A method for predicting the impact of climate change on slope stability

J. Buma · M. Dehn

Abstract A major effect of man-induced climate change could be a generally higher frequency and magnitude of extreme climatological events in Europe. Consequently, the frequency of rainfall-triggered landslides could increase. However, assessment of the impact of climate change on landsliding is difficult, because on a regional scale, climate change will vary strongly, and even the sign of change can be opposite. Furthermore, different types of landslides are triggered by different mechanisms. A potential method for predicting climate change impact on landsliding is to link slope models to climate scenarios obtained through downscaling General Circulation Models (GCM). Methodologies, possibilities and problems are discussed, as well as some tentative results for a test site in South-East France.

Key words Climate change · Landsliding · General circulation models · Slope models · Downscaling

Climate change and landsliding

Recent predictions of climate change as a consequence of increased greenhouse-gas production suggest that Europe will experience a higher frequency of extreme rainfall events (Cubasch and others 1995). This could increase the frequency of occurrence of high pore pressures, and thus the activity of rainfall-triggered landslides (Beniston and Douglas 1996). However, the spatial pattern of landslide (re)activation is likely to be complex, as different areas in Europe will experience variable changes in the magnitude and frequency of precipitation. Moreover, different types of landslide will respond either to meteorological changes in the long term (monthly or yearly rainfall) or short term (daily or weekly rainfall) (Asch 1996).
A potential method for predicting the consequences of climate change is to link conceptual slope hydrology/stability models to climate scenarios produced by General Circulation Models (GCMs). GCMs are successful in simulating the large-scale state of the atmosphere (Gates and others 1996). However, their low horizontal resolution (about 250 × 250 km) inhibits their direct use for climate impact studies on the local scale, such as landslide studies. The use of downscaling techniques, which derive regional meteorological parameters from large-scale atmospheric structures, circumvents this difficulty.
In the present study the combination of downscaled climate scenarios and slope hydrology and stability models is critically examined. Future possibilities of the method will be discussed using a case-study from Barcelonnette, SE France (Fig. 1), as an example. Furthermore, a number of problems encountered are highlighted.

General methodology

GCMs have so far been the only tools to obtain quantitative indications of climate change (Trenberth 1996). They are therefore a prerequisite in order to assess the impact of future climate change on slope stability. However, GCM results have to be downscaled from the large to the local scale in order to apply them to regional or local studies. Different downscaling techniques exist for obtaining relations between the two scales. An outline of these techniques is given in a later section. In landslide studies, air pressure, which is well simulated by GCMs, can be used as a large-scale variable to produce precipitation as a local variable. Downscaled precipitation is then used as an input parameter to the slope hydrology model. This provides groundwater or pore pressure series as output (Fig. 2). By comparing this output series with threshold groundwater conditions derived from back-analysis of the landslide with a slope- stability model, indications for slope stability can be obtained.
It is very important to recognize that GCMs provide projections of the large-scale state of the atmosphere and oceans. The output of GCM experiments should not be

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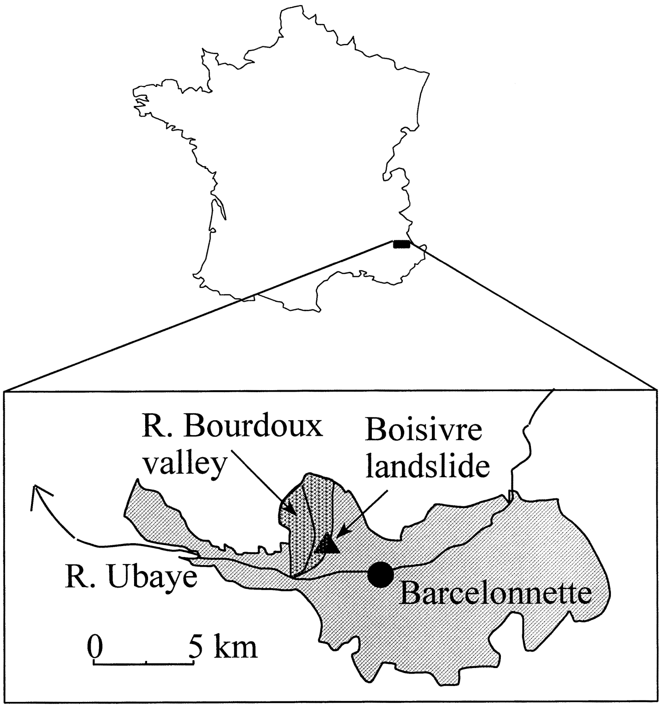

