Potential Effects of Climate Change on Slope Stability in Unsaturated Pyroclastic Soils

Emilia Damiano and Paola Mercogliano

Abstract

Landslides are one of the most dangerous natural hazards since they degrade the productivity of soils, harm people, and damage property. Slope failures are caused by a combination of several factors; in unsaturated granular deposits which are often susceptible to rapid catastrophic landslides induced by rainwater infiltration, climatic conditions play a fundamental role. Therefore, global warming due to the greenhouse effect and changes in precipitation and evaporation patterns might affect future landslide hazard.

The paper reports the results of a complex investigation in a sample site, including in situ suction and precipitation monitoring, soil characterization and numerical simulations which allowed us to focus on some aspects of climate change on slope behaviour.

Keywords

Shallow landslides • Unsaturated soils • Climate change

Introduction

Rapid rainfall-induced landslides, involving slopes covered by shallow deposits of unsaturated granular soils, occur everywhere in the world. Stability of the deposits that often lie on steep slopes with inclination higher than the friction angle of the soils in saturated conditions, is ensured by the positive effect of matric suction on shear strength of the soils. The stabilizing effects of partial saturation on strength can be accounted for by a simple extension of the Mohr-Coulomb criterion (Fredlund and Rahardjo 1993):

$$\tau_{lim} = [c' + (u_a - u_w) \tan \phi_b] + (\sigma - u_a) \tan \phi' \quad (1)$$

where:

c' and ϕ' are the cohesion and the friction angle in conditions of complete saturation;

$(u_a - u_w)$ is the matric suction (difference between air pressure, u_a, and pore water pressure, u_w);

$(\sigma - u_a)$ is the net stress;

ϕ_b is the friction angle related to suction.

In this simplified approach, the strength envelope of unsaturated soil is parallel to the envelope for fully saturated conditions and the higher resistance associated to partial saturation is due to an intercept of cohesion related to suction through the term $(u_a - u_w)\mathrm{tg}\phi_b$. In the described hypotheses, as rainwater infiltration proceeds, suction decreases and causes a reduction in the intercept of cohesion, leading to slope failure. It is worth noting that increase in the degree of saturation leads also to progressive increase in hydraulic conductivity of the soil.

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Depending on slope morphology, in shallow deposits a very small suction is often enough to ensure quite high safety factors. Thus, the triggering of a landslide is not a common phenomenon. Indeed, the covers often exhibit a high unsaturated hydraulic conductivity which, even during the most intense rainfall events, usually prevents the soil from approaching saturation, especially when they lie directly upon a fractured pervious bedrock. Furthermore, during the dry periods between rainfall events, the soil loses part of its water content, mainly by evaporation, favoured in many cases by the presence of vegetation: as a consequence, only intense rain storms occurring after prolonged rainy periods may lead the soil to such wet conditions as to trigger slope instability.

In general, a rational procedure to link climate forecasting to prediction of slope failure at a local scale should include: (i) identification of the climatic factors which might affect slope response; (ii) in-depth knowledge of the geomorphological context and of geotechnical and hydraulic characteristics of the soils involved; (iii) building reliable numerical models for both climatic and slope stability forecasting; (iv) prediction of landslide triggering probability based upon climate change scenarios. Despite the apparently simple described procedure, the high uncertainty in future climate parameters and the complex climate-landslide interaction (landslide is related to climate via the non-linear soil-plant-atmosphere system) make it very hard to draw general conclusions. Moreover, to complete the assessment, scenarios of other than climatic factors should be included in the approach: landslides result from interdependent spatio-temporal processes, including hydrology, vegetation surcharge (weight of vegetation), root strength, soil conditions, bedrock, topography, and human activities. However, such impacts are currently speculative and will be difficult to unravel from anthropogenic effects (Sidle 1992).

Based on such considerations the present study analyses some aspects of the interaction between climatic factors and slope behaviour through the results of 10-year in situ monitoring, an in-depth investigation of soil properties and numerical simulations of the hydrological behaviour of the sample slope of Cervinara in Campania (southern Italy), representing a typical geomorphologic context subjected to shallow landslides in unsaturated granular soils.

Climate Scenarios in the Mediterranean Area

In order to investigate the impacts that change in some climatic factors such as rainfall patterns, drought periods or evapotranspiration could induce on slope stability, the future trend of climate scenarios for the Mediterranean area was evaluated.

The analysis was performed by numerical COSMO Climate Local Model (COSMO CLM) (Rockel et al. 2008), developed by the German Weather Service and updated by the European CLM-Community. Although it can be used with a spatial resolution between 1 and 50 km, the adopted non-hydrostatic formulation of the dynamic equations without any scale assumption makes it eligible especially for use at a horizontal grid resolution of about 20 km and below (Böhm et al. 2006). These high resolutions allow a better description of the terrain orography than the global model, where there is an over- and underestimation of valley and mountain heights, leading to errors in precipitation estimation, as this is closely related to terrain height. Moreover, non-hydrostatic modelling provides a good description of the convective phenomena, which are generated by vertical movement (through transport and turbulent mixing) of energy (heat), water vapour and momentum. Convection can redistribute significant amounts of moisture, heat and mass on small temporal and spatial scales. Furthermore convection can cause severe precipitation events (i.e., a thunderstorm or cluster of thunderstorms).

The mathematical formulation of COSMO-CLM is based on the Navier–Stokes equations for a compressible flow. The atmosphere is treated as a multicomponent fluid (dry air, water vapour, liquid and solid water) for which the perfect gas equation holds, and subject to the gravity and to Coriolis forces. The model includes several parameterizations, in order to allow, at least in a statistical manner, for several phenomena that take place on unresolved scales, but that have significant effects on the meteorological scales concerned (e.g., interaction with the terrain orography).

In the present work climate predictions were obtained with COSMO-CLM (version 4.8) forced by the global model CMCC-MED (Gualdi et al. 2011). The IPCC emission scenarios used is the A1B. The simulation was performed over Italy at a spatial resolution of 8 km with 184×230 grid points and 40 vertical levels. The time step used for the time resolution is 50 s, while the period considered is 1965–2100.

The COSMO CLM model is widely used in Europe and has been validated in different projects and geographical areas (Rockel and Geyer 2008; Bucchignani et al. 2011) in order to analyze its capability to capture European climatic features. Comparison of predicted data and observations shows that COSMO CLM has a cold bias during the winter while it exhibits a warm bias in summer over large parts of Europe (http://climaqs.vito.be/deliverables/nonconf/Deliverable%201.1%20Nudging-ready%20version%20of%20COSMO.pdf).

