect

measures, [*Vazquez et al*., 1997] estimated a rainfall of 180 mm for 30 September, and a consequent flow rate of 950 m^3/s over a 7.5 hour period. The strong current and the large volume of water carried by El Cajoncito stream caused the collapse of the dyke. The resulting 2 m height avalanche washed away the human settlements formed to a major extent by wood and cardboard housing; 10,000 to 12,000 people were left homeless. Although there is not comprehensive sediment related disasters database in Mexico, historical records shown that the most disastrous sediment related disasters that occurred inside Mexican territory were associated with the rain as a triggering factor [*Alcantara-Ayala*, 2008].

Through all its history, the state of Nuevo Leon has been targeted by several hurricanes causing several sediment related disasters and socio-economical damages in the urban areas, especially the hurricane events occurred in 1988 (Hurricane Gilberto) and in 2005 (Hurricane Emily) have been devastating for the residents of Nuevo Leon state. In recent years, hurricane events and their intensity appears to increase along with an increment of number and severity of sediment related disasters in Nuevo Leon [*Sanchez-Castillo et al*., 2012]. In 2010, hurricane Alex was the first hurricane of the season to hit the state of Nuevo Leon, causing serious damages in all the municipalities that comprise the state affecting more than 4 millions of inhabitants by flood and sediment related disasters and causing the death of at least 51 people along its path.

Is it necessary to establish rainfall criteria, until now inexistent in the area, to allow citizens and authorities to identify and assess the risk associated with sediment related disasters The objectives of this study are to analyze the rainfall conditions during hurricane events and heavy rainfall episodes to establish critical rainfall for warning in Nuevo Leon state.

2. STUDY AREA

The state of Nuevo Leon is located in the northeast part of Mexico; its territory covers 64,220 square kilometers. The study area is surrounded by Sierra Madre Oriental, a chain of mountains aligned Northwest-Southeast with maximum elevations of 2,500 m.a.s.l and valleys between 500 and 600 m.a.s.l. **(Fig. 1)**.

Inside the study area lies the NE part of Sierra Madre Oriental in the sector known as "La curvatura de Monterrey" and in small portion located in NW, the cross mountains and the border area of Sierra Madre Oriental provinces and the Gulf Coastal Plain. Tectonically the Laramide orogeny is what gave rise to the folding of the area, which was subject to compressive stress oriented NE-SW, resulting in NW-SE oriented structures, as it is the whole of the Sierra Madre Oriental. The stratification is composed of sedimentary rock essentially of marine origin and in smaller proportions, continental in some parts the stratification is almost vertical thus, sediment related disasters are common. Ranges in age from late Jurassic to late cretaceous, with Cenozoic continental clastic sediments and is divided mainly by three lithological groups: limestone, shale-conglomerates and sandstones [*Secretariat of Sustainable Development of Nuevo Leon state*, 2013]. Nuevo Leon has an extreme climate and there is very little rainfall through all the year; the average annual rainfall from 1970 to 2009 was of 852 mm (**Fig. 2**).

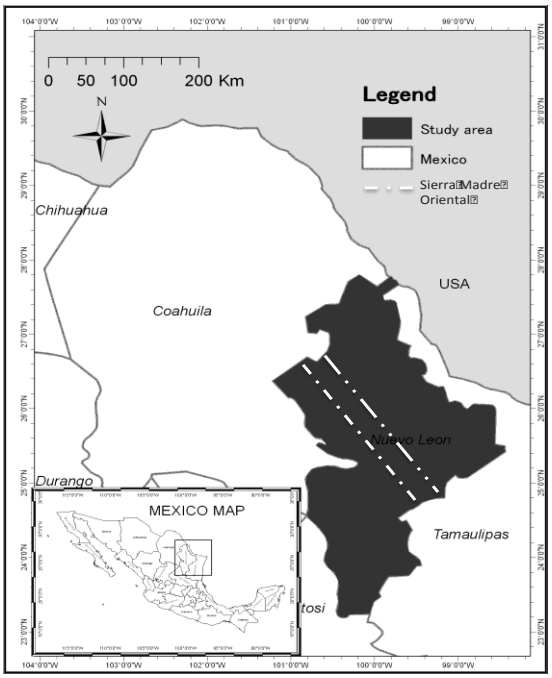

Fig. 1 Study Area in Nuevo Leon, Mexico

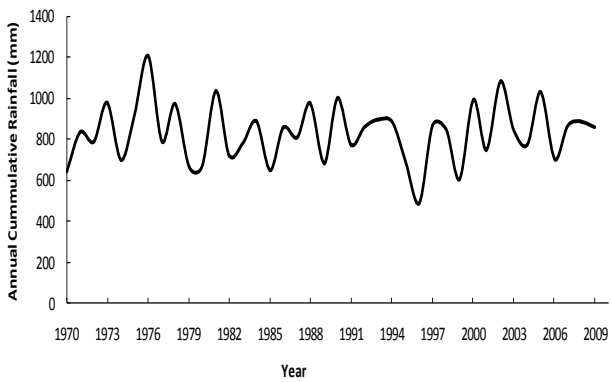

Fig. 2 Fluctuation of the annual cummulative rainfall in Nuevo León from 1970 to 2009.

