Centro Euro-Mediterraneo per i Cambiamenti Climatici

Research Papers
Issue RP0103
December 2009

Division: Impacts on Soil and Coasts

A study on climatologic aspects for forecasting of shallow landslides in pyroclastic soils due to climatic change

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SUMMARY This report contains the results of bibliographic research and numerical simulations aimed to the individuation of a simple and rational procedure to investigate the effects of climate change on the behaviour of slopes in unsaturated pyroclastic soils affected by flowslides. The analysis of a future scenario have been performed using the hand-made code I-MOD3D for the study of seepage processes and stability analysis, firstly validated on a period two years long on the base of in situ suction and rainfall monitoring, using as climatic boundary conditions the results of numerical analysis performed by the climatologic team of C.I.R.A. by using the COSMO-CLM climatic model.

CONTENTS

1. Foreword

Slope failures are caused by a combination of several factors, such as climatic conditions, geological features, topography and vegetation. In regions where the groundwater table is usually deep and soils are unsaturated, climatic conditions may significantly affect slope stability. In fact, while during dry periods the soil usually experiences high matric suction (i.e. negative pore-water pressure) which contributes to the shear strength of the soil, during prolonged wet periods matric suction decreases, causing a reduction of the shear strength and eventually inducing slope failure. This aspect is dominant in unsaturated pyroclastic deposits of Campania Region where landslides are primarily induced by rainfall.

The main goal of the ongoing research is the individuation of a simple and rational procedure to link weather forecasting to prediction of slope failure. In general, for each kind of landslide this procedure requires: i) the individuation of the climate factors which can influence on the slope response; ii) the knowledge of the geomorphological context and the geotechnical characteristics of the involved soils; iii) the validation of numerical models for both climatic change and slope stability forecasting; iv) the prediction of landslides activity basing on climate change. Despite of the simple described procedure, the complexity of both climatic and geotechnical aspects and their interaction make very hard the landslide forecasting as it is well known by scientific community.

2. Literature Overview

Landslides are one of the most dangerous natural hazards since they degrade the productivity of soils, harm humans, and damage property. Climate parameters affecting pore water pressure fluctuations can, in many cases, trigger slope instability and hence landslide activity (extended and intense rainfall is the most common triggering mechanism of landslides worldwide). Therefore, global warming due to the greenhouse effect and changes in precipitation patterns and air temperature might have influences on future landslide activity.

The assessment of the effects of global warming is, however, very difficult since it requires the development of a multidisciplinary methodology to analyse quantitatively the impacts of climate change on the activity of different type of landslides which can take into the account that landslide triggering systems show complex responses in relation to geotechnical, hydrological, and climatic properties (van Ash, 1997).

Effects of past, present and future climate characteristics can be assessed by field evidence, landslide monitoring or by mechanistic models through the use of climate parameters simulated by general circulation models GCMs. However, there are a series of problems related to that approach. First, 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 simulated time series. Then, the climate-landslide coupling itself is complex, because climate is related to landslides via the nonlinear soil water system (Crozier, 1997). Therefore, there is no unique relationship between climatologic characteristics and the frequency of soil slips (van Asch, 1997).

Physically based models of rainfall-induced landslides have been used to model and understand this complex interaction (Brooks, 1997) and to derive thresholds for the

hydrological triggering system under different conditions. However, more research is needed to understand these relationships, and to relate them to known past climates.
This problem is nowadays faced by scientific community and by governments which are funding a number of research projects (such as TELSEC, GACH2C project, C-CIARN, etc.) aimed to individuate future landslides scenarios in wide areas of the world.
At the present, the complexity of the relationships between climate and landslides seems to make not feasible the establishment of ‘‘universal laws’’ all over Europe (TELSEC). On the other hand, it seems possible to establish for some areas a cumulative rainfall-duration threshold for the reactivation of landslides. In other words, the assessment of landslides forecasting is not realistic if applied to entire regions or countries but it has to be done for each singular geomorphologic scenario characterized by a well-defined type of slope movement. In fact, as an example, typically deep-seated, slow moving landslides (e.g., earthflows, slumps) are triggered or reactivated by an accumulation of precipitation over several weeks or months. In contrast, shallow, rapid landslides (debris avalanches, debris flows) usually initiate during individual intense or large storm events. Hence, successfully predicting landslide hazards in large regions greatly depends on our ability to individuate climate triggers for each type of landslides and to link meteorological conditions with various types and extents of slope failures.
Different authors in the last decades approached to the evaluation of landslides forecasting starting from various future climatic scenarios. As a result, general indications have been given about linking the various steps for prediction of future landslide activity. As suggested by Dehn & Buma (1999) a general framework could be used which consider the following pattern:

1. *Identification of relevant climate input*

The first step is the individuation of the climatic parameters which play the dominant role in triggering landslides. Here arises the problem that landslides are a very heterogeneous process group and they show a wide range of triggering mechanisms, even if only climate-related triggers are considered. In general and as a first approach, they could be roughly subdivided into major groups with precipitation as main triggering factor (Collison, 1996; van Asch, 1997): deep seated landslides with shear planes at depth greater than 10m, shallow landslides with shear planes at 1–10m depth, and landslides with superficial shear planes, e.g., debris flow. For these three cases, different hydrologic systems and, hence, climatic input variables have to be considered ranging from yearly, monthly or daily precipitation to short-term intensities.
In fact, even in similar conditions, precipitations might have different influences basing on the examined landslide (Terzaghi, 1950). This aspect is well highlighted in fig.1, that reports the cumulated annual precipitation and the frequencies of different types of soil movements in a same area of California, USA, during a period 45 years long. As it can be noted, the annual precipitation can be correlated only with the deep movements, while the frequencies of the shallow landslides are independent from the annual precipitation. Thus, the identification of relevant climatic variables is the first necessary information to appropriately select climate change scenarios.

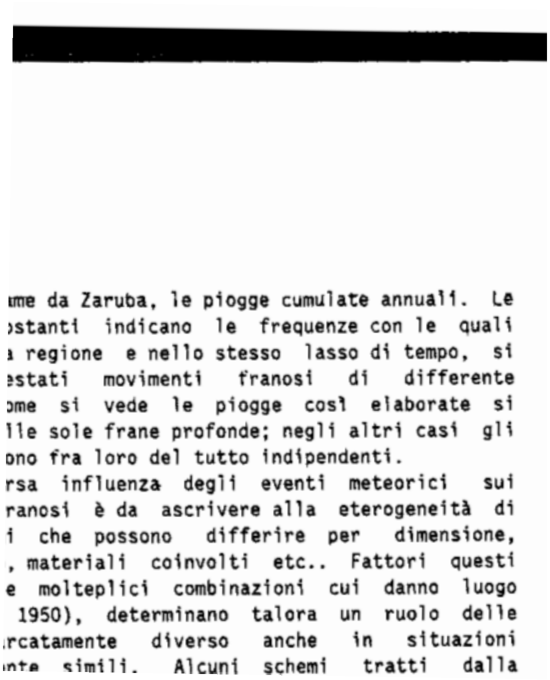
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Figure 1. Cumulated annual precipitation and frequency of different type of landslides (Sangrey et al., 1984).

2. Sensitivity of landslides to climate change

If some input climatic parameters can increase the frequency of landslides, some other factors related to climatic change, like material availability, changes in the soil properties, etc., can decrease it and should be tested in a sensitivity analysis. As an example, in the case of debris slides or debris flows if no debris is available, even the heaviest rainfall cannot trigger a mobilization. On the contrary, since debris availability is increasing by means of melting glaciers and permafrost following global warming, as outlined in Zimmermann and Haeberli (1992) and Dikau et al. (1996), increasing temperature alone could increase the frequency of debris flows.
Moreover, for other types of mass movements, other factors might be important, e.g.,
- changing land-use, induced by human activities or due to climate change;
- vegetation succession due to climate change;
- changing weathering regime due to climate change;
- changing slope geometry due to landsliding or other processes, and

While the first three points are also related to climate, the latter is dependent mainly on the geomorphological process system. All these factors can, however, play an important role in changing the overall susceptibility of a slope to climatic factors, even if their evaluation is often only qualitative.

3. Techniques to obtain local climate change scenarios

After identifying relevant climate parameters, it is necessary to forecast their future trend. To this aim downscaling techniques have to be used in order to derived the required information from Global Circulation Models (GCM) simulations.
Several downscaling techniques are described in the literature. They range from simple empirical–statistical relationships between large-scale atmospheric variables and local target climatic parameters (von Storch et al., 1993; Lettenmaier, 1995; Zorita et al.,

1995) to physically based regional climate models which are nested within GCMs (Giorgi et al., 1994; Frey-Buness et al., 1995). The first type of techniques is based on the linking between homogeneous long time series of the input parameter at the local scale and one or several atmospheric variables like sea level pressure or geopotential heights on the large-scale. It seems to be suitable for modelling of landslide activity but its limitation lies on the assumption that the relationships obtained under present conditions will also hold true under a changing climate (Buma & Dehn, 1998).

4. Linking climate change data and impact model

The long pathway from greenhouse gas emission scenarios to climate change impact studies is shown in fig. 2. Emission scenarios published by the IPCC (Houghton et al., 1992) are based on assumptions about global demographic and economic growth and energy supplies. Using these scenarios GCMs simulate future climates on the large-scale, which can be used to derive local climate scenarios with techniques mentioned before.

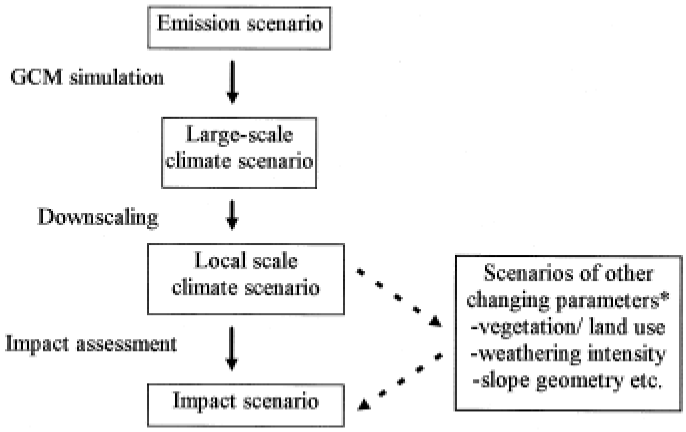

Figure 2. Chain of scenarios and modelling steps leading to local climate change impact scenario. Solid arrows are obligatory, dashed arrows are supplementary (Dehn & Buma, 1999).

After the derivation at the local scale climate scenario, the effect at ground of the climate change can be simulated trough the use of different methods: in general, they are essentially physically based and empirical models, depending on the scale of the evaluation. In fact, physically based models link the rainfall event and the landslide event making use of expensive equations aimed to reproduce the physical processes occurring in the slope as a result of the meteorological phenomena (infiltration, evapotranspiration, runoff, etc.) and their effects on slope equilibrium (i.e., Iverson, 2000). To this aim they need accurate data regarding the geomorphology of the slope and the physical, mechanical and hydraulic properties of the soils and due to their inherent computational complexity, they can be utilized only at a site size approach in order to evaluate the future scenario for a single slope.
Conversely, empirical models rely on simple correlations between measured rainfall and observed landslides, aimed to attribute triggering thresholds to rainfall characteristics. Usually, as illustrated in fig. 3, the threshold is represented, in the space of rainfall related variables (intensity, duration and/or cumulative precipitation), as a surface separating two domains where the combination of variables corresponds, respectively, to slope failure and slope stability (Guzzetti et al., 2007).

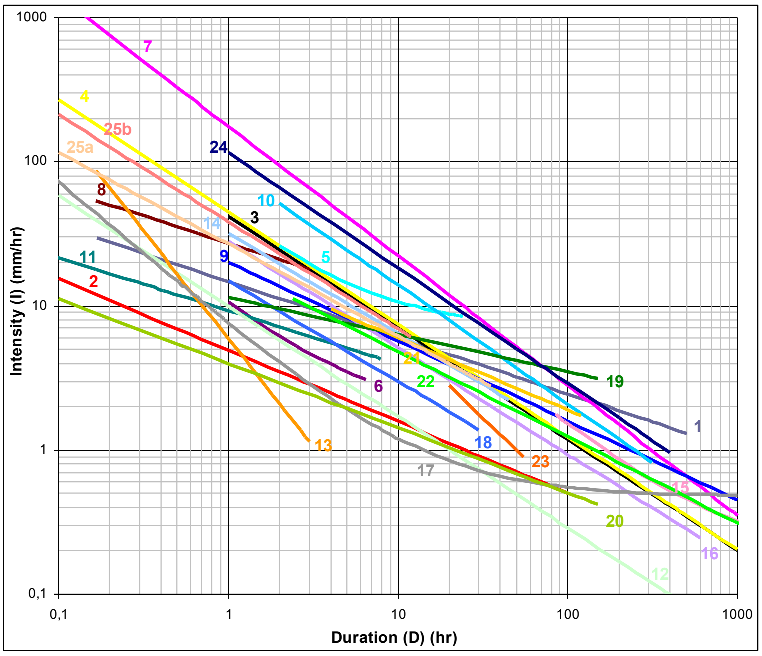

Figure 3. Different worldwide empirical rainfall thresholds (Guzzetti et al., 2005).

All the found trends show substantial differences due to the various geologic, geomorphologic and climatic contexts in which they have been evaluated, but they also show a common feature consisting in the fact that the critical rainfall intensity decreases as the duration of the triggering event increases.

