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Architectures and Tools to Analyse the Impact of Climate Change on Hydrogeological Risk on Mediterranean Area

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SUMMARY This document describes the numerical models and tools constituting the integrated system for the qualitative and quantitative assessment of the hydrogeological risks due to climate change developed in the framework of the GEMINA project (product P91). In particular the work package 6.2.17 “Analysis of geological risk related to climate change” has as main goal the analysis of landslides, floods and droughts risks related to climate change conditions on the Mediterranean area. The integrated system combines, in appropriate way, high-resolution regional climate scenarios, impact models and statistical downscaling techniques. All these are described in the current document. In addition, this document contains a description of the test cases on which the integrated system will be verified.

Keywords: Climate Change, Soil Impact, Hydrogeological Risk, Downscaling

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INTRODUCTION

This report is aimed to define the general objectives of GEMINA wp 6.2.17 “Analysis of the hydrogeological risk related to climate change” and to describe the work plan to achieve these objectives. This document defines the architecture of the simulation system, the main features of the tools adopted and the strategy for the verification of the integrated system. The main goal of the wp 6.2.17 is to provide an evaluation, qualitative and quantitative, of the hydrogeological risk in some typical contexts of the Mediterranean area. In particular, the focus will be on landslides, floods and droughts risks. The research activity will also analyse the role of the uncertainties of the complex relationship between “climate change and hydrogeology” at regional scale on risks evaluation.

MOTIVATION

The warming of the climate system in recent decades is evident from observations showing an increase in global average air and ocean temperatures, a widespread melting of snow and ice, and a global rising of sea level. Several studies show that most of the observed increase in global temperatures since the mid-20th century is related to the observed increase in anthropogenic greenhouse gas concentrations. This climate warming may cause an intensification of the water cycle, which is strongly dependent on the atmospheric temperature, and may determine a change in many components of the hydrological cycle such as: precipitation patterns, intensity and extremes; atmospheric water vapour; evapotranspiration; soil moisture and runoff. However, it is difficult to identify long-term trends for the components of hydrological systems as they are often masked by their significant natural variability, on time-scales from interannual to decadal. This variability, together with limitations in the spatial and temporal coverage of monitoring networks, can explain the current substantial uncertainty in trends identification of hydrological variables [3]. Many hydrological simulations predict a change in the hydrological cycle, but these projections are typically affected by several sources of uncertainty, in fact, in addition to the uncertainty of the considered hydrological model, there is also the uncertainty related to the fact that these models use, as input, the results of climate simulations, which in turn are characterized by a certain uncertainty. A further problem is related to the different spatial scales of climate models and hydrological models. A number of methods have been used to handle these scale differences, ranging from the simple interpolation of climate model results to dynamic or statistical downscaling methods, but all these methods introduce other uncertainties into the projections [3]. This work is aimed to evaluate variations in the hydrogeological risks (in particular floods and landslides) due to climate change and the main goal of this research activity is to correctly model the link between hydrological and climate models. In particular the focus will be on the Mediterranean area. In this region, according to Christensen et al. (2007) [14], annual mean temperatures will rise more than the global average and the warming is likely to be largest in summer (figure 1). Moreover, in the Mediterranean area the majority of the models foresee summers characterised by an increase, in frequency, of extreme daily precipitation despite a decrease in average precipitation. Thus this tendency can lead to longer dry periods, increasing the risks of droughts, interrupted by extreme intense precipitation, enhancing the risk of floods [3]. This scenario of hydrologic and climatic variability is also associated with an increase in the vulnerability of the territory. This increased environmental vulnerability is mainly related to anthropogenic effects and is caused by exces-

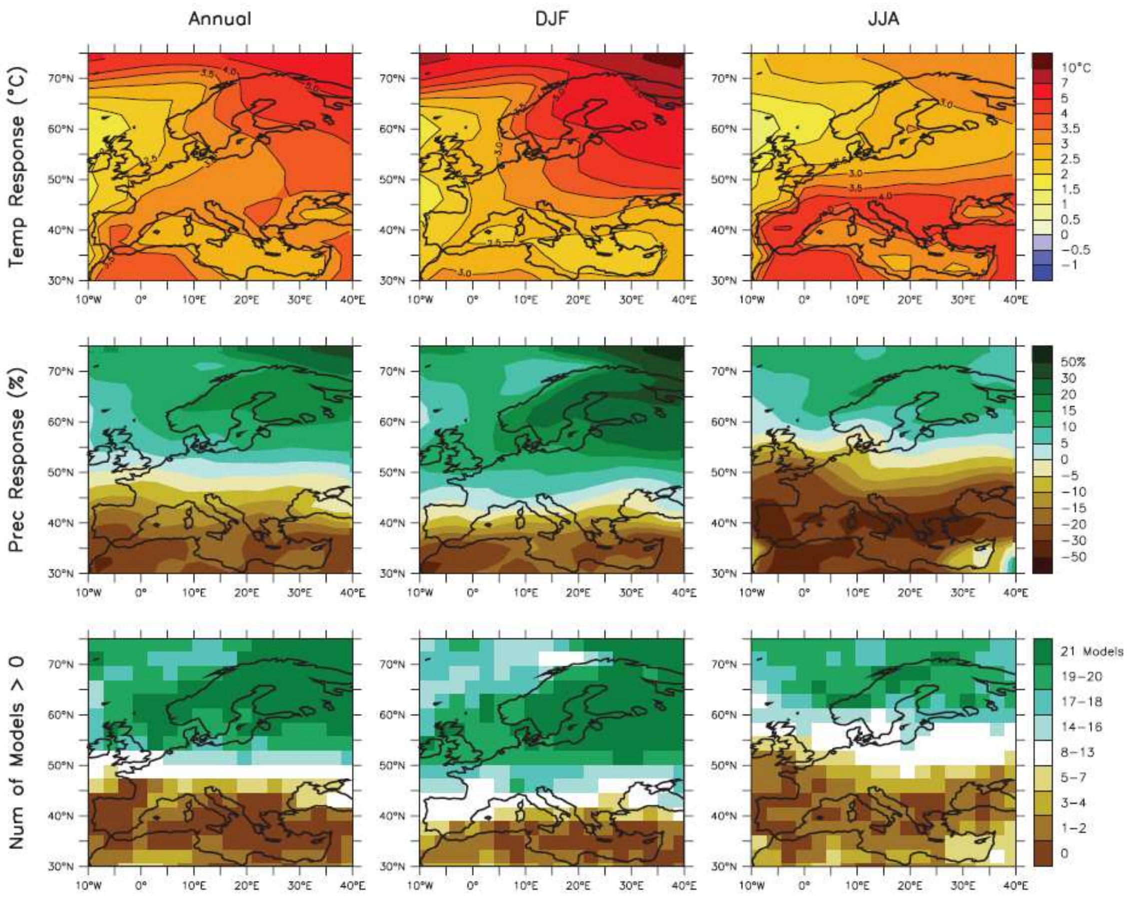


Figure 1:
Temperature and precipitation changes over Europe from the Multi-Model Data set (MMD)-A1B simulations (PCMDI). Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation [14].

sive urbanization and by inappropriate modes of socio-economic development, infrastructure and human settlements. These problems are very critical in Italy, due to the presence of many small catchments which tend to quickly overflow in response to heavy rainfall, even of short duration, especially in specific conditions of the soil. In the Mediterranean basin, due to the complex topography and coastlines, current AOGCMs (Atmosphere-Ocean General Circulation Models) are still too coarse to capture the fine scale structure of the climate change signal as they can only provide broad scale type of informations. As consequence, high resolution modeling (RCM or downscaling techniques) is necessary to simulate surface climate change over Mediterranean region, especially for use in impact assessment studies [27]. On the basis of what has been observed so far is clear that the relationship between “climate change and hydrogeology” is very complex and difficult to evaluate because it is affected by different sources of uncertainty. Furthermore is evident that an important aspect for the evaluation of hydrogeological risks is the need to have high-resolution climate simulations, especially on a region with a complex orography such as Italy (which is the area under test). These are the main reasons that justify the objective of this research, that is the realization of an integrated system of numerical models and tools for the qualitative and quantitative evaluation of the hydrogeological risks in some typical contexts of the Mediterranean area. This integrated system has the purpose of combining, in appropriate way, high-resolution regional climate scenarios, impact models and statistical downscaling techniques.

