Assessing the influence of climate change on the activity of landslides in the Ubaye Valley

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ABSTRACT: Effects of past, present and future climate characteristics on landslide activity can be assessed by historical information, geomorphological evidences, and modelling of slope hydrology and mechanics. However there are a series of problems related to that approach. First, quantitative assessments of the spatial and temporal relationships between climate and landslide occurrences are often hampered by the inaccuracy and uncertainty of the historical records, and by the scarcity of climate data in mountain areas. Second, the climate-landslide coupling is complex, because climate is related to landslides via the nonlinear soil water system. Process-based models have been proposed to understand this complex interaction. However, landslide triggering systems show complex responses in relation to geotechnical, hydrological, and climate properties. Third, the uncertainty in future climate parameters is high, especially if the time context is greater than weather records or because of the low-resolution of the downscaled climate time series. The objectives of this paper is to present some results on the climate-landslide relationships for two landslide types observed in the Ubaye Valley, and to propose a method for assessing the impacts of climate change on landslide frequency.

1 INTRODUCTION

Many factors can affect landslide incidences including climate characteristics, seismic activity, human activity or compound factors. As a consequence, the causation between climate and landslides have never been simple, and is regarded by many researchers as problematical (Corominas, 2000), especially in terms of spatial and temporal scales. Climate acts as a complex agent on the magnitude and frequency of landslides via the nonlinear soil water system (Iverson, 2000; Bogaard & van Asch, 2002). Consequently, combining regional and local analyses is necessary to minimize the effects of predisposing factors such as geo(morpho)logic conditions and landscape history, to elucidate the relationships between climatic factors and landslides. Moreover, understanding landslide hydrology and landslide mechanics is the basis for quantitative assessments of the possible influence of climatic changes on slope stability.

This work deals with the understanding of changes in the activity of rainfall-controlled landslides in the Ubaye Valley (South East France) in the last century by combining archive analysis, field investigation, hillslope monitoring and model simulations. The work presents a method for assessing the climate change impacts on landslide frequency by combining climate time series predictions and hydrological-slope stability modelling. The main hypotheses of the work are:

1) The analysis of the climate-landslide relationships in a specific climatic sub-zone and ecoregion (20 x 30 km) characterized by a mountainous Mediterranean climate.

2) The analysis of the climate-landslide relationships for the recent time (e.g. last 50 years of the 20th century); influences of climate variation since the last deglaciation are not considered. Climate records since the late 1900s indicate a limited magnitude of climatic changes: the variability of 10-years average parameters (rainfall amounts, mean temperatures) is quite small though higher variability is observed on smaller time scales.

3) The analysis of the temporal pattern of landslides observed in a geologically homogeneous lithology (black marls). The work focuses on the characterization of two rainfall-controlled landslide types representative of the study area: rotational or translational slides occurring in moraine deposits and at the contact with the black marls bedrock, and deep-seated large mudslides occurring in weathered and reworked black marls.

4) The identification of the hydrological and geomechanical mechanisms controlling the behaviour of the landslide types, and the possibility to reproduce their -observed- temporal pattern with a simple process-based slope model.

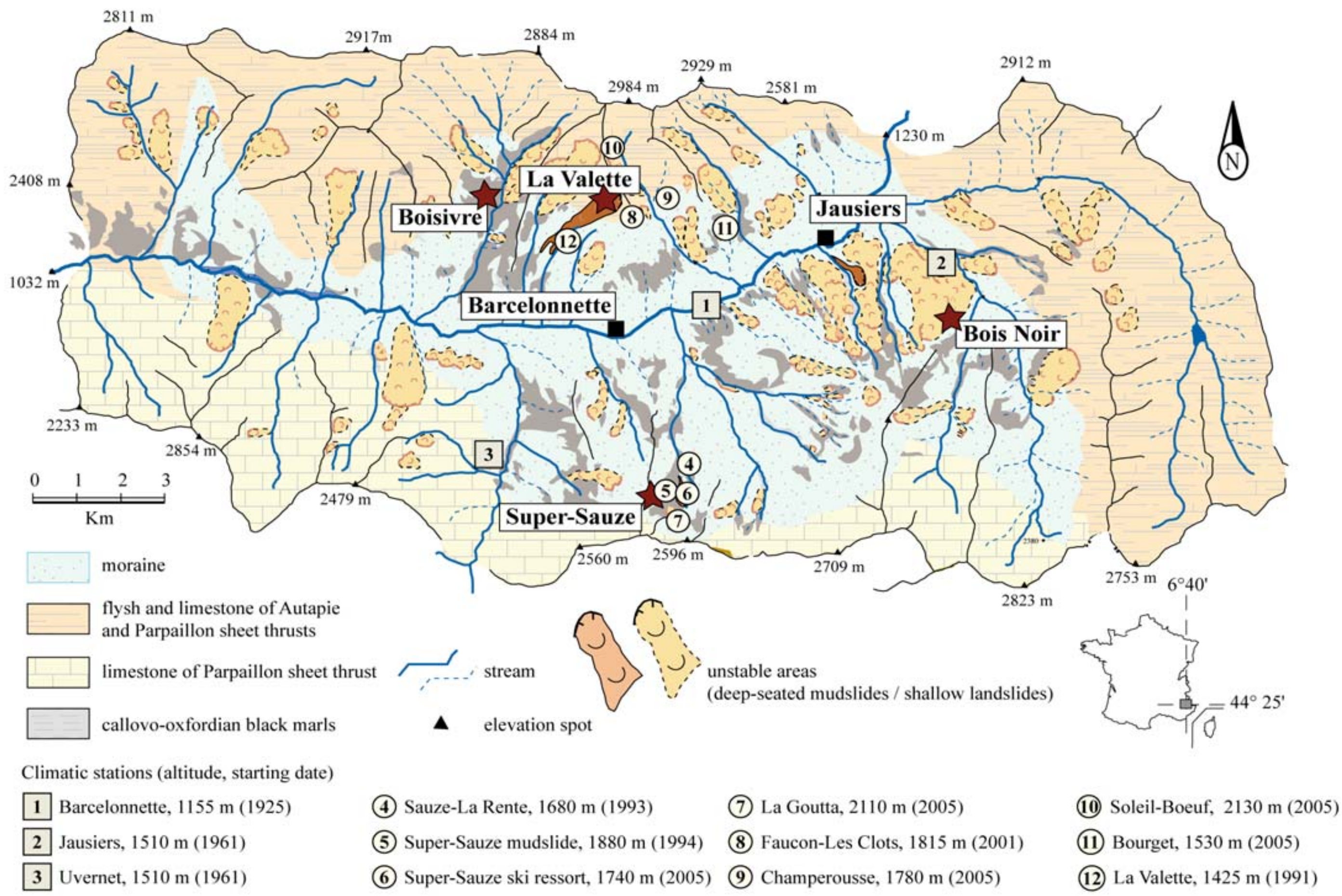


Figure 1. Geomorphology of the Barcelonnette Basin and location of the meteorologic station and study sites mentioned in the text.