The study area is located in the Metropolitan area of Monterrey, the most populated area of the state with a total population of 4,036,112 people. The rapid population growth coupled with the significant industrial development that have occurred in the metropolitan area have led to several environmental impacts, many building are raised on steep slopes causing sediment related disasters and even more when hurricanes strike the metropolitan area.

3. METHODOLOGY

Daily rainfall information from meteorological stations of the metropolitan area of Monterrey owned by the SMN (Meteorological National Service of Mexico) was used due to the lack of hourly rainfall information, along with sediment related disaster reports obtained from the records from Civil Protection of Nuevo Leon and historical records from the local newspapers.

Rainfall criteria for sediment related disasters warning was established using the method of standard rainfalls for warning applying Hirano's mathematical model of debris flow (Eq. 1a) [*Hirano,* 1997; *Kubota et al.,* 2008; *Hasnawir and Kubota*, 2009].

$$\frac{Q_s(t)}{A} = r(t)\eta_0 M \qquad (1a)$$

This equation treats the volume or scale of the mass movements induced by rainfall. In the study area, only large-scale debris flows or large landslides can reach downstream infrastructures or properties and cause the disasters.

Equation 1a indicates that the runoff intensity of sediment related disaster is in proportion to the rainfall intensity at the time r(t) and the cumulative rainfall up to that time η_0, jointly. This means that a constant value of Q_s/AM (where *Qs* = discharge or volume of mass movement and AM= watershed volume) is shown as a hyperbola on a $(r(t)\eta_0)$ plane as schematically illustrated in **Fig.3**.

An empirical method by use of hyperbola-like curve on the $(r(t)\eta_0)$ plane has been widely used to forecast the occurrence of sediment related disasters. (Hirano, 1997).

The critical line is determined by the relation between critical rainfall intensity (R_{ic}) and total rainfall in the period (R_t) (Eq.1b). In where R_{ic} = critical rainfall intensity, R_t = total rainfall in the period, *C* = constant value of Q_s/AM and *t* = elapsed time.

Hence, the *Qs/AM* curves can be the critical line of disaster occurrence i.e. the disaster thresholds. The warning line is determined by one day before rainfall condition reaching the critical line, Eq.1c. Where R_{max} is the maximum rainfall intensity in earlier data in the past (mm/hr) and R_{iw} is the rainfall intensity for warning line.

$$R_{ic}R_t = C, R_{ic} = C / R_t \qquad (1b)$$

$$R_{iw} = C/(R_t + R_{\max}) \qquad (1c)$$

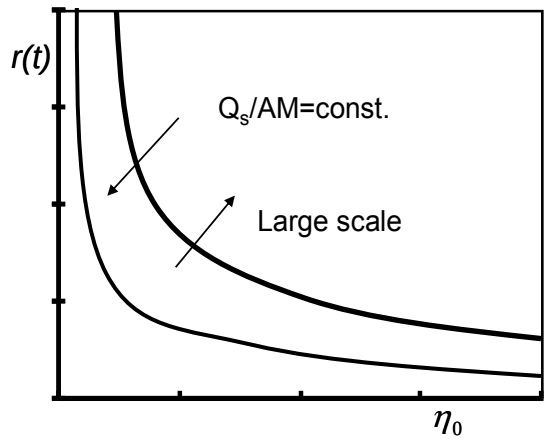

Fig. 3 Schematic diagram for forecasting debris flow discharge [*Hirano*, 1997]

4. RESULTS AND DISCUSSION

4.1 Historical rainfall information and sediment related disasters during Hurricane events in Nuevo Leon state

Rainfall pattern during the occurrence of nine hurricane events during the period of 1970 to 2010 and the frequency of sediment related disasters from 1988 to 2010 was analyzed, the reports of years with hurricane events of 1971, 1975 and 1983 were deleted due to the lack of historical reports of sediment related disasters. Hurricane Alex in 2010, showed the highest cumulative precipitation with 773.8 mm. And also the maximum number of reported sediment related disasters in all hurricane events in the metropolitan area of Monterrey, an increment of rainfall amount and frequency of sediment related disasters was observed from the years of 2000 to 2010 (**Fig. 4**). Rainfall information during the raining season: May to September from the years of 2008 to 2011, shown that the year that shown the maximum number of sediment related disasters was 2010 (**Fig. 5**).