ARCHITECTURE OF THE SIMULATION SYSTEM

The global climate models (GCMs) are very important to study the current climate and to obtain projections on the future climate using different anthropogenic emission scenarios [53]. The most important advantage from using GCM outputs is the guaranteed physical consistency between variables [32]; [28]; [48], however they are not adequate for climate regional studies [15], to support impact studies and for studies on adaptation strategies to climate change. The generation of climate scenarios at higher resolution is needed for these goals [25]. The need for site or regional scenarios of climate change for impacts studies has existed since years and has thus resulted in the development of different methodologies for deriving such information [36]. These methodologies are known as “downscaling” and the interest toward them is also confirmed by the existence of different nationals and internationals initiatives (see WCRP CORDEX and Giorgi et al.(2009) [26]). Downscaling techniques have been designed to bridge the gap between the information that the climate modelling community can currently provide and that required by the impacts research community [69]. A downscaling at regional scale of the GCM scenarios can be provided with two different methods: statistical or dynamical downscaling. In the architecture presented in this work they are both implemented, at first a RCM is used to provide a spatial downscaling of the GCM and therefore a statistical downscaling, named MOS, is applied to the RCM output to remove the bias of the model output. RCMs are numerical climate models nested on the GCM, usually using a one-way nesting procedure. This technique consists of using outputs from GCM simulations to provide initial and driving lateral boundary conditions for high-resolution RCM simulations, without feedback from the RCM to the driving GCM. This technique derives finer resolution climate information from coarser resolution GCM. RCM provides output only for a part of the globe at a finer spatial resolution (see figure 2). The RCM adopted in this architecture is COSMO CLM. It provides output in a spatial range among 1 and 50 km and it doesn’t use the hydrostatic approximation as the GCM. The reasons to adopt an RCM in the architecture are different:

- validation and present-day climate experiments with RCMs have shown that, when driven by analyses of observations, RCMs simulated realistic structure and evolution of synoptic events;
- compared to the driving GCMs, RCMs generally produced more realistic regional detail of surface climate, representing the input for impact models [67];
- RCMs can provide more detailed information on climate extremes, often more important than knowledge of average properties. This behaviour is noted in several studies, for example the simulation performed in the PRUDENCE project (Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects , 2002-2005) [11].

Nevertheless, the use of RCM introduces further factors of uncertainty in the climate simulations with respect to GCM and the RCM performances are critically affected by the quality of the driving data provided by GCM. In order to provide climatological input to impact models is suggested by different studies the necessity to apply procedures of calibration and downscaling of the RCM simulations through a statistical

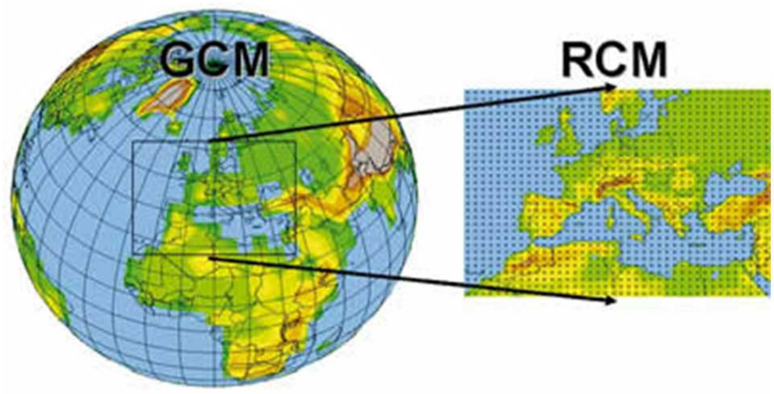


Figure 2:
Representation of dynamical downscaling.

downscaling procedure. The statistical downscaling (SD) techniques are based on statistical models applied on historical data [68]; [5]. They can provide data at higher spatial resolution, in respect to the RCM and GCM. These features are very useful for impact studies, because they often depend strongly on the fine scale climate conditions. Statistical downscaling techniques capture the empirical relationship between variables on a large scale of GCM (“predictors”, such as the geopotential to 500 hPa, temperature at 850 hPa) and the local variables (“predictands”, for example the precipitation at a specific location). Statistical downscaling methods cover: regression models, weather pattern classification schemes, weather time series generators and combinations of the above mentioned techniques. In general, these models are at first calibrated using data from the reanalysis (as ERA40 or NCEP reanalysis) - following the approach called Perfect Prognosis (PP) - and then applied to the scenarios of GCM. One of the main advantages of these SD techniques is that they are much less computationally expensive than to run physical simulations with RCM. For this reason is also easier to provide an ensemble of high resolution climate scenarios and, therefore, an assessment of the uncertainty in future scenarios. The main disadvantages, on the other side, are: the need of large amounts of observational data to establish statistical relationships among variables and the fact that relationships between predictands and predictors are valid only within the range of the data used for calibration, and future projections may lie outside of this range [21]. The increasing availability of regional simulations re-analysis driven (for example the ones produced by projects such as ENSEMBLES [64]) has led some authors to recently suggest the possibility to combine the advantages of the downscaling methods: dynamical and statistical. This is realized by the MOS (Model Output Statistics) downscaling, which is a statistical downscaling applied to the output of a RCM [37]. In this case, the predictor is directly the output variable of a RCM (as the precipitation of the regional model), which is empirically related to the observed variable (precipitation in a local station or in an interpolated grid point) through the algorithm downscaling statistics. This approach allows local adaptation of the outputs from regional models using high-resolution observations. RCM output, calibrated by MOS downscaling (mainly applied to temperature and precipitation), is then used as input for impact models. Two different impact typologies are considered in this research activity: floods and landslides. A huge part of the research activities is constituted by development and verification of impact simulation models and by development of a correct link between these models and climatological models, previously described. Floods and landslides phenomena are simulated using different simulation models. Follows a description of impact simulation models used in this work.

A flood model requires a hydrological model and a hydraulic model. The first one determines the runoff generated by a rainfall event and provides hydrographs at different location. Hydrographs describe the variation of water level/river discharge in time, due to the rainfall event. The hydrologic model, fed by the hydrographs modeled by the hydrological model, deals with the propagation along the river of the flow discharge considering the river sections geometry, position, and eventually presence of bridges or other structures and their geometry, river roughness and flow-height relationship (rating curve). The hydrological component of a flood modeling system can be based on distributed models, computationally demanding and requiring a detailed description of the territory in terms of topography, quantity and intensity of precipitation, soil saturation, soil properties and land use, or on lumped models that are less demanding in terms of data and computational load. However distributed models results provide more information than lumped models since they take into account also the spatial distribution of the inputs (rainfall patterns).

Rainfall-induced landslide modelling approaches are usually classified as local models if they focus on single landslide processes or regional models if they show greater spatial extent. The first ones allow detailed investigation about triggering and failure processes while the second ones generally are used to analyze landslide susceptibility or eventually landslide risk. In both cases, it needs to deal with two problems: hydraulical and mechanical. The most comprehensive way, although much more complex, is to analyze the coupled problem solving in numerical way the simultaneous equations governing the phenomenon (consistency equations, continuity equations for each system component, constitutive equations, equations of state). Because of remarkable complexity of the approach, simplifying the problem through appropriate assumptions, it's often preferred to solve in series the two aspects; in this way, the hydraulic problem passes to the mechanical one the soil pore water pressure values. Under such hypotheses, adopting increasing complexity approaches, the hydraulic problem can be handled adopting steady-state conditions, closed-form solutions for water continuity equations, numerical solutions for water continuity equations under isothermal condition or via thermo-hydraulic approach models (to take into account properly the soil-atmosphere interaction). Similarly, for the mechanical problem, it is possible to utilize empirical relations (for example in order to relate pore pressure and slow movements) or simplified models (infinite slope, limit equilibrium methods).

The figure 3 shows the simulation chain architecture adopted in this research activity.

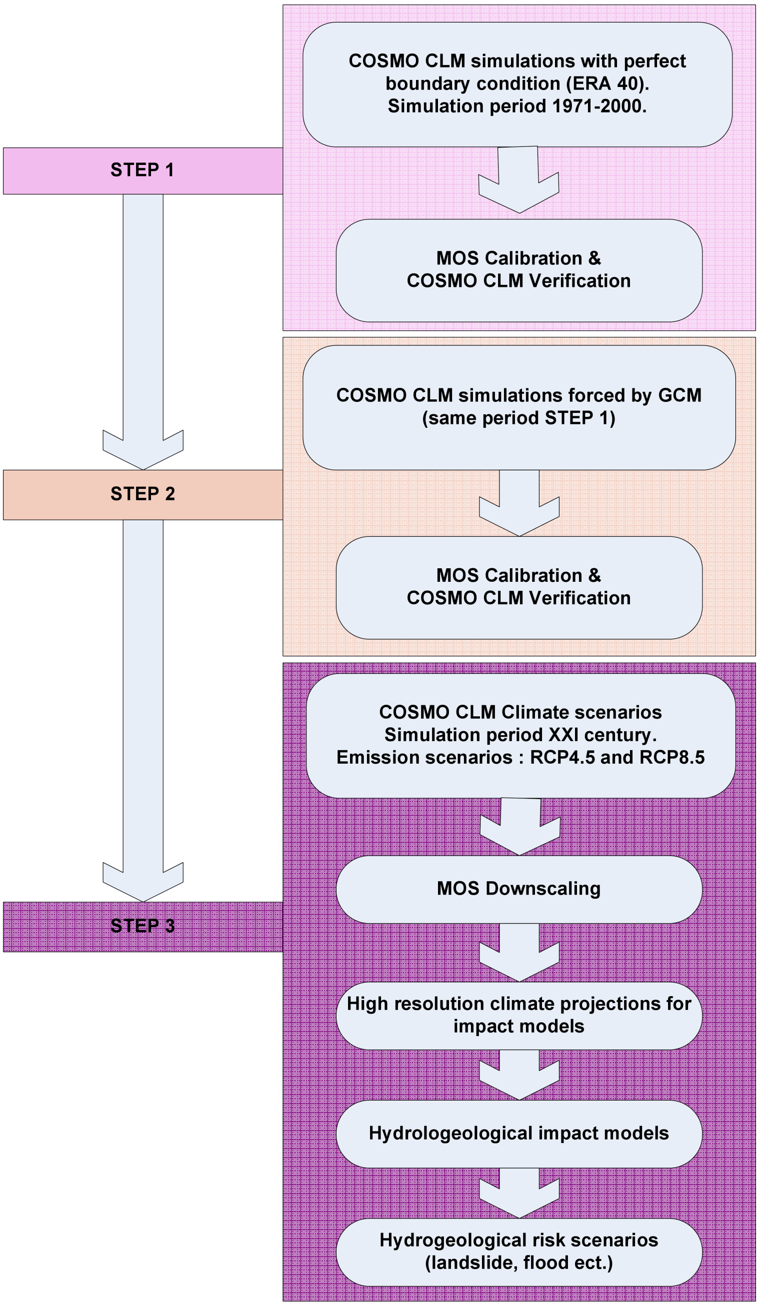


Figure 3:
Simulation chain architecture.