For the present simulation the COSMO CLM was also validated by comparing predicted data with global satellite observations (Mitchell and Jones 2005) averaged on the period 1971–2000. The results show a quite good capability

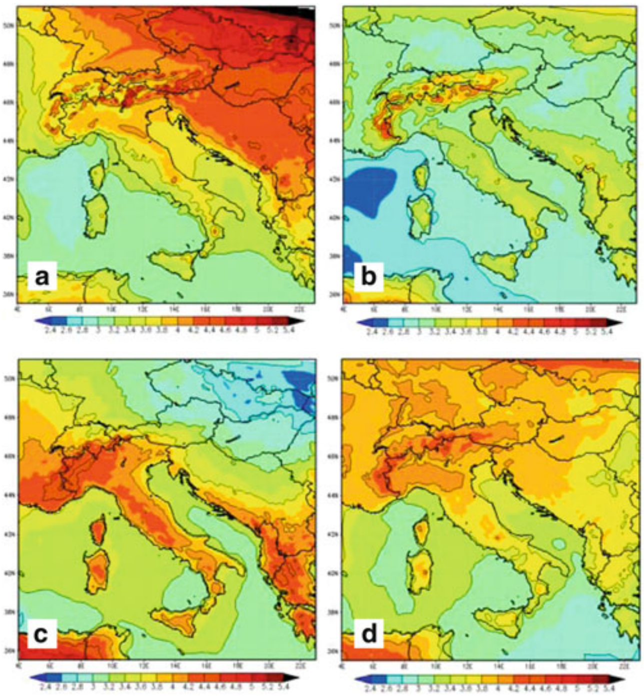


Fig. 1 COSMO CLM daily T2m mean seasonal difference between 2071–2100 and 1971–2000 CLM: (**a**) winter, (**b**) spring, (**c**) summer and (**d**) autumn

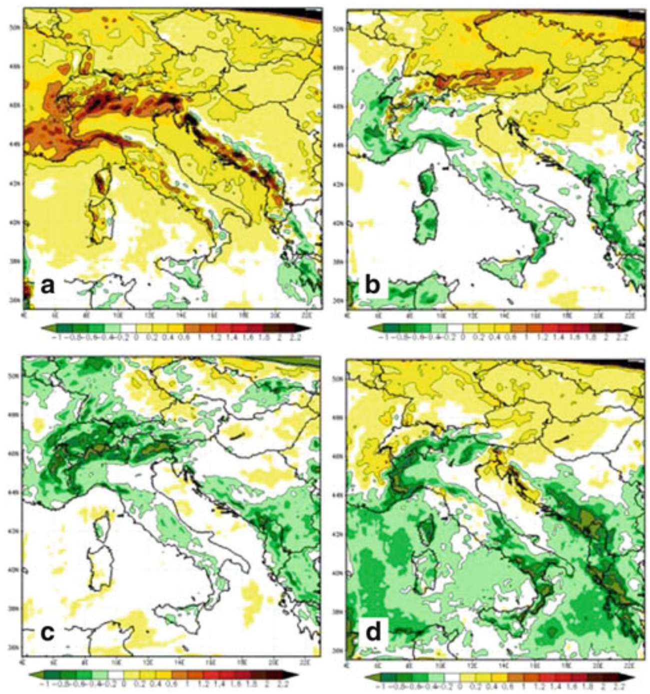


Fig. 2 COSMO CLM daily precipitation seasonal averaged difference between 2071–2100 and 1971–2000 CLM: (**a**) winter, (**b**) spring, (**c**) summer and (**d**) autumn

of the model to capture the mean features of the Italian climate (Bucchignani et al. 2011).

As regards the future predictions of the climate on Italy's land area, the simulation results are illustrated in Figs. 1 and 2 in terms of mean seasonal air temperature (at 2 m) and daily precipitation anomalies between periods 2071–2100 and 1971–2000. For the period 2071–2100 such scenarios indicate:

- an increase in the air temperature especially during the summer (Fig. 1c);
- a general decrease in terms of daily precipitation, except for the winter period when the projection indicates a slight increase (Fig. 2a).

The COSMO CLM simulations are in good agreement with the IPCC (International panel on Climate Change) reports on the Mediterranean area (Solomon et al. 2011) which indicate a general agreement among different regional climate projections on the following climate features:

- an increase in mean temperature in all seasons, with the greatest warming in summer;
- an increase in terms of intensity, duration and frequency of extreme temperature events. In particular, maximum summer temperatures are likely to increase by more than the average;
- a higher spatial variability of the seasonal precipitation; in particular a decrease is evident in most European areas, especially in summer;
- an increase in the intensity of the extreme precipitation;
- a decrease in the annual number of precipitation days;
- an increase in the risk of summer drought.

Physical Characterization of Unsaturated Granular Shallow Covers

The complexity of infiltration processes in unsaturated soils requires the use of a numerical model to predict the hydrologic slope response to rainfall. The reliability of the model has to be proven through preliminary calibration, given the variability in soil parameters, the uncertainties in the initial and boundary conditions, the simplified assumptions made, followed by validation based upon in situ monitoring data. To this aim, data from the Cervinara site were used.

In December 1999, several landslides triggered by heavy rainfall occurred in the mountainous area of Cervinara, about 40 km northeast of Naples. One of these assumed the characteristics of a flowslide, occurring along a fairly regular slope with an average inclination of 40° formed by a shallow primary deposit of unsaturated layered air-fall pyroclastites overlying fractured limestone. The slope is covered by chestnut trees which are regularly cultivated. Since that event, a complex investigation has been carried out including field suction and rainfall readings (Damiano et al. 2012) and laboratory testing about mechanical and hydraulic