5) The introduction of meteorological parameters, characterizing a climate change scenario, as boundary conditions to the slope hydrology and stability models (Buma & Dehn, 1998). The 'changed' meteorological parameters (e.g. time series) are issued from the downscaling of General Circulation Models (GCMs) at the local scale of the study area.

Considering the above mentioned hypotheses and the small magnitude of climatic variations during the interval (1950-2005) in which landslide data have been analysed, it is possible to consider modern climatic records as representative of the actual climate-landslide relationships, and to further apply climate change scenarios to model landslide frequencies. Besides the proposed methodological framework to assess impacts of climate changes on landslide activity, the paper discusses the differences in landslide frequencies observed on the period 1950-2005 and simulated for the period 2069-2099.

2 CHARACTERISTICS OF THE STUDY AREA

The Ubaye Valley is representative of climatic, lithological, geomorphological and landuse conditions observed in the South French Alps, and is highly affected by landslide hazards (Flageollet et al., 1999). Within the valley, the Barcelonnette Basin (Fig. 1) extends over an area of 200 km², from 1100 m to 3100 m a.s.l, where Quaternary glaciers and about 26 torrents have carved out a large tectonic window in autochtonous Jurassic marls very sensitive to weathering. Black marls are overlaid by flyschs and limestones of allochtonous sheet thrusts, and mostly covered by moraine and deposits. The slope gradients range from 20° to 50°.

The study area is located in the dry intra-Alpine zone, characterized by a mountainous Mediterranean climate with a high inter-annual rainfall variability (735 ± 400 mm over the period 1928-2005), a mean annual temperature of ca. 7.5°, and the presence of a snow pack on the upper slopes for 4 to 6 months. Melting of the snow cover adds to the effects of rain in the triggering of landslides in spring. Locally, summer rainstorms can be intense, yielding sometimes intensities of more than 40 $mm.h^{-1}$.

These predisposing geomorphologic and climatic factors explain the occurrence of several landslide types in the area. The La Valette, Poche and Super-Sauze mudslides are significant examples of large and active landslides affecting black marls slopes for several decades. The moraine slopes are highly affected by shallow rotational and translational slides triggered at the contact with the lithic bedrock (Thiery et al., submitted). Finally, the torrents are experiencing the occurrence of muddy debris flows since more than 100 years (Remaître et al., 2005).

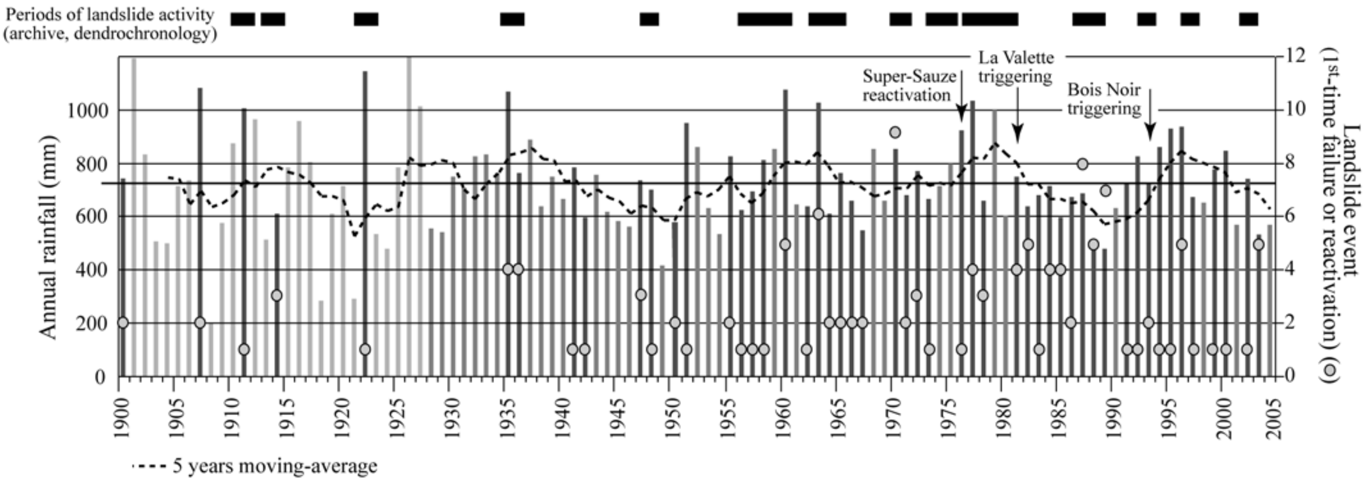


Figure 2. Annual rainfall and references of landslide activity (archives investigation e.g. RTM dataset, dendrochronology analyses).

3 CLIMATE-LANDSLIDE RELATIONSHIPS

The climate-landslide relationships have been analysed for the recent time (period 1950-2005) at several time intervals in order to attempt to determine climate conditions (and possibly rainfall thresholds) able to trigger or reactivate landslide in the study area.

The long-term rainfall pattern indicates cyclic variations of 10-15 years of the annual rainfall amount (Fig. 2). These variations comprised periods of 5-7 years of annual rainfall amounts in excess to the mean annual rainfall observed for the period 1900-2004. For example, two large mudslides were triggered or reactivated during periods of excess cumulative rain: the Super-Sauze mudslide had a major reactivation in the end of the 1970s and the La Valette mudslide occurred in 1982 (Fig. 2). As well, the Bois Noir translational slide occurred during the most recent period of excess cumulative rain at the beginning of the 1990s (Fig. 2). However, some relatively dry periods (like the period 1982-1990) are also characterized by the occurrence of landslides, testifying of the complexity of the landslide-climate relationships. On longer time scale, datings of eccentricities of tree rings in some slopes of the study area demonstrated landslide frequencies of ca. 4 ± 2 years (Verhaagen, 1988; Buma, 2000), indicating climate characteristics favorable to a continuous activity of slope processes. However, as frequently observed elsewhere, rainfall is one of the factors that accelerate or triggers landslides, together with other factors such as landuse or tectonic activity (Corominas, 2000). At the monthly scale, no systematic correlation has been made evident between rainfall amounts and landslide frequency, though the spring (deep mudslide) and summer seasons (shallow slump) are the most favourable periods for landslides. At the daily scale, on the basis of about 20 events for which an exact date of occurrence is available, two types of climate situation have to be considered (Fig. 3):

1) Type A situation is characterized by heavy daily rainfall following a 30-days dry period. For most of the observed landslide events, this climate situation corresponds to violent summer storms. The triggering of shallow slumps, translational slides, hillslope mudflows and/or channel debris flows is usually associated with this type. Although, the correlation between landslide events and the rainfall of the triggering date is quite good, no threshold can be established due to the inaccurate knowledge on rainfall variability, especially in the upper part of the hillslopes. For these reasons, several meteorologic stations have been installed around landslide areas since 1993 (like in the Sauze and Faucon catchments; Fig. 3, Fig. 1).