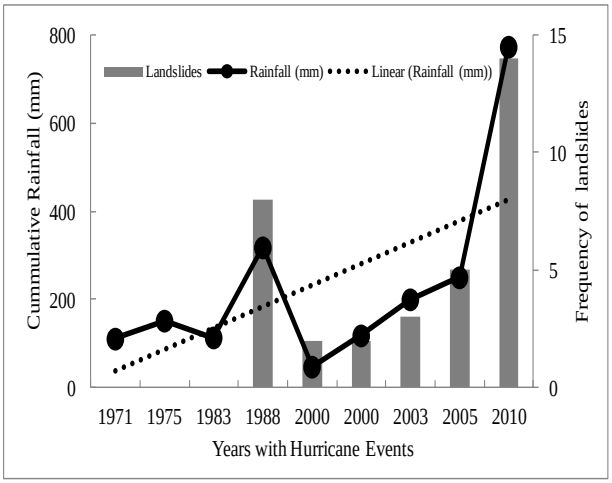

Fig. 4 Cumulative Rainfall (mm) during hurricane events and Frequency of Landslides

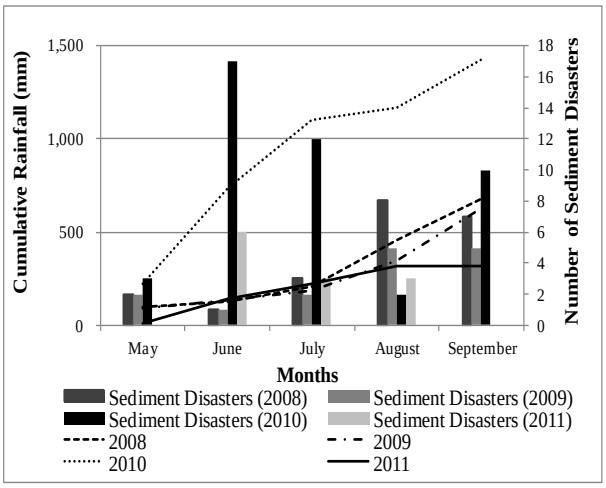

Fig. 5 Cumulative Rainfall from 2008 to 2011 and events number of Sediment disasters during rainy season

4.2 Rainfall conditions and sediment related disasters during Hurricane Alex

Hourly rainfall information from a private meteorological station recorded a maximum rainfall intensity of 71 mm/hr, between 10:00 and 11:00 hours on July 1, 2010 (**Fig. 6**). Incidence of sediment related disasters started at 422.5 mm of cumulative precipitation. The damage in Nuevo Leon state was severe, 843.65 kilometers in roads were damaged, the bridges and drainage system in the metropolitan area adjacent to the Sierra Madre Oriental were destroyed and a total of 3,340 million of Mexican pesos were invested in the reconstruction of infrastructure damages for Hurricane Alex. **Fig. 7** shows damages in the metropolitan area of Monterrey and San Pedro Garza Garcia, on 1st of July of 2010.

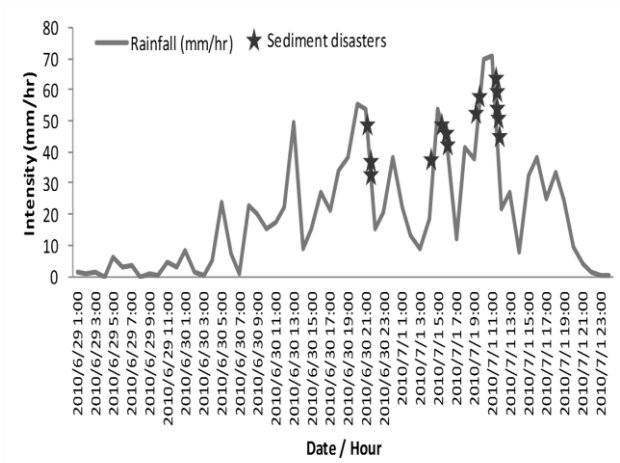

Fig. 6 Hourly rainfall pattern and sediment disasters during Hurricane Alex (June 29 ~ July 1, 2010)

Fig. 7 Sediment related disasters in Nuevo Leon state on 1st of July of 2010: a) Colonia Cumbres, in the metropolitan area of Monterrey, b) San Pedro Garza Garcia, NL.