Fig. 1
Location of the Boisivre landslide in the Barcelonnette basin, SE France

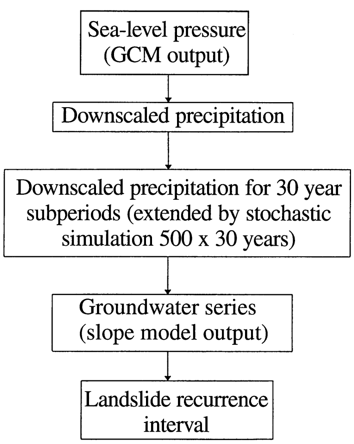

Fig. 2
General scheme of combined downscaling and slope stability modelling

interpreted as a forecast but rather as one of many possible states of the atmosphere given certain boundary conditions and prescribed parameters. Therefore, only the statistics of climatic variations are meaningful, but not single values of certain years (Trenberth 1996). Consequently, this is also the case with downscaled precipitation derived from these GCMs. In other words, the temporal occurrence of a distinct landslide event in the future cannot be forecast; rather, the probability that a landslide will occur in a certain time-span, or the recurrence interval of landsliding ( ), can be assessed.

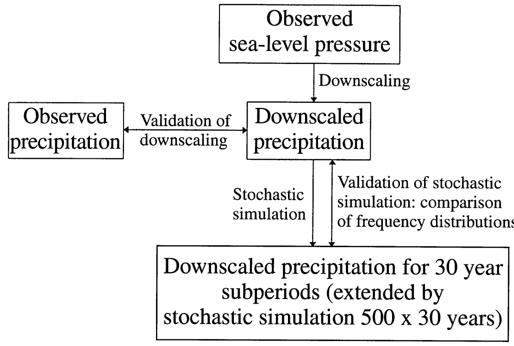

Fig. 3
Validation of downscaling and stochastic techniques

In order to assess changes in landslide recurrence due to climate change, the downscaled precipitation series has to be subdivided into subperiods. These must be long enough to obtain reliable frequency distributions of precipitation, and short enough to minimize the effect of trends influencing the shape of these distributions. A length of 30 years seems appropriate since many meteorological services base their climatic data on statistics of 30 years of meteorological records. However, a 30-year precipitation series is too short to produce reliable recurrence intervals of whatever phenomenon. Therefore, the frequency distributions are used in a stochastic (Monte Carlo) simulation of precipitation in each subperiod, which allows it to include a greater range from the precipitation probability distribution than when using only the original downscaled series. Thus, a large number (e.g. 500) of 30-year precipitation series are generated, providing, after slope modelling, an equally large number of groundwater series, and values. Because an assessment of a *change* in landslide recurrence intervals over a period is desired, values of must then be compared for the various subperiods.
Before this procedure, depicted in Fig. 2, can be adopted, it is necessary to validate the downscaling and stochastic simulation techniques. This validation is illustrated in Fig. 3. The downscaling technique is validated by comparing values of observed and downscaled precipitation for a certain time-interval in the past. The stochastic simulation technique is validated by comparing the frequency distributions of the source series and the generated series.

Review of different downscaling techniques

Physically based models

Dynamical
Dynamical downscaling approaches use a one-way nested modelling technique. A high-resolution regional climate model (for example weather-forecast models) (High-reso-

lution limited area model), with grid-point distances of approximately 50 km is nested into a GCM. The regional model derives meteorological boundary conditions from the GCM output. Details of topography or large lake systems can in this way be considered in the regional climate model with a physically based approach. An example for Europe is given by Marinucci and Giorgi (1992).

Statistical-dynamical

A combined statistical-dynamical approach was developed by Frey-Buness and others (1995). In this approach a regional-scale dynamical model is statistically linked to large-scale information using the frequency distribution of classified weather situations. This is computationally more economical than pure dynamical models.

Subgrid parameterization model

To meet both detailed physical representations and computational efficiency, Ruby Leung and Ghan (1995) developed a subgrid parameterization of the influence of topography on clouds and precipitation. In order to obtain this, a surface elevation model, a simple airflow model and a thermodynamic model are applied. In this way subgrid-scale information of precipitation can be obtained.

