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ELDEWAS - Online early warning system for landslide detection by means of dynamic weather nowcasts and knowledge based assessment

O. Krol, [a] **T.Bernard**[a]

[a] *Fraunhofer IOSB, Fraunhoferstrasse 1, 76131 Karlsruhe, Germany*
(Oliver.Krol@iosb.fraunhofer.de, Thomas.Bernard@iosb.fraunhofer.de)

Abstract: In many alpine and low mountain regions landslide events occur more frequently during the last years induced by a growing number of hazards. Since these events often cause high material damage with corresponding costs and/or even personal injury, there is an increasing demand of early warning systems in order to minimize the impact of the events. Currently static hazard index maps are used which indicate areas with a high disposition for landslide. These hazard index maps are derived from information about slope, land use, geotechnical structure, etc. Depending on crisp criteria (e.g. threshold parameters) several disposition classes are derived. Since these static disposition or susceptability maps do not consider up to date information and short-term conditions (e.g. precipitation, temperature), obviously the current danger of landslide events may differ considerably. Hence the key idea of ELDEWAS is to merge the static information with online data (e.g. from dynamic weather nowcasting) in order to detect the high danger landslide areas in real-time. The central challenge developing such an early warning system is to consider all available data (e.g. weather nowcasts, soil measurement data) and sources of knowledge (e.g. geological expert knowledge in terms of maps and heuristic expert knowledge; geological, hydrogeological and physical models). Obviously enhanced information fusion methods are required in order to deal with this very heterogenous sources of information in real-time. Especially the representation of the expert knowledge is crucial. In ELDEWAS the expert knowledge is represented by means of IF-THEN rules based on Fuzzy Logic. These rules in general can easily be formulated by the experts. Using Fuzzy Logic avoids crisp thresholds and binary decisions and hence provides an evaluation close to human decision makers. Static parameter maps represent the factors triggering landslide that can be merged in a case-dependent way and where the results correspond to current disposition for landslide/ mudflow. The weather nowcasting is computed by the software package INCA (Integrated Nowcasting through Comprehensive Analysis) that adopts forecasts from numerical weather models to a given topography by incorporating current measurements. This procedure allows a spatial and temporal refinement of the meteorological forecast/ nowcast. First results of the application of ELDEWAS to landslide detection for Lower Austria are presented.

Keywords: Fuzzy logics, landslide, mass movement processes, early warning system

1 Introduction

1.1 State of the art in landslide risk assessment

The Alpine region has always been subject to the risk of landslide, avalanche, debris flow and flooding. But also low mountain regions have to spend more and more attention to this topic. Many of these events are sudden, violent and unforeseeenable in their timing and often causing an enormous material damage or even danger to human life. Therefore the interest in predicting such phenomena increase and in the focus of research work. An introductory work to this topic is given by Oddsson [1996], where different types of mass motion processes are discussed as well as the aspects of stability analysis. Especially the contributions of Bollinger [1996], Bucher [1996], Schindler [1996] and Madson [1996] should be emphasized here. A deeper insight into the current state of the art and actual applications can be found in the results of the InterReg IIIb project CatchRisk [2006]. Here the main objectives were the development of databases and information systems for assessing hydrogeological parameters, by analyzing how landslides begin within the Alpine catchment areas, evaluating the danger levels regarding alluvial fans and the floors of valleys. The main purpose is to indicate to public administrations which procedures are most suitable for evaluating these risks in Alpine areas, so as to allow correct territorial planning.
Another field of research is concerned with how climate change effect the activity of landslide. Collison et al. [2000] investigated the impact of climate change with respect to the South East of England, whereas Malet et al. [2007] considered the climate-landslide relationship with respect to the Ubaye valley. The current knowledge about the effect of climate change to landslide activity is summarized in Huggel et al. [2012].
A first disposition model (SLIDISP) was already developed in 1996 by Liener et al. [1996] which took a digital elevation model (DEM) into account with a resolution of 25*25 m^2. Combining the slope information from the DEM with information about effective cohesion and effective angle of internal friction of different lithologic types delivered a hazard index map. This ‚SLIDISP' model was also applied by Tobler et al. [2006] within the CatchRisk project. With respect to debris flow events Gamma [2000] developed a simulation program ‚dfwalk' for the detection of dangerous zones.
All investigations require failure criterias of the soil-slip systems. Hamberger [2007] tried to find sets of parameters enabling the separation of soil-slip areas from non-soil-slip areas in a reliable manner. Applying different classification methods - support vector machines, linear discriminant analysis and classification trees - to the data the most essential parameters predicting the failure of a soil-slip system were determined with the range of uncertainty.
We subsume that so far in all investigations and research known to us no dynamic data were taken into account. This combination is of high interest to decision makers in disaster mangement