4.3 Standard rainfalls for sediment related disasters warning

Critical precipitation indicates the amount of rainfall from the time (zero point) in which a sharp increase in rainfall intensity is observed and the triggering of the first landslide or maximum cumulative rainfall, or the combination of cumulative rain and antecedent rain [*Hirano*, 1995; *Kubota*, 1995]. The duration of the critical rainfall event is the time that elapses from the beginning of critical precipitation to activate landslides.

In this study, 70 rainfall events with the total period (Rt) and maximum rainfall intensity (Rmax,mm/day) recorded from 1970 to 2008 were analyzed for warning on sediment disaster in Nuevo Leon, Mexico, using the method of standard rainfalls for warning [*Hirano*, 1997; *Kubota et.al.*, 2008]. Three types of events were taken into account for this analysis, sediment disaster occurred during heavy rainfall episodes, sediment disasters occurred during hurricane events and minor sediment flows, the latter is classified as non disaster because generally, minor discharges does not reach populated areas and do not cause disasters. An event of maximum rainfall intensity of 68.2 mm/day during heavy rainfall episodes and 85.4 mm/day during hurricane events were observed as grounds of sediment related disaster in the study area. **Fig. 8** illustrates when rainfall exceeds the critical line, disastrous sediment disaster may be occur. If rainfall continues and exceeds the warning line, people need to be evacuated from the prone area immediately. However when rainfall condition below the critical line only minor sediment flows may occur.

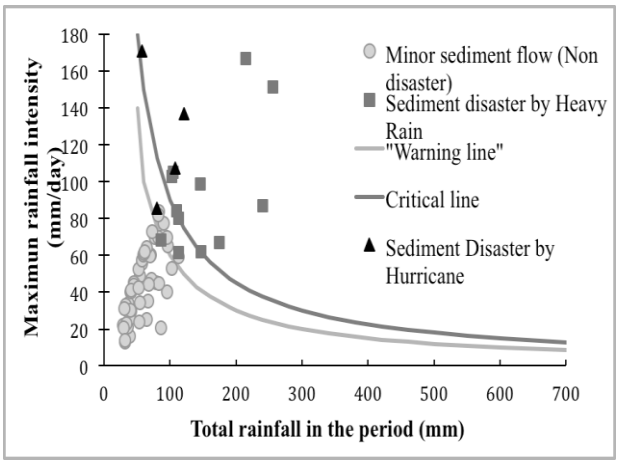

Fig. 8. Standard rainfalls for warning and evacuation against sudden sediment related disaster in Nuevo Leon, Mexico

5. CONCLUSION

Maximum intensity that triggered sediment related disaster during a heavy rainfall episode was of 167 mm/day and during hurricane event was 171 mm/day. The minimum intensity in where a sediment related disaster was observed in case of heavy rainfall was 68.2 mm/day and during hurricane 85.4 mm/day. In this area the rainfall warning and sediment related disaster mitigation should be implemented.

REFERENCES

Alcantara-Ayala I. (2008): On the historical account of disastrous landslides in Mexico: the challenge of risk management and disaster prevention. Adv. Geosci., 14, 159–164.

Aleotti, P. (2004): A warning system for rainfall-induced shallow failures, Engineering Geology, Vol. 73, pp. 247-265.

Bonnard, Ch., and Noverraz, F. (2001): Influence of climate change on large landslides: assessment of long term movements and trends. Proc. of the International Conference on Landslides: causes impact and countermeasures, Gluckauf, Essen, Davos, pp. 121–138.

Brand, E.W., Premchitt, J., and Phillipson, H.B. (1984): Relationship between rainfall and landslides in Hong Kong. Proc. of the IV International Symposium on Landslides, Toronto, Vol. 1, pp. 377–384.

Campbell, R.H. (1975): Debris flow originating from soil slip during rainstorm in southern California. Q. Enginerring Geologist , Vol. 7, pp. 339 – 349.

Cancelli, A. and Nova, R. (1985): Landslides in soil debris cover triggered by rainstorm in Valtellina (Central Alps, Italy), Proc. Of the IV International Conference on Landslides, Tokyo, Vol. 1, pp. 267– 272.

Cannon, S.H. and Ellen, S.D. (1985): Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California, California Geology, Vol. 38, No.12, pp. 267–272.