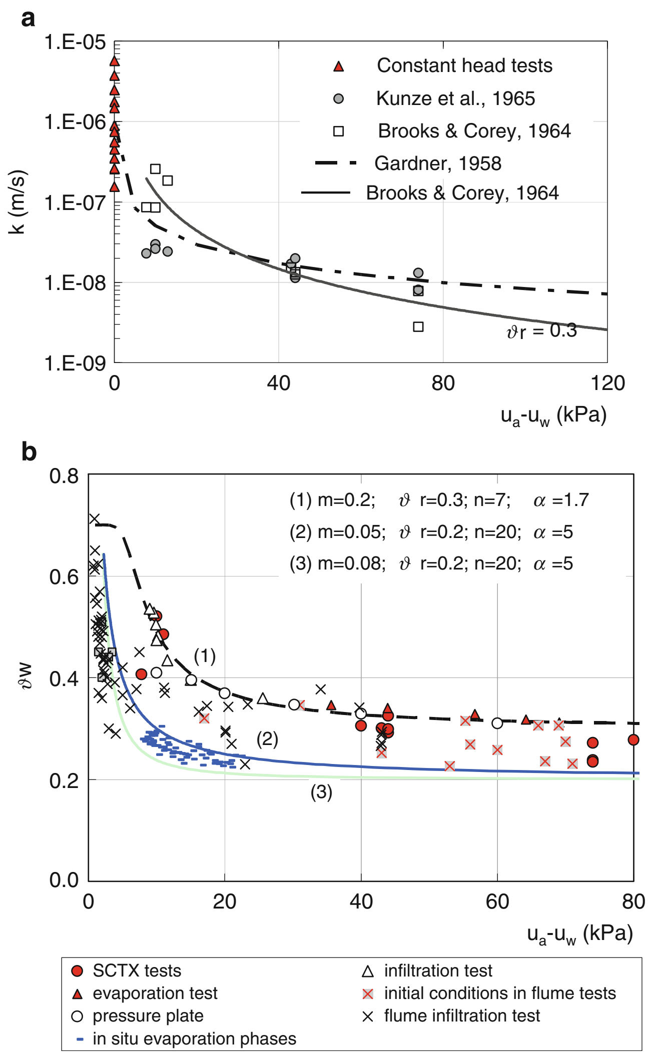


Fig. 3 Hydraulic properties of volcanic ashes: (**a**) conductivity function; (**b**) soil water retention curve (SWRC) (after Damiano and Olivares 2010)

properties of the soils (Lampitiello 2004; Olivares and Picarelli 2003; Damiano and Olivares 2010; Greco et al. 2010).

Figure 3 shows the functional relationships between hydraulic conductivity and matric suction (Fig. 3a) and volumetric water content θ_w and matric suction (Fig. 3b).

The saturated permeability of Cervinara volcanic ashes measured in constant head tests under mean effective stresses between 20 and 640 kPa ranges between $1.5E^{-7}$ and $5E^{-6}$ m/s. The unsaturated hydraulic conductivity k_{unsat} was obtained through:

- The interpretation of suction equalization stages in suction-controlled triaxial tests SCTX as described by Kunze et al. (1968);
- Applying the Brooks and Corey expression (1964) for the degrees of saturation measured in the SCTX tests, assuming as residual volumetric water content $\theta_r = 0.3$ and as saturated hydraulic conductivity $k_{sat} = 1E^{-6}$ m/s.

The results, fitted in Fig. 3a by the permeability functions derived by Gardner's expression (1958) and by Brooks and Corey's expression (1964), show that for the range of suction between 0 and 80 kPa, hydraulic conductivity decreases by about two orders of magnitude as suction increases.

Figure 3b reports the experimental data in terms of volumetric water content (θ_w) versus matric suction ($u_a - u_w$) obtained through:

- Conventional laboratory long-term tests (SCTX tests; evaporation and infiltration tests; pressure plate);
- Flume infiltration tests on small-scale slopes subjected to rainfall until failure;
- In situ monitoring during evaporation periods;

and the best fitting of the experimental data sets derived by the van Genuchten expression (1980).

The obtained soil water retention curves (SWRC) are typical of granular soils with a low air-entry value, low residual water content and a transition zone with a steep slope. However, the SWRC extracted by flume infiltration tests and in situ measurements show a different trend characterized by a lower air entry value and a steeper slope of the curve in the transition zone. This reveals the substantial influence of the procedure adopted to retrieve the SWRC. Indeed, notice that experimental data obtained through conventional tests are determined under equilibrium conditions, whereas data from both in situ monitoring and flume infiltration tests are related to transient conditions.

Modelling the Behaviour of Unsaturated Shallow Granular Covers

Exploiting the observed range of variability of hydraulic parameters, numerical sensitivity analysis (Table 1) was performed to reproduce the Cervinara in situ measurements and to stress the influence that the various hydraulic parameters have on the rainwater infiltration processes. In the following, the results are shown in terms of variability of k_{sat} (and hence of the k_{unsat} function) and ($\theta_s - \theta_r$) since the analysis highlighted that their influence on the transient regime of the groundwater flow is stronger than that of the other parameters. In the analysis θ_s was assumed equal to mean soil porosity 0.7.

The period between January 2006 and December 2007 was selected to validate the model. The reproduction of two annual measurement cycles ensures that the effects of the established initial conditions vanish.

Numerical analysis were carried out by means of the home-made finite volumes code I-MOD3D (Olivares and Tommasi 2008) under the assumption of isothermal conditions for a rigid unsaturated porous medium neglecting the flux of the

Table 1 Set of parametric analysis

Analysis	Conductivity	m	k_{sat} (m/s)	θ_r
$C_{1,2,3,4,5,6}$	$K_{unsat} = k_{sat} * S_e^{\wedge 3}$	0.05, 0.08	$1 \cdot 10^{-7}$	0.1, 0.2, 0.3
$C_{7,8,9,10,11,12}$	$K_{unsat} = k_{sat} * S_r^{\wedge 3}$			
$C_{13,14,15,16,17,18}$	$K_{unsat} = k_{sat} * S_e^{\wedge 3}$	0.05, 0.08	$1 \cdot 10^{-6}$	0.1, 0.2, 0.3
$C_{20,21,22,23,24,25}$	$K_{unsat} = k_{sat} * S_r^{\wedge 3}$			
$C_{26,27,28,29,30,31}$	$K_{unsat} = k_{sat} * S_e^{\wedge 3}$	0.05, 0.08	$5 \cdot 10^{-6}$	0.1, 0.2, 0.3
$C_{32,33,34,35,36,37}$	$K_{unsat} = k_{sat} * S_r^{\wedge 3}$			

Sr degree of saturation
Srr residual degree of saturation
Se = [(Sr − Srr)/(1 − Srr)] effective degree of saturation

