Changing patterns in climate-driven landslide hazard: an alpine test site

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Abstract The aim of this work is to develop a methodology for integrating climate change scenarios into quantitative hazard assessment and especially their precipitation component. The effects of climate change will be different depending on both the location of the site and the type of landslide considered. Indeed, mass movements can be triggered by different factors. This paper describes a methodology to address this issue and shows an application on an alpine test site.

The proposed approach is based on coupling a hydrological model (GARDENIA®) with a slope stability model (ALICE®), estimating safety factors spatially. From a DEM, land-cover map, geology, geotechnical data and so forth the program classifies hazard zones depending on geotechnics and different hydrological contexts varying in time. The methodology is applied to the Ubaye valley (France) using present and past climate conditions.

Keywords: hazard, landslide, climate change, hydrology

Introduction

In the next century climate change will lead to a modification of various meteorological parameters. The modifications of precipitation quantities and the variations in the spatial and temporal distributions of extreme events are some of the probable changes that should have an important impact on rainfall-induced landslides. However, development plans and mitigation measures are often designed for estimated impacts from hazard assessments based on past data and existing contexts, neglecting potential influences due to global change. These changes should be incorporated in the decision making process so that measures and plans will have longer validity.

In order to estimate the changing pattern of landslide activity, we present in the following a combination of models used to integrate these rainfall scenarios into quantitative landslide hazard assessments.

Models and Method

Models

GARDÉNIA

The GARDÉNIA® v.7.0 software package has been developed by BRGM for lumped hydrological modelling of rainfall–runoff and aquifer level (Thiery, 2003). The GARDÉNIA® model simulates the water cycle from rainfall received by the soil surface until the outlet, either as the discharge rate or as the aquifer level at a given point. The hydrological system is modelled by a system of 3 or 4 tanks (top tens of centimetres of soil, where evapotranspiration occurs; an intermediate level, where runoff occurs; and one or two aquifer zones, with delayed flows).

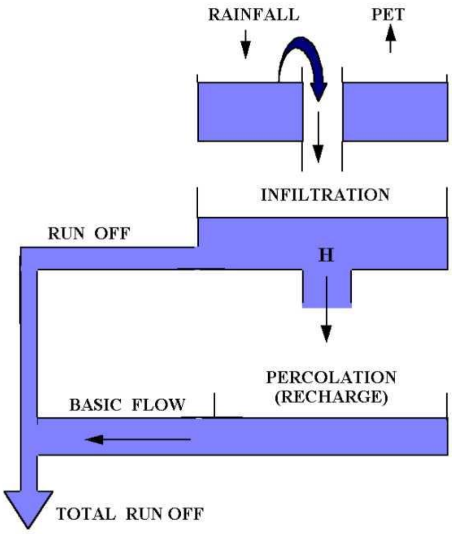

Figure 1: Schematic representation of GARDÉNIA®'s operating principle

Hence, it allows the simulation of the relationships between series of:

• discharge data of a spring or stream and rainfall amounts received by the corresponding basin; and

• piezometric levels in an aquifer and amounts of rainfall received by the corresponding basin.

This modelling involves 4 to 6 lump parameters (soil and atmospheric characteristics). These parameters have to be calibrated using rainfall and water level data from past records.

ALICE®, Assessment of Landslides Induced by Climatic Events

ALICE® (Sedan, 2011) is a software developed by BRGM whose main function is to produce landslide hazard maps, based on slope stability analysis, at various scales, from the single slope to hundreds of square kilometres. It was conceived as a tool within quantitative landslide risk assessment, which could be applied homogeneously on the whole French territory. Its principal components are:

• a finite slope stability model using the method of Morgenstern and Price (1967) applied at regular intervals of the 2D topographic profiles;

• a geographical Information System (GIS) since the software operates spatially; and

• the management of the variability and uncertainties of geotechnical parameters (through probability distributions).

The results are expressed either as a safety factor or a probability that this safety factor is below unity (instability).

A more detailed description of the software can be found in (Olivier et al., this issue).

In ALICE®, water in soil influences pore pressure. For the moment, the water component is simply introduced through the level of the saturated layer.

Method

The methodology proposed in this work is based on the coupling of both tools described above (Figure 2).

1 - GARDENIA converts meteorological inputs (either from past observations, current predictions or climate change models) into filling ratios of the different tanks.