1.2 Objectives: Consideration of dynamic data

The current research is mainly concerned with the determination of the essential parameters influencing the landslide activity and to generate hazard index maps with respect to different process types which is important for territorial planing. In contrast to this the present approach considers additionally dynamic data like precipitation, temperature or wind velocity. By this approach the actual current danger should be estimated which is interesting for disaster management. The result could be warnings similar to weather warning or warnings for road safety. The evaluation bases on the same parameters as the hazard index maps, but additional dynamic effects are considered.
A second aim is to install knowledge based evaluation algorithms for deriving results that

are closer to reality and to achieve a better reliability on the warnings. The methods of fuzzy logic are appropriate since there are parameters and combinations of them which can not be quantified clearly, e.g. the effective angle of internal friction or unique criteria of failure. It depends on the process type, for instance, which parameters and how the thresholds have to be chosen (Kienholz [1996]).

2 THE ELDEWAS SOLUTION CONCEPT

2.1 The basic idea

Th basic idea of the ELDEWAS system is to merge static information in shape of maps with dynamic weather data about temperature, precipitation, wind velocity, etc. for deriving an reliable estimation of the actual current danger of mass movements in a particular region of interest. The results are the base for a warnings preserving people from injury.

2.2 The INCA-CE Project

The present work is part of the European Interreg IV project INCA-CE [2009-2013] that has the objective to improve the INCA Software of ZAMG (central agency for meteorology and geodynamics, Vienna) with respect to functionality and stabiliy. Furthermore it should be introduced as a standard tool in the central european region in order to bring the nowcast results into application, namely as input for hydrological forecasts, road safety prediction and as additional information for disaster management. The last aspect motivates the development of ELDEWAS which should be a tool for detecting areas with a high susceptibility with respect to landslide events.

2.3 Data requirements and processing

Since the main idea of ELDEWAS is the detection of dangered locations with respect to mass movement processes for certain regions spatially distributed information in the shape of electronic maps must be involved. These maps must be available as grids, such that pointwise calculations are possible. In principle one can say that the finer the resolution of data the better the results. In the present context a minimal resolution of 50 metres should be given whereby all grid maps must have the same resolution.
In contrast to static maps the resolution of dynamic data can differ massively. Currently, the INCA system is able to deliver the results in a 1km by 1km scheme, that is quite high. Principally, the resolution of weather data is independent of the static map resolution.
Prospectively, also additional weather stations information should be considered as well, whereby here the integration of different data structures has is a challenge. ELDEWAS merges the static information from maps and the dynamic data from the weather service. At the current state of the system the user can implement fix threshold values which are applied to the evaluation of the data. In future the evaluation will be performed in terms of fuzzy logic as depicted in figure 1. As in GIS systems all grid points fullfilling the corresponding conitions are filtered by the thresholds. These grid points are indicated and returned to the decision makers.
For the evaluation of the susceptability with respect to landslide the user can apply a hazard index map, if it is available. Alternatively, the system allows the creation of a new hazard index map by defining the parameters of relevance and the thresholds. ELDEWAS merges the data and filters the grid points that fullfill the conditions of high susceptability with respect to landslide. The advantage here is that updated data can be used whereas the static maps are fix and valid for the state of knowledge when it was generated.
Beside the current dataset of precipitation two aspects of the dynamic are of essential