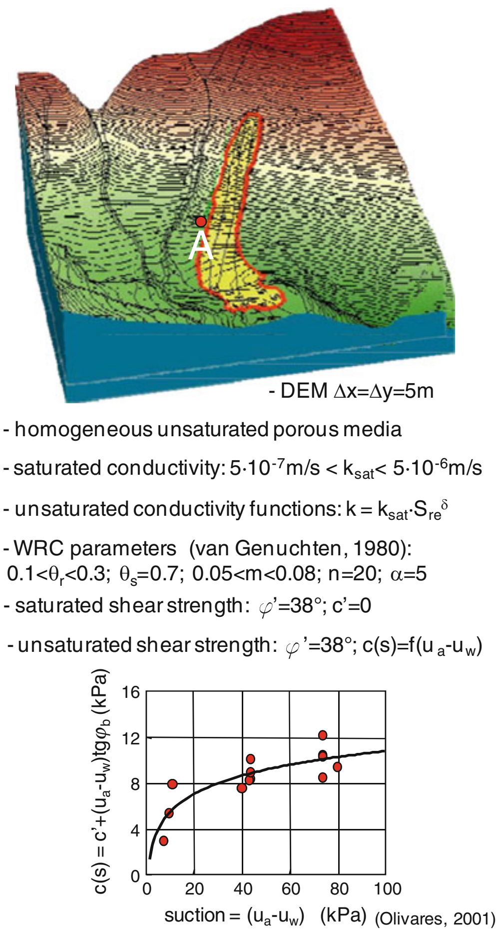


Fig. 4 Digital Terrain Model (DTM) of the Cervinara slope

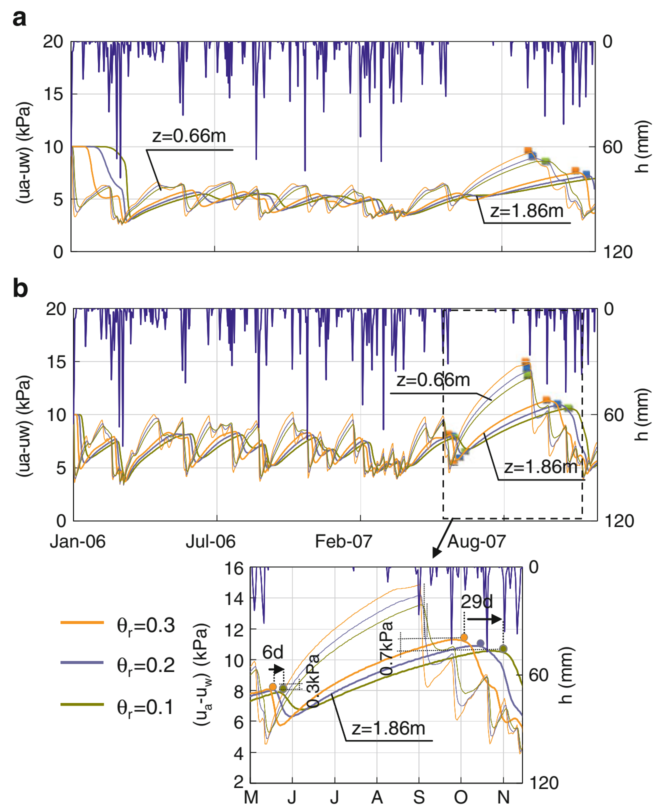


Fig. 5 Comparison of numerical simulations at various θr for: (**a**) $k_{sat} = 1 \cdot 10^{-6}$ m/s; (**b**) $k_{sat} = 5 \cdot 10^{-6}$ m/s

gas phase. The slope was schematized as a homogeneous deposit with a 3D mesh derived by DEM (with dx = dy = 0.5 m) using a dz = 0.12 m (Fig. 4). The initial condition in terms of suction was established from in situ measurements, adopting a constant suction profile equal to mean suction (10 kPa) recorded at the beginning of 2006. At the ground surface two boundary conditions were imposed: average daily rainfall intensity or evaporation flux during dry days, evaluated from in situ suction measurements and illustrated in the following section (Fig. 8b). For the lateral and base surfaces a condition of free flow was assumed.

In Fig. 5a,b the results of numerical simulations C16, C17, C18 and C29, C30, C31 performed adopting the two higher saturated hydraulic conductivities and exploiting the variability of θ_r are compared in terms of suction trends at two different depths (0.66 m reported as thin lines and 1.86 m as bold lines). In the same figure blue lines indicate the recorded daily precipitation heights (h).

As expected, conductivity influences both the time needed for the effect of initial conditions to vanish (from 12 to 62 days for $k_{sat} = 1E^{-6}$ m/s and from 1 to 10 days for $k_{sat} = 5E^{-6}$ m/s at a depth of 1.86 m) and the propagation time of wetting fronts caused by the rainfall pattern. This is revealed by the smoother shape of suction trends for the

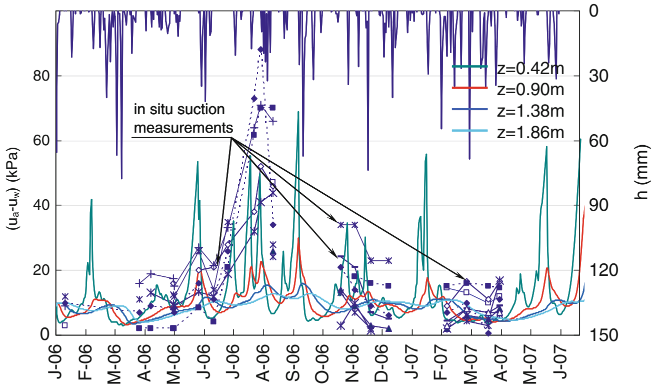


Fig. 6 Comparison between in situ measurements and numerical analysis

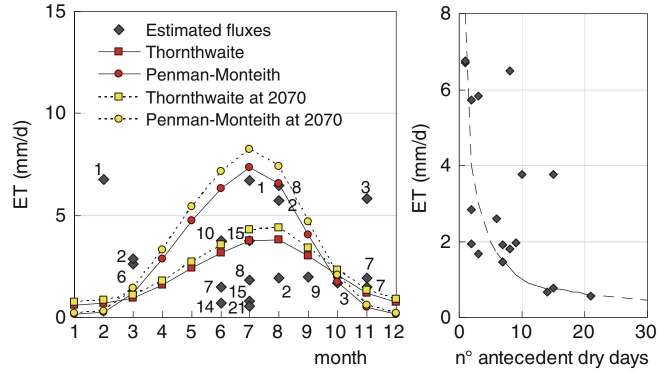


Fig. 7 (**a**) Potential and actual estimated ET fluxes; (**b**) actual ET fluxes plotted against number of antecedent dry days

adopted lower value of k_{sat}. Obviously, conductivity greatly influences the peaks of suction and the range of suction variation within two consecutive relative maxima. Indeed, under the same suction level a higher k_{sat} corresponds to a higher k_{unsat} which, in turn, corresponds to faster groundwater processes, both in infiltration and evaporation.