Empirical models calibration need only accurate historical data regarding the chronological individuation of landslide triggering and the knowledge of rainfall conditions occurred before slope failure. Due to their higher simplicity, empirical models constitute integral part of various worldwide operational landslides warning systems, adopted by local governments to mitigate the risk connected to the landslide events (Brand et al., 1984; Wilson et al., 1993; Iwamoto, 1990; D'Orsi et al., 1997; Sirangelo et al., 2007) and they are also utilized to evaluate future landslide scenarios at a scale greater than the slope scale (Jakob and Lambert, 2009).

A common shortcoming of all the above cited methods is that often the role played by soil conditions at the beginning of rainfall event is neglected or only indirectly taken into account through antecedent cumulated rainfall. Unsaturated soil behaviour during infiltration is instead strongly influenced by its initial condition, expressible either as initial water content or as initial matric suction, and this is one of the key factors of greatest uncertainty which have to be strongly taken into the account in the assessment of impact scenario.

To complete the assessment of future changes, scenarios of other than climatic factors should be included in the approach (as already indicated in fig.2 by dashed arrows). In fact, landslides result from interdependent spatio-temporal processes, including hydrology (rainfall, evapotranspiration, and groundwater), vegetation surcharge (weight of vegetation), root strength, soil condition, bedrock, topography, and human activities. Among these the land use practices that exacerbate landsliding, roads/trails and forest conversion to agriculture (typically associated with burning) exert the greatest impacts. Climate change scenarios that promote higher intensity storms, more rainfall, and

vegetation with weaker root structure or less root biomass will likely increase landslide susceptibility; however, such impacts are currently speculative and will be difficult to unravel from anthropogenic effects (Sidle, 1992).
At this regard it is interesting to note that relatively static environmental factors (i.e., elevation, slope, aspect, and topographic curvatures) exhibit negligible changes in their state through time differently from dynamic factors such as climatic or human activities, which tend to alter landslide susceptibility through time (Wu and Sidle, 1995). To predict the spatial and temporal patterns of areas susceptible to landslides, taking into the account also the effect of vegetation (in terms of species, age, density) and root strength usually multi-factor empirical assessment methods are utilized. However, a dynamic distributed physically based slope stability model (dSLAM) was developed by Wu and Sidle (1995) which includes the infinite slope model, a kinematic wave groundwater model, and a dynamic vegetation growth model including continuous changes in root cohesion and vegetation surcharge. The dSLAM model uses individual hourly rainfall hyetographs for event simulations or long series of random rainstorms for long-term simulations. Slope stability is simulated using the spatial distribution of the factor of safety (FS), which is the ratio of resisting and driving forces favouring failure. Application of dSLAM is feasible only in areas with sufficient information on the spatial variability of the input parameters.
However, since this is not an easy task, the direct effect of climate change on the landslide process can be assessed as a partial approach to the problem.
Actually, every link of the chain shown in fig. 2, is affected by uncertainty: it depends on quality of GCM simulations, quality of downscaled scenarios, quality and resolutions of the impact models, which are often strong simplifications of reality, and errors in input data (Dehn and Buma, 1998). Hence, in all cases it is important to quote all underlying scenarios, models and assumptions included in the approach to make it as transparent as possible (Arnell, 1995).
Following the complex chain described above, in general, the effects of global changes on landslide susceptibility and frequency and, in particular, the described step 4 “linking climate change data and impact model”, can be evaluated using two main approaches: a mesoscale approach and a site size approach, described in the next, which differ essentially for the dimension of the observed area.

Mesoscale approach

The evaluation of future landsliding scenarios due to climatic changes at regional scale seems to be attractive since it will be used for planning of urban, industrial and rural areas. This approach is often adopted when the investigated area is characterized by the same geomorphology and by a similar type of landslide. More difficult is the evaluation of future landslides frequency when the area is affected by different kind of soil mass movements since, as mentioned above, they are triggered by different climatic factors.
Using a regional scale approach, in order to assess the response of slopes to climatic change it is necessary the individuation of models simpler than those used in a site approach, since they have to evaluate the changing in safety conditions of a wide territory. At this aim, two main roads are used for linking weather and climate information to landslide initiation based on:

1. simple rainfall — landslide thresholds;
2. numerical codes for analysis at areal scale

The first method can be mainly used for estimating the probability that a landslide can be triggered by a given rainfall event, but it doesn’t give the information about the mass

movement localization: hence, it can be used only in order to evaluate the changes in frequency of landslides due to climate change. The second method is based on the use of numerical codes like TRIGRS (Baum et al., 2002) and SHALSTAB (Dietrich et al., 2001) which adopt strong simplifications of the real processes governing the movement's activation but, in a wide territory, it can give a first indication of slopes prone to fail where finest analysis have to be made (see Technical Report: "*Codici di calcolo per la modellazione dei processi di infiltrazione nel sottosuolo e l'analisi degli effetti al suolo*").
Many studies focused on the relationship between slope instability onset and pluviometric pattern at regional scale, trying to correlate single types of landslide occurrence to rainfall trends. The trends are usually empirically determined and they can be referred to rainfall intensity and duration and/or rainfall height or to a combination of such factors for given period of time (for details see "Technical Report: *AMRA: Analisi della bibliografia*"). The most utilized thresholds are those which link intensity and duration of the triggering pluviometrical event to shallow landslides and debris-flows (Caine 1980, Cannon e Ellen 1985, Wieczorek 1987, Crosta e Frattini 2001). More recently, in order to try to take into the account the moisture conditions of the soils prior to fail, other relationships have been proposed which link the cumulated rainfall in a period antecedent the landslide with the rainfall height on the triggering event (Giade et al. 2000, Nadim 2009): a recent summary of the numerous worldwide empirical rainfall-landslide relationships can be found in Guzzetti et al. (2008).
Some studies on the impact of predicted climate change on landslide have been done using such approach. For instance, Jakob and Lambert (2009) tried to evaluate climate change effects on landslides along the southwest coast of British Columbia in Canada affected by a number of debris-flows. At this aim the Authors used two rainfall thresholds for the urban landslides on Howe Sound and the North Shore Mountains (fig.4) which link the antecedent precipitation (taken as the 28-day accumulated precipitation) and the relatively intense short-duration event able to trigger a landslide (if sufficient antecedent precipitation has fallen) since they are the precipitation-based factors favouring the occurrence of these kind of landslides.
The reliability of climate models used in the research was evaluated trough the comparison between the 'present-day' simulations in terms of statistics of 28-day and 1-day accumulations with those from rain-gauge observations.
It's interesting to note that such comparisons made with a group of independent models have shown that the mean produced by averaging over all the models tends to exhibit a smaller departure from observations than any of the individual models. This observation is useful since it suggests that means computed over all the modelled climate change simulations appear to be a reasonable measure of the true conditions resulting from climatic change.

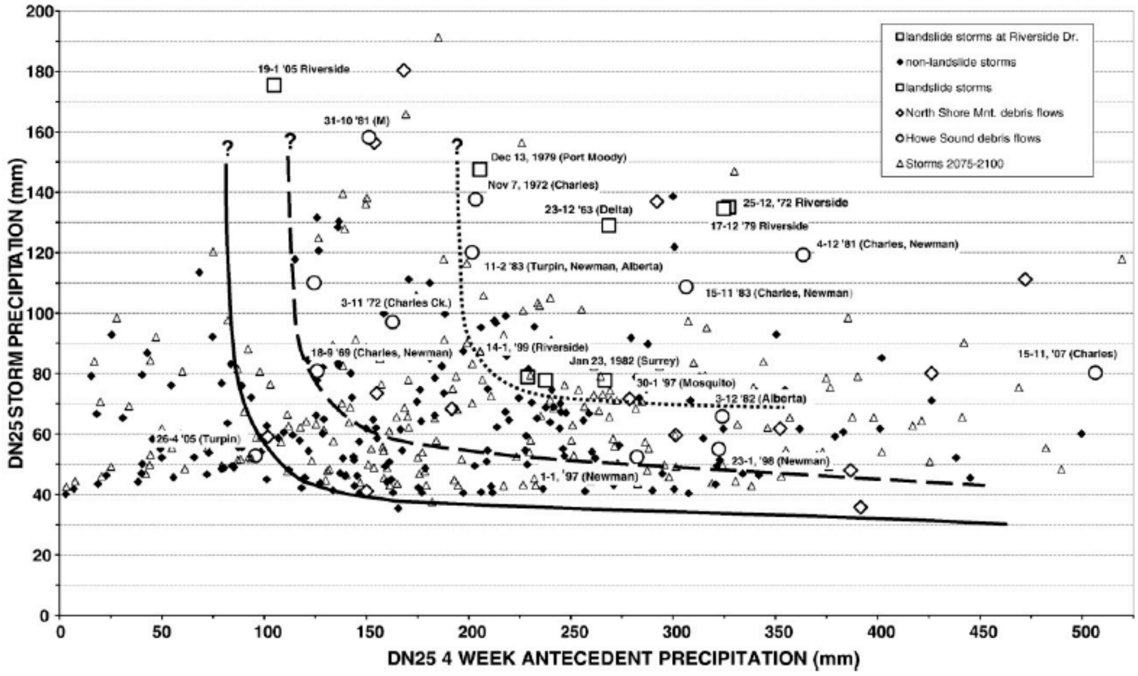

Figure 4. Landslide rainfall-treshold for British Columbia (Jakob and Lambert, 2009).

The evaluation is done by constructing modelled and observed probability density functions (pdfs) for the 28-day and the 1-day accumulations which are reported in fig. 5. where the bold curves are the model pdfs. Considering the great variation of the observation-based pdfs, it can be assumed that the modes of the simulated precipitation agree well with the observed modes of precipitation except for the most intense 24-hour precipitations: the modelled frequencies of the large accumulations (N35 mm/d), those favourable to landslide occurrence, are much less than the corresponding observed frequencies.

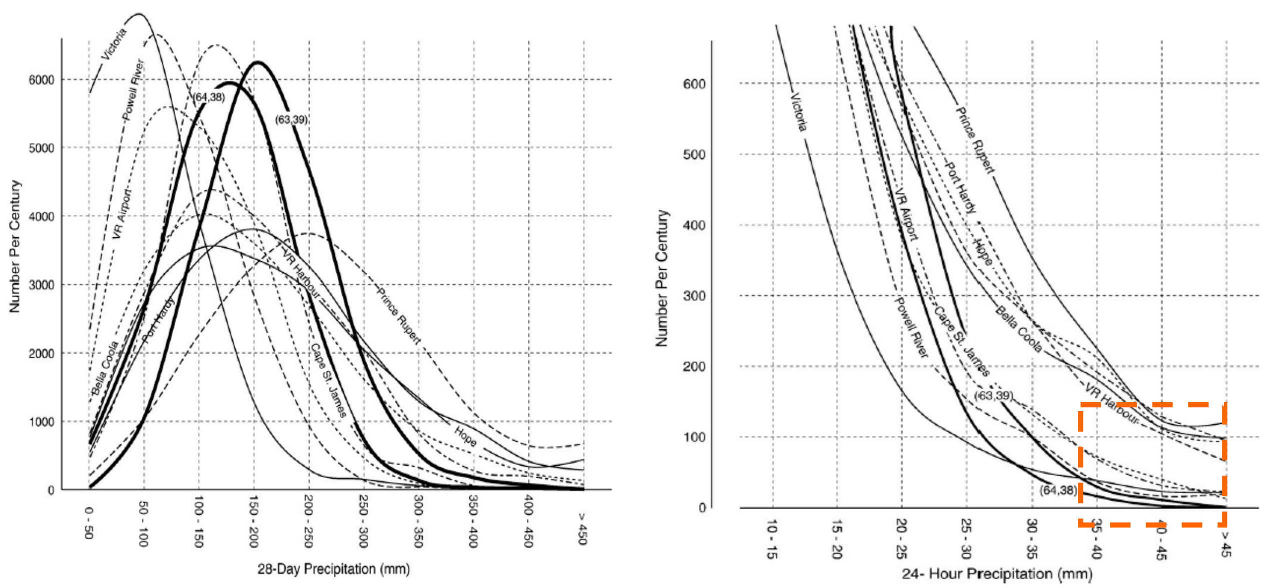

Figure 5. Landslide rainfall-treshold for British Columbia (Jakob and Lambert, 2009).

In order to correct these underestimation of the triggering rain events the Authors use a statistical technique to relate the short-term rainfall to monthly rainfall. In order to extract a relation between these two variables, the short-term rainfall amounts observed at North Vancouver over periods of 1 to 48 h are plotted against the total monthly rainfall and power law curves of the following form are fitted to the data:

$P_{short} = A(P_{month})^{K}$ (1)

where P_{short} is the short-term precipitation; P_{month} is the monthly precipitation; and A, K are parameters obtained by fitting Eq. (1) to the data (fig. 6).