MODELS AND TOOLS ADOPTED IN THIS PROJECT

THE REGIONAL CLIMATE MODEL COSMO CLM

At CMCC, the regional climate model COSMO-CLM [49] is currently used to perform climate simulations: it is the climate version of the COSMO LM model [54], which is the operational non-hydrostatic mesoscale weather forecast model developed initially by the German Weather Service and then by the European Consortium COSMO. Successively, the model has been updated by the CLM-Community, in order to develop also a version for climate application (COSMO CLM). It can be used with a spatial resolution between 1 and 50 km even if the non hydrostatic formulation of the dynamical equations in LM made it eligible especially for the use at horizontal grid resolution lower than 20 km [7]. These values of resolution are usually close to those requested by the impact modellers; in fact these resolutions allow to describe the terrain orography better than the global models, 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 the non-hydrostatic modelling provides 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. 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 thunderstorms). Another advantage related to the usage of COSMO CLM, with respect to other climate regional models available, is that the continuous development of LM allows improvements in the code that are also adopted in the climate version, ensuring that the central code is continuously update. The mathematical formulation of COSMO-CLM is made up of the Navier-Stokes equations for a compressible flow. The atmosphere is treated as a multicomponent fluid (made up of dry air, water vapour, liquid and solid water) for which the perfect gas equation holds, and subject to the gravity and to the Coriolis forces. The model includes several parameterizations, in order to keep into account, at least in a statistical manner, several phenomena that take place on unresolved scales, but that have significant effects on the meteorological interest scales (for example, interaction with the orography). The main features of the COSMO CLM simulation are:

- nonhydrostatic, full compressible hydro-thermodynamical equations in advection form;
- base state: hydrostatic, at rest;
- prognostic variables: horizontal and vertical Cartesian wind components, pressure perturbation,temperature, specific humidity, cloud water content. Optionally: cloud ice content,turbulent kinetic energy, specific water content of rain, snow and graupel;
- coordinate system: generalized terrain-following height coordinate with rotated geographical coordinates and user defined grid stretching in the vertical. Options for (i) base-state pressure based height coordinate, (ii) Gal-Chen height coordinate and (iii) exponential height coordinate (SLEVE) according to Schar et al. (2002) [50];
- grid structure - Arakawa C-grid, Lorenz vertical grid staggering;

- time integration: time splitting between fast and slow modes (Leapfrog, Runge-Kutta);
- spatial discretization: 2° order accurate Finite Difference technique;
- parallelization: Domain Decomposition (MPI as message passing S/W);
- parameterizations:
    - Subgrid-Scale Turbulence;
    - Surface Layer Parameterization;
    - Grid-Scale Clouds and Precipitation;
    - Subgrid-Scale Clouds;
    - Moist Convection;
    - Shallow Convection;
    - Radiation;
    - Soil Model;
    - Terrain and Surface Data.

MOS DOWNSCALING FOR HYDROLOGICAL APPLICATION

INTRODUCTION TO MOS DOWNSCALING

Turco et al. (2011) [60] tested the performance of a MOS implementation of the popular analog methodology applied to calibrate RCM-precipitation outputs over Spain (hereafter referred to as "*MOS analog*"). The *MOS analog* method improves the representation of the mean regimes, the annual cycle, the frequency and the extremes of precipitation for all RCMs, regardless of the region and the model reliability (including relatively low-performing models), while preserving the daily accuracy. In this project we want to implement this methodology in northern Italy, with a special emphasis on the analysis of its applicability in a modelling chain to study the impact of climate change on hydrology. This section is organized as follow: firstly the MOS methodology is briefly described, then the methodologies to verify the simulations are presented and, finally, the expected results are discussed.

METHODOLOGY

MOS BASED ON ANALOGS. A detailed analysis of the *MOS analog* method is reported in Turco et al. (2011) [60]. Here it has been reported a summary for the reader's convenience. The analog method is based on the hypothesis that "analogue" weather patterns (predictors) should cause "analogue" local effects (predictands). This leads to a simple algorithm to infer the local occurrence associated with a given predictor (atmospheric pattern) based on the historical occurrences of a set of analog days (with closest predictors). This is simply done by considering the historical local occurrences corresponding to the atmospheric patterns closest/analog to the target predictor. Figure 4 illustrates this relatively simple method. It basically consists in two steps. For the day A in a future or in a test period:

1. the closest historical predictor B (the analog) considering the Euclidean distance between the two raw predictor fields (according to Matulla et al. (2008) [38] this is a reasonable first choice among the standard measures of similarity) is found,

2. then, the local precipitation observed, b, correspondent to the analog day B, is used as the downscaled precipitation of the day A (i.e. a=b).

Then these steps are repeated for each days to downscaled. Note that it is also possible consider larger number of analogs, but a single analog has the advantage to maintain the spatial coherence of the observed field. Besides, a test on a larger number of analogs were also conducted, but a single analog exhibited the best performance. For these reasons in this work we will consider a single analog for each day to downscaled.

As in Turco et al. (2011) [60], we will firstly consider the ERA40-driven RCM simulation in order to limit the influence of the quality of the GCM boundary condition in the calibration/verification step. Note that the application of this method to downscale future RCM scenarios (driven by GCMs simulations) is technically straightforward, since the analog search would consist in matching the future RCM predictor patterns and the closest historical pattern from the reanalysis-driven RCM control simulations. Besides, Turco et al. (in preparation) show the applicability of the "*MOS analog*" method to downscale the ENSEMBLES transient RCM simulations (i.e. the GCM-driven RCMs).

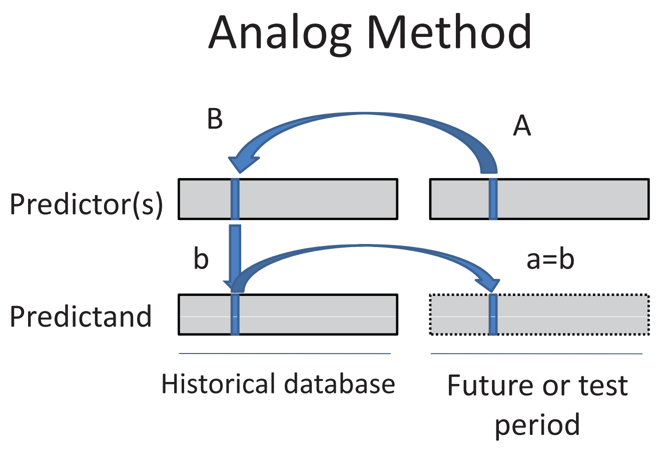


Figure 4:
Schematic illustration of the analog method (adapted from Fernandez and Saenz (2003) [20])

VERIFICATION MEASURES. Firstly, since the main limitation of the statistical downscaling methods is that related to the stationarity problem, we will apply the test of robustness proposed by Gutierrez et al. (submitted). This test consists in comparing the biases of the downscaled outputs in ”random” and ”extreme” (e.g. the wettest or driest years) sub-periods.

Secondly, since the objectives are to improve and to downscale the COSMO-CLM output in a hydrological context, we will focus on some important characteristics for hydrological applications:

1. spatial coherence of the variables,
2. physical consistency between the variables (e.g. between temperature and precipitation),
3. temporal dependence of spatial pattern (e.g. autocorrelation).

The first point is satisfied since each simulated day is an actual day from the database of observations. Consequently the MOS analog method maintains the spatial coherence. The other two points need to be carefully studied. Regarding the physical consistency between the variables, a possible comparison measure is to calculate some climate variables in which both temperature and precipitation play a role, as for example the days with snow or the ”precipitation minus evaporation” climatology. Other property (3) very important (and difficult to achieve) is related to the temporal dependence of spatial pattern, i.e. the dependence between the patterns of successive days. To verity it we plan to estimate the autocorrelation of the temperature and some specific index for the precipitation, as for example, p_{00}, that is, the probability of no precipitation, given no precipitation the previous day (and also p_{11}, p_{10} and p_{01}).

EXPECTED RESULTS.