Statistical models

The statistical approaches generally rely on three assumptions. First, the large-scale parameter is simulated well by GCMs. Second, most of the regional climatic variation is determined by large-scale atmospheric conditions. Third, the relationship between them is stationary under climate change.

The procedure adopted in the statistical models is as follows (Heyen and others 1996):

a large-scale parameter G has to be identified which controls a local parameter L;

a statistical relationship between L and G has to be found;

the relationship must be validated with an appropriate method;

if the relationship is confirmed, G from GCM experiments can be applied to estimate L.

Empirical-statistical downscaling

Patterns and time-series of both large-scale atmospheric conditions and local-scale meteorological data are used to establish empirically a linear regression model. This model is based on empirical orthogonal functions (EOFs, also known as Principal Component Analysis) and a canonical correlation analysis (CCA). Details are given in Storch and others (1993) and Heyen and others (1996). Because the relationship is purely statistical, a further physical interpretation of the results is necessary. Based on the statistical-regression model, local climate change is calculated from large-scale conditions derived from GCM experiments. The technique was used for example by Storch and others (1993) and Gyalistras and others (1994).

Analog techniques

In analogue approaches rainfall amounts of distinct stations are linked to the large-scale state of the atmosphere using analogue situations (Zorita and others 1995). In this approach a pool of observations of large-scale atmospheric states, e.g. sea-level pressure (SLP), and the local-scale precipitation is built. Then the SLP of another observation period or of several GCM runs is compared with the pool. The closest SLP pattern is chosen as an analogue circulation pattern. The precipitation amount observed simultaneously with this circulation pattern is in a next step assigned to the estimated precipitation. In a similar way but using an empirically defined finite set of circulation patterns as analogues, Bárdossy and Plate (1992) developed a downscaling approach for hydrological applications.

To apply any statistical downscaling approach, two basic conditions need to be satisfied. Firstly sufficiently long meteorological time-series must be available; and secondly, the homogeneity of these series may not be affected by changes in the instrumentation or location of the meteorological station. This is especially important for precipitation, which can vary significantly over relatively short distances.

Choice of downscaling technique for application in slope hydrology models

The choice of the downscaling technique to be applied in slope stability modelling depends on several factors (Table 1). Firstly, the spatial scale at which the landslide model is calibrated determines whether the spatial resolution of downscaled precipitation should be regional or local. Secondly, the temporal resolution of the output is of importance, in particular with respect to the type of landslide of concern (see Table 2). The time-scale at which a landslide is triggered following a precipitation event must correspond with the temporal output resolution. For example, a downscaling method producing monthly precipitation scenarios will be more useful for landslides triggered by long-duration low-intensity precipitation than for those triggered by high-intensity, short-duration summer storms.

Differences in seasonal performance of the downscaling methods must also be regarded, because the precipitation regimes triggering landslides are often peculiar to one or more distinct month or season.

From a practical point of view, the amount of computing time and computer memory required to store and process the data is a third important consideration. Yet another important criterion is whether or not the downscaling technique requires any physical details about the processes involved as input. If it does then, in general, it will be more difficult to obtain all the data required for

Table 1
Features of five downscaling approaches cited in literature; stat.1 = empirical-statistical after Storch and others (1993); stat.2 = statistical-analogue after Bárdossy and Plate (1992); stat.3 = statistical-analogue after Zorita and others (1995); subgrid-p. = subgrid-parameterization after Ruby Leung and Ghan (1995)

	dynamical	stat.1	stat.2	stat.3	subgrid-p.
spatial resolution	grids of about 50 × 50 km	distinct locations	locations and catchments	distinct locations	ca. 2 × 2 km
highest temporal resolution	variable, daily	variable, well established monthly	daily	daily	daily, monthly
CPU time and data amount	high	low	low	low	medium
physical details required	yes	no	no	no	yes
calibration	high	medium	medium	medium	medium

Table 2
Properties of landslide types with respect to climatic triggering in mid-latitudes (after Asch 1996)

	debris flows	flat slides	deep seated slides
depth of shear plane	superficial	1–10 m	10–40 m
hydrological system	surface flow	infiltration, percolation, evapotranspiration	(regional) groundwater flow
climatic trigger	high *event-based* precipitation intensities	high *daily/monthly* effective precipitation	high *monthly/yearly* effective precipitation

application of the technique and it will be more time and CPU consuming.