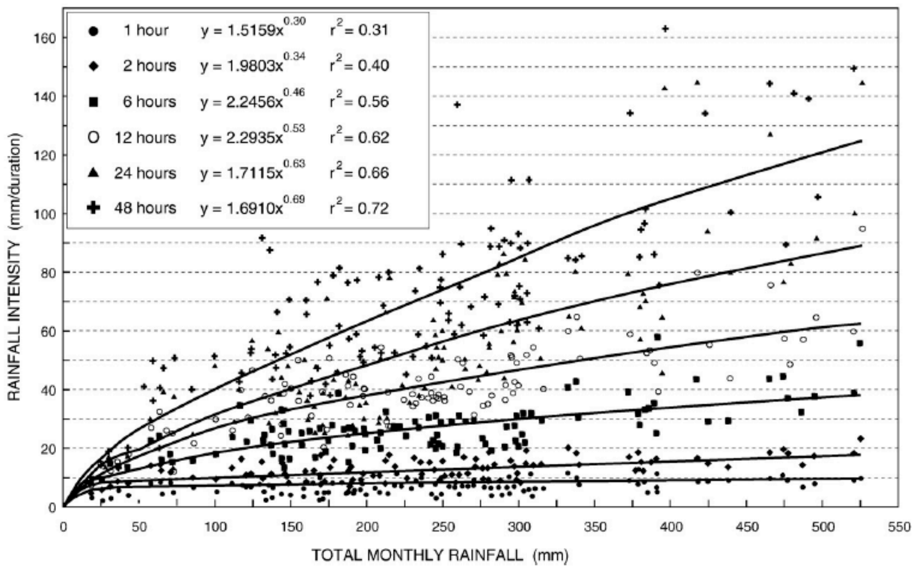

Figure 6. Rainfall intensity versus total monthly rainfall for North Vancouver (Jakob and Lambert, 2009).

By using this law the future modelled short-term precipitation amounts are derived directly from the monthly estimated rainfall. In this way is possible to evaluate the future changes of the two triggering landslide factors, which were estimated in an average increase of slightly over 10% during the twenty-first century for the 28-day precipitations and of a slightly larger than 6% increase in the short-term precipitations. The effect of the increase in precipitations on the occurrence of landslides can be evaluated on the graphs of fig. 4 where each datapoint of non-landslide triggering storms must be adjusted by 10% (horizontal axis) and 6% (vertical axis) respectively for a hypothetical period between the years 2075 and 2100 (triangles in fig. 4). This corresponds to a 28% increase in debris flow occurrence assuming that all other factors (i.e. degree of forest cover, land-use, type and distribution of tree cover, forest fire frequency) remain constant.

The adopted approach is useful as an assessment of future landslide occurrence for specific regions but, as also stated by the Authors, the evaluation of changes in landslide frequency–magnitude relationships as a consequence of climate change remains still highly speculative. Moreover, by using this kind of approach the crucial factor of air temperature, and hence of evapotraspiration which takes effect in the hydraulic processes of the shallow unsaturated soils subjected to landsliding, is completely neglected: in fact, the rainfall thresholds are valid only for the present-day conditions taking into the account the net precipitation (rainfall minus evapotraspiration) in an intrinsic manner which cannot be extrapolated to the future.

The use of numerical codes for analysis at areal scale can overcome this problem.

Depending on the spatial and temporal resolution desired, and the extent and duration to be simulated, a range of different approaches can be used for areal analysis. Due to constraints on computing time and the problems of parameterisation, scenarios where a long period of simulation or a large spatial extent are required generally use simpler hydrology models, while smaller problems can be tackled with greater resolution and numerical complexity.

For instance, Collison et al. (2006) used an intermediate approach in the analysis of the changes in landslide frequency and magnitude in Lower Greensand Escarpment near Hythe, Kent, in SE England mainly affected by shallow (2–3 m) translational slides and rotational slumps. The approach involves the following steps:

- the development of a layered one-dimensional hydrology model to estimate the mean water table depth of the entire escarpment in response to rainfall and temperature (evapotranspiration);
- digital terrain modelling to distribute the land-average water table across the escarpment using subcatchment delimitation and calculation of the landslide topographic index (Bevan and Kirkby, 1979);
- application of the infinite slope model for factor of safety analysis using the digital elevation model (DEM) grid of slope angles and the model values of water table height;
- GIS analysis of instability for each slope unit on the Roughs escarpment.

Starting from the results of GCM downscaling for the investigated area which indicate that the greatest change in precipitation will occur over the next 50 years whereas temperature, and therefore potential evapotraspiration will increase steadily until 2080 (in the final scenario the EVTo outstrips mean P indicating a greater soil moisture deficit than at present), the Authors stated that climate change is unlikely to have dramatic consequences on the frequency of large landslides, but small changes in the distribution of water table depths may significantly decrease periods of small scale instability. However, the adopted approach is heavily related to the assumption made. Finally, the GCM data available for this study were only obtainable as monthly average temperature and rainfall (though data are currently available on daily time steps). Since most landslides of the Roughs respond to rainfall at higher resolutions than this, some form of data dissaggregation is necessary.

Recently, a tentative to take into the account for dynamic processes of the slopes has been made by Gorsevski et al. (2006). In the research a GIS-based modeling approach that includes representation of the uncertainty and variability inherent in parameters is presented. In this approach, grid-based tools are used to integrate the Soil Moisture Routing (SMR) model (Boll et al., 1998; Frankenberger et al., 1999) and infinite slope model with probabilistic analysis. The SMR model is a daily water balance model that simulates the hydrology of forested watersheds by combining climate data, a digital elevation model, soil, and land use data. The infinite slope model is then used for slope stability analysis. Monte Carlo simulation is used to incorporate the variability of input parameters and account for uncertainties associated with the evaluation of landslide susceptibility. This integrated approach was adopted for Clearwater National Forest in north central Idaho, USA, subjected to debris flows. The model was first calibrated with observed daily climate and stream flow data for the year with landsliding, before it was used to simulate spatial and temporal landslide susceptibility for a 30-year period. Even if the research seemed to show that landslide susceptibility is strongly influenced by natural processes and human activities in space and time, the quantitative results are strongly affected by the limited sampling of landslide events and they cannot be assumed as realistic.

3. The case study of Cervinara in Partenio Mountains in Campania

In the last decades a number of catastrophic flowslides took place in Campania. The localization of these events since 1580 is illustrated in fig.7 : it shows that the slopes interested by soil movements are mainly located in the Appennine chain surrounding the Mt. Somma-Vesuvius where pyroclastic soils (mainly ashes and pumices) accumulated essentially by air-fall deposition in the last tens of thousands of years as a result of volcanic activity.

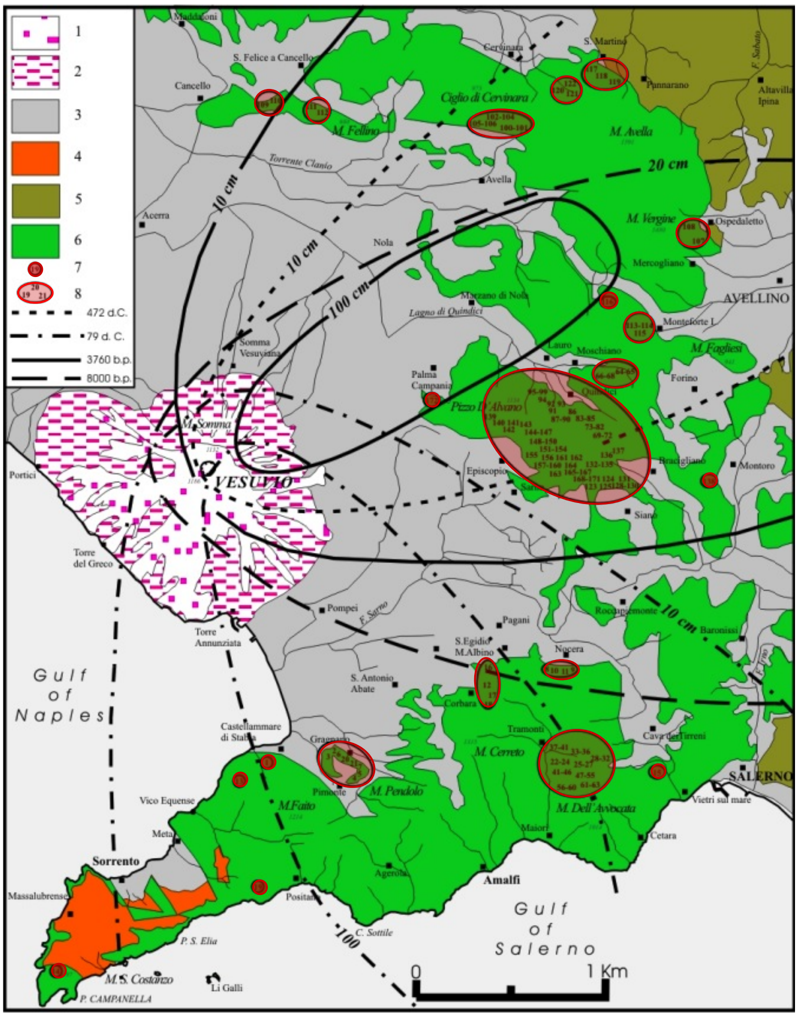

Figure 7. Distribution of flowslides in the air-fall pyroclatic deposits of Campania (modified after Di Crescenzo e Santo, 2005).

The Avella and Partenio Mountains, Sarno Mt. and Lattari Mt. in the Peninsula Sorrentina are susceptible landsliding areas (see *Technical Report: AMRA -"Messa a punto di modelli geotecnici per la simulazione degli effetti al suolo delle precipitazioni"*): among these the Partenio Mountains located north-eastern of Naples have been selected for an estimation of future landslide scenarios since they well represent a typical geomorphological context characterized by alternating layers of pumices and volcanic ashes resting on fractured limestone (macroarea A in the cited TR).The soil stratigraphical sequence in this area is illustrated in fig.8 : from top to bottom, there is a first ashy layer rich in roots and humus (layer V), a layer of pumices of centimetric dimensions (layer A) (not always present), another ashy layer (B) followed by a stratum of finest pumices (C) and, at the end of sequence, a layer of weathered ashes (D).

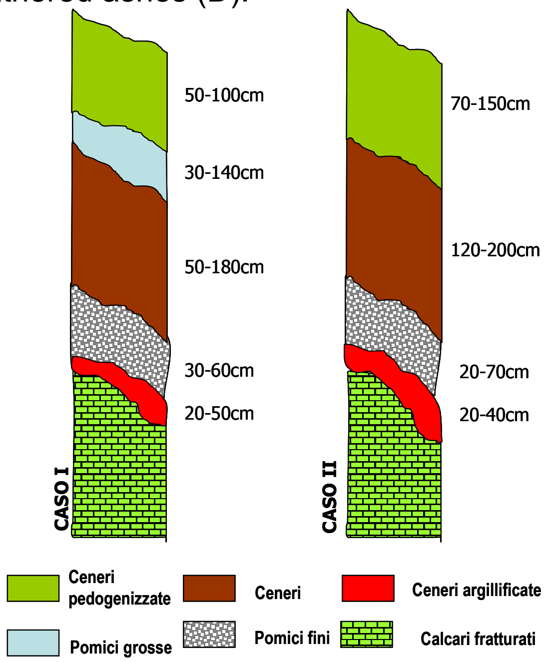

Figure 8. Typical sequences of Mt. Partenio

The approach used to assess future landslide scenario is the site size approach focused on Cervinara slope which in 1999 has been involved in a catastrophic flowslide and which has been well investigated in the past. In particular, in situ investigations and monitoring of suction and rainfall are available (Damiano, 2004) as well as mechanical and hydraulic properties of the soils (Olivares and Picarelli, 2003; Olivares and Damiano, 2007; *Technical Report: AMRA "Laboratory experiments on the response of model slopes subjected to rainfall*).
From a climatic point of view this area presents characteristics quite variable due to its location at the interface between the two climatologic areas of Piana Campana and of Apennine Chain. Above all its position influences the rainfall regime. A rain-gauge installed and managed by S.I.M.N. Agency (after 2002 substituted by Civil Protection) is located few kilometres from the instrumented slope (S. Martino Valle Caudina). It gave information about the rainfall regime of the area since 1919 but it ran continuously only since 1963. In fig.9 the cumulated yearly rainfall height and maximum daily rainfall height are reported for three decades of the last century which show the variability of the rainfall regime. The yearly rainfall height are quite variable ranging from a minimum of 564mm of height in 1992 to a maximum of 2330mm in 1983. At the same time even the maximum daily precipitation has a wide variability ranging from 32mm of rain fallen in 1992 to 180mm in 1968.

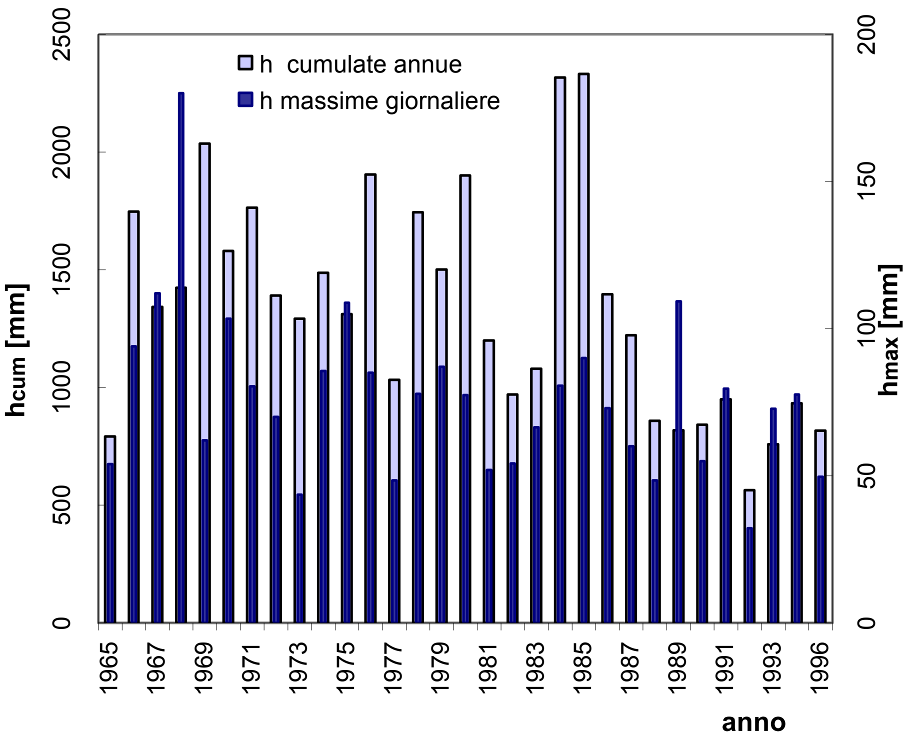

Figure 9. Observed yearly cumulated and daily rainfall at Cervinara site (Damiano, 2004).