2 - The filling ratio of the intermediate tank is then converted to the level of the saturated layer into ALICE® using minimum and maximum piezometric maps. These maps are established thanks to piezometric data and SIG hydrological calculations weighted by experts.

3 – ALICE® computes probabilistic distributions of the safety factor for each profile.

4 - Susceptibility (equal to the probability of the safety factor being below unity) is mapped.

Hence, after a calibration phase for both tools, based on available observations of rainfall events, water table levels and historical landslides, this methodology computes an estimate of the susceptibility for rainfall-induced landslides that could occur at the regional scale. Meteorological events gather all information from forecasts for near-future events to scenarios from climate change models for further periods. This is particularly useful in evaluating changing patterns of landslide activities due to climate change.

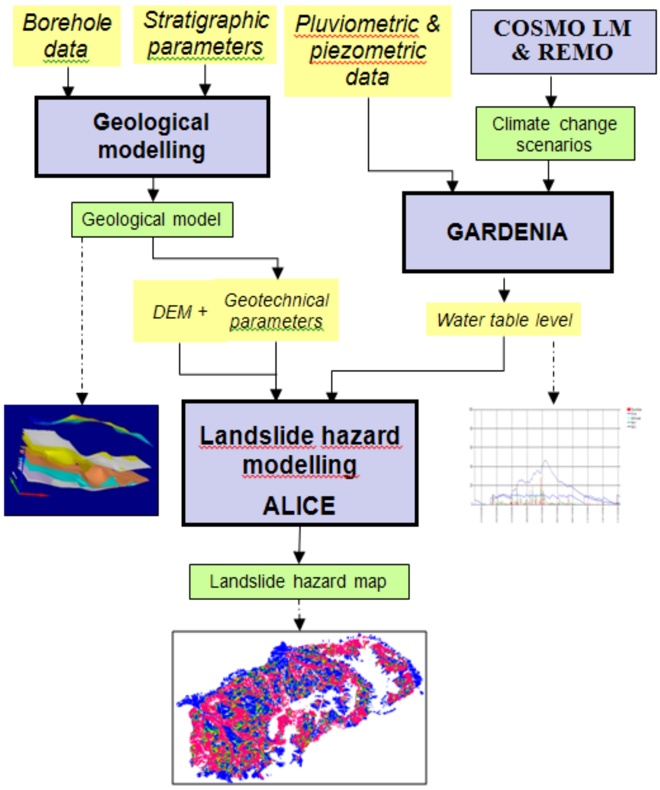

Figure 2: Chain of the methodology for coupling the hazard assessment tool with the hydrological model

Application to an Alpine site: the Ubaye valley

Site presentation

The studied site is a 350 km² zone, situated in the south of France in the département Alpes de Haute Provence around the municipality of Barcelonnette. It is located in a mountainous area, reaching altitudes of approximately 3100 m, with an average altitude of 1100 m, and it is crossed by the Ubaye River.

The Barcelonnette Basin is characterized by a asymmetric valley. The north-facing slope is characterized by allochtonous sandstones outcrops and autochthonous marls. Dominated by black marls covered by moraine deposits (2 to 20 m), its gentle slopes (10-30°) present an irregular topography with steep convex, planar and hummocky slopes. On the other side, the south-facing slope presents the steepest slopes (35-75°) which associated bar rocks on the upper part (45-75°), and screes on the lower part (35-50°). The lower slopes associates convex and hummocky slopes (15-30°) and are covered by moraine deposits (Malet, 2003).

The landslide hazard is high in this area, the slopes being notably affected by severe gullying and both shallow and deep-seated large landslides (for example La Valette and Super-Sauze). Currently, many factors tend to make slopes unstable such as a dry and mountainous Mediterranean climate, with strong inter-annual rainfall variability.