Case-study

The methodology outlined in the foregoing sections was applied to a small landslide in the Barcelonnette basin, SE France (Fig. 1). The geology of this small landslide can be characterized by a top colluvial layer (thickness 1.5 m), underlain by a weathered marl layer (thickness 6 m) which overlies the bedrock of unweathered 'Terres Noires' Jurassic marls (Caris and Asch 1991). Geophysical and tensiometric measurements revealed that the landslide is triggered by high groundwater levels in the weathered marl layer. This layer drains during summer when evapotranspiration normally is greater than precipitation. Several months of above-average winter precipitation (more than about 90 mm/month) are required to raise the groundwater level again sufficiently to trigger the landslide (Caris and Asch 1991).
The simplified Janbu stability model was applied to back-calculate a threshold groundwater level for triggering of the landslide, using geotechnical data (Caris and Asch 1991). This was combined with a hydrological model consisting of two linear reservoirs placed in series, representing the two geological layers of the landslide. The temporal distribution of solid and liquid precipitation was simulated in the following simple manner. As long as mean monthly temperature exceeds 0 °C, precipitation is handled as rainfall. Below this value, it is stored as snow. In the first following month with mean positive temperature, all the stored snow is released as snowmelt. This model was calibrated in such a way that in periods of landslide activity inferred from dendrochronological dating (Asch and Steijn 1991), groundwater levels exceeded the identified threshold. Precipitation and temperature data from Météofrance were utilized for this calibration. For the derivation of precipitation scenarios for the combined slope model, the empirical-statistical downscaling approach was chosen because of (1) its monthly output resolution, corresponding with the inferred landslide response time to precipitation, (2) its low requirement of computing time and data amount, and (3) its good performance for precipitation of the winter season in other studies (Storch and others 1993; Gyalistras and others 1994). Scenarios of mean daily air temperature, which is simulated in a more reliable way by GCMs, were obtained by interpolation from GCM gridpoints, and subsequent stochastic simulation.
Table 3 shows calculated recurrence intervals for triggering of landslide movement ( ) in relation to climate change. Precipitation scenarios were downscaled from monthly SLP of a simulation with a coupled ocean-atmosphere GCM (ECHAM4/OPYC3) of the Max-Planck-Insti-

Table 3
Tentative recurrence intervals of movement for the Boisivre landslide

Stochastically generated precipitation input series	Meteofrance 1928–1970 (observed)	GCM 1928–1970 (control run)	GCM 1971–2000 (scenario)	GCM 2021–2050 (scenario)	GCM 2069–2099 (scenario)
mean annual precipitation (mm)	721	722	712	648	635
landslide recurrence ρ (years)	12	7	60	1×10^3	5×10^3

tut für Meteorologie, Hamburg. The horizontal resolution of this T42 model is approximately 250×250 km. The GCM is forced starting with observed greenhouse-gas concentrations from 1860–1990. After 1990 the greenhouse-gas concentrations according to the IPCC scenario IS92a (Houghton and others 1992) were taken as forcing (Roeckner and others 1996). Due to a simulated general decrease in precipitation, the frequency of landslide triggering of the landslide is simulated to decrease dramatically in the next century.
Because the table is the result of a tentative modelling effort, it should be regarded as an example of what is or will be possible with the presented approach. It cannot yet be regarded reliable because of many problems, and the study has been carried out at this stage merely to reveal these problems. In the following, a number of them will be discussed.

Problems related to the downscaling method

Figure 4 shows observed and downscaled Barcelonnette precipitation for the period 1928–1994. The downscaling technique reproduces the observed data with limited success; the variance explained by the regression between observed SLP and observed precipitation amounts to 31%. Consequently the variability of the downscaled precipitation series is lower than that of the observed series. In the presented case-study a simple inflation of variance was carried out as a first approach. However, because the character of the missing variance is unknown a random-based approach would be more convenient. This can be done by adding a 'noise' component to the series, since $\sigma^2_{tot}=\sigma^2_{explained}+\sigma^2_{noise}$. Whether red noise (dependent on the past) or white noise (entirely independent) should be added, depends on the autoregressive character of the observed precipitation series. Two possible causes for the modest proportion of explained variance in Barcelonnette precipitation are (1) that SLP may not be the only major control of this variable, due to local factors like e.g. orography, and (2) that the adopted downscaling approach may not be able to seize the total amount of correlation between the two variables.