3.1 Validation of COSMO-CLM model for climatic forecasting at Partenio Mountains

The climate forecasting for the XXI century in the selected area has been done by the climatologic research team of C.I.R.A. by using COSMO-CLM climatic model. COSMO-CLM is a non–hydrostatic regional model for the simulation of atmospheric processes. It has been developed by the DWD–Germany and by the COSMO consortium for weather forecast services. Successively, the model has been updated by the CLM-Community, in order to develop also climatic applications. The non-hydrostatic modelling allows providing a good description of the convective phenomena, which are generated by vertical movement (through transport and turbulent mixing) of the properties of the fluid as energy (heat), water vapour and momentum. This is very effective, in order to prevent phenomena such as landslides and floods. Convection can redistribute significant amounts of moisture, heat and mass on small temporal and spatial scales. Furthermore convection can cause severe precipitation events (as thunderstorm or cluster of thunderstorm).
COSMO-CLM can be used for simulations on time range up to a century, with a spatial resolution between 1 and 50 km; at such resolutions, terrain height is better described with respect to the global model, where there is in over/underestimation of valley/mountain heights resulting in errors for precipitation estimation, which is closely related to terrain height.
COSMO-CLM considers limited domains, so it is not possible to impose physical boundary conditions, therefore they are obtained in a numerical manner by means of a dynamical downscaling technique, from a global climatic model (e.g. ECHAM, or ERA40 reanalysis).
The discretization of the fluid dynamics equations is performed by using finite difference approximation, on a computational grid defined in a rotated spherical coordinate system.

Three time integration algorithms are available: the first one is based on a second order accurate Runge-Kutta method on two time levels; the second is based on the “horizontal explicit - vertical implicit” variant of Leapfrog scheme, the third based on a semi-implicit Leapfrog scheme on three time levels.
The numerical code produces solution fields in GRIB or NETCDF format. Once that the solutions have been generated, the required data such as total precipitation and two-meters temperature, are extracted by using specific software such as CDO.
In the present study, a computational grid characterized by a spatial resolution of 14 km (0.125^0) has been employed.

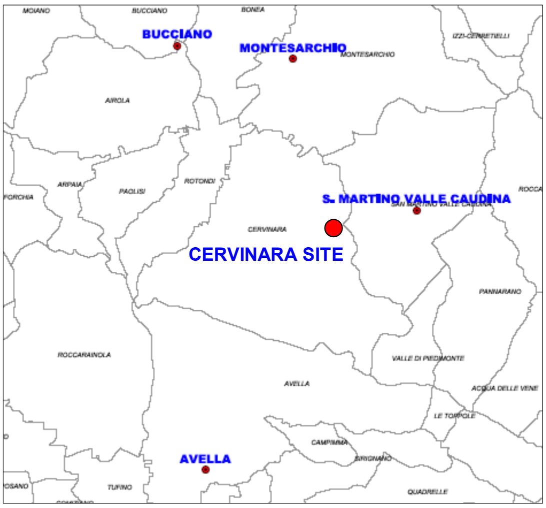

Figure 10. Position of the monitored slope and nearest meteorological stations by S.I.M.N. Agency

In order to provide some measure of the reliability of model used to perform analysis of future trends of air temperature and precipitations (factors of interest in flowslides occurrence), the present-day simulation of monthly mean air temperature and daily rainfall has been compared with observations in an area of about 10kmx10km near Cervinara. In this area data from three meteorological stations (red points in fig.10) and from a rain-gauge (S. Martino Valle Caudina in fig.10) managed by S.I.M.N. Agency are available.
The results in terms of mean summer and winter temperature for a 25 years period are reported in fig.11. The comparison between observed and simulated temperature are in good agreement both for winter and summer mean temperature: the circulation model seems to correctly capture the trend of variation in temperature which presents a slightly increase over years.
Regarding the validation of the model with respect to precipitation, a number of comparison have been made, starting from those in terms of yearly cumulated rainfall, up to seasonal precipitations and daily rains. In fig.12 are illustrated the daily rainfall heights observed at the S. Martino V.C. rain-gauge (blue line) and the simulated ones (red line) for the period 1966-1996 together with the cumulated values. A first look at the diagram highlights that the most intense precipitations are not well simulated both in terms of quantities of fallen rain and frequency. In fact, looking at the fig.13, where only the events characterized by a rainfall height greater than 50mm have been reported, it can be seen that the model doesn’t match the magnitude and the frequency of heavy rains predicting only a percentage of about 11% of the most severe daily rains (13 predicted events against the 114 observed).

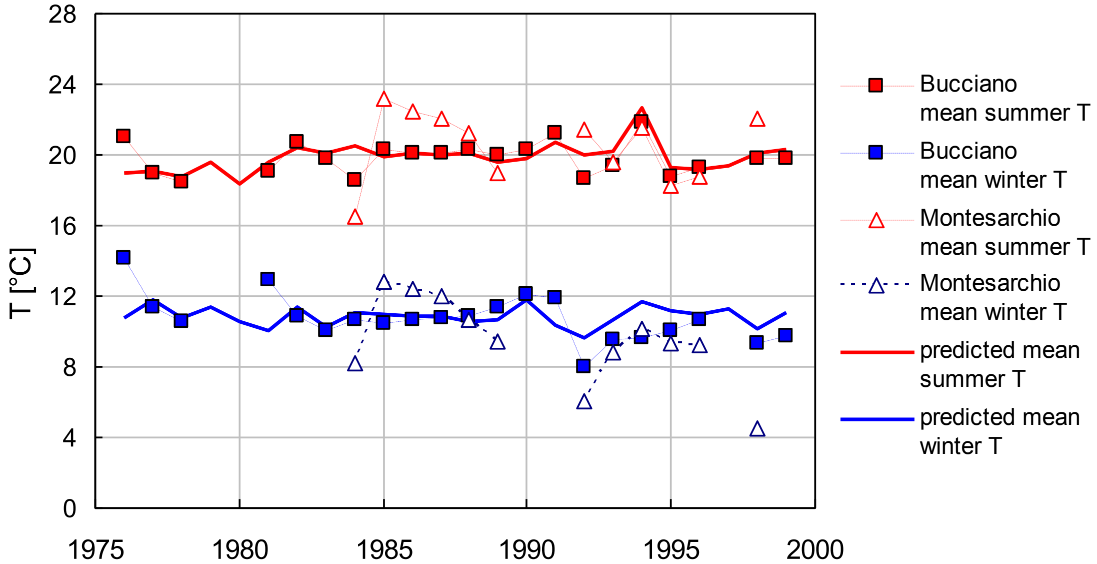

Figure 11. Mean winter and summer temperature from experimental and simulated data.

In terms of cumulated values, illustrated as bold lines in fig.12, the model heavily underestimates the quantities of fallen rain (about 25% of observed rainfall) since it predicts a 10m of cumulated precipitations against the observed 40m in 30 years. Moreover, the error seems to be not systematic since also the trends of the cumulated rain differ: while the predicted one has a linear growth, the real one has an appreciatively parabolic tendency. Only in the last years of the comparison the curves seem to reach a similar qualitative trend.

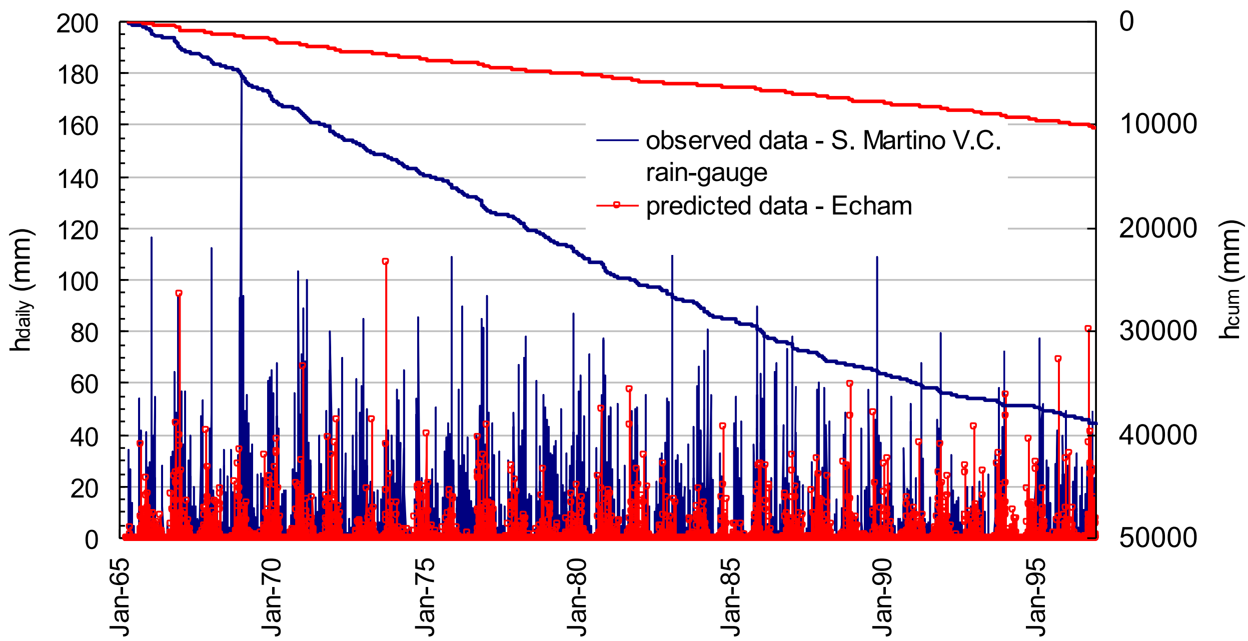

Figure 12. Experimental and simulated daily and cumulated rainfall for the period 1966-1996.

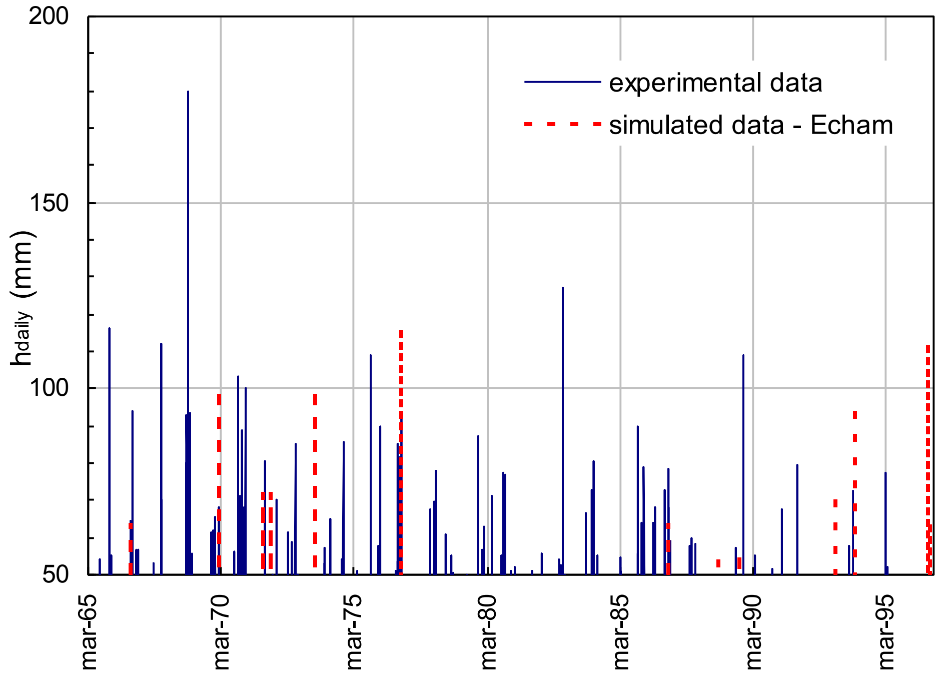

Figure 13. Experimental and simulated heaviest rains for the period 1966-1996

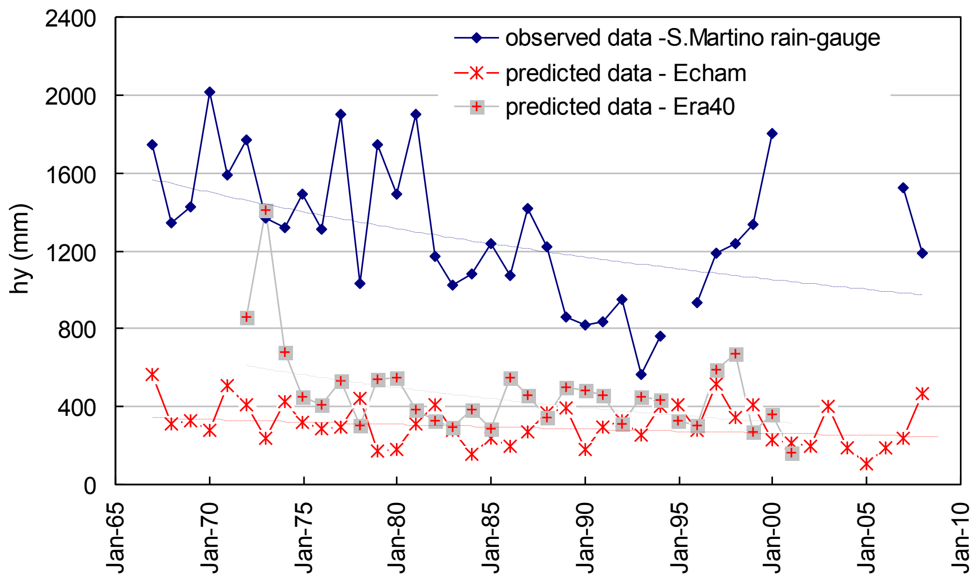

Figure 14. Experimental and simulated annual cumulated rainfalls over the past four decades.