The overall objective of this work is to develop regional scenarios for temperature and precipitation at daily scale by means of a statistical downscaling method, useful as input fields of a hydrological model. The overall objective leads to three specific aims:

1. the analysis of some aspects (e.g. autocorrelation) of the observed precipitation and temperature variability in the Northern Italy,
2. the implementation/improvement of the "*MOS analog*" method for hydrological application,
3. as a by-product, the evaluation of the RCM outputs.

FLOODS AND DROUGHTS SIMULATION MODELS

HYDROLOGICAL AND HYDRAULIC MODELS IN PO FLOOD EARLY WARNING SYSTEM (PO-FEWS)

The Po-FEWS is a sophisticated system environment designed for embedding an operational flood forecasting system. The philosophy of the system is to provide an open shell system for managing the forecasting process. This shell incorporates a comprehensive library of general data handling utilities, allowing a wide range of forecasting models to be integrated in the system through a published open interface. Po-FEWS constitutes a Multi-Model system (MUMO), in which forecasts for sub-basins of the Po and the Po river are performed with three different parallel model chains. Each chain consists of a hydrological model simulating the response of the basins and a river routing model for flood wave propagation. The implemented models are: NAM, HEC-HMS and TOPKAPI for the hydrological models, coupled with the hydrodynamic models MIKE11, HEC-RAS, SOBEK, PAB respectively. Moreover, users can configure an additional chain to simulate particular cases like dam breaks, levee breaks, and morphological changes on the river during the flood event [10]. Figure 5 presents the modeling system. To simulate the hydrological response of the basins the rainfall-runoff models consider the topography, quantity and intensity of precipitation, soil saturation, soil properties and land use. To simulate the flood wave propagation the hydrodynamic models consider the river sections geometry, position, and eventually presence of bridges or other structures and their geometry, river roughness and flow-height relationship (rating curve).

To process the uncertainty of the results (predictive uncertainty) a Multivariate Conditional Processor is implemented in FEWS. The Multivariate Conditional Processor is a probabilistic approach to uncertainty and can be built considering probability distribution function of hydrometric observations conditioned from hydrometric forecast. The Multivariate Conditional Processor combines observations with one or more models' forecast in a multi-Normal space, by transforming observations and model forecasts in a multivariate Normal space through the Normal Quantile Transform [55]. This method allows to account for the uncertainty due to model (input forcing, initial and boundary conditions, parameters) and provides an estimate of the probability of occurrence of forecast based on the available information.

HYDROLOGICAL MODELS

The hydrological component is simulated through physically based models of surface runoff, subsurface flow, evapotranspiration, flow discharge. The simulation is performed in each chain by one of the following models: HEC-HMS, NAM and TOPKAPI.

THE HEC-HMS MODULE

HEC-HMS (Hydrologic Modeling System - Hydrologic Engineering Center) is a public domain software developed by the US Army Corps of Engineers available on `www.hec.usace.army.mil/software/hec-hms/`. HEC-HMS converts precipitation excess over a watershed to overland flow and channel runoff. Hydrological elements are connected in a dendritic network to simulate runoff process, while interception, evaporation and infiltration processes can be represented with mathematical models, more of one is generally available for representing each flux, see figure 6. The HEC-HMS outputs are hydrographs ready to be use for studies of

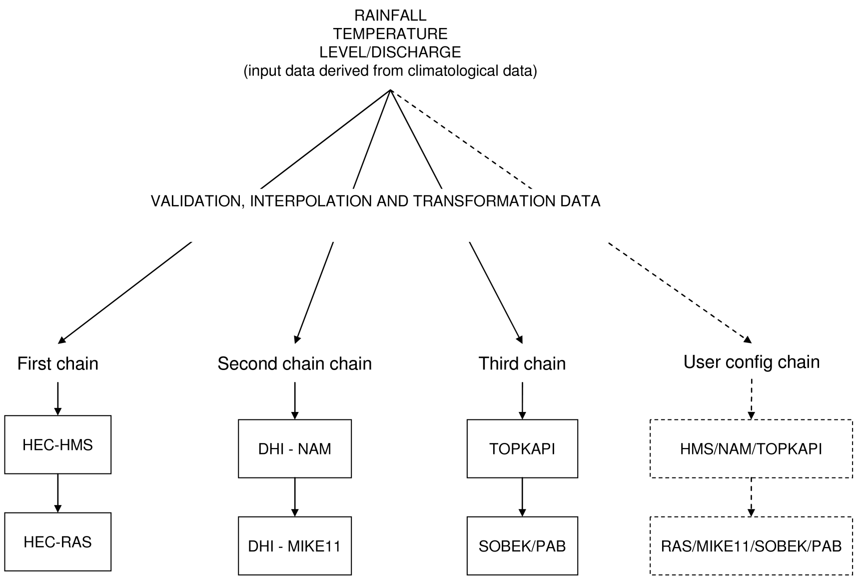


Figure 5:
Scheme of Po flood forecasting system [10]

water availability, flow forecasting, flood damage reduction, floodplain regulation, etc. [61].

THE NAM MODULE The rainfall-runoff model (NAM) is a proprietary software developed by Danish Hydraulic Institute in Denmark. NAM is a watershed lumped-parameter model based on a conceptual representation of the land phase of the hydrological cycle. The hydrological model simulates the rainfall-runoff process occurring at the catchment scale, see figure 7. The minimal meteorological inputs requested are precipitation, potential evapotranspiration, temperature and radiation time series. The knowledge of temperature and radiation time series is important for simulating snow accumulation and snow melting processes. On the basis of meteorological inputs the model provides time series of catchment runoff, subsurface flow contribution to the channels, soil moisture content and ground water recharge. The catchment runoff is divided into three flow components: overland, interflow and baseflow. The rainfall-runoff processes is simulated by varying the water content into four interrelated storages (snow, surface, lower/root zone, ground water) each of them representing a physical process [63].

THE TOPKAPI MODULE TOPKAPI (TOPographic Kinematic APproximation and Integration) is a physically based distributed rainfall-runoff model. The TOPKAPI model couples the kinematic approach with the topography of the catchment and transfers the rainfall-runoff processes into three 'structurally-similar' zero-dimensional non-linear reservoir equations. The non-linear reservoir equations derive from the integration in space of the non-linear kinematic wave model: the first represents the drainage in the soil, the second represents the overland flow on saturated or impervious soils and the third represents the channel flow. The integration of the fundamental

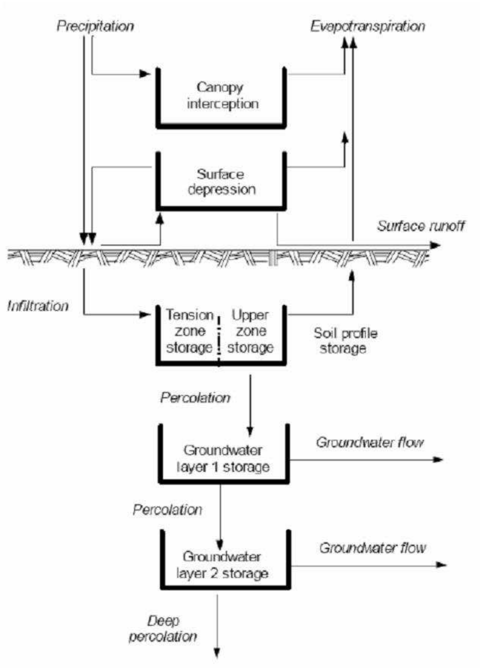


Figure 6:
Conceptual scheme of the continuous soil moisture account in HEC-HMS [61].

equations is performed for each of the cells discrediting the basin. The TOPKAPI model is structured around five modules that represent: evapotranspiration, snowmelt, soil water, surface water and channel water components respectively, figure 8. The soil water component is affected by subsurface flow (or interflow) in a horizontal direction defined as drainage; drainage occurs in a surface soil layer, of limited thickness and with high hydraulic conductivity due to its macroporosity. The drainage directly contributes to the flow in the drainage network and is a factor regulating the soil water balance, particularly in activating the overland flow process. The soil water component regulates the functioning of the contributing saturated areas, that regulates the surface water component. The evapotranspiration is taken into account as water loss, subtracted from the soil's water balance [57].

THE HYDRAULIC MODELS

The hydraulic component is simulated through physically based models of flow discharge. The simulation is performed in each chain by one of the following models: HEC-RAS, MIKE 11, SOBEK, and PAB.