The enlargement of Fig. 5b for the period May–November 2007 shows the effect of $(\theta_s - \theta_r)$ on the transient regime flows. In particular, the range of suction variation decreases with increasing differences $(\theta_s - \theta_r)$ whereas the delay of the infiltration process at different depths increases. Indeed, comparing the results at 1.86 m of depth obtained with $\theta_r = 0.3$ and $\theta_r = 0.1$, at the beginning of September 2007 after a prolonged dry period (Fig. 5b), the suction peak decreases by about 6 %, while the delay is about 29 days. After a wet period, as in May 2007, owing to the higher degree of saturation, the suction minimum increases by about 3 %, while the delay is definitely lower (about 6 days). Once again this has to be linked to the values assumed by k_{unsat} which, starting from a given suction level, are lower in the case of SWRC with higher $(\theta_s - \theta_r)$. This effect becomes significant when the soil approaches low degrees of saturation, i.e. during dry periods, whereas it tends to vanish when high water contents are reached, i.e. during wet periods (differences in terms of SWRC due to different θ_r are negligible approaching complete saturation).

Figure 6 shows the output of the numerical simulation C23, which represents the best approximation of the monitoring results, compared with suction measurements performed at different depths (50–220 cm) available during the period from January 2006 to July 2007. The best fitting was obtained using the unsaturated conductivity function $k_{unsat} = k_{sat}S_r^3$ with $k_{sat} = 1E^{-6}$ m/s, and the SWRC described by $\theta_s = 0.7$, $\theta_r = 0.1$, $m = 0.08$, $n = 20$, $\alpha = 5$ van Genuchten parameters which provided the best agreement with both the trend and the peaks of matric suction although the maximum suction values recorded during the dry period could not be reproduced. However, fair agreement during wet periods was reached.

It is worth noting that the adopted hydraulic functional relationships differ from those which fit the experimental data with particular reference to SWRC determined through conventional laboratory tests. This highlights the importance of the availability of in situ measurements to validate the model since laboratory investigations on small soil samples and in conditions often different from those present at the slope scale are sometimes not representative (due to different rates of the processes, heterogeneity, presence of roots, etc.. . ..).

Impacts of Climatic Factors on Slope Response

To analyse the role of climatic factors on slope response, soil-atmosphere water exchanges were evaluated. Various formulations are available in the literature to estimate potential infiltration and evapotranspiration, but evaluation of the actual values assumed by the water exchanges at the soil-atmosphere boundary is somewhat more complicated since it depends on atmospheric conditions as well as soil properties, layering, presence of roots, vegetation, etc. However, this is a crucial point.

To this aim, some indications are provided by in situ monitoring. Suction data collected from 2001 to 2008 at different depths in Cervinara site enabled estimation of the flux of water towards the ground surface during dry periods (Damiano et al. 2012). The estimated fluxes are compared in Fig. 7a with two of the most common literature expressions for potential evapotranspiration ET, Thornthwaite (1946) and Penman-Monteith (Monteith 1965) respectively based on the mean monthly air temperature and the mean climate and vegetation characteristics using climatic data records at the Montesarchio and Trevico weather stations, about 10 and 50 km from Cervinara.

The diagram shows that both Thornthwaite and Penman-Monteith ET values are strongly related to the seasonal cycle while the measured ET rates do not show a clear trend over the year. Moreover, in contrast with the intuitive perception the lowest ET rate (0.5 mm/day) occurred in the hot month of July, the highest (7 mm/day) in the cold month of February. However, the diagram in Fig. 7b, which reports the calculated fluxes as a function of antecedent dry days (indicated by labels in Fig.7a), suggests that actual evapotranspiration is strongly affected by top soil moisture, which decreases with time during dry days, and only indirectly by air temperature and relative humidity. In general, the higher the number of dry days, the lower is the flux rate even though a unique correlation cannot be found: however, the variable fluxes estimated after the same number of dry days suggest the important role of the initial soil moisture conditions.

Formulations from the literature can be used to evaluate the impact of future climate scenarios on the ET regime under the heavily simplified hypothesis that vegetation will not be affected by climate change. The expected temperature increase of 0.05 °C per year (Damiano 2009) over the next 60 years provides the potential ET trends reported as yellow points in Fig. 7a, causing an increase smaller than 1.0 mm/day. Thus, potential ET is expected to remain in the actual range of values. Based on this consideration, in simulating future slope behaviour the ET fluxes imposed as the boundary condition at ground surface during dry periods will be assumed equal to the trend line plotted in Fig. 7b.

At the same time, changes in the duration of dry periods are not expected to affect significantly annual cumulative evapotranspiration significantly. As shown, the ET flux is highly related to soil moisture conditions, and in the considered unsaturated granular covers, with a relatively high saturated conductivity and a low air-entry point, it rapidly decreases as a function of antecedent dry days, reducing to less than 2.0 mm/day after 7 days, since an abrupt conductivity reduction occurs. Hence, an increase in drought periods could lead to a local increase in ET fluxes, but to a substantially equal amount of cumulative ET.

In order to investigate the potential effects of climate change on the stability of steep slopes in unsaturated granular soils, we performed a series of analyses of the hydrologic behaviour of the Cervinara slope, for the duration of 1 year, and compared the results in terms of suction and safety factors with the corresponding values assumed during the reference year 2006, characterized by a slightly higher total precipitation than the 1965–2010 average (1,350 mm). In particular, to highlight the effects of expected changes in the annual precipitation regime, three different yearly hyetographs, obtained by modifying that observed during 2006, were applied as a boundary condition at ground surface:

- Scenario A1: increase in storm intensities and number of dry days, with no changes in cumulative annual precipitation;
- Scenario A2: increase in storm intensities during winter;
- Scenario A3: heavy rainfall event added at the end of winter.