Obviously, there is a not satisfying agreement also in terms of annual precipitations: fig.14 illustrates the experimental data at the S. Martino V.C. rain-gauge starting from 1969 till 2007 in comparison with simulated rainfall as derived from both the global climatic model ECHAM and the reanalysis ERA40. As discussed above, it has to be noted the great variability of the experimental data characterized by an average value of 1300mm and a standard deviation of about 360mm which makes hard the prediction of each single annual value. This difficulty in the prediction of precipitation unfortunately is a common feature of all the climatological models, and could be mitigated by using a bias correction technique or by increasing (if possible) the spatial resolution. However, neither an average

quantitative estimation of the fallen rain is feasible both the analysis having underestimated the observed rain of about 75%. Similarly to the cumulated rainfall, the trends of annual precipitation differ especially in the first decades of comparison while they seem to reach a similar form in the last years.
In order to well investigate into this aspect, due to the lack of continuous data from the S. Martino V.C. rain-gauge in the first decade of the XXI century, the simulated annual precipitations have been compared with the experimental data from the other rain-gauges located in the area as illustrated in fig.15. Indeed, even if the quantitative estimation of the fallen rain is not realistic, the trend of the annual precipitations seems to be captured by the model in the last 20 years, especially if compared with the average values of the recorded yearly precipitations.

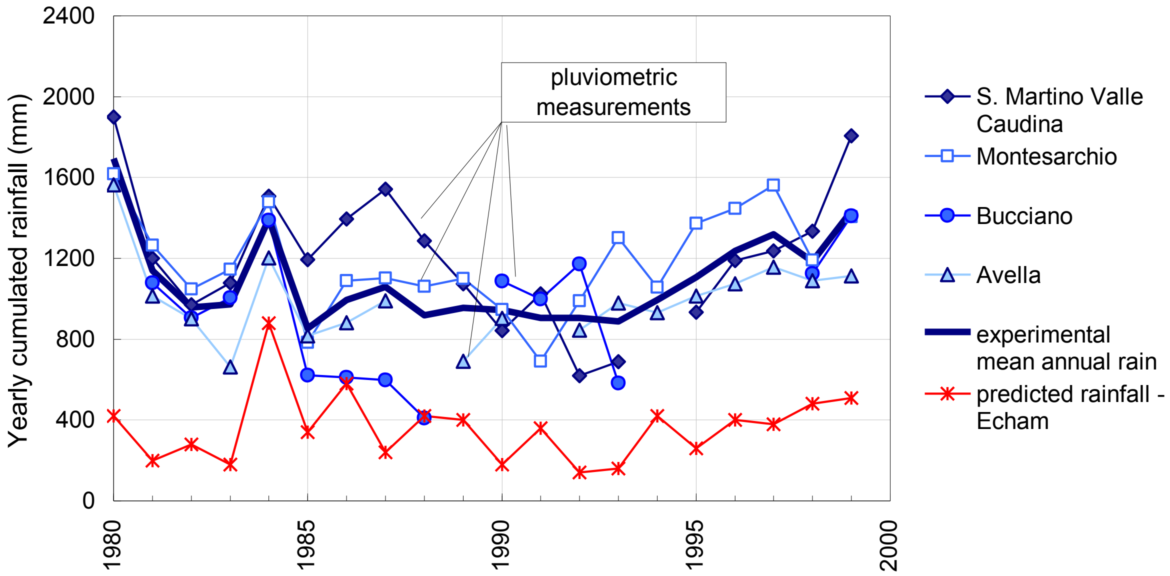

Figure 15. Comparison between experimental and simulated annual cumulated rainfall.

Analyzing the seasonal precipitations it can be seen that the modelled summer rain are underestimated more than the winter ones: in fact, as illustrated in fig.16, the average percentage of summer rainfall with respect to the cumulated yearly rainfall is of 17% in the case of predicted rainfall and of 31% for real summer rain leading to an underestimation of about 14%.

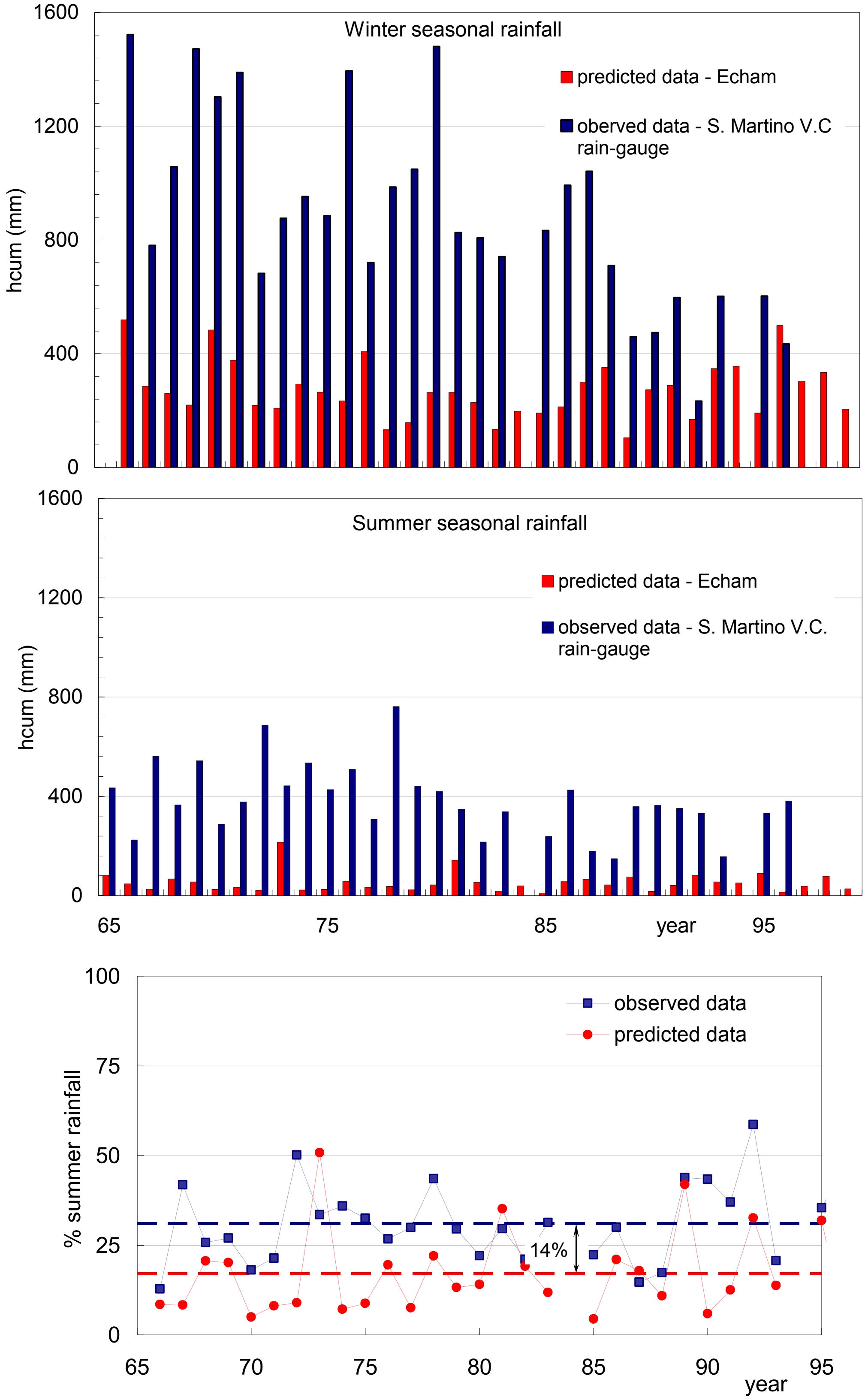

Figure 16. Comparison between experimental and simulated seasonal precipitations over the past three decades and percentage of summer precipitation with respect to annual cumulated rainfall.

Since the key factors for flowslide triggering in pyroclastic soils are antecedent precipitations (taken as the 30-day cumulated rainfall) and 24-h rain, further comparison in terms of monthly rain and daily rain have been done: the results are illustrated in fig.17 which reports the probability density functions. The data are not in a satisfactory agreement considering that the mode of the 24-h predicted rainfall is lower than the observed one and, in particular, the modelled frequencies of the most intense accumulations (n>50mm/d), those favourable to landslide occurrence, are much less than the corresponding observed ones. Regarding the frequencies in terms of 30-day precipitations the modelled frequencies show a mode qualitatively similar to the real one even if the most intense rainy periods (starting from 100-150mm/30d) are underestimated too. However, considering the great variation among the observed cumulated yearly rainfall, it has to be expected an analogous variability also in the probability density functions for daily and monthly rainfall and, hence, the comparison between simulated and real rain have to be done adding data from other stations.

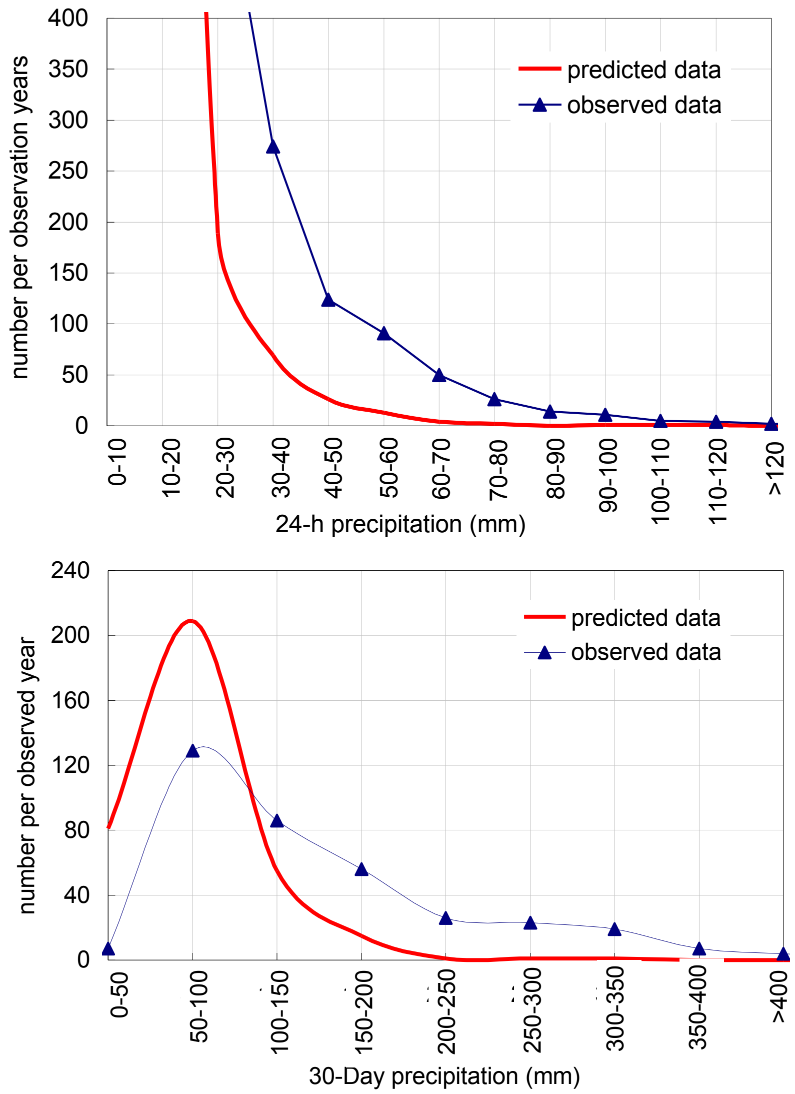

Figure 17. Probability density functions of 24-h precipitation and 30-day precipitation.

In conclusion, COSMO-CLM estimated rainfall is relatively inaccurate when compared with experimental present-day data. In fact, even if the trend of cumulated yearly rainfall seems to be captured, either the amounts and frequencies of 24-h precipitations are not. Therefore, it can be noted that the modelled rainfall cannot be used without adjustment. A statistical procedure should be used to this aim but it requires the availability of a greater number of experimental data for the examined area.