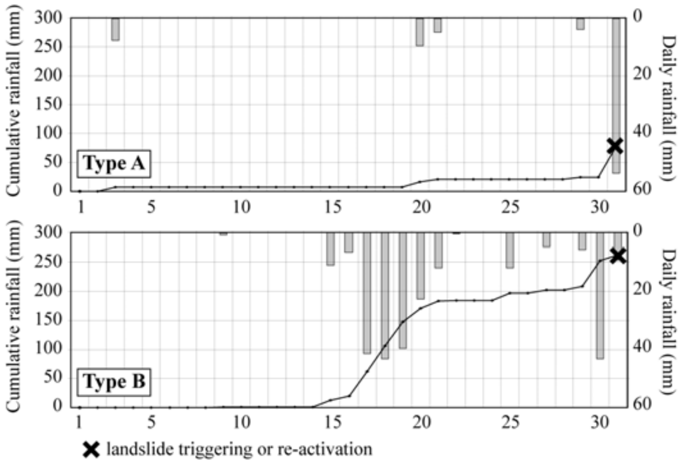


Figure 3. Schematic climate situations of landslide triggering or reactivation in the Barcelonnette Basin. Example of a landlside observed on 15 September 1960 (Type A), and of a landslide observed on 16 November 1963 (Type B). The X-coordinate represents 'day' from the onset of failure.

2) Type B situation is characterized by heavy cumulative rainfall distributed over a 30-days very humid period. This climate situation characterizes either the progressive saturation of the topsoil, the rising of a permanent groundwater table and the build-up of positive pore pressures. Cumulative rainfall over a short period is often enough to trigger

or reactivate a landslide, though little rainfall is observed at the date of occurrence. Triggering or reactivation of deep-seated mudslides are frequently associated with this type (Malet et al., 2005).

Thus, as often observed elsewhere, rainfall is one of the most important elements to be considered in landslide triggering/reactivation. The complexity of the landslide-climate relationships suggests the use of modelling techniques, validated on well-documented sites, to gain knowledge and identify possible trends in landslide frequency.

4 METHODOLOGY TO INVESTIGATE THE EFFECTS OF CLIMATE CHANGE ON LANDSLIDE FREQUENCY

The proposed methodology simulates the effects of climate change on landslide frequency with process-based models of slope hydrology and slope stability. Climate change scenarios (e.g. climate variables) of General Circulation Models (GCMs) are used as input conditions for the slope models. These climate scenarios are within the range for which the slope models have been elaborated and validated. Figure 4 depicts the general methodology of combined downscaling of GCMs and slope stability modelling.

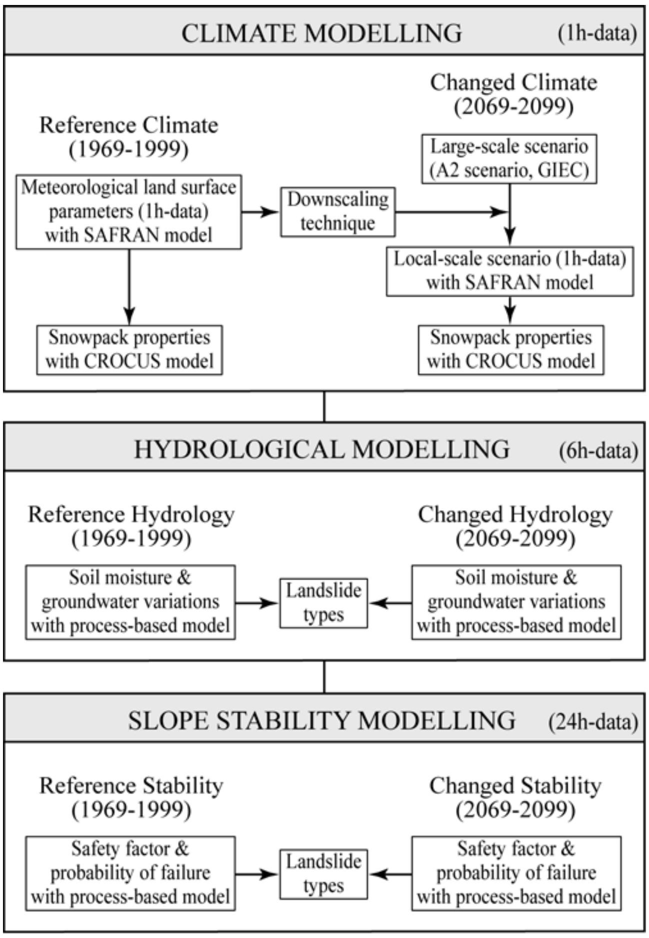


Figure 4. Chain of modelling steps for local assessment of the effects of climate change on slope stability and landslide frequency.

The models are applied on two unstable slopes (Fig. 1) for which detailed information on slope geometry, hydrology and activity is available:

1) The Super-Sauze mudslide is a clay-rich flow-like landslide developed in weathered black marls (thickness varying from 10 m to 20 m), and characterized by a complex vertical structure (Malet & Maquaire, 2003). Groundwater fluctuations are controlled by water infiltration both in the soil matrix and in large fractures as well as recharge from the torrents bordering the landslide (Malet et al., 2005; Montety et al., 2007). The mudslide is persistently active since the late 1960s, with velocities comprised between 0.005 to 0.3m.day^{-1}. Acceleration periods (not exhaustive) have been observed in 1978-1982, 1995, 1999, 2000, 2006.

2) The Boisivre rotational landslide is a slump characterized by a top morainic layer (thickness 1.5 m), underlain by a weathered and unsaturated black marl layer (thickness 5 to 6 m) which overlies the bedrock of unweathered marl (Mulder, 1991). Landslide activity is a consequence of high groundwater levels in the weathered marl layer and the temporal occurrence of a perched water table in the top moraine deposits (Caris & van Asch, 1991). The landslide has been active for decades with a return-period for reactivation of ca. 3-4 years.