THE HEC-RAS MODULE Hydrologic Engineering Centers River Analysis System (HEC- RAS)) is a public domain software developed by the US Army Corps of Engineers available on `www. hec.usace.army.mil/ software/hec-ras/`. HEC-RAS allows to perform one- dimensional steady and unsteady flow river hydraulics calculations over a network of natural and constructed channel, sediment transport computation and water quality analysis. The steady flow water surface profile component models water level under subcritical, supercritical, and mixed flow river regime. The unsteady flow component models storage areas and hydraulics connections between storage areas, it has been developed mainly for subcritical flows. The sediment transport component models the one-dimensional sediment transport/movable boundary resulting from scour and deposition processes. The water quality analysis component can perform analysis of temperature and transport of some water quality constituents in riverine waters [62]. HEC-RAS solves the mass conservation and momentum conservation equations with an implicit linearized system of equations using Preissman's second order box scheme. In a cross section, the overbank and channel are assumed to have the same water surface, though the overbank volume and conveyance are separate from the channel volume and conveyance

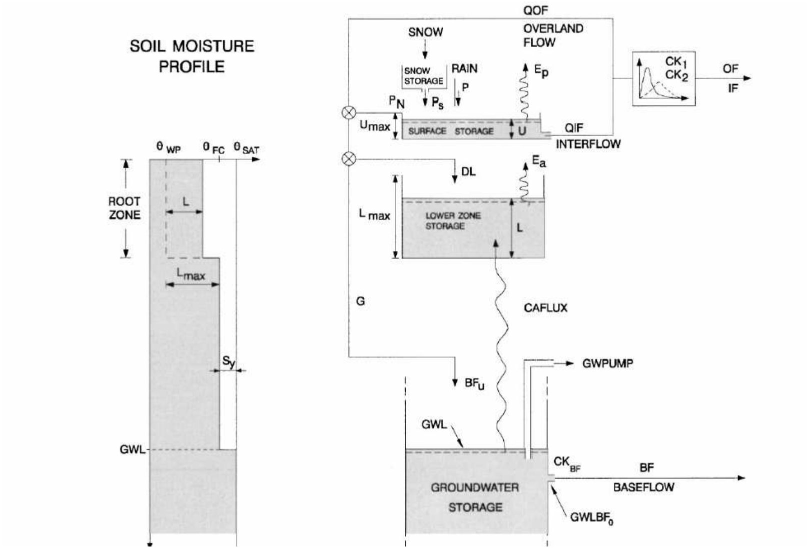


Figure 7:
NAM model structure.

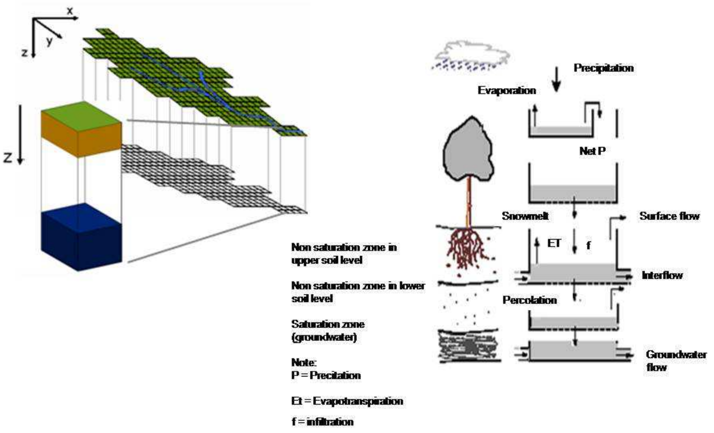


Figure 8:
Scheme of TOPKAPI

in the implementation of the conservation of mass and momentum equations. The state variables for the numerical scheme are flow and stage, which are computed and stored at each cross section. Plots of flow and stage are available for selected cross sections at a user specified time interval. The hydraulic resistance is based on the friction slope from the empirical Manning's equation, with several ways of modifying the roughness. Roughness can be characterized with Manning's coefficient or roughness height's.

THE MIKE 11 MODULE MIKE 11 is a proprietary software developed by Danish Hydraulic Institute in Denmark. MIKE 11 is a one dimensional river model, that simulates flow and water level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies. The software provides fully dynamic solution to the complete nonlinear Saint Venant equations, diffusive wave approximation and kinematic wave approximation, Muskingum method and Muskingum-Cunge method for simplified channel routing. It is able to automatically adapt to subcritical flow and supercritical flow and it can handle the presence of standard hydraulic structures such as weirs, culverts, bridges, pumps, energy loss and sluice gates. The water level and flow are calculated at each time step, by solving the continuity equation and the momentum equation. The water level is calculated at each cross section and interpolated elsewhere. The flow is calculated at points midway between neighboring water level points and at structures. The hydraulic resistance is based on the friction slope from the empirical equation, Manning's or Chezy. Water levels at Po river section, simulated by MIKE 11, are post-processed using an ARMA model of the 3rd order and the associated flow rates are derived through the rating curve.

THE SOBEK MODULE SOBEK was developed by WL Delft Hydraulics in full partnership with the Institute for Inland Water Management and Waste Water Treatment (RIZA) of the Netherlands government. SOBEK is a one-dimensional open-channel dynamic numerical modeling system, capable of solving the equations that describe unsteady water flow, salt intrusion, sediment transport, morphology and water quality (DELTARES). The software carries out one-dimensional hydraulic calculations of an area that is schematized by a network of open water channels. All calculated quantities are cross section averaged values. A network can consist of several branches with bifurcations, cross sections can vary within a branch.

THE PAB MODULE Parabolic And Backwater (PAB) is a method for solving gradually varied flow equations. The method introduced by Todini and Bossi (1986) [56] is based on calculation of hydraulic jump profiles (calculation of the water levels from downstream to upstream in a slow current) and flow propagation as an impulsive response of a parabolic type (flow transfer from upstream to downstream). The method has the advantage of being unconditionally stable.

LANDSLIDES SIMULATION MODEL

The selected tools to comprehend the effects of climate changes on the slope stability are two: the first one, I-MOD3D is a regional model implementing both the hydrological and geotechnical module; the second one, Vadose/W, is a commercial code allowing to carry out slope scale analysis; through this code, it is possible to investigate only the hydrological slope behaviour ; the pore water pressures, representing one of the code outputs, are hence used to estimate the slope stability conditions through, considering the problem to analyze, experimental relations or widely used approaches (infinite slope model, limit equilibrium approaches). I-MOD 3D is a 3D home-made code developed at the Geotecnical Laboratory of Second University of Naples [42]; [17]; [41]. The code is built as a Visual Basic Application for ARC-GIS. It can be considered consisting of two modules: a hydrological model which estimates the slope response to soil-atmosphere interaction essentially in terms of soil water content and soil water pressure and a geotechnical module which performs stability analyses adopting the scheme of the infinite slope.

HYDROLOGICAL MODULE

For what concern the hydrological module, the code solves the Richards (1931) [47] equation in numerical way through a 3D Volume Finite approach. The equation regulates the water flow within the unsaturated soil in transient conditions under the assumptions of isothermal condition and rigid soil skeleton; it can be obtained imposing the principle of conservation mass for an element of unsaturated soil (equation (1) in figure 9). For partially saturated soils, the specific discharge term is described by the D'Arcy-Buckingham law extension for unsaturated soil of the D'Arcy Law (equation (2) in figure 9). The hydraulic conductivity represents the constant of proportionality relating flow rate to the hydraulic head gradient; it can be considered as constant for saturated soils (k_s) while it is a decreasing function of the water content in unsaturated soils as, decreasing the pores filled with water, the ability of the soil to conduct flow is diminished. It is worth remembering that, for partially saturated soils, the soil pores contain air and water, usually at pressures different from each other. This is possible because they are separated by thin membranes formed by water molecules, commonly called menisci; they, being capable of supporting tensile stresses, allow the air pressure, u_a , (usually equal to atmospheric pressure u_{atm}) can be greater than the pressure water, u_w. As, for the hydro-mechanical issues, the two variables are involved through their difference, the variables matrix suction $s = u_a - u_w$ is widely used . Moreover, in order to reduce the number of variables, is introduced the relationship between θ and s also known as soil-water characteristic curve; matrix suction increases as the water content decreases; generally speaking, it shows a typical S-shape in semilogarithmic scale (see figure 10). A represents saturated volumetric water content, B the residual volumetric water content while C, known as air bubble pressure value, is suction value beyond which the medium begins to desaturate; the point D is the inflection point. Experimentally, it can be observed that this relationship is function, in the special way, of soil grain size and water salt content; moreover, it shows an hysteretic behaviour depending on whether wetting or drying paths are considered. For what concern the soil-water characteristic curve, I-MOD 3D, at the moment, adopts the formulation of van Genuchten (1980) [65]; the approach adopts three parameters taking into account the suction at the inflection point (directly correlated to air bubble suction value), grain size medium distribution and the non-symmetric be-