3.2 Validation of numerical model for seepage analysis in slopes

The complexity of the infiltration process in unsaturated soils requires the use of a numerical model to predict the response of a slope to rainfall. The reliability of the model can be improved through preliminary calibration (given the variability in soil parameters) and validation through back-analysis of in situ monitoring.
At this aim the site of Cervinara has been chosen since it was instrumented with a series of tensiometers stations and a rain-gauge since 2002.
A first series of 2D analysis were carried out using the finite element program SEEP/W code (produced by the GEO-SLOPE International Ltd), which solve the Richards' equation taking into account the adopted slope geometry. Analysis were performed under isothermal conditions for an unsaturated porous medium neglecting the flux of the gas phase and under the assumption of rigid soil skeleton.
The validation of the numerical model was done through the reproduction of in situ measurements. The period between May 7th and August 11th 2002, characterized by abnormal rainfall after a prolonged drought, was selected to validate the model. The slope was schematized with a 2D mesh characterized by stratigraphy illustrated in fig.18 using a dz=0.12m.

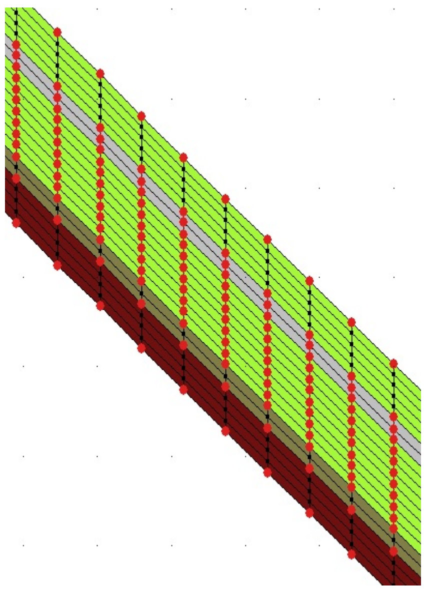

Figure 18. Schematization of the adopted geometry and mesh.

At the ground surface two conditions were used: average daily rainfall intensity from monitoring during rainy days or evaporation flux during dry periods considering the value suggested by Thorntwaite (1948) for unsaturated soil. For the lateral and base surfaces, in order to reproduce an unbounded seepage condition (the correct boundary condition is

only known at some large, i.e. infinite, distance to the edge of the problem) infinite elements have been used.
The initial condition in terms of suction was established from field measurements, adopting a suction profile based on in situ measurements at the data corresponding to the start of the analysis as illustrated in fig.19.

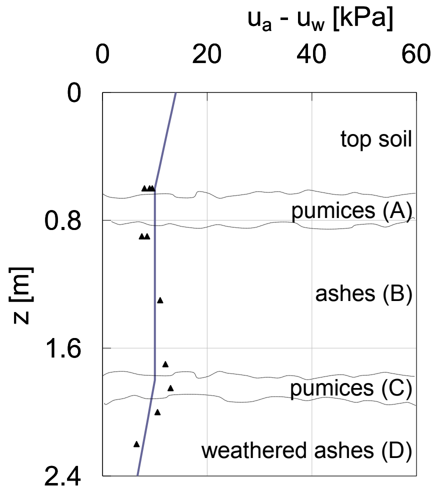

Figure 19. Initial conditions adopted in the numerical analysis (dots indicate in situ measurements) (Damiano and Olivares, 2010)

For the hydraulic and mechanical characterization of the soils the results of laboratory tests have been used (Picarelli and Olivares, 2003; Olivares and Tommasi, 2008; *Technical Report: "AMRA - Laboratory experiments on the response of model slopes subjected to rainfall*). In particular, the ash (B) is characterized by an effective friction angle of 38° and a nil value of cohesion c', while weathered ash (D) has a peak and critical state-strength characterized by ϕ' and c' equal to 31° and 11kPa and 35° and 0 respectively. Since the undisturbed sampling of pumices is not feasible, a value of 44° for friction angle was assumed.
The saturated permeability of volcanic ashes (B and D) and pumices (A and D) was assumed equal to the maximum values obtained through constant head tests respectively on undisturbed and reconstituted samples. The values adopted in the analysis are:

- for top soil and ashes (B) $k_{sat}=5\cdot10^{-7}$ m/s;
- for pumices (A) $k_{sat}=1\cdot10^{-6}$ m/s;
- for pumices (C) $k_{sat}=6\cdot10^{-6}$ m/s;
- for ashes (D) $k_{sat}=1\cdot10^{-8}$ m/s.

The unsaturated permeability functions are described by the expression:

$$K = K_{sat}\, S_r^{3}$$

The characteristic curve of volcanic ashes (B) and pumices extrapolated by flume tests were fitted by the expression proposed by van Genuchten (1980), while those related to weathered ashes (D) derived from literature data (see *Technical Report: "AMRA - Laboratory experiments on the response of model slopes subjected to rainfall*).
The results of this first series of analysis are not satisfactory since they highlighted that the code is not able to reproduce the response of a steep slope when tilted infinite elements

are used: in this case, the solution becomes suspect and one has to be make a careful assessment of the results to make sure they are reasonable.
A reasonable behaviour is reached only in the upper section of the slope (fig. 20) where the effect of lateral flux in negligible and the soil always remains in a condition of partial saturation but it cannot be assumed as representative of the real processes which establish in a steep slope.

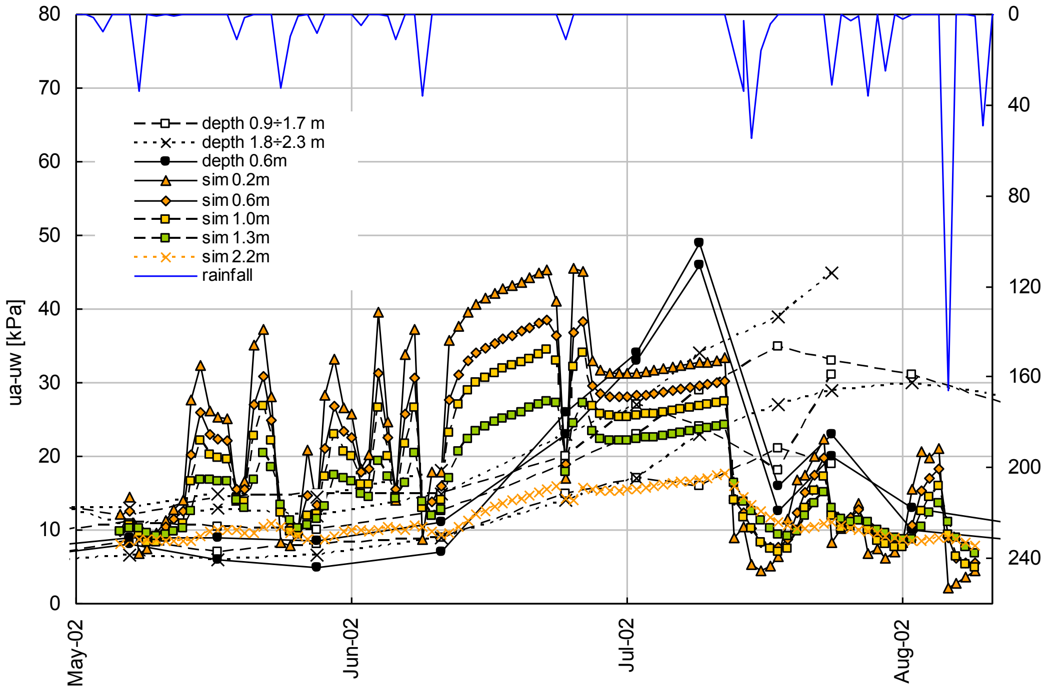

Figure 20. Comparison between in situ suction measurements and results of numerical analysis: a) upward and; b) in the middle of the slope.

In order to overcome this problem, another series of numerical analysis have been done using the hand-made I-Mod3D code developed in VBA application for AR-COBJECTTM/ARCGIS 9.2TM to automate the mesh-generation starting from a Digital Terrain Model (fig.21). Even in this case the analysis was performed under isothermal conditions for a rigid unsaturated porous medium neglecting the flux of the gas phase. A condition of free flow along the base and the lateral sides of the slope was adopted. For simplicity, in the following only the results in a point along the slope corresponding to the position of a tensiometers station are shown.

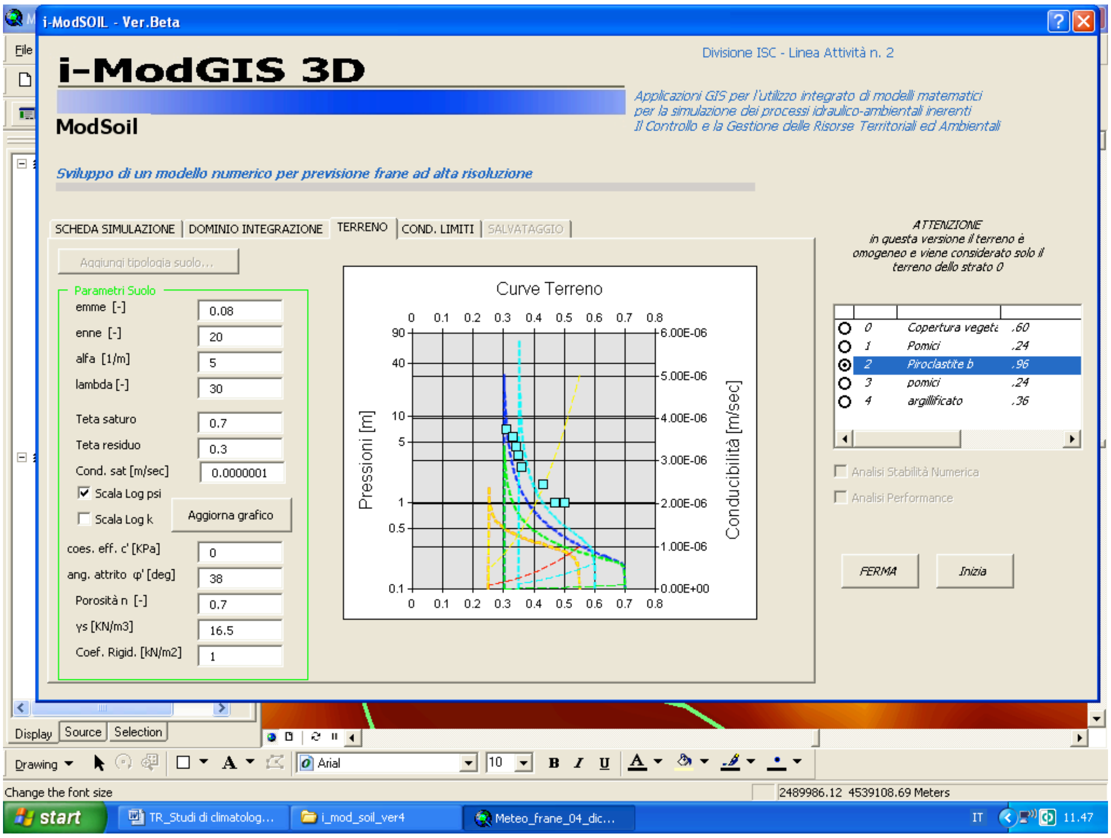

Figure 21. I-Mod3D code: panel for insertion of soil retention curves

The validation of the model has been done on the base of in situ suction measurements during the years 2006-2007. The initial condition in terms of suction has been established from field measurements.

A comparison between the monitoring measurements and numeric simulations is shown in fig.22. In the figure the results at the four depths of 0.60m, 0.95m, 1.50m and 2.00m, corresponding to the depth of devices are illustrated. Obviously, the in situ measurements are discontinuous (points in fig.22) and the lines between the measurements do not represent the real values of suction.

Fair agreement was obtained along all the depth, although the simulated values during dry period in the superficial layer are in some cases lower than the real ones: this is probably due to the potential evaporation flux adopted which in the analysis does not change as a function of seasonal regime, and also to the effect of transpiration at the upper boundary due to the presence of a grassed surface that was not considered in the analysis. In fact, no data about humidity, net radiation, air and soil temperature are available for the Cervinara site and an estimation of evaporation was done by using the approach proposed by Penman (1948) for a saturated surface, and extended by Wilson (1990) for an unsaturated surface, illustrated in fig.23. In particular, the proposed curve has been modified considering a value of 2.5mm per day as minimum evaporative flux (curve 4 in fig.23) since, analyzing in situ suction profiles during dry periods, it seems that lower values don't verify.

In general, the agreement between numerical and experimental data during wet periods suggests that the code can be a suitable tool to evaluate the pore pressure variation due to rain water infiltration in unsaturated soils.