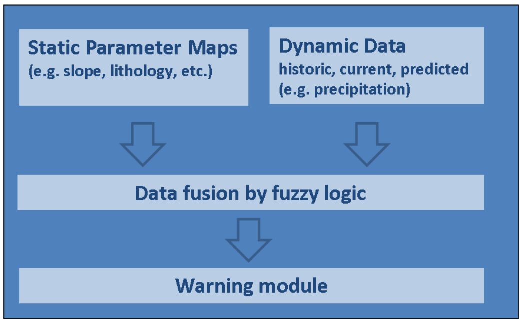


Figure 1: Concept of ELDEWAS

meaning with respect to a prediction of mass movement processes:

1. ELDEWAS calculates integrated values for different time horizons, that means one get the sum value for the precipitation of the last 6, 12, 24 or 48 hours. This could give a hint with respect to the soil moisture and an estimation for the soil saturation. Combining this with information about the soil stucture a further parameter effecting landslides can be incorporated into the susceptability consideration.
2. Based on the nowcasts of the meteorological service ELDEWAS can also provide the trend of the precipitation for the next 6 hours. This is also a essential information for the decision makers in the disaster management. Assuming that the present disposition at a specific point is quite high but subcritical, the information about the trend of precipitation in the next few hours could make them to alert or not.

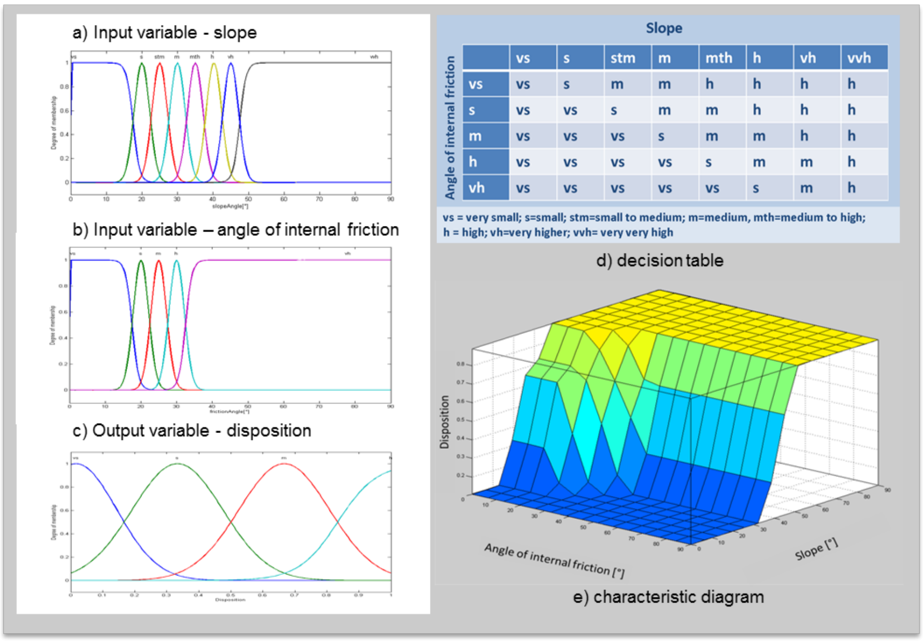
This additional information is the surplus value of ELDEWAS in contrast to the concept of static hazard index maps. ELDEWAS provides a estimation about current actual danger of landslide in consideration of the sound disposition, but also with respect to instantaneous weather conditions.