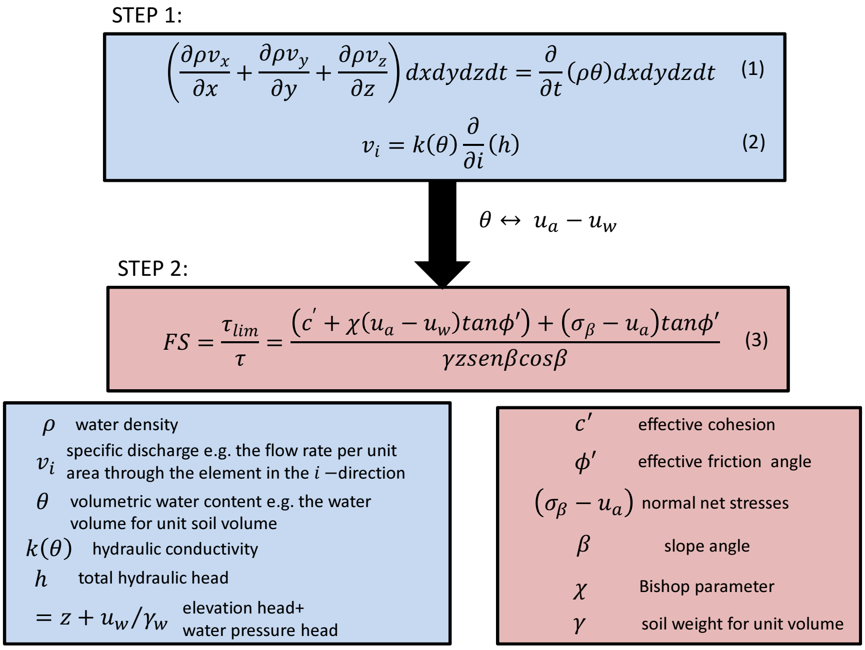


Figure 9:
IMOD 3-D operating diagram

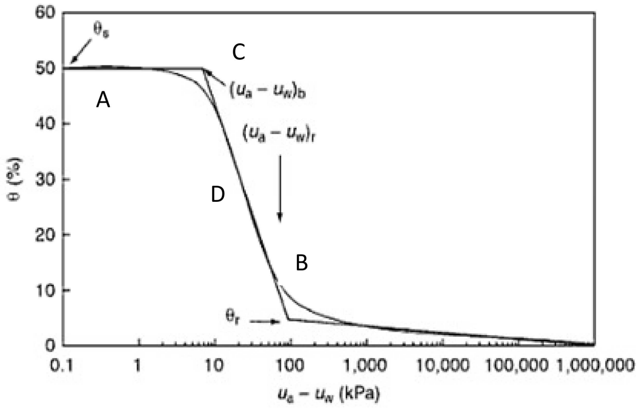


Figure 10:
A typical S-shape for soil-water characteristic curve

haviour of the curve respect to the inflection point. This relation is widely used in all soil sciences because of its ability to effectively reproduce, thanks to the three parameters, the hydraulic soil behaviour. For what concern the unsaturated permeability function, the code adopts three formulations:

- Brooks and Corey (1964) [9] particularly suitable for coarse grained soils;
- Gardner (1958) [24];
- Arbhabhirama and Kridakorn (1968) [1].

The three approaches utilize two parameters: the first one related to air bubble suction value and the second one taking into account the next descending trend of the function. Alternatively, I-MOD 3D allows the user to enter own relationships found through field experimentation and/or laboratory tests (as function of matrix suction or volumetric water content). For saturated soils, the equation (1) can be still used assuming, in the positive pore-pressure region for the volumetric water content variation, the coefficient of monodimensional compressibility instead of the slope of soil-water characteristic curve; physically, it describes how much a saturated soil volume shrinks or swell under a unit variation of pore pressure. Obviously, the resolution of PDE (1) requires the imposition of boundary conditions. As upper boundary condition, at the ground surface, can be imposed a Dirichlet condition (established values of suction) or a Neumann condition (water inflow or water outflow); in both cases they may be imposed as a function of time. Via these conditions, a rainfall history can be easily used at the ground surface; in the same way, the option of imposing outgoing flows can allow to set values of evaporation if known or predictable through other tools. This can be of particular usefulness for soils characterized by low permeability and/or high retention capacity; these properties can make significant on the stability conditions rainfall effects over a large meteorological window. Over this time span, the suction values within the soil can be profoundly affected not only by precipitation, even by the evaporative flows. As lower condition, similarly, can be imposed suction values or water fluxes; through these ones, can be simulated, for example, the presence of a water table (suction equal to zero) or of an impervious bedrock (water flux equal to zero in the direction orthogonal to the bottom layer).

GEOTECHNICAL MODULE

I-MOD 3D adopts the infinite slope model to analyse the slope stability conditions. The infinite slope model for homogeneous layer balances the destabilizing forces of gravity and the components of the resisting forces on a failure plane parallel to the slope surface. By adopting the Mohr-Coulomb failure criterion, the factor of safety (FS) can be expressed by the relation (3). Then, the link between hydrological and geotechnical module is constituted by the water pressure values. In the (3), in addition to the terms (first and third in the numerator) usually used for soils saturated, the second term takes into account the effect of the suction on the shear resistance. In fact, the presence of the menisci, at the contact points between the soil particles, produces an increase of the normal stresses acting between the grains, and then a further contrast to the sliding. Therefore the increase in suction is responsible for an increase of shear resistance. The parameter χ was proposed by Bishop (1959) [8]; it is equal to 1 for saturated soils, 0 for dry soils while, in intermediate conditions, it is a function of soil water content. Between the different approaches in the literature for the estimation of χ, there are:

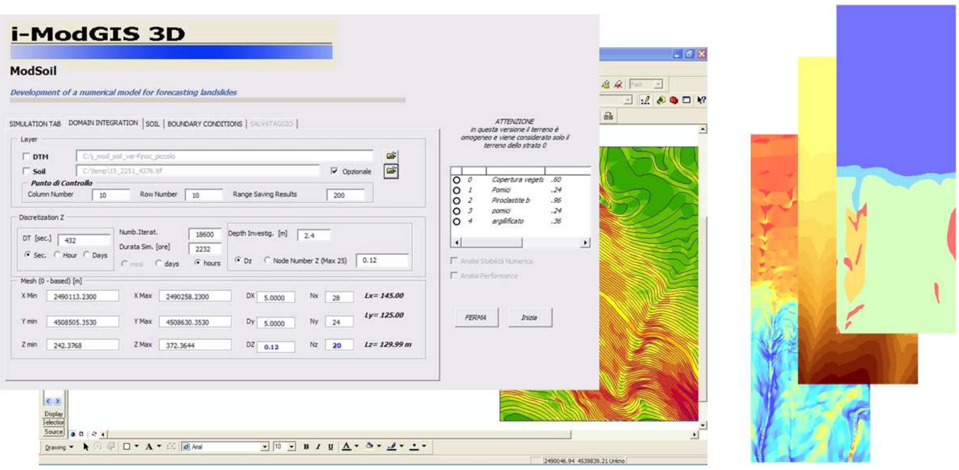
- Khalili and Khabbaz (1998) [35]: Bishop parameter is assumed as function of suction;

- Vanapalli and Fredlund (2000) [66]: Bishop parameter is assumed equal to effective saturation degree;

- Oberg and Sallfors (1997) [40]: Bishop parameter is the ratio between actual and saturated volumetric water content.

The major innovation of I-MOD is represented by the numerical solution of equation (1). In fact, all the other distributed physically based models implement closed-form solutions to estimate soil water pressure distribution within the soil. If, on the one hand, the numerical resolution require more computational resources limiting the use of the code at the basin scale rather than at the regional scale, on the other hand, it allows to avoid the restrictive assumptions of the closed form solutions about the preferential directions of the water flows within the soil (e.g. parallel to the slope or vertical), the effective time window for the precipitations (both related, primarily, to the soil type) and the boundary conditions. Moreover, the numerical resolution of equation (1) and the adoption of the relationship (3) allows to consider, indistinctly, stability conditions for saturated or partially saturated soils. First attempts to develop a simulation chain has been carried out in meteorological field: in this case, the first step is constituted by the COSMO-LM model (a mesoscale meteorological model); the second is a downscaling module which is used to establish the boundary conditions for the geotechnical module at the basin scale; between the first two tools and I-MOD-3D (the last step of the model chain) there is an interface able to automatically define the soil domain to analyse starting from a Digital Terrain Model, and to capture the forecasted rain from the downscaling module. The attempts refer to the case-histories of Cervinara and Nocera Inferiore, two cities located in the Campania Region where the slopes, covered by pyroclastic soils, are affected, in the last years, by frequent instability events. They return satisfactory results. A last significant remark concerns the pre- and postprocessor phases already implemented in I-MOD 3D: two examples are referred in figure 11 and figure 12.

Vadose/W code solves, via a numerical approach (finite element for spatial discretization, finite differences for temporal integration), the simultaneous equations governing the Wilson (1990) model [70]. It allows to estimate, in bidimensional conditions, pore water pressure, pore vapour pressure and temperature within the soil and so, to take into account, in a proper way, the soil-atmosphere interaction (not only in terms of infiltration, as for an isothermal approach, but also of evaporation). Indeed, if the potential evaporation is, primarily, function of the meteorological forcings (weakly related to the soil conditions through the roughness and albedo), the actual evaporation depends not only on the above variables but also (mainly) on soil water content/water pressure/vapour pressure. The Wilson approach is based on an extended version of the Penman equation, able to take into account partial saturation soil conditions. Evaporative flux, representing upper boundary condition, is itself a function of the variables within the soil (temperature, water pressure, vapour pressure); thus, for its definition, it needs to solve simultaneous equations forming the model. According to Wilson (1990) [70] and Milly (1982) [39] approaches , the first equation constitutes a generalized version of the Richards equation modified to consider phase changes, vapour diffusion, and entire gas phase diffusion within the medium. The second equation regulates heat transfer



i-ModGIS 3D

ModSoil

Development of a numerical model for forecasting landslides

Layer

☐ DTM C:\i_mod_soil_ver4\noc_piccolo

☐ Soil C:\temp\15_2251_4376.tif ☑ Opzionale

Punto di Controllo

Column Number 10 Row Number 10 Range Saving Results 200

Discretization Z

DT [sec.] 432 ● Sec. ○ Hour ○ Days

Numb.Iterat. 18600

Durata Sim. [ore] 2232 ○ mesi ○ days ● hours

Depth Investig. [m] 2.4

● Dz ○ Node Number Z (Max 25) 0.12

Mesh (0 - based) [m]

X Min 2490113.2300 X Max 2490258.2300 DX 5.0000 Nx 28 *Lx= 145.00*

Y min 4508505.3530 Y Max 4508630.3530 Dy 5.0000 Ny 24 *Ly= 125.00*

Z min 242.3768 Z Max 372.3644 DZ 0.12 Nz 20 *Lz= 129.99 m*

ATTENZIONE
in questa versione il terreno è omogeneo e viene considerato solo il terreno dello strato 0

○	*0*	*Copertura veget*	*.60*
○	*1*	*Pomici*	*.24*
○	*2*	*Piroclastite b*	*.96*
○	*3*	*pomici*	*.24*
○	*4*	*argillificato*	*.36*

☐ Analisi Stabilità Numerica

☐ Analisi Performance

Figure 11:
Pre-processor phase: data input.