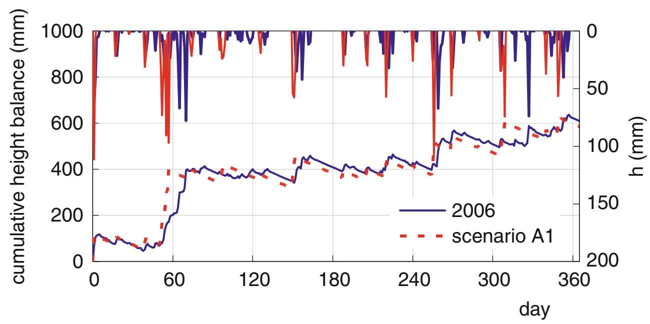


Fig. 8 Scenario A1: adopted hyetograph and cumulative in-out balance

Scenario A1 is the most representative of the COSMO CLM projection. The others (A2 and A3) focus on the predicted increase in storm intensities during winter. In particular, they allow to investigate the relationship between triggering event and antecedent rainfall.

Slope stability was analysed on the basis of the simple infinite slope hypothesis which leads to the following expression of safety factor:

$$FS = \tau_{lim}/\tau = \{[c' + (u_a - u_w)\tan\phi_b] + (\sigma_\alpha - u_a)\tan\phi'\}/(\gamma z \sin\alpha\cos\alpha) \quad (2)$$

where

τ_{lim} is the shear strength of soil along a plane parallel to the ground surface (1);

$(\sigma_\alpha - u_a)$ is the normal net stress along a plane parallel to the ground surface;

γ is the unit weight;

z is the depth from the ground surface;

α is the slope inclination angle.

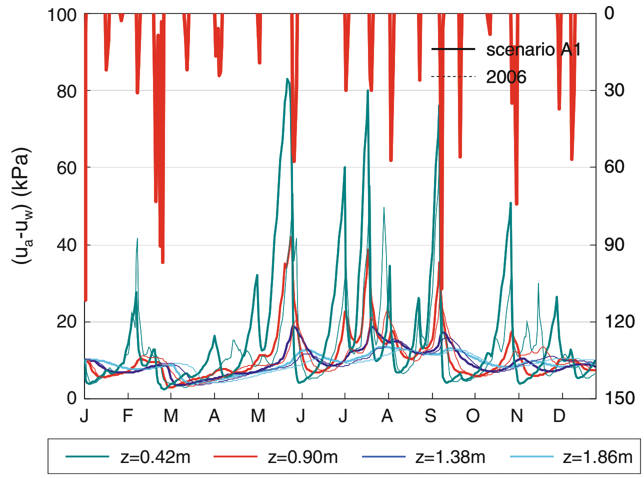
The experimental relationship determined by Olivares (2001) for Cervinara volcanic ashes, plotted in Fig. 4, was used to evaluate apparent cohesion due to suction $(u_a - u_w)$ $\tan\phi_b$.

Scenario A1

The hyetograph concerning scenario A1 was derived from the reference one by concentrating the rainfall height of three consecutive days in a single rain event, in such a way as to obtain a decrease in rainy days and an increase in rainfall intensity for each storm, without variation in annual precipitation.

Figure 8 shows the reference (year 2006) and the modified hyetograph (scenario A1) in terms of rainfall heights and cumulative in-out height balances estimated by subtracting the ET heights (calculated with the expression of Fig.7b) to the precipitation heights, neglecting surface

Fig. 9 Scenario A1: suction evolution at four depths compared with 2006 values



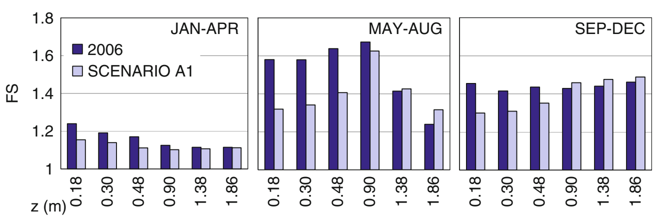


Fig. 10 Scenario A1: minimum FS values by depth compared with corresponding values for 2006

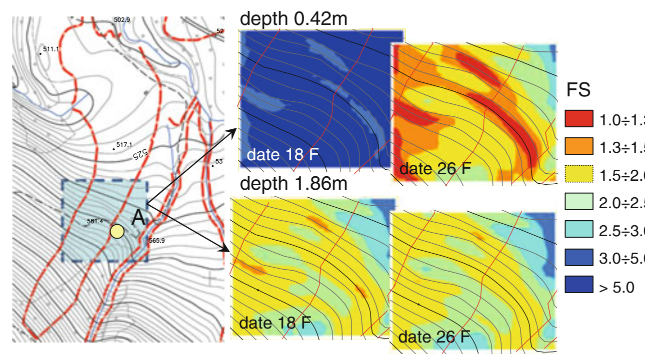


Fig. 11 Scenario A1: FS maps at two depths before and after the rainstorm of 18–26 February

runoff. The adopted procedure, in this case, led to a 44 % increase in dry days and a slight decrease in cumulative infiltration height (4 %).

The results of the analysis are reported in Fig. 9 in terms of suction at four depths evaluated at point A in Fig. 4. Comparing the simulated values with those regarding the real rainfall pattern in 2006 (dashed lines) it may be recognized that during summer and autumn the soil experiences an increase in maximum values (ranging from +2.5 % at a depth of 1.86 m to +45 % at a depth of 0.48 m) and a decrease in minimum values (−21 % at a depth of 0.48 m and −2 % at a depth of 1.86 m). The coupled effect of higher storm intensities and prolonged dry periods modifies the groundwater flow regime, inducing wider variations particularly in upper soil layers. At the end of the simulation year, characterized by a more intermittent rainfall pattern, suction assumes values similar to the initial ones even if a different vertical profile can be recognized.

Figure 10 reports the minimum values that safety factors assume at different depths during three periods of the year compared with the corresponding values for 2006. As expected, the minimum values are those corresponding to the highest depths at the end of the winter, which attain values similar to those obtained for the real hyetograph. On the contrary, the FS of the shallowest layers, up to a depth of 0.9 m, is less than the 2006 one throughout the year, with a more significant decrease (up to 50 %) during summer and autumn.

