ABSTRACT

Landslide early warning systems are non-structural risk mitigation strategies aiming at dealing with intolerably high probabilities of landslide occurrence by reducing risk through the reduction of the exposed elements. The majority of landslide early warning systems deal with rainfall-induced landslides. The systems can be classified, as a function of the scale of analysis, into: "local" and "regional" systems. Several differences exists among these two different types of warning systems, such as: the actors involved in the process, the monitoring tools, the variables selected to define triggering thresholds, the way the warnings are issued and spread to the public. This work exclusively deals with regional landslide early warning systems (ReLEWSs). These systems are used to assess the probability of occurrence of landslides over appropriately-defined homogeneous alert zones of relevant extension, typically through the prediction and monitoring of meteorological variables, in order to give generalized warnings to administrators and the population. At first, a detailed review of the structure and the functioning of these systems is presented. The information has been gathered mainly from the literature, with the exception of the regional system operating in Campania region, Italy, the municipal system of Rio de Janeiro, Brazil, and the national Norwegian landslide early warning system. The functioning and the structure of the latter two systems have been analyzed in greater depth thanks to research periods spent, respectively, at the GEO-Rio foundation in Rio de Janeiro and at The Norwegian Water Resources and Energy Directorate (NVE) in Oslo. In literature, several authors provided a general description of the structure of a landslide early warning system. Starting from the analysis of these contributions, an original scheme and the main components of such systems for rainfall-induced landslides forecast is proposed. The scheme is based on a clear distinction among the following components: correlation laws, decisional algorithm and warning management. Subsequently, the functioning of the reviewed ReLEWSs has been described according to these components, with a special attention on how the performance of the various warning models was assessed. It is straightforward that a periodical assessment of the technical performance

of a landslide early warning system, in terms of evaluation of the warning issued in relation to the landslides occurred, is a required task in order to continuously keep the system reliable. Nevertheless, no standard requirements exist for assessing the performance of regional warning models (ReWaMs) and, typically, this is evaluated by computing the joint frequency distribution of landslides and warnings, both considered as dichotomous variables. Herein, an original methodology to assess the performance of ReWaMs, called the "Event, Duration Matrix, Performance" (EDuMaP) method, is proposed. The performance is evaluated taking into account: the possible occurrence of multiple landslides in the warning zone; the duration of the warnings in relation to the time of occurrence of the landslides; the warning level issued in relation to the landslide spatial density in the warning zone; the relative importance system managers attribute to different types of errors. The applicability of EDuMaP method is tested considering three different ReLEWSs: the municipal early warning system operating in Rio de Janeiro (Brazil); the Norwegian landslide early warning system; the landslide early warning system for hydro-geological risk management of the Campania region, Italy. The main differences among these systems are discussed in great detail, mainly dealing with the functioning and the databases available for the three case studies. The LEWS operational in Rio de Janeiro is employed to issue a certain level of warning in four warning zones in which the municipality is divided. The warnings can be issued at any time during the day if the monitored rainfall exceeds pre-identified thresholds. The Norwegian landslide early warning system is employed to issue daily warnings adopting variable warning zones. In the LEWS of the Campania region each municipality has a reference rain gauge for which three different rainfall threshold are specified for the activation of 3 warning levels. The EDuMaP method was successfully employed to assess the performance for all these case studies, thus underlying the wide applicability of the method, which can be easily adopted to evaluate the performance of any regional landslide early warning systems for which landslides and warnings data are available. For the three case studies, sensitivity analyses are also conducted by varying some of the input parameters of the EDuMaP method. The results of these analyses indicate that the input parameters most affecting the performance of the warning models are: i) the landslide density criterion used to differentiate among the classes of landslide events; ii) the database on landslides considered in the simulations; iii) the time set

as the minimum time interval between landslide events; iv) the area of analysis; v) the time frame of the analysis. In conclusion, the analyses prove the applicability of the EDuMaP method in evaluating the performance of real case studies related to ReLWaMs characterized by different decisional algorithms, components and input parameters. The method can also be used as an effective tool to calibrate a warning model by back-analysing landslide and warning data in test area with the aim of defining the set of warning criteria which maximises the model performance.