Corominas, J. and Moya, J. (1999): Reconstructing recent landslide ac- tivity in relation to rainfall in the Llobregat river basin, Eastern Pyrenees, Spain. Geomorphology, Vol. 30, pp. 79–93.

Crosta, G. (1998): Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environmental Geology, Vol. 35 (2 – 3), pp. 131 – 145.

Flentje, P., Chowdhury, R.N., and Tobin, P. (2000): Management of land- slides triggered by a major storm event in Wollongong, Aus- tralia. Proc. of the II International Conference on Debris-Flow Hazards Mitigation, Mechanics, Prediction and Assessment, Taipei, pp. 479–487.

Guzzetti, F., Crosta, G., Marchetti, M., and Reichenbach, P. (1992): Debris flows triggered by the July, 17–19, 1987 storm in the Valtellina Area (Northern Italy). Proc. of the

VII International Congress Interpraevent 1992, Bern, Vol. 2, pp. 193–204.

Hasnawir, and Kubota, T. (2009): Analysis for Early Warning of Sediment-Related Disaster in Mt. Bawakaraeng Caldera, South Sulawesi, Indonesia, Journal of the Japan Society of Erosion Control Engineering, Vol.62, No.4:285, pp. 38–45.

Hirano, M. (1995): Characteristics of debris flow in Unzen Volcano, proceedings of the international Sabo symposium, Tokyo, Japan, 107-114.

Hirano, M. (1997): Prediction of debris flow for warning and evacuation. In: Armanini A, Michiue,M. (eds) Lecture notes in earth sciences, Recent developments on debris flows. Springer,Berlin Heidelberg New York, Vol. 64, pp.7–26.

Kubota, T., (1995): Study on neural network system for critical rainfall determination of debris flow warning and evacuation at volcanic area, proceedings of the international Sabo symposium, Tokyo, Japan 99-106.

Kubota,T., Cantu-Silva I. C, and Hasnawir (2008) The warning standard rain of sediment runoff and shallow landslides along the mountainous torrent, Proc. of the 1st world landslide forum, pp. 325-328.

Lumb, P. (1975): Slope failure in Hong Kong. Quarterly Journal Engineeering Geologist , Vol. 8, pp. 31–65.

Ministry of Land, Infrastructure and Transport of Japan. (2004): Guidelines for Development of Warning and Evacuation System Against Sediment Disasters in Developing Countries, pp. 8-28.

Morgan, B.A., Wieczorek, G.F., Campbell, R.H., and Gori, P.L. (1997): Debris flow hazards in areas affected by the June 27, 1995 storm in Madison County, Virginia. USGS Open File Report, pp. 97 – 438.

Paronuzzi, P., Del Fabbro, M., and Maddaleni, P. (2002): Frane super- ficiali tipo slide debris flow causate dal nubifragio del 21/22 giugno 1996 nella Val Chiarso` (Alpi Carniche, Friuli). Memorie della Societa Geologica Italiana, Vol. 57, pp. 443–452.

Polloni, G., Ceriani, M., Lauzi, S., Padovan, N., and Crosta, G. (1992): Rainfall and soil slipping events in Valtellina. Proc. of the VI International Symposium on Landslides. Christchurch, Vol. 1, pp. 183–188.

Sanchez-Castillo L, Kubota T, and Cantu-Silva I., (2012): Hurricane Incidence and Sediment disasters under the climate change in Nuevo Leon, Mexico. 3rd Conference on Forest and Water in a Changing Environment.

Sandersen, F., Bakkeoi, S., Hestnes, E., and Lied, K. (1996): The influence of meteorological factors on the initiation of debris flows, rockfalls, rockslides and rockmass stability. Proc. of the VII International Symposium on Landslides, Trondheim, Vol. 1. Bal- kema, Rotterdam, pp. 97–114.

Secretariat of Sustainable Development of Nuevo Leon state. (2013): Atlas of risk for the state of Nuevo Leon, Vol 1, pp.8-22.

Wieczorek, G.F. (1987): Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. In: Costa, Wieczorek (Eds.), Debris Flows/Avalanches: Processes, Recognition and Mitigation. Reviews in Engineering Geology, vol. 7. Geological Society of America, pp. 23 – 104.

Vazquez, M. T., Dominguez, R., Fuentes, O., and Maza, J. A., (1997): Flash floods in Mexico, in: Twenty Years Later What Have We Learned Since the Big Thompson Flood, edited by: Gruntfest, E., Proceedings of the Meeting held in Fort Collins, Colorado, July 10–13, 1996, Natural Hazards Research and Applications Information Center, Boulder, Colorado, Special Publication No.33, 153–160.