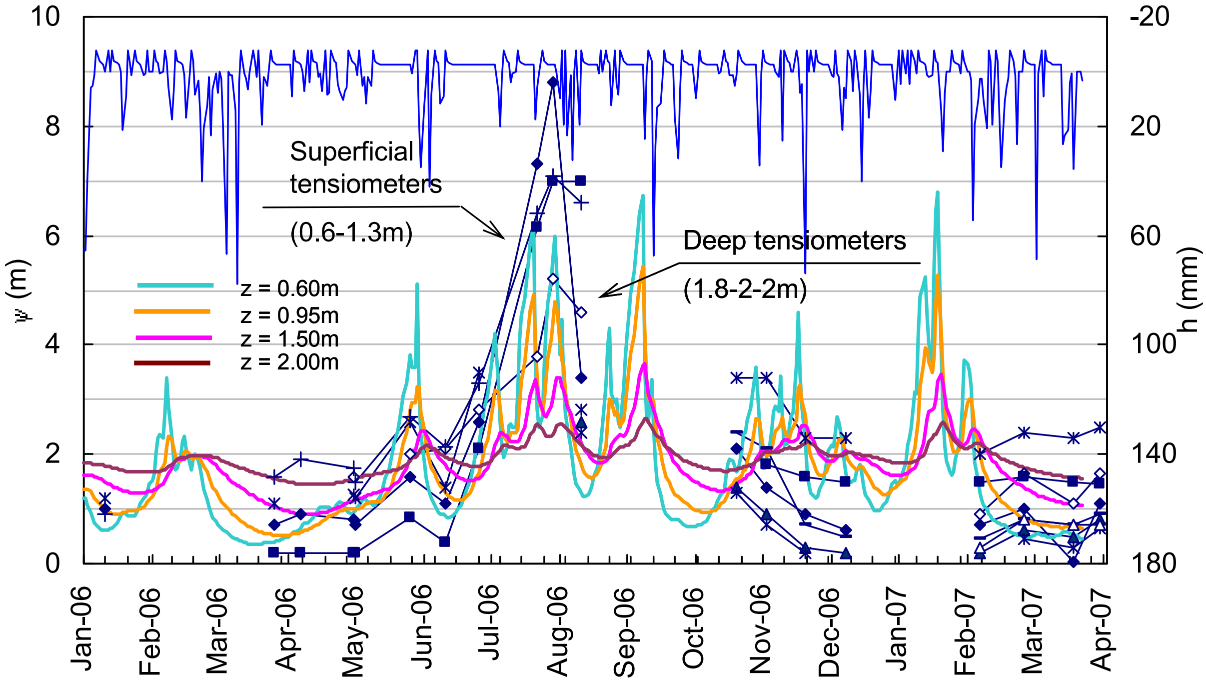

Figure 22. Comparison between suction measurements and numerical analysis performed by using I-MOD3G code.

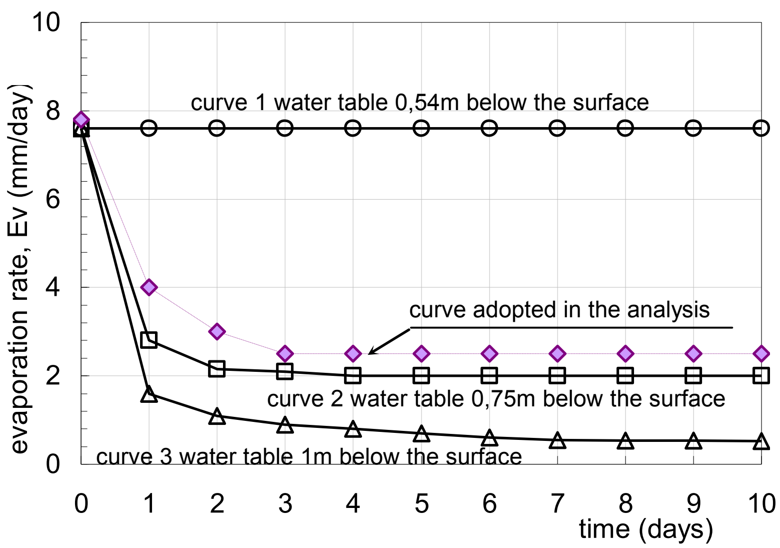

Figure 23. Evaporation rate versus time obtained by the modified Penman Equation for the Beaver Creek sand with water table located at various depths (from Wilson, 1990) and adjusted to Cervinara site.

Since, according to several Authors, rainfall induced landslides in granular soils are generally quite shallow and present a failure surface more or less parallel to the ground surface (this was also observed in the case of Cervinara flowslide) such a condition allows to calculate the safety factor in the hypothesis of infinite slope. The average slope in the investigated area is higher than the friction angle of some layers owing to the cover; in fact, as shown, the friction angle of the intermediate volcanic ash is 38° while the average slope is about 40°. This implies that the stability conditions of the slope are governed by

the cohesion intercept due to suction: using the relationship between suction and cohesion indicated by Olivares (2001) for volcanic ashes it is possible to assess the safety factor of the slope with reference to slip surfaces parallel to the ground surface.
Figure 24 reports the evolution of the safety factor with time accounting for the value of suction obtained by the numerical analysis at the four investigated depths. Due to lack of data, the analysis have been carried out adopting for the top soil the same cohesion versus suction relationship used for the intermediate volcanic ash.
It can be noted that the critical surface is located at the bottom of the volcanic ash at a depth of 2.00m from ground surface where the safety factor assumes values of about 1.5. The greatest changes occur in the top soil, where the safety factor is strongly and quickly affected by the effects of rainfall. Besides, during the chosen time range the safety factor remains always quite high during dry period while it approaches values near 1.3 after intense rain periods as in May 2007corrsponding to a more superficial critical surface (1.5m from ground surface).

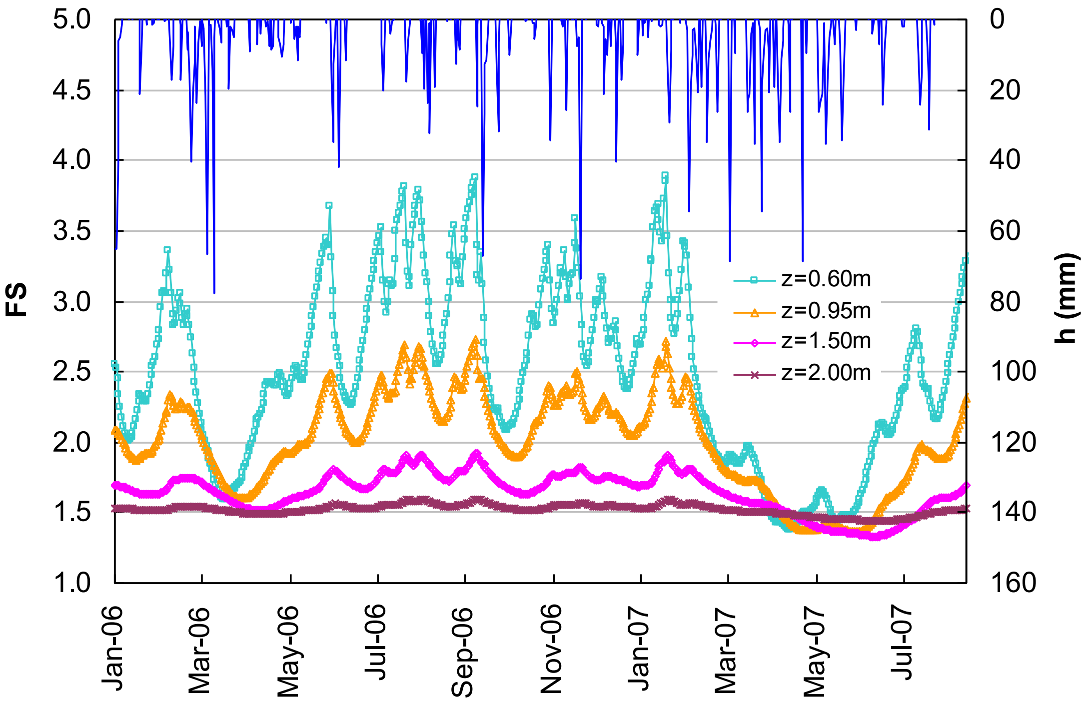

Figure 24. Evaluation of safety factor at four depths during the present-day period from January 2006 to August 2007.

3.3 An assessment of potential future scenario in Cervinara

An assessment of future stability conditions of the Cervinara slope which takes into the account the climatic change has been done evaluating the hydrologic response and, hence, the changes in safety factor of the slope, during the years 2059-2060. The evaluation has to be considered only as an application of the above described procedure since, at the moment, a better calibration of the climatologic model is necessary. In fact, the following analysis strongly depend on the hypothesis done in order to adjust the result of climatic forecasting.

Since the model well agrees with measurements in terms of air temperature (fig.11) no adjustment has been required in terms of temperature. The estimated future trends of mean annual, winter and summer temperature are reported in fig.25: according to the IPCC 2007 report, in the next century a global earth temperature increase is expected, and in the examined area a growth of about one degree per 20 years, even if a non-linear manner, is predicted. The increasing temperature obviously will influence the evapo-transpiration flux: in the analysis this effect has been considered by using the Thorntwaite (1948) formulation for the evaluation of the monthly potential evapotranspiration flux starting from predicted mean monthly values of temperature. The entire amount of the potential evapotraspiration monthly flux has been divided up the dry days (using the trend of the curve 4 in fig.23 adopted in the validation of seepage numerical model). In the analysis has not been considered the effect of a change in the land-use which, obviously, might influence the transpiration regime.

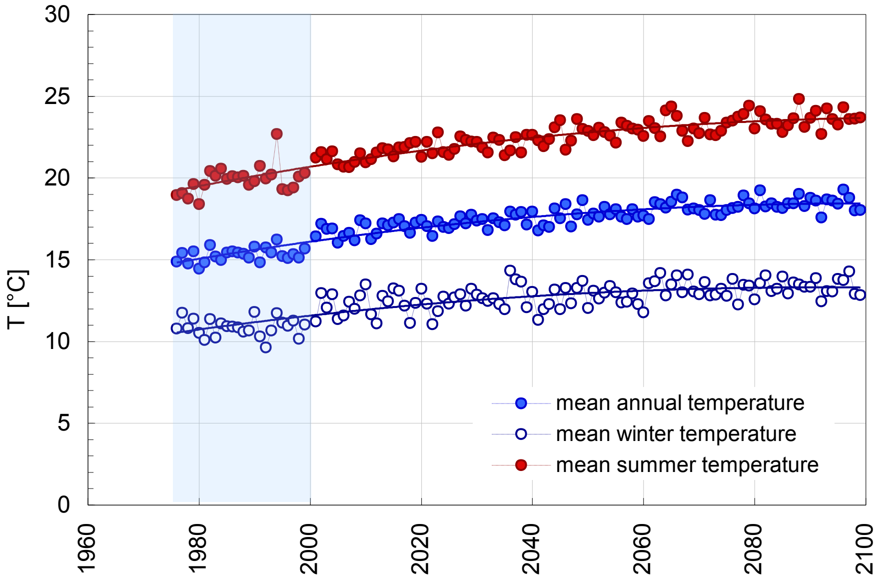

Figure 25. Predicted mean temperature in the XXI century

In terms of precipitations, the most interesting consideration regarding the modelled rain for XXI century are that:

- the trend of yearly cumulated rainfall shows a decrease with an average gradient of 1.1mm per year (fig.26);
- the 24-h frequencies, reported in fig.27, show an increase of daily rains in the range between 30-60mm of rain height while the most intense events will not modify substantially.

This seem to suggest that in the examined area the climate change will occur with an increase in temperature, a decrease in the annual precipitations and a frequency of the rainstorms similar to the actual.

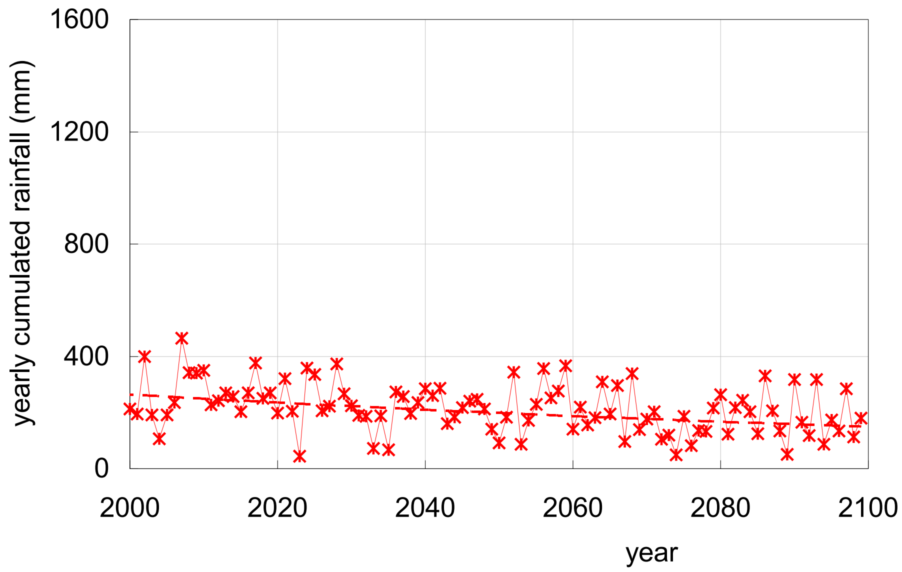

Figure 26. Predicted yearly cumulated rainfall over the XXI century

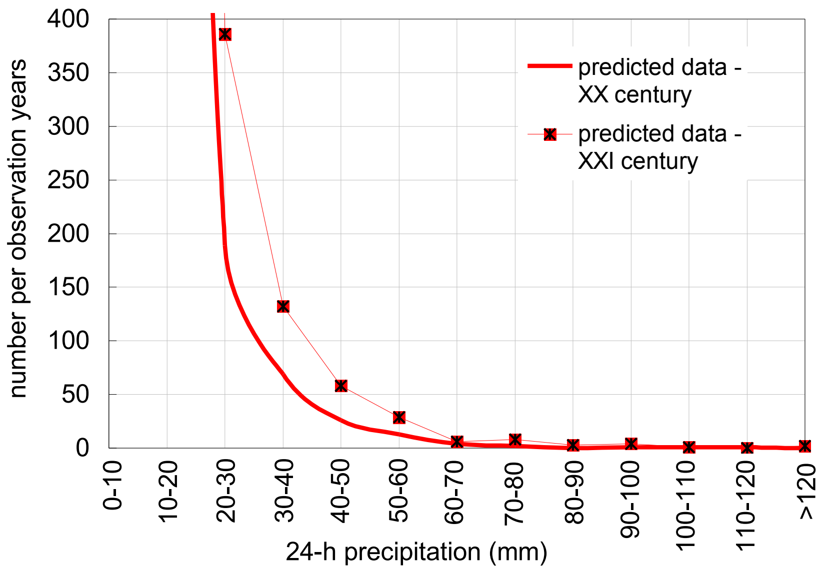

Figure 27. Comparison between pdfs simulated 24-h rains for past XX century and XXI century.