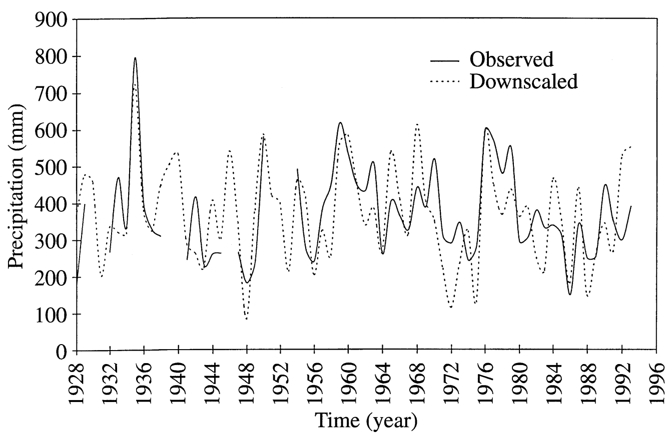

Fig. 4
Observed (data from Météofrance; *solid line*) and estimated (*dashed line*) winter precipitation in Barcelonnette, 1928–1994. Estimation is based on downscaling observed sea-level pressure and the subsequent inflation of variability

Problems related to the stochastic simulation procedure

In this case-study the precipitation scenarios were generated using only mean and standard deviations of the source frequency distributions. This proved to be insufficient to reproduce these distributions adequately. This inadequacy is serious since the slope model appears to be very sensitive to variations in the frequency distribution of the input precipitation series. However, prospects for improvements of the stochastic simulation procedure are good.
It is suspected that missing values in the Barcelonnette precipitation series could affect the shape of the frequency distribution of Barcelonnette precipitation to a considerable extent, and hence also the character of the precipitation scenario that is used as input to the slope model.

Problems related to the slope hydrology/stability model

Some hydrological processes on the landslide, in particular the temporal distribution of solid and liquid precipitation, snow storage and snowmelt, are poorly quantified. Consequently these processes are modelled in a very simple manner, mostly using literature values. Because the slope model was calibrated in a very rough way (only dendrochronological datings were used because piezometric records were suspected to be unreliable), it may be possible that the obtained calibration is not unique, i.e. it is possible that more or less the same results can be obtained with slightly differing configurations of model parameter values, still within the range of literature values. Assessment of the influence of this uncertainty on the final values is absolutely necessary to validate the whole approach.

Problems relating to GCMs

Because GCM simulations are the starting-point of the overall methodology, the performance of the respective GCM is of great influence for the validity and accuracy of the modelled r of landslide triggering. In order to check the reliability of the results, the modelling should be carried out using different GCM simulations which also include the effects of aerosols, for example sulphate particles. Furthermore Monte-Carlo GCM simulations such as described by Cubasch and others (1994) could be used to derive model-independent background noise of the scenarios.

Conclusion

The prediction of climate change impact on slope stability using downscaled climate data and slope hydrology / stability models is still in an experimental phase. However, as a first step this study has been very useful in highlighting many problems. Because some of these problems can be solved by selecting more intensively monitored landslides, and others can be dealt with by improvements in the applied methods, we feel that the approach has good prospects for providing reasonable estimates of future landslide activity. However, it is very important to realize that other processes, such as the geomorphological development of the slope, may modify the state of a landslide in such a way that they enhance or counteract the effect of climate change to a considerable extent.
If this is the case, future landslide recurrence intervals obtained with this method represent nothing more (but also nothing less) than a 'partial development' due to climate change. If this is combined with an assessment of the effect of these other processes, a more complete picture of the temporal trend in landslide activity could be achieved.
Lastly, it should be noted that the presented results suggest a decrease in local winter precipitation in Barcelonette, whereas for Europe a general increase in precipitation is expected, as already pointed out in the introduction. This illustrates the importance of regional climate change impact studies using downscaling techniques.

Possibilities for regionalization

In the Barcelonnette basin, many landslides occur in the same geological setting (Terres Noires). If these landslides are of a size similar to the studied landslide, they may have similar hydrological thresholds for triggering of movement. In such a case, the precipitation scenarios could be used with the general shortcomings of point data in mountain environments. However, it is not yet clear to what extent small variations in threshold values influence the results. Some site-specific knowledge is probably required to fine-tune these values.

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