2.4 Knowledge Representation by means of Fuzzy Logic

Basic idea of fuzzy logic. An introduction to the theoretical fundaments of fuzzy systems is given by e.g. Takagi and Sugeno [1985]. A fine technical introduction with practical examples can be found in the matlab help function entry of the fuzzy toolbox by Jang [1998]. In general the generation of a fuzzy inference scheme can be summarized by:

1. Determination of the most important input and output variables
2. Determination of the relevant value range
3. Definition of membership functions (fuzzyfication)
4. Formulation of expert knowledge in terms of *if-then-rules* (inference)
5. Selection of logical relationships and formalisms

The main advantage of applying fuzzy logic methods is that also data that are hard to measure can be incorporated by means of linguistic variables, i.e. you can also use imprecise data. Furthermore, you can model complex nonlinear functions and consider experience of experts quite easily. Finally, the concept of fuzzy logic systems is quite easy to understand and the common natural language can be used.



	vs	s	stm	m	mth	h	vh	vvh
vs	vs	s	m	m	h	h	h	h
s	vs	vs	s	m	m	h	h	h
m	vs	vs	vs	s	m	m	h	h
h	vs	vs	vs	vs	s	m	m	h
vh	vs	vs	vs	vs	vs	s	m	h

Figure 2: a)-c) Membership functions of input (angle of internal friction and slope)and output (disposition) variables; d) decision table; e)characteristic diagram for disposition with respect to angel of internal friction and slope

Fuzzy logic in the context of landslide modelling. The present development in ELDEWAS is the incorporation of expert knowledge by fuzzy methods as described in the previous subsection. This includes the development of a GUI that allows the definition of membership functions and rule tables.

In the context of landslide modelling the use of fuzzy logics can make sense in many

Substrate	Angle of internal friction $\varphi[^\circ]$
clay, silty clay	$0-15$
silt, sandy silt	$15-20$
silty sand, clayish sand	$20-25$
sand, grit and mixtures	>30

Table 1: Relation between Substrate and angle of internal friction

aspects. The consideration of different substrate types, for instance, corresponds to the angle of internal friction that usually requires mathematically crisp thresholds The relation between substrate type and angle of internal friction can be found in table 1. In reality the properties of substrates and the assignment to particular classes often is difficult. Here the fuzzy logic allows a characterization which is more manlike, since expressions like 'small', 'high' or 'low ' are used which correspond to the concept of linguistic variables.
In our example we like to consider only two input variables (internal friction and slope) and one output variable (disposition). Figure 2a-c) shows membership functions for the input and output variables. The input variables can take 8 and 5 different linguistic values, respectively, such that in total 40 rules have been formulated, which base on Tilch et al. [2008]. Two rules anybody can comprehend are:

IF *slope is* very high **AND** *internal friction is* small **THEN** *disposition is* high.

IF *slope is* small **AND** *internal friction is* small **THEN** *disposition is* very small

The latter rule shows that if the slope is small the susceptability becomes completely independent of the substrate and the corresponding angle of internal friction. These rules can also be found in figure 2d) that represents the rule table covering the full range between $0°$ and $90°$ for the slope and the angle of internal friction. In general we can state, that the susceptability increases with higher slopes and decreasing angle of internal friction since the resistance against the downhill-slope force becomes smaller.
Of course one can add another input variable like land use, for instance, where different types of land use effect in a more or less stabilizing way. Forest for instance has a stabilizing effect and decreases the susceptability on land slide.
The result is a characteric diagram 2e) of the disposition in terms of the slope and the angle of internal friction that bases on the decision table in 2d). Once this diagram is known for a given set of input values the disposition can be calculated immediately. In the context of landsliding also other parameters could be expressed by linguistic variables easier than they could be measured. If we think about the current state of soil moisture after a longer rain period, it is hard to quantify by measurements. Nevertheless, experts have experience when the moisture is subcritical or when destabilizing ranges are reached. Measuring this kind of parameters exhaustively for a whole region is impossible, but often experts are able to estimate them in rough categories. By means of fuzzy logic even this knowledge can be made accessible for the evaluation of dangers.