In order to evaluate the future climate scenario, some corrections have been adopted in terms of precipitations that are:

- since the simulated and experimental trends of annual precipitation are quite similar in the last decade of XX century, it has been assumed that the future simulated trend is correct but the values of predicted annual precipitations have been increased of 650mm in order to match the mean observed values (fig.28);
- considering that rainy days are underestimated and, in details, the summer precipitations more than the winter ones, the annual added rain height has been inserted in the phyetogram in a different percentage during summer and winter periods. Apart from this correction, the added rain height has been inserted in the predicted hyetogram in a random mode;

- no adjustment in terms of maximum daily rain and 30-day precipitations have been done.

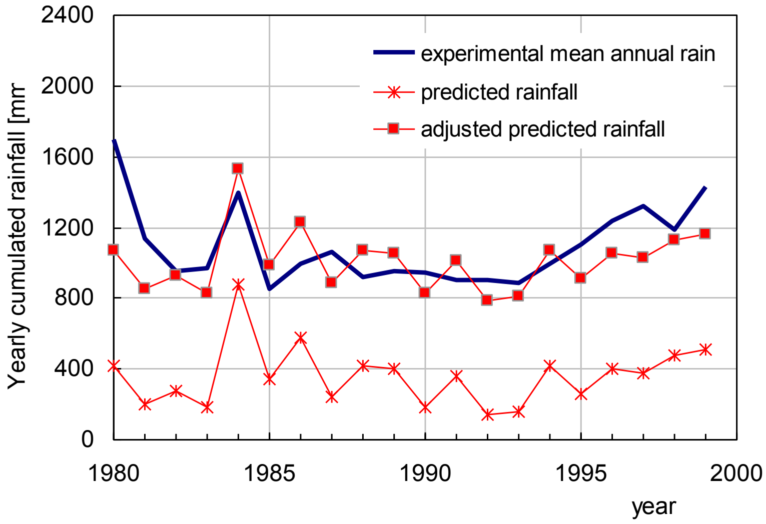

Figure 28. Predicted and adjusted yearly cumulated rainfall compared with experimental values

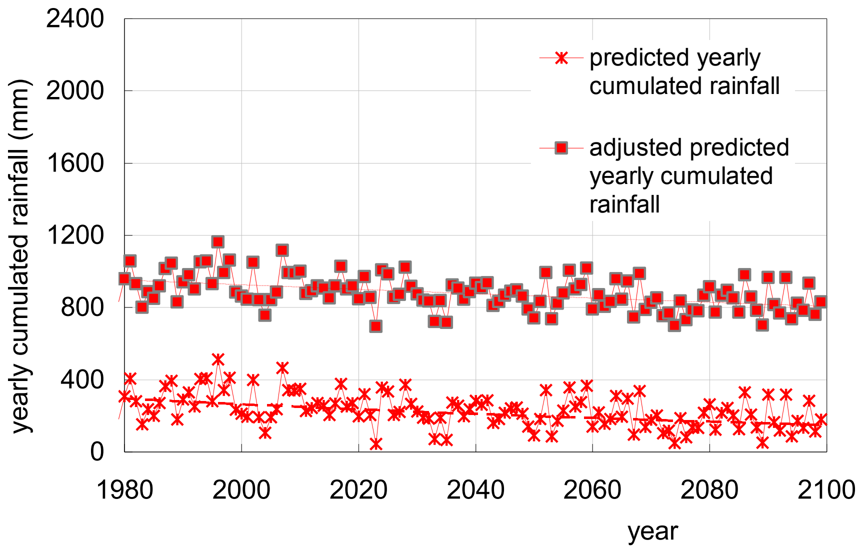

Figure 29. Predicted and adjusted yearly cumulated rainfall until 2100.

The effect of increasing temperature and decreasing precipitations will favour the evapo-transpiration and, hence, will reduce the infiltration. This effect is highlighted by the results of numerical analysis carried out for years 2059-2060 and reported in fig.30: higher values of suction, corresponding to lower soil moisture conditions, are reached along the entire depth accompanied with stronger sudden variation during the rainy days. An evaluation of the future stability condition of the slope shows that, with respect to the present-day simulation, a global increase in safety factors occurs all-over the depth which remains always higher than 1.5 (fig.31). Besides, it seems that the critical surface remains the deepest one (at 2.00m) even after the heaviest storms but this is probably due to the fact that the climatologic model can't individuate the highest rainfall. At least, the observation of the trends of safety factors seems to show that a little gradual increase occurs during the simulated years suggesting that, under the hypothesis done, one has to expect a progressive improvement in stability condition of the Cervinara slope.

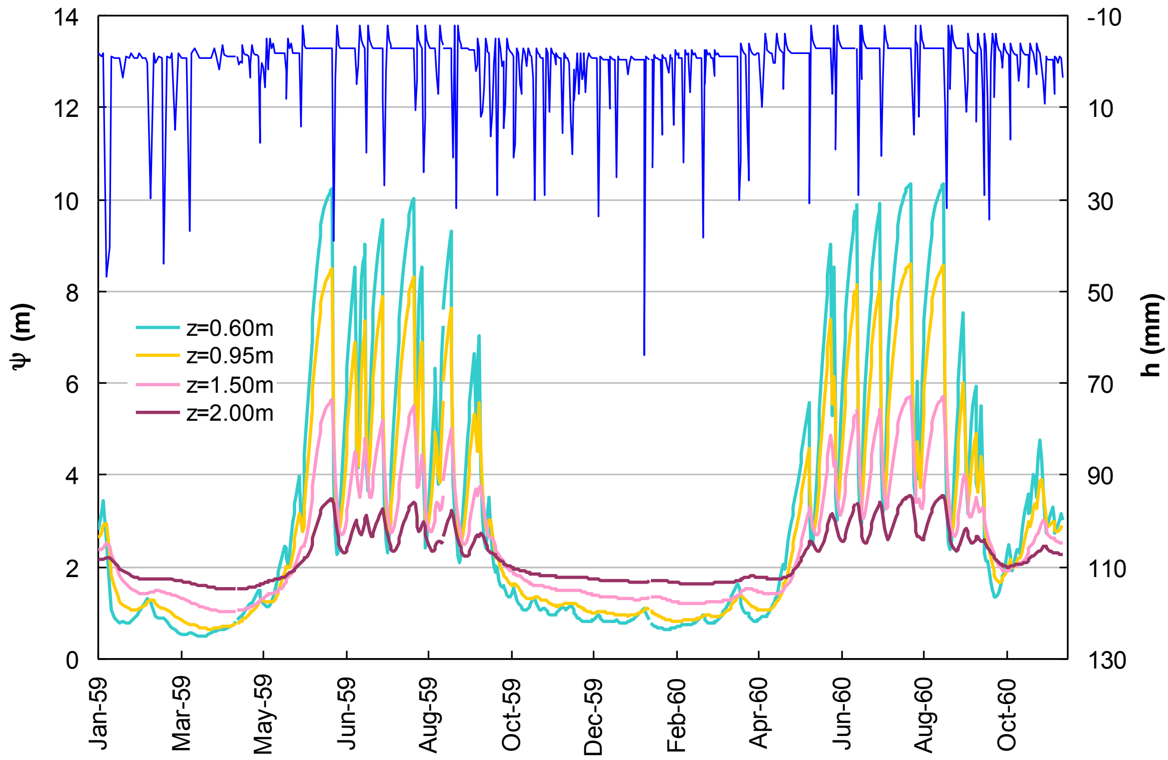

Figure 30. Simulated trend of suction at four depths during 2059 and 2060 years.

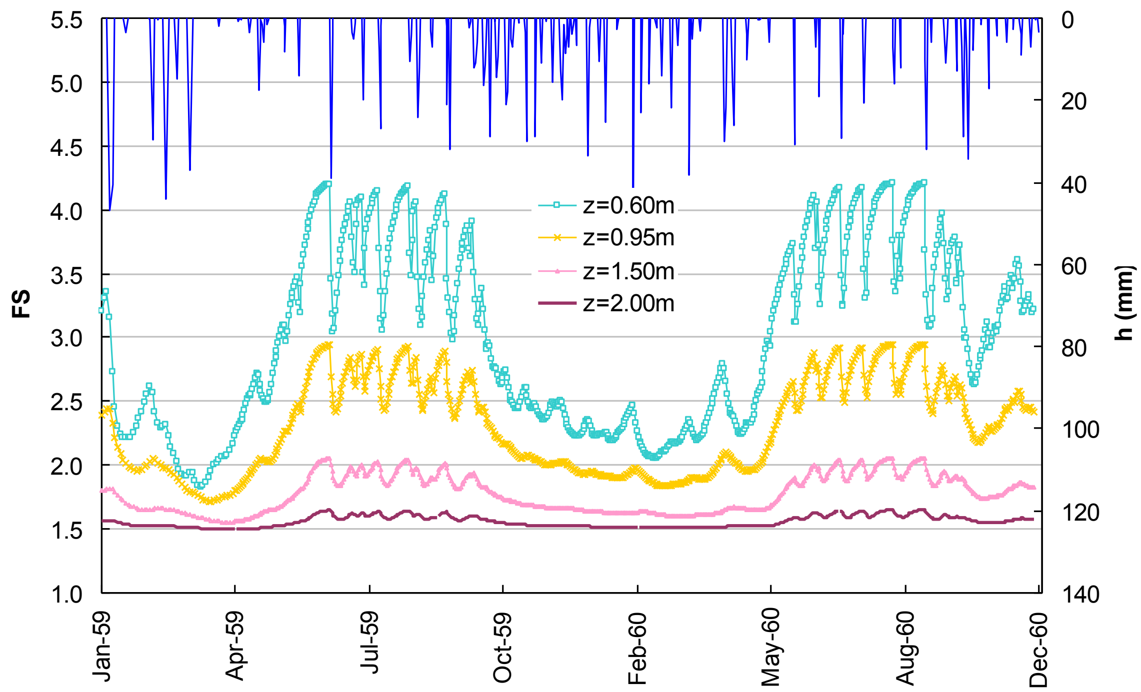

Figure 31. Future scenario at 2060 in terms of safety factor of Cervinara slope

4. Conclusive remarks

Predicting impacts of potential climate change on slope stability is complex: impacts could be both negative and positive for warming climate scenarios, depending on storm pattern changes which are uncertain. On the base of this consideration, in this Technical Report an attempt to link climatic change to slope stability for the case of a slope in pyroclastic soils in Campania has been done. The proposed approach requires three main steps:

- the individuation of the main climate factors which influences the behaviour of the slope;
- the validation of both climatic and hydrological models used to evaluate the future trend of rainfall and mean temperature and, in cascade, the future response of the investigated slope, on the base of measured suction data;
- the forecasting of the slope behaviour on the base of the future climatologic scenario.

The first step has been pursued on the base of literature case histories similar to the analyzed one and on detailed study of the slope response, which reveal that the controlling factors of rapid shallow landslides in pyroclastic granular soils are essentially the heavy rainfall events and the antecedent 30days precipitation together with evapo-transpiration which strongly affect the initial soil-moisture conditions.

To face the second step is essential to have a good and long series of experimental data in order to validate the numerical codes. In the case of climatologic model COSMO-CLM the comparison between the results of analysis and experimental data for a 30-years long period (1996-2006) highlights that the model is able to capture the mean monthly temperature but heavily underestimates the annual precipitation, the most intense rainfall heights and the number of rainy days: thus, this step revealed that an appropriate statistical correction of numerical data is necessary. On the contrary, the validation of I-MOD3D code used for the analysis of infiltration process (made on the base of a 14 months-long period during 2006-2007 where experimental data from in situ monitoring were available) reveals that a fair agreement between numerical and monitored suction has been reached: this suggests that the code can be used as a tool for the assessment of the behaviour of the slope.

At least, an evaluation of the long-term behaviour of the investigated slope at the year 2060 has be done considering the climate scenario furnished over the next century by the climatologic group of C.I.R.A. which indicates an increase in temperature, a decrease in annual cumulated precipitation and a substantial similar distribution of most intense rainfall events.

The combined effect of an increasing temperature, which will promote a stronger evaporation, and of a decreasing rainfall will lead to a reduction of net infiltration. This fact can affect the initial soil-moisture conditions increasing the mean values of suction and, hence, since no variation seems to be attended in terms of intense rainfall events, the stability condition of the slope will globally increase over the years. However, this assessment of future scenario is strongly affected by the hypothesis done and has to be considered only as an attempt to utilize a procedure for predicting impacts of potential climate change on slope stability of shallow pyroclastic soil deposits.

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