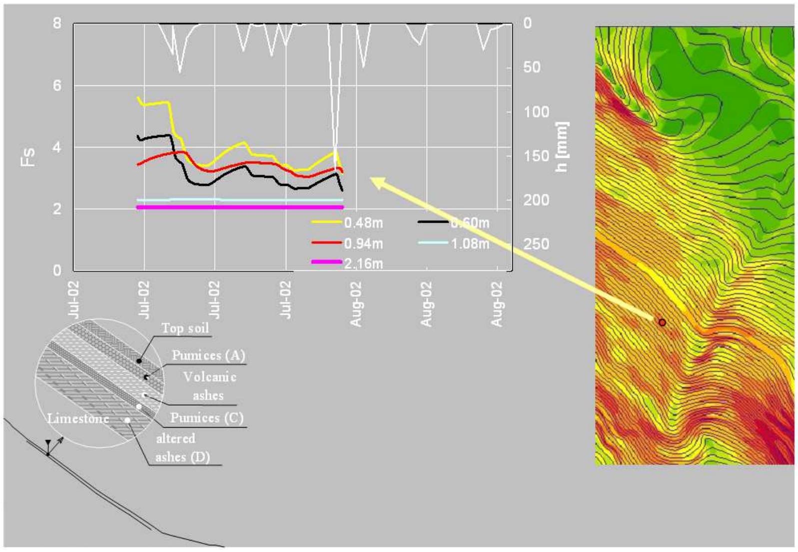


Figure 12:
Post processor phase:contour maps of safety factor FS.

processes; it enables to estimate heat transfers due to conductive, convective and phase change dynamics. The budget between unknows and equations is closed by Edlefsen and Anderson (1943) [19] relationship. To solve the simultaneous equations, it is necessary to feature hydraulic and thermal soil behaviour. In particular, for all involved soils, the first one needs to define soil-water characteristic curve and permeability function (see above) while the second one requires to estimate volumetric heat capacity (change of a unit volume's heat content under a variation of a degree) and soil thermal conductivity (quantity of heat transferred through a unit area in a unit time per unit change in temperature). In order to adopt the Wilson-Penman approach (originally developed for bare soils) for vegetated surfaces, in the code is implemented the Tratch (1996) [59] approach. Following this, the vegetation contribution to evapotranspiration processes is modelled through Leaf Area Index (one-sided green leaf area per unit ground surface area) regulating how energy is available for evaporation processes from bare soils and how for transpiration dynamics, root depth defining the soil layer in which the plants can obtain the needed water and plant moisture limiting function estimating, in percentage terms, the decreasing ability of plants to extract water from the soil as soil suction increases.

SYSTEM VERIFICATION

This section describes the datasets used in this activity and the test cases that will be developed to verify the proposed integrated system. They only represent an initial inspection, which will later be expanded to other regions of the Mediterranean area.

OBSERVED DATASETS

To test the integrated system previously presented, given that the observed climatic data may have important uncertainties, we want to analyse different datasets.

ARPA Piemonte dataset. This is a gridded high-resolution (0.125° x 0.125°, approximately 15 km x 15 km) dataset of observed data of precipitation and temperature at daily scale, which is publicly available for research activities (see `http://rsaonline.arpa.piemonte.it/meteoclima50/index.htm`). This dataset was produced using data from quality-controlled stations from the ARPA Piemonte Agency, covering the Piemonte region, North-West of Italy over the period 1957-2009.

Alpine precipitation dataset. The "Alpine Precipitation Analyses from High-Resolution Rain-Gauge Observations" represent a comprehensive set of mesoscale gridded daily precipitation (in mm) for the period 1971-1998 with resolution of 0.25° x 0.17° (see `http://www.map.meteoswiss.ch/map-doc/rr_clim.htm`). This dataset was created by the Swiss Federal Institute of Technology Zuerich (ETH) and makes use of an unique dataset of rain gauge observations from the high-resolution networks of all Alpine countries. These networks constitute one of the densest meteorological observing systems over complex topography world-wide (figure 13).

E-OBS gridded dataset. It is a European daily high-resolution (0.25° x 0.25°) gridded data set (figure 14) for precipitation, minimum, maximum, and mean surface temperature and sea level pressure (see `http://eca.knmi.nl/download/ensembles/ensembles.php`) for the period 1950-2010. This dataset has been designed to provide the best estimate of grid box averages rather than point values to enable direct comparison with RCMs ([29]).

ARCIS. The project ARCIS (Climatological Archive for Northern Italy) is currently being carried out by the Regional and Provincial Environmental Agencies (ARPA and APPA) and by the Operational Meteorological Centres of Civil Protection Agencies of Northern Italy (see `http://www.arcis.it/E_index.shtm`). ARCIS objective is to build a data-base for the daily climatological data of precipitation and minimum and maximum temperature for the period from 1961 to 2005 in Northern Italy (figure 15). This dataset will be used once it will be available.

ARPA Emilia Romagna dataset. ARPA Emilia Romagna dataset for rainfall includes more than 1000 raingauges (figure 16), some of them starting from 1916. The majority of data are available since 1951. Dataset for minimum and maximum temperature, instead, includes about 600 measurement stations (figure 17) with observations since 1987.
Finally, dataset for river water level/flow

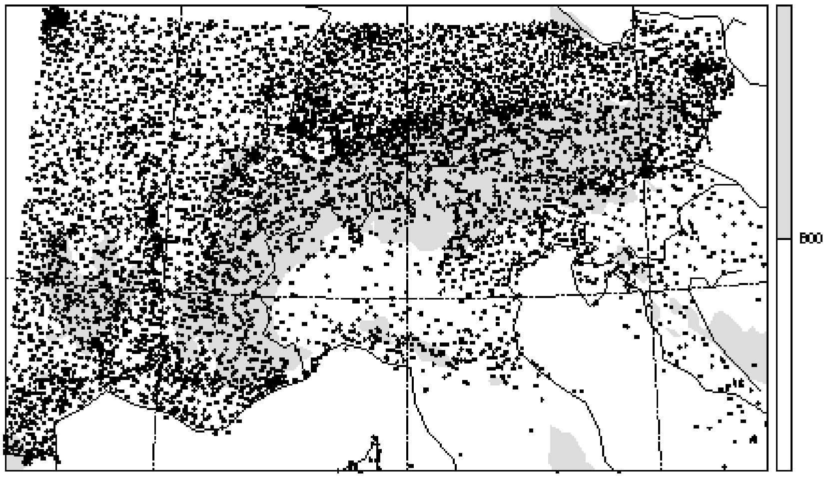
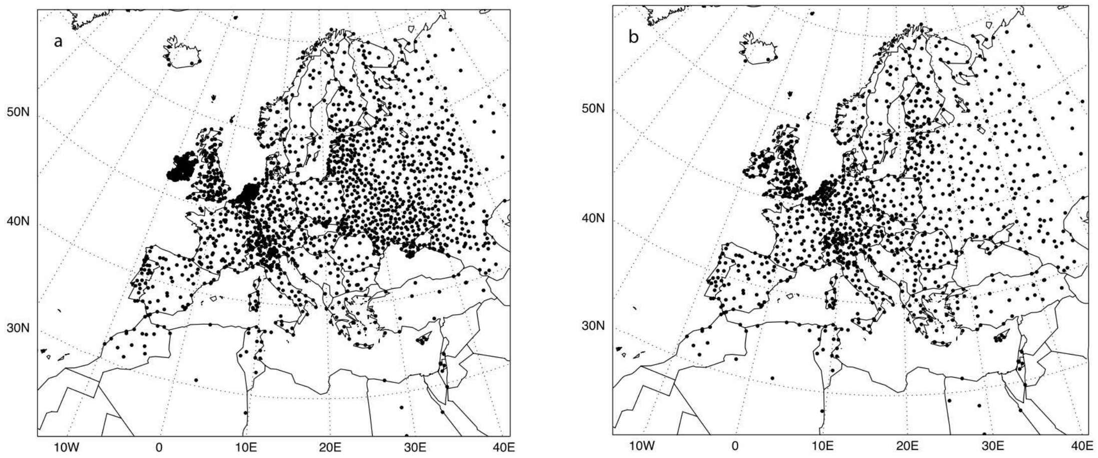
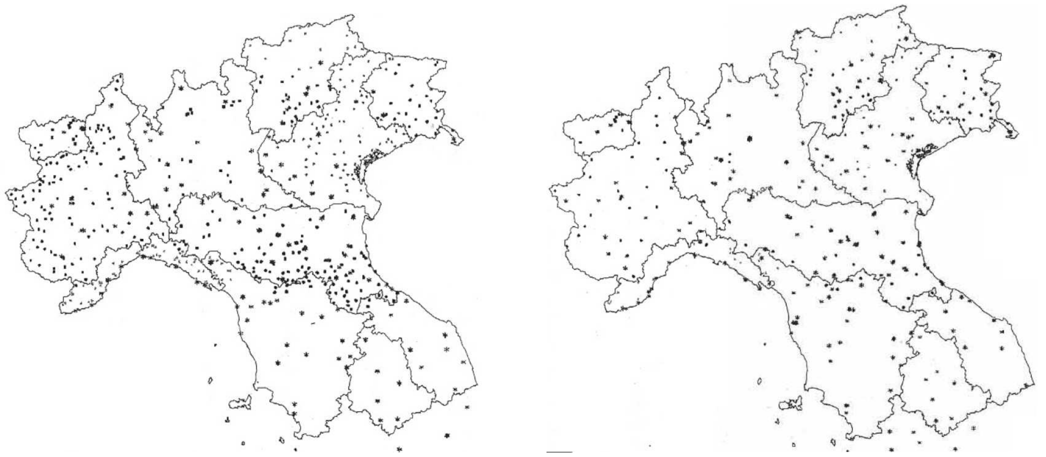