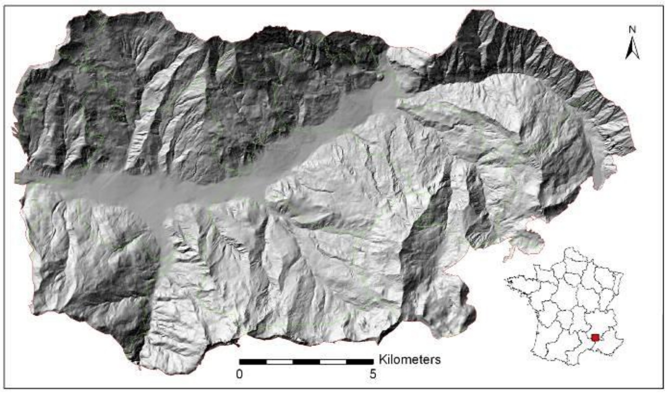

Figure 3: Study area location

Data

Climate data

The regional climate model REMO (Jacob, 2001) provides basic information on possible future changes in the European climate until the end of the 21st century at a spatial scale of 25km. These simulations have been carried out under the SRES emission scenario A1B within the European ENSEMBLES project. They have been used as boundary conditions of dedicated REMO simulations at a very high resolution of 10 x 10 km² for the period 1950-2050 in the area of the Alps.
The second phase of the study consists in applying the non-hydrostatic COSMO Lokal Modell with a resolution of 3.8 x 3.8 km² to the results of the REMO simulations. In this way, a physically consistent simulation of small scale climatic features, e.g., local precipitation extremes and other landslide triggering events, is possible and can be linked to geo-mechanical models used for high resolution case studies.

Geotechnical data

A simplified geological model has been established from an engineering soil map (Thiéry, 2007). For the first ALICE® runs, it has been decided to divide the area in 10 different geotechnical zones. Each zone is represented by a soil column made of 3 layers called soil units (the lower one is bedrock). Each soil unit is characterized by its thickness and several geotechnical parameters such as friction angle, dry density and cohesion. Because laboratory tests do not always supply large-scale parameters some of them have been determined thanks to expert judgement. In a first step, constant values have been used.

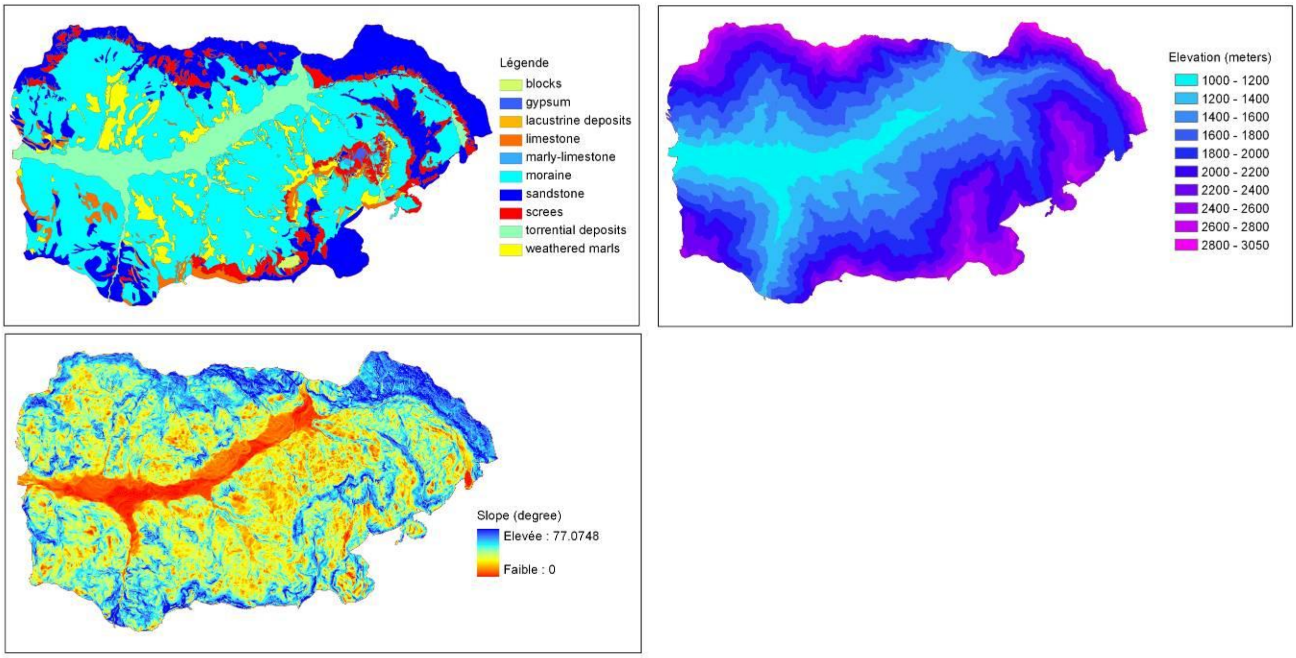

Figure 4: Main data used in the model: geotechnical zones, elevation model (resolution: 10 m) and slope map (resolution: 10 m)

First modelling scenario

Before being able to use climate change data (COSMO Lokal Modell simulations were still running when the study began), the methodology was tested using 3 different water table scenarios. These scenarios cover the two extreme cases: the minimum water level (filling ratio=0), corresponding to a drought period and the maximal one (filling ratio=1), corresponding to period of heavy and lasting rainfall; and an average situation (filling ratio=0.5). The safety factor calculation also needs the landslide type (rotational or translational) and its length. These parameters were defined for the whole studied area and, for now, only 50m-rotational slides were considered.