4.1 *Slope Hydrology Model*

The Slope Hydrology Model (van Beek, 2002; Malet et al., 2005) uses net precipitation, temperature and net radiation, as well as geometrical and hydrological characteristics, in order to simulate water flows within the slope. The hydrological model consists of three permeable reservoirs and the underlying impervious bedrock. It describes saturated and unsaturated transient flows in the vertical and lateral directions assuming freely drainable water. Storage (antecedent soil moisture condition) and fluxes (precipitation P, infiltration I, evaporation Ep, surficial runoff R, percolation in the unsaturated zone Pe, saturated lateral flow Q_{sat}) are considered in the different reservoirs and define the hydrological balance of the system (Fig. 5a). Groundwater generation is simulated by imposing boundary conditions: the lower boundary condition is state-controlled and is specified as fixed value for the matric suction; the upper boundary condition is flux-controlled and account for the climate inputs at the surface. A complete mathematical description of the model can be found in van Beek (2002).

The dynamic model is implemented in the PCRASTER GIS package (Wesseling et al., 1996). This approach provides a unified theoretical description of most of the water fluxes observed within a landslide, and allows the easy integration of complex geometry as the effects of topography can readily be incorporated and GIS routine functions can be used to define flow paths in each soil layer.

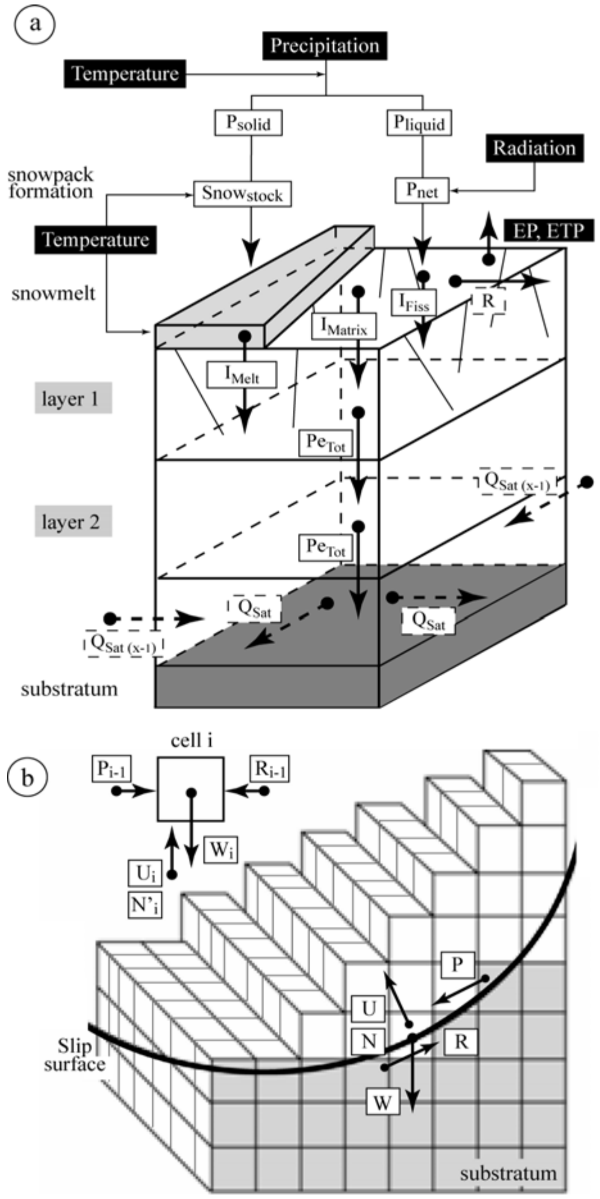


Figure 5. Architecture of the hydrology (5a) and slope stability (5b) model. (a) Schematic representation of the storages and fluxes simulated by the hydrological model, and relation between the calculation cells; (b) Schematic representation of the force diagram used in the slope stability model for each calculation cell i. W is the total weight, U is the pore pressure force at the base, N is the effective normal force, P is the pressure term, R is the resisting shear force.

4.2 *Slope Stability Model*

The Slope Stability Model is a limit equilibrium model loosely coupled to the hydrological model (e.g. the simulated groundwater levels define the pore pressures introduced in the slope stability model). The model calculates the safety factor of the slope, which is the ratio between the available total resisting forces and the total driving forces. The resisting forces decreases with increasing pore pressure and when the safety factor drops below unity, failure is predicted. The limit equilibrium approach only considers yielding by plastic failure and uses the Mohr-Coulomb failure criterion. The stability of the slope is calculated with the Janbu force diagram (Janbu, 1957). This allows to take into account non-uniformly distributed forces throughout the soil mass and the effects of interslice forces. Slope stability is therefore dependent, not of the local cell attributes only, but of several adjacent cell attributes (Fig. 5b). This is only possible because detailed geometries (e.g. slip surface depth) are available for both landslides.

Quantification of slope stability is deterministic and requires the inputs of the slip surface depth and the geotechnical properties. Probability of failure is determined by the uncertainty in the shearing resistance estimated from the observed distribution of the geotechnical parameters (Maquaire et al., 2003).

4.3 *Climate Modelling for the 20th & 21th centuries in the Ubaye Valley*

The climate modelling part of this study comprises the simulation of meteorological surface parameters for the last 30 years of the 20th and 21th centuries:

1) Several meteorological surface parameters have been computed at an hourly timestep for the period 1969-1999 with the SAFRAN model (Durand et al., 1993; 1999). SAFRAN is a meteorological application used for more than 10 years in real-time avalanche hazard forecast. SAFRAN is able to spatialize meteorological parameters for several slope configurations (elevation, aspect) by combining observed meteorological surface data, preliminary estimations of general circulation fields (ERA-40 reanalyses) through appropriate downscaling operators, and climate classifications (synoptic weather types). The reanalyses of the ERA-40 outputs (ECMWF, 2004) have been used at a spatial scale of ca. 125 km for the last 30 years.

Time series of air temperature, air humidity, wind speed, rain and snow precipitation, long-wave radiation, direct and scattered solar radiation, infra-red atmospheric radiation and cloudiness were simulated. Quality of the regionalization operators has been tested at Barcelonnette site, without using the observed meteorological dataset in the SAFRAN simulations.

Comparison of the datasets indicates good agreement of the simulated climate with the observation at a daily time scale (Fig. 6). The simulated time series were then re-calculated in order to take into account local topographical settings (elevation, aspect, slope gradients, orographic mask); this has allowed to correct the time series from the effects of the relief on the initial radiation, temperature and air humidity fields. The SAFRAN downscaling operators are integrating composite large-scale data fields of GCMs, classification of weather types, and site observations. These operators are used in routine for snow avalanches hazard forecast.