In depth the FS slightly increases from May to December owing to the different amounts of infiltrated rainfall. In fact, the effects of a given amount of rainfall falling in a shorter time remain confined in the shallowest layers. Afterwards, during dry periods, evaporation subtracts parts of the infiltrated water, thus reducing the leakage towards the deepest layers. Hence, the suction trend and, in turn, the FS in depth are influenced by the cumulative effects of rainfall events during the previous months rather than by the single storm event. Thus, the increase in storm intensities, if not accompanied by a related increase in cumulative monthly precipitation, essentially affects the superficial layers, reducing the stability only of the shallowest covers, while the main climatic factor influencing the stability of the entire underlying cover is cumulative monthly rainfall.

The distribution of FS at depths of 0.46 and 1.86 m evaluated before and after the rainstorm of 18–26 February is illustrated in Fig. 11. It suggests that rainfall patterns similar to scenario A1 would lead to an increase in the probability of very shallow landslides occurring.

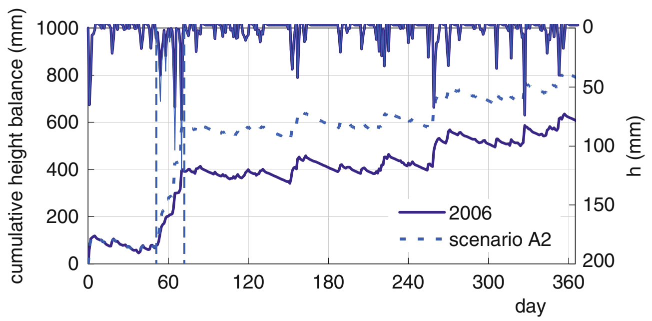


Fig. 12 Scenarios A2: adopted hyetograph and cumulative in-out balance

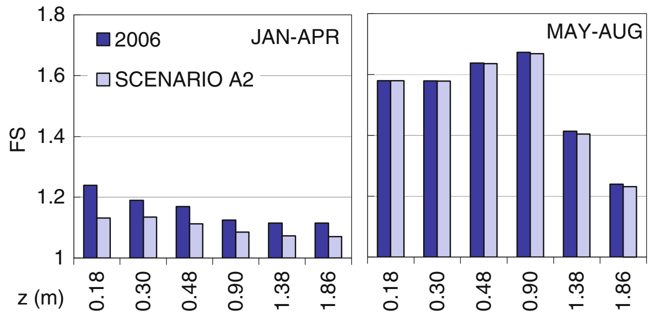


Fig. 14 Scenario A2: minimum values of FS by depth compared with values assumed during 2006

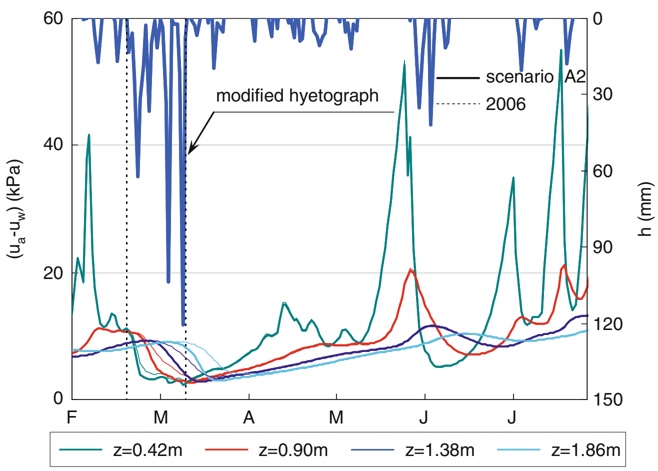


Fig. 13 Scenario A2: suction evolution at four depths compared with 2006 values

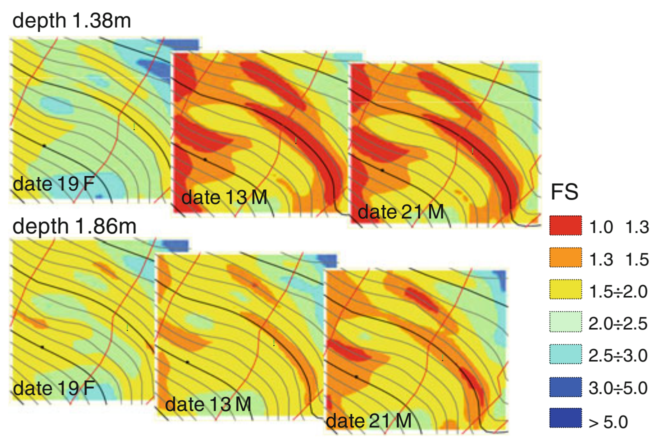


Fig. 15 Scenario A2: FS maps at two depths before, at the end of, and after the rainstorm of 20 February–13 March

Scenario A2

For scenario A2 the daily precipitation intensity of the events occurred between 20 February and 13 March 2006 was increased by 50 % (Fig. 12). This way, as for scenario A3, an annual precipitation increase of about 30 % was imposed which still remains in the range of normal variation of actual annual cumulative precipitation (ranging from 780 mm in 1988 to 1,930 mm in 2010).

The effects of scenario A2 are illustrated in Figs. 13 and 14 respectively in terms of suction trend and minimum safety factors from January to August since no significant differences, with respect to 2006, can be noted starting from 2 months after the end of the modified rainfall.

The increase in rainfall intensity determines quick response at every depth and, even if it seems to produce only a slight decrease in suction (in the order of hPa), the effects on slope stability are significant since a 35 % decrease in FS along the entire thickness occurs with a minimum value close to one (1.06 at a depth of 1.38 m). This is due to the strong non-linearity of the relationship between suction and apparent cohesion at such low stress levels.

The time evolution of FS at the critical depths of 1.38 and 1.86 m across the increased rainy period is illustrated in Fig. 15. In this case, prolonged intense rainfall significantly affects the stability of the intermediate and deep layers. Major effects are recognized at intermediate depths where the soil experiences a diffuse decrease in FS first and for longer.

Scenario A3

Scenario A3, aimed at evaluating the effect of higher concentrations of storm events at the end of the rainy season, was obtained by introducing a rainfall event, identical to the intense event of 5–12 March 2006, on April 04, when the results of numerical analysis for the reference year indicate that the minimum suction values at a depth of 2.2 m had been attained. The obtained hyetograph is reported in Fig. 16.