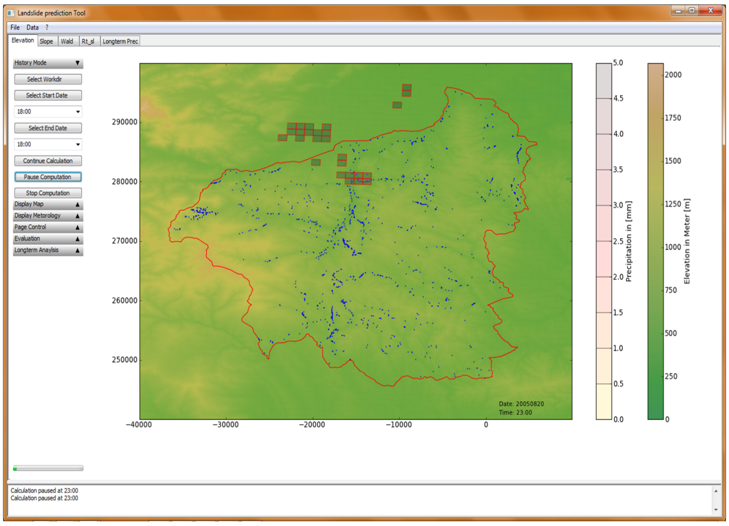


Figure 3: Graphical user interface of ELDEWAS: Blue grid points represent points of high disposition, magenta grids points points of high danger, red boxes represent cells with a precipitation rate $\geq$ 5mm/15 min

3 Application

3.1 Database

ELDEWAS was developed by means of the results in the BUWELA Project in Lower Austria (Tilch et al. [2008]). The aim of this work was to develop of a concept for disaster

management with respect to natural dangers. But the focus was on processes of mass motion. Some results of this project were available, especially the static hazard index maps (Tilch et al. [2008]). The BUWELA region in Austria covers a region of about 1000 km^2 in the east of Austria. The available maps have a resolution of 50 to 100 metres.
The dynamic data provided by the INCA System (ZAMG) are available with a resolution of 1 km^2 covering whole Austria. The INCA output can be precipitation, temperature, wind velocity and others. The main idea of INCA is to adopt the results of a numerical weather model by local measurements or radar and satelite measurements to the geomorphological conditions. Currently, only historical precipitation data from 2005 to 2008 are offline available, but in the end they should be loaded online from the ZAMG server.

3.2 First results

In first tests input parameters governing the disposition were the substrate type, slope, forest stand and precipitation rate. The selection encompassed all grid points where the slope was greater than 30°, no forest and an angle of internal friction lower than 20°. In figure 3 the blue points fullfill the conditions. The red boxes indicate all cells extending the precipitation rate of 5mm/15 minutes and blue points within red cells are coloured in magenta as critical. The corresponding coordinates are returned such that the decision makes know which region possibly gets critical.
In a next step a validation has to be performed comparing the results of model run with corresponding meteorological records with historical events. One event could be from 2005 in Klingfurth, where indeed a landslide event took place. These investigations and tests are still ongoing, but at the moment there is lack of information of historical events.

4 Summary and Outlook

In the present work we introduced the ELDEWAS system for early landslide detection and warning. The system is able to merge static maps about parameters effecting landsliding with dynamic meteorological data like precipitation. It provides a possibility to set threshold values for different parameters which define a set of grid points for which the sound disposition with respect to landslide is high. The functionality was demonstrated by an example of the BUWELA region.
This approach allows to consider data that are hard to measure or information from an incomplete knowledge base. Furthermore it is possible to describe nonlinearities and resembles the human way of thinking and assessment.
We highlighted this method by a small example in the context of landslide events where we defined membership functions, created a rule table and finally derived a characteristic diagram of disposition in dependency of the input variables.
The current work focusses on validation of the resulting models by real historical events and the evaluation of the ELDEWAS approach.

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