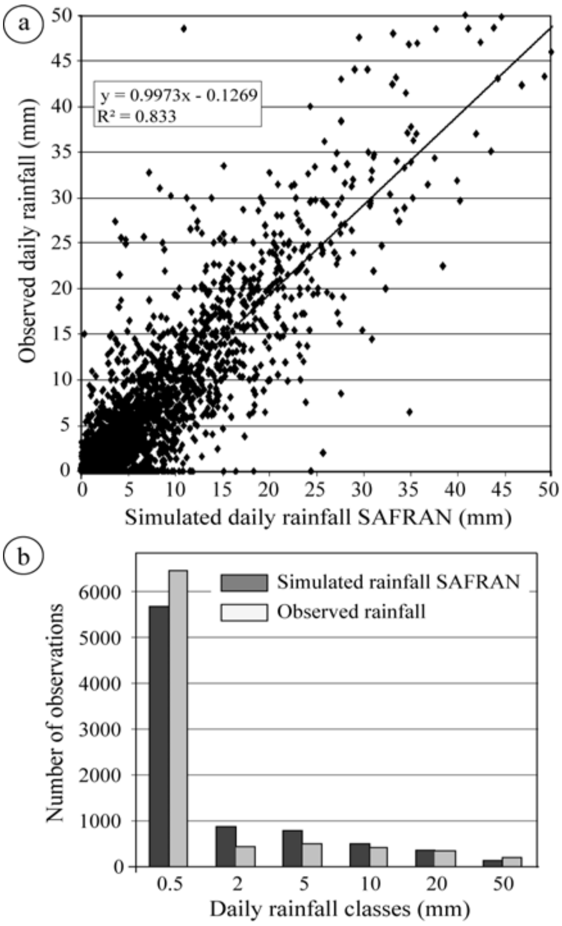


Figure 6. Meteorological land surface parameters observed and simulated with SAFRAN for the period 1969-1999 at Barcelonnette. (a) Rainfall amounts; (b) Rainfall frequencies.

2) The disaggregation procedure used to simulate the meteorological parameters over the period 1969-1999 has then be applied to the outputs of the climate change scenario A2 of GIECC over the Alps for the period 2069-2099.

As the ARPEGE-IFS GCM is a simplification of the atmosphere system, the simulated daily variability is quite different from the observations (Gibelin & Déqué, 2003; Déqué et al., 2006) with an underestimation of the extreme values. Therefore, the local climate is only characterized from a statistical viewpoint. A perturbation method has been used in order to downscale the parameters to the local scale with the constraint to keep constant the density function of the ARPEGE-IFS GCM simulation for the period 2069-2099 for each SAFRAN parameters. The method, which presents a high temporal coherence does not take into account climate evolution in terms of frequency of weather types or modification in the frequency of extreme events. The average values of the perturbations associated to the A2 climate change scenario are presented in Figure 7. The main characteristics of the changed climate for Southeast France are: a) higher temperatures in summer, b) more rainy winters, c) drier summers, d) a decrease in soil water content except for winter freezing areas.

A regional operator, based on the minimisation of the XY and Z distances between the study sites and the ARPEGE-IFS GCM grid outputs has been used. Hence, it was possible to compare the Probability Density Functions (PDFs; Fig. 8a), and the corresponding centiles (Fig. 8b), obtained with the disaggregation of the reference (1969-1999) and changed (2069-2099) climate. The differences observed are important, e.g. the average annual temperature rises from 2.4°C to 6.2°C over one century, and the distribution is shifted towards the extreme values. A climate change operator was defined from the analysis of the reference outputs (1969-1999) and the changed outputs (2069-2099) (Fig. 8b). For a X-coordinate on Figure 8b, which represents a centile of the temperature distribution, the probability to obtain a temperature equal or lower than the reference climate or the changed climate is equal. Figure 8b indicates that the increment between two populations varies according to the reference temperature.

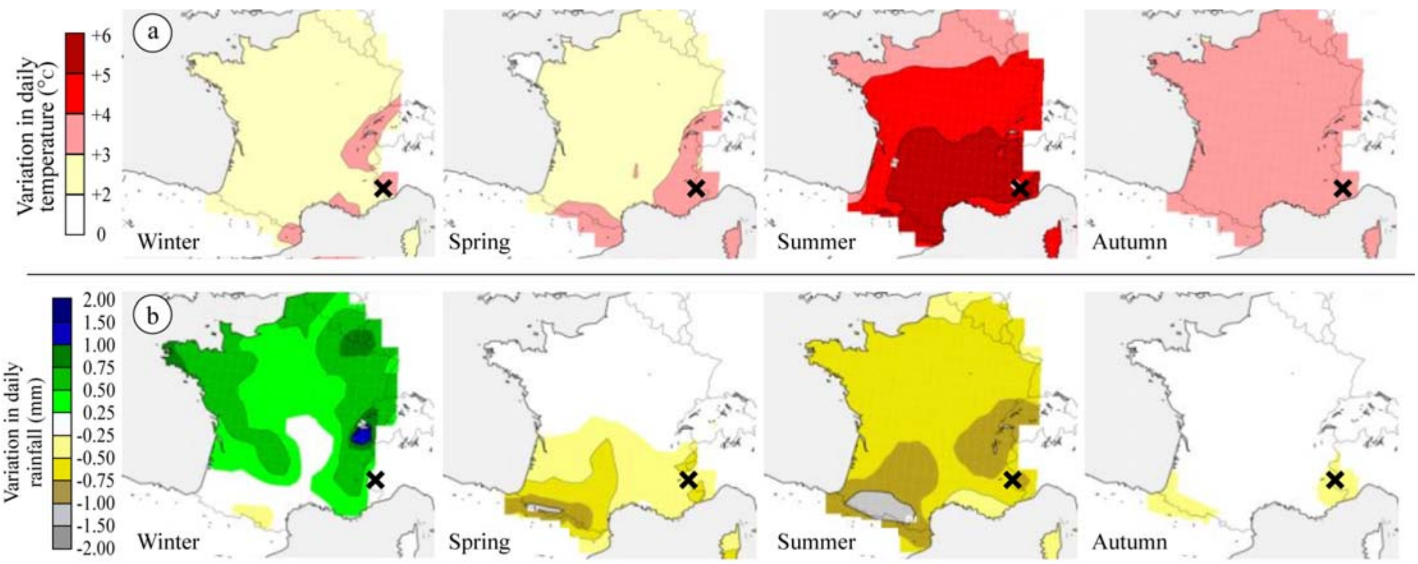


Figure 7. Impacts of climate change with the ARPEGE-IFS experiment based on the A2 scenario of GIECC. (a) Temperature; (b) Daily rainfall.