Unlike scenario A2, the slope hydrological response is affected for a longer period, as indicated by the significant suction decrease observed at any depth for 5 months after the event of 4–11 April (Fig. 17). In this case suction shows a greater than 50 % reduction in minimum and

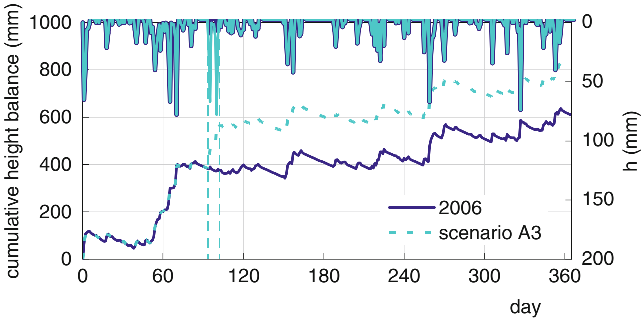


Fig. 16 Scenarios A3: adopted hyetograph and cumulative in-out balance

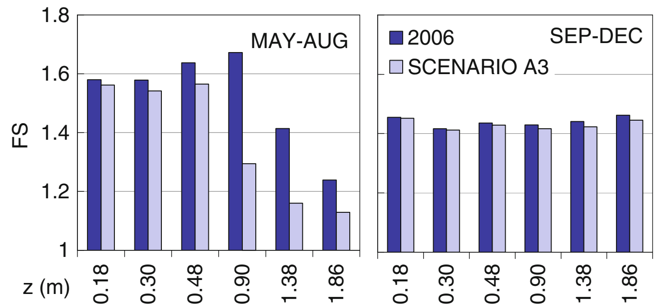


Fig. 18 Scenario A3: minimum values of FS by depth compared with values assumed during 2006

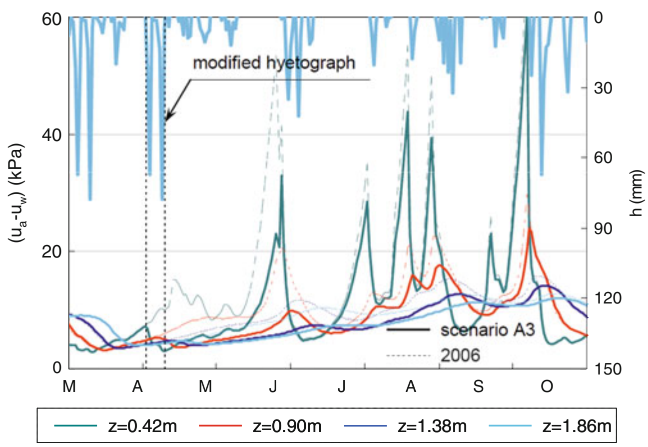


Fig. 17 Scenarios A3: suction evolution at four depths compared with 2006 values

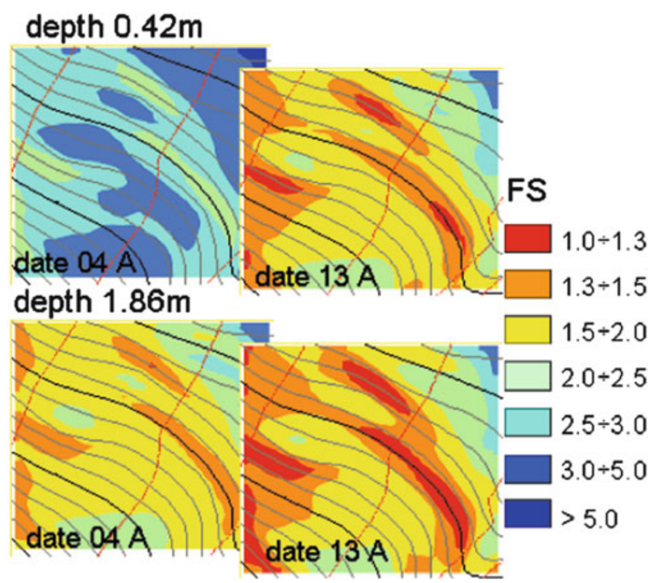


Fig. 19 Scenario A3: FS maps at two depths before and at the end of the storm event of 4–11 April

maximum values with a consequent smoothness of the shapes of suction trends.

The relatively high unsaturated conductivity profile of the cover at the beginning of rainfall causes rapid infiltration towards the deepest layers (about 20 days against about 60 days obtained in the parametric analysis C16 for $k_{sat} = 1e^{-6}$ m/s). As a consequence, even a single storm event can affect the suction trend in depth, inducing a strong reduction in FS (Fig. 18). Comparison between FS maps at the depths of 0.42 and 1.86 m before and after the rain storm (Fig. 19) highlights that the highest decrease in FS occurs in upper layers but in depth absolute minimum values are reached just at the end of the rain storm.

Slight increase in rainfall intensity could lead to slope failure affecting the entire thickness of the cover. This is probably what occurred in Campania in 1998 when at the beginning of May a series of catastrophic flowslides triggered by an intense storm involved the entire pyroclastic covers of the slopes surrounding the towns of Sarno, Quindici and Bracigliano (Cascini et al. 2000).

Conclusions

In this paper the potential effects of climate change in the Mediterranean area on the stability of steep slopes in shallow unsaturated granular covers have been investigated. Extensive experimental and mathematical investigation on pyroclastic covers indicates that in order to effectively model the mechanical and hydrological behaviour of such slopes, it is worth supplementing the usual laboratory tests with data from in situ monitoring since slope response to rainfall is affected by soil characteristics as well as by rainfall variability. By applying a simplified mathematical model validated on field data, the effects of climate changes estimated with the COSMO CLM regional climate model have been investigated. This entailed an increase in the intensity of the extreme precipitation mainly concentrated during winter and a decrease in the number of rainy days.

The results of the analysis appear to indicate that, under the assumed simplified hypothesis:

– Increases in air temperature and in the number of dry periods are not expected to affect annual cumulative evapotranspiration significantly;
– An increase in storm intensities and dry period durations would affect the stability conditions of the shallowest layers;
– An increase in seasonal cumulative rainfall might induce instability of the entire cover especially when intense storms occur at the end of the rainy season, i.e. at high soil moisture contents.

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