Results

The whole chain was run with the 3 different filling ratios, providing 3 maps of safety factors (Figure 5). These preliminary results show that, as expected, an increase of the water content of the soil (e.g. in our case due to a long period of rainfall) induces a reduction in the safety factor, and a decrease in the water level makes the slopes more stable. These changes are not uniform over the area. Effects of water-table changes are more pronounced on profiles with steepest slopes.

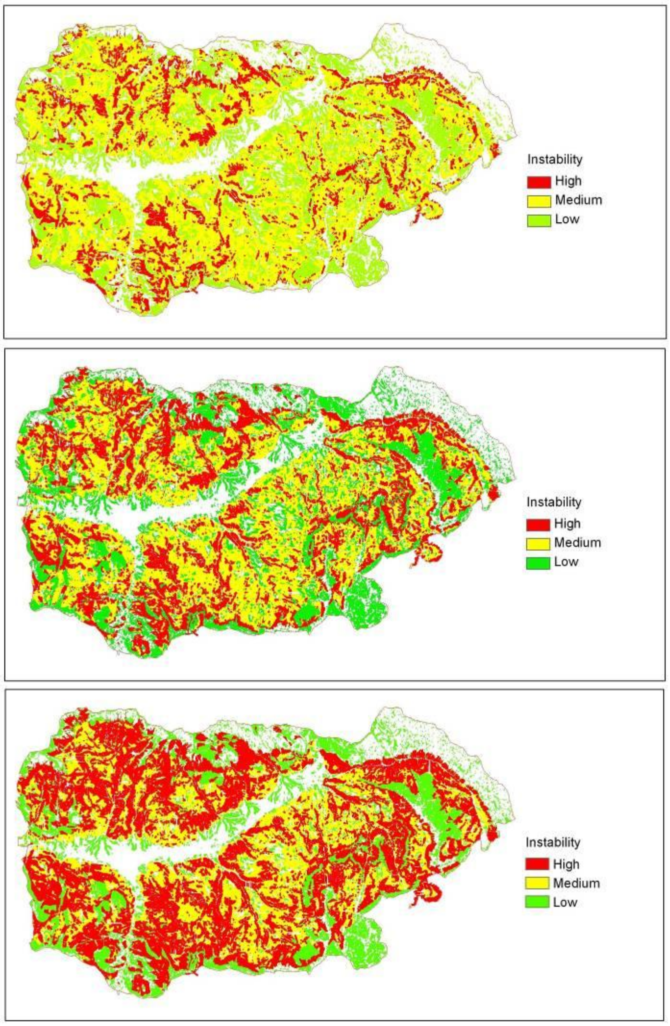

Figure 5: Representation of instability resulting from the simulations using the 3 different filling ratios. The ratio is 0 (top), 0.5 (middle) and 1 (bottom).

Conclusion and perspectives

Dealing with risks requires an evaluation of what the future could be. Thus, changes in triggering factors have to be taken into account in hazard assessment, and not only qualitatively, but also quantitatively. In order to cope with this issue, a method was proposed here.

A hydrological model (GARDENIA®) is combined with a quantitative landslide assessment model (ALICE®) to allow the integration of climatic scenarios into landslide susceptibility mapping.

The results presented here are only preliminary results and were shown to demonstrate the feasibility of the method. In the near future, the following developments will be presented.

- Uncertainties and variability of the geotechnical parameters would be quantified thanks to probabilistic distributions.
- Monte Carlo simulations will be performed to provide probabilistic information on safety factors.
- The hydrogeological model will be completed, taking into account the unsaturated part of soils.
- Analysis will be done for the different types and lengths of landslides, which occur in the area.
- Geotechnical models will be refined.
- Climate change data will be used to evaluate changing patterns of landslide activity.

Acknowledgments

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