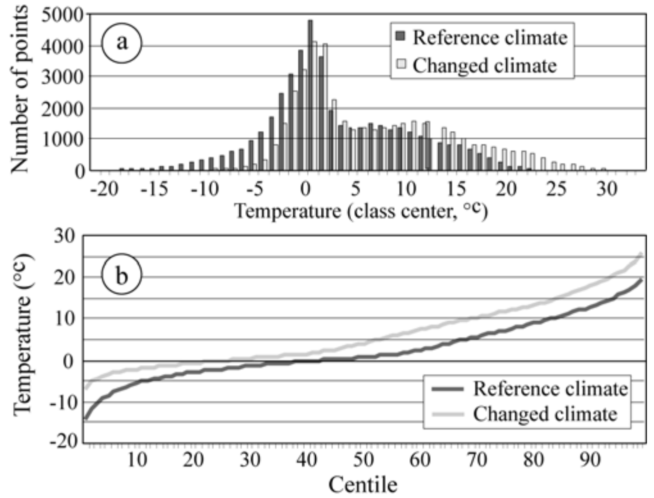


Figure 8. Impacts of climate change at Super-Sauze (1800 m). (a) Probability Density Functions of air temperature for the reference climate (1969-1999) and the changed climate (2069-2099). (b) Centiles of air temperature derived from Figure 8a.

Then, the operator has been applied to the reference dataset computed by SAFRAN in order to create a 'climate change' dataset which fits the statistical distribution of the changed climate. The average values of the variations of several meteorological parameters are presented in Table 1.

	T	RH	P_L	P_S	N	W	Q
Z = 1800 m	+3.8	-2.4	+0.11	-0.5	-4	-0.04	+23
Z = 2100 m	+3.8	-2.3	+0.47	-0.6	-4	-0.02	+26

Table 1. Average impacts (30 years) of the climate change scenario A2 on several meteorological parameters downscaled on local sites of the Barcelonnette Basin, at respectively 1800 m and 2100 m a.s.l. T is air temperature (°C), RH is relative air humidity (%), P_L is liquid precipitation (mm), P_S is solid precipitation (mm), N is nebulosity (1/100^e), W is wind velocity (m.s^{-1}), Q is total surface energy potential (W.m^{-2}).

4.4 *Snowpack modelling*

As snow cover has a critical influence on landslide activity in the study area (Malet et al., 2005), a detailed simulation of the snowpack properties has been realised. The CROCUS model (Brun et al., 1989; 1992) is able to simulate all the mass and energy transfers within the snowpack, as well as the snow characteristics, including the presence of liquid and melting waters.

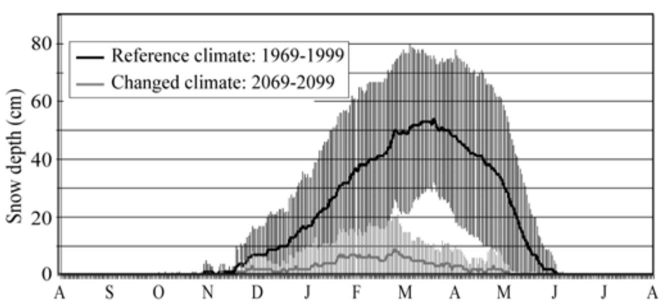


Figure 9. Impacts of climate change at Super-Sauze (1800 m) in for the daily average snow depths. The X-coordinate represents the months (from August to July); the vertical lines express snow depth variability.

Figure 9 represents the average daily values of snow depths for the two climates at 1800 m. a.s.l. The impact of climate scenario A2 is particularly dramatic for snow depth at this elevation.

5 APPLICATION TO THE METHODOLOGY TO THE SELECTED SITES

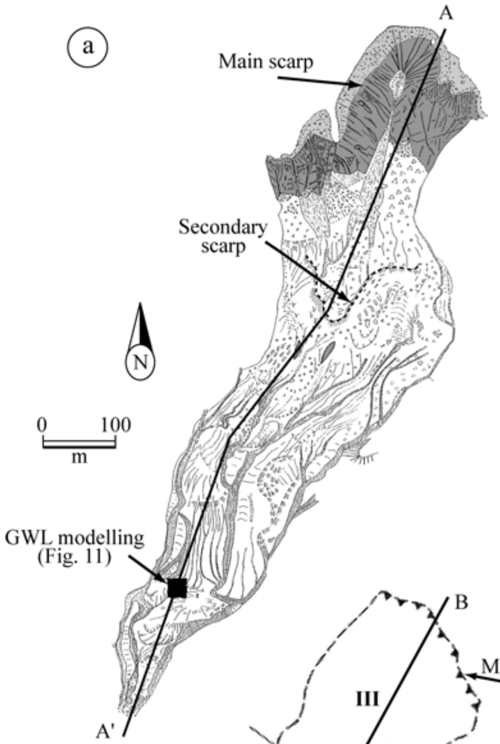
5.1. Model implementation

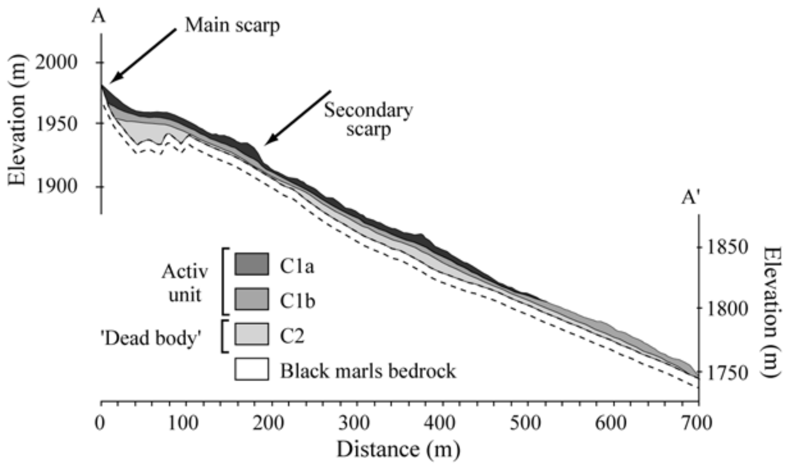
The slope models have been applied to the sites assuming a compromise between the complex topography of the landslides and the distribution of soil properties. In both cases, a cell resolution of 5 m has been used. Geometry of the layers is derived from detailed geotechnical and geophysical investigations (Malet & Maquaire, 2003; Caris & van Asch, 1991). Depth of the slip surface is known for both sites, and is therefore fixed in the model. Hydrological and geotechnical properties (Fig. 10) are derived from both laboratory and soil characterization, and further optimisation of the model performance on the basis of multi-source field observations (Malet et al., 2005). The assigned parameters values are indicated on Figure 10. The timestep resolution has been set at 6 hours for the groundwater modelling, and 24 hours for the slope stability modelling. At Super-Sauze, model performance has been extensively validated on several piezometers and monitoring periods (Malet et al., 2005); at Boisivre, the hydrological model has been tuned against the groundwater simulations of Caris & van Asch (1991). Both experiments show good agreement with the observations.

5.2. Simulated hydrology and probability of failure for both sites and climate

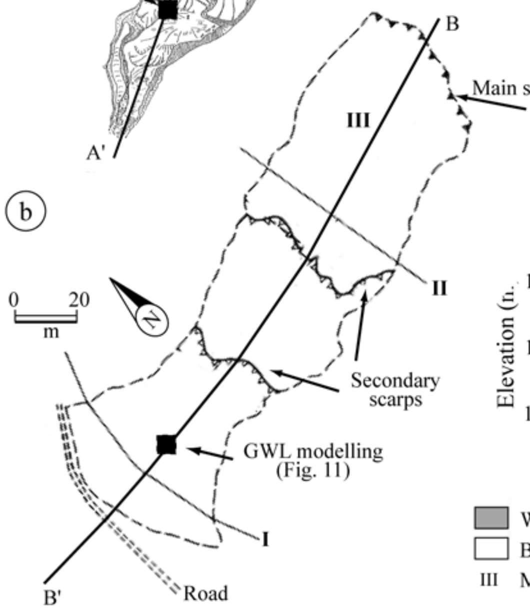
Figure 11 shows the results of the groundwater modelling for the reference climate and the changed climate for both sites. Uncertainties were considered in the simulation by performing 100 model runs with many possibilities of model input values (e.g. average hydrological and geomechanical parameter values and their variation range).. Therefore, the model outputs in Figure 11 represent the average groundwater levels (GWL) of 100 model runs.

The hydrological model simulates a general decrease in both GWLs and amounts of water storage in the unsaturated soil in the next century. This is particularly true for the Boisivre landslide with a decrease in the average GWL of ca. -2.3 m in comparison to the reference climate (Fig. 11). GWL lowering is explained by a marked decrease in soil effective porosity (e.g. soil moisture in the unsaturated topsoil) with the changed climate, resulting in less vertical percolation to the saturated zone.





Hydrological parameters	Model input values		Geotechnical parameters	Model input values	
	Sauze	Bois.		Sauze	Bois.
Kv_1 (cm.d^{-1})	0.40	0.40	γ_d (kN.m^{-3})	15	16
Kv_2 (cm.d^{-1})	0.30	0.30	γ_w (kN.m^{-3})	17	19
Kv_3 (cm.d^{-1})	0.30	/	ϕ_1 (°)	28	32
Rat_K (-)	0.01	0.01	ϕ_2 (°)	28	25
θsat_1 (-)	0.38	0.38	ϕ_3 (°)	24	/
θsat_2 (-)	0.24	0.24	c'_1 (kPa)	2	2
θsat_3 (-)	0.21	/	c'2 (kPa)	2	1
$\lvert h \rvert_{BC}$ (m)	2.98	2.98	c'_3 (kPa)	1	/



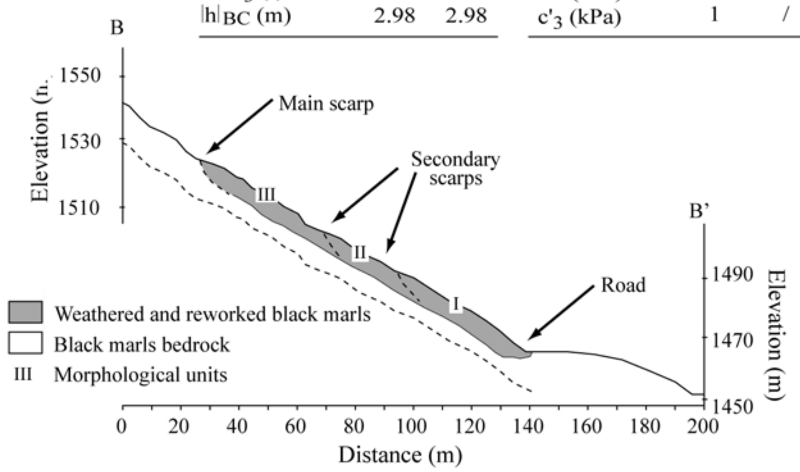


Figure 10. Geomorphological maps of the investigated sites, cross-section and hydrological and geotechnical properties used in the model runs. (a): Super-Sauze mudslide; (b): Boisivre translational slide (modified from Caris & van Asch, 1991). K_v is Saturated vertical conductivity; Rat_K is Ratio Lateral/Vertical conductivity; θsat is effective porosity; $\lvert h \rvert_{BC}$ is matric suction at bedrock; γ_d is dry bulk density; γ_w is wet bulk density; ϕ is angle of internal friction; c' is effective cohesion. The lettering in index represents the soil layers. The parameter values are average values of laboratory tests or field tests.

This result has to be related to higher potential evapotranspiration in the changed climate than in the reference climate for this landslide situated on the south-facing hillslope of the Ubaye Valley.

At Super-Sauze, the average GWL is lowered of ca. -0.6 m with the climate change scenario. This result may be explained by relatively small variation in the yearly amounts of rainfall on the north-facing hillslope in the changed climate; in terms of water supply, the decrease in snow depths (Fig. 9) seems to be compensated by higher amounts of liquid rainfalls in the winter season which does not change the hydrological behaviour of the landslide.

As a consequence, the slope stability model simulates a general decrease in landslide activity which is particularly marked for the Boisivre landslide. The frequency of unstable areas (Fig. 12) is calculated according to the total area of the landslide (e.g. a frequency of 0.5 indicates that 50% of the calculation cells have a safety factor value lower than 1.1). The most interesting result of this exercise is that parts of the landslides will still fail or be reactivated in the next century, though a decrease in unstable cells of 10 to 20 % is simulated.

5.3. Discussion

Results of the impact scenario must be interpreted cautiously. First, our approach presupposes that the geometry of the landslides does not vary over time (e.g. a static safety factor is evaluated at each time step for a fixed calculation grid). Therefore, dynamic deformation models should be used to increase the reliability of the impact assessments.

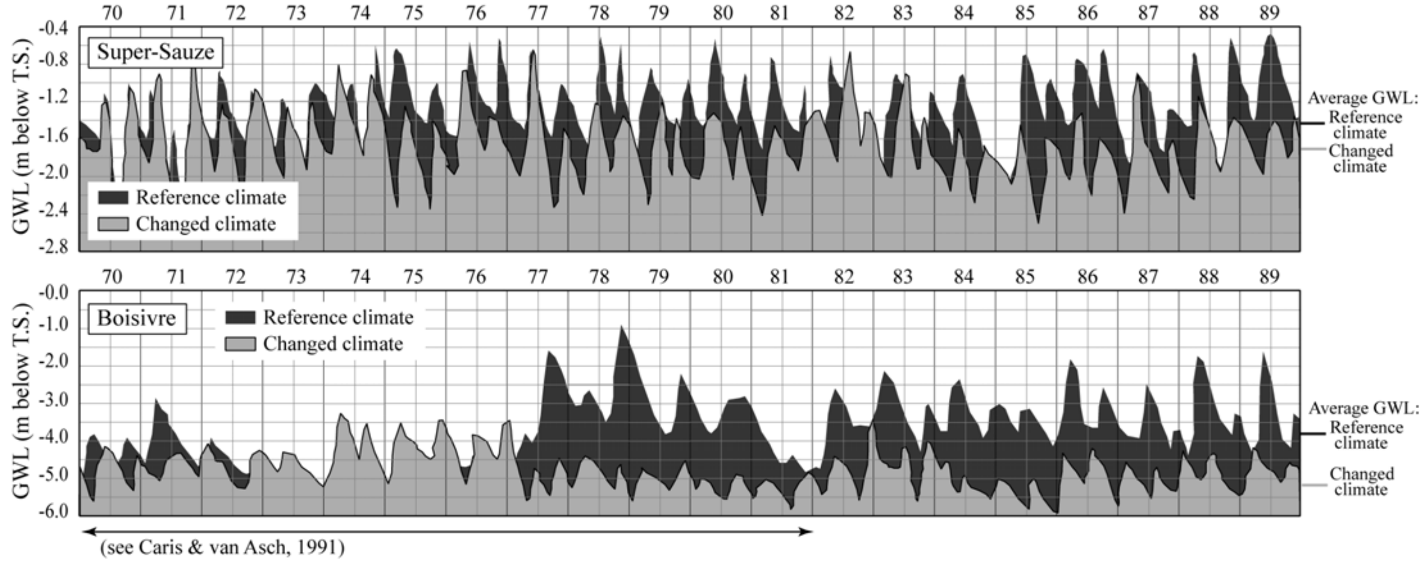


Figure 11. Simulated hydrology of the landslides for the reference climate and the changed climate. Simulations were carried out with the entire set of meteorological land surface data for the period 1969-1999 and 2069-2099. The model outputs for the period 1970-1989 and 2070-2089 are presented. The model outputs consist in the average groundwater levels of 100 model runs.

Second, only the meteorological inputs are considered in the slope models; many other factors like landuse changes, material availability or vegetation-feedback mechanisms are also controlling landslide frequency. Finally, given the large uncertainties in our knowledge of the landslide mechanisms, in the simplification of our models and in the forecast of future climate time series, probabilistic analyses should be considered in the impact assessments. Several model runs should be performed with PDFs of the meteorological, hydrological and geomechanical parameters in order to compute PDFs of groundwater levels and safety factor values. This was not within the scope of this paper, but should be tested.

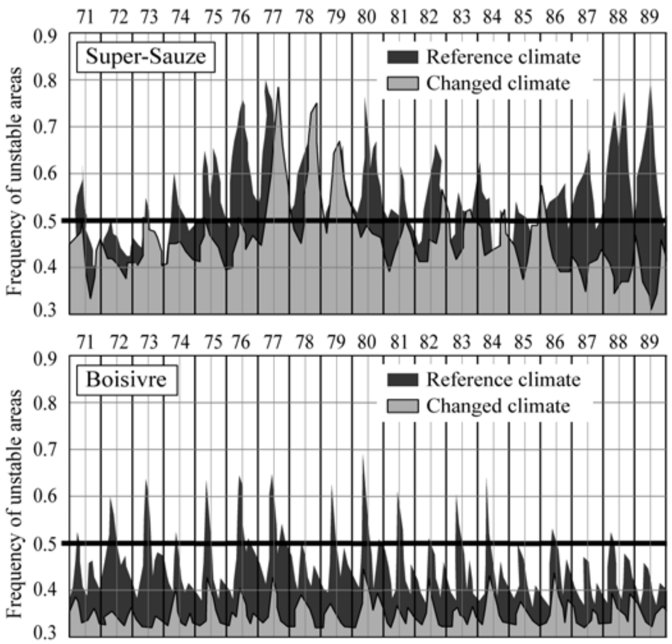


Figure 12. Frequency of unstable areas calculated with the pore pressures simulated by the hydrological model, for the reference climate and the changed climate. The model outputs for the period 1970-1989 and 2070-2089 are presented.

6 CONCLUSIONS

This paper describes a methodological framework to assess the influence of climate change scenarios on slope hydrology and landslide frequency by combining climate modelling, groundwater modelling and slope stability modelling. A scheme to simulate high-resolution time series of meteorological land surface parameters is proposed. Climate modelling associates a disaggregation procedure to downscale the climate general circulation parameters at the site scale taking the A2 climate change scenario of GIECC as a guess for the future climate, and two meteorological process-based models to spatialize the dataset and evaluate snow properties.

The simulated meteorological parameters are used as boundary conditions in a process-based groundwater model able to reproduce spatially variable ground water flows. The time-dependent hydrological behaviour of two unstable slopes are evaluated, and assessed against monitoring data. A slope stability model is then applied in order to evaluate a time-dependent safety factor in relation to pore pressure variations.

For the climate change scenario hypothesized, and given the uncertainties associated to the climate parameter modelling and the very simple concepts used in the groundwater and slope stability models, the impact simulations indicate:

(1) on the south-facing slopes, a drastic reduction of slope instability for rotational slides, associated to an increase in evapotranspiration and a consequent decrease in soil moisture and effective soil porosity in the unsaturated topsoil;

(2) on the north-facing slopes, influence of climate change for mudslides is limited with a quite small reduction in slope instability. This situation is

explained by a small variation in the total yearly rainfall amounts (e.g. the critical decrease in snow depths observed in winter seems to be compensated by an increase in liquid rainfalls).

Although the process-based models used in this study do not claim to simulate all behaviour, they do establish some interesting trends in impact assessments of climate change on slope stability. This study indicates also that more understanding about site-specific landslide activity and mechanisms is very important to forecast 'reliable' scenario. Long-term monitoring and modelling of selected pilot study sites (e.g. hydrology and kinematics) is necessary to regionalize the information and to reduce the uncertainties in our simulations.

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