Figure 13:
The diagram depicts the station coverage of the “Alpine Precipitation Analyses from High-Resolution Rain-Gauge Observations”.The distribution of stations is fairly balanced over the northern and western portions of the analysis domain, while the coverage is less dense and less homogeneous for the southern region (northern Italy).



(a) Precipitation (b) Temperature

Figure 14:
The complete gridding region, showing the station network for (a) precipitation and (b) temperature of the E-OBS dataset.



(a) Precipitation

(b) Temperature

Figure 15:
Station network for (a) precipitation and (b) temperature of the ARCIS dataset.

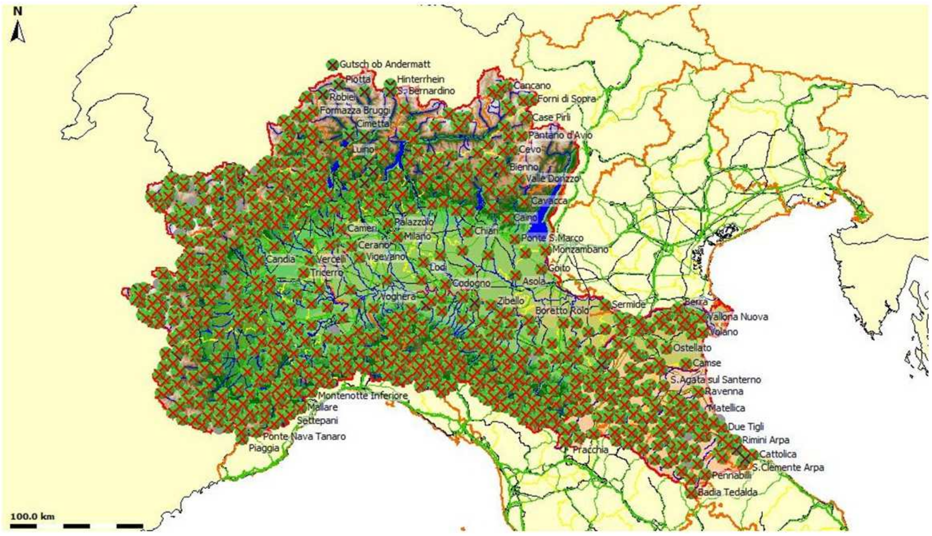


Figure 16:
Location of available raingauges.

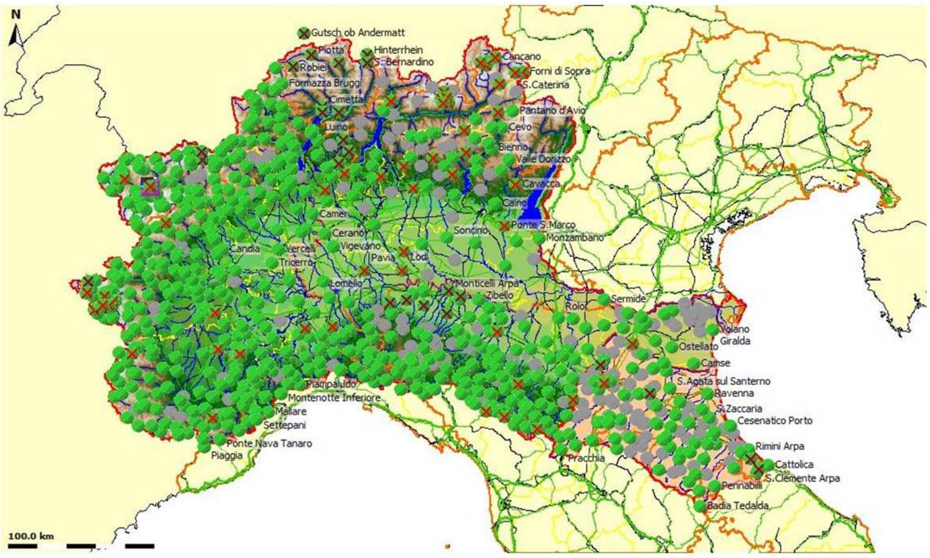


Figure 17:
Location of the available temperature stations.

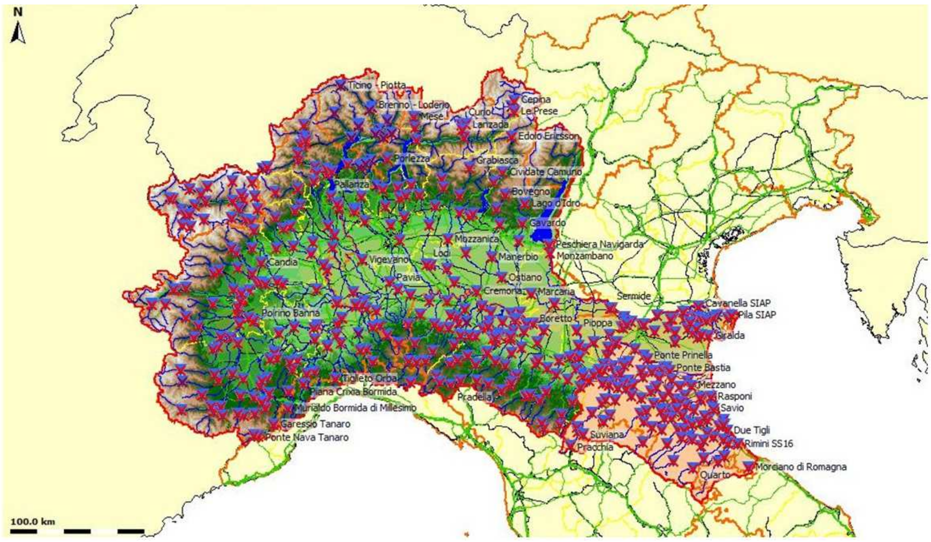


Figure 18:
Location of the available flow level station.

discharge includes about 250 measurement stations (figure 18) with observations since 1923 for the Po river. For the most of the stations data are available only for the last 10-15 years.
The data acquisition frequency is hourly and the dataset is daily updated.

Datasets for landslides simulation model. The available data for the three case histories referred in are:

- for Orvieto site, meteorological data with daily resolution (minimum and maximum temperature and rainfall heights) have been measured by the station of the State Hydrographic Survey, the station has been working continuously since 1920 except for some stops in the 1940s and the late 1970s. Pore water pressure values (through Casagrande type piezometers) and displacements (through inclinometers) have been measuring since 1982 in a monitoring station located in the area involved in the 1900 Porta Cassia slide. In more recent times, additional measurement stations were installed (2 in 1996 in the same area of the 1900 Porta Cassia slide and 4 in 1998 three in the slide area and the fourth outside the slide area). All the monitoring stations are equipped with Casagrande-type piezometers for pore water pressure measurements in stiff clays and clayey debris; four of them allow also measurements within the softened clay layer.
- for Cervinara site, since 2002 the slope involved in the 1999 flowslide has been monitoring. Five tensiometer stations allow to measure the negative water pressures at different depths within the soil profile (top soil, intermediate and deep layers of volcanic ashes) while a tipping-bucket rain-gauge (sensitivity 0.2 mm) records the rainfall heights with high temporal resolution.
- for Fosso San Martino site, published in situ data (Bertini et al., 1984) regarding this landslide refer to a 6-year monitoring period (from 1980 to 1985); pore water pressure values, measured by elctropneumatic piezometric cells, are available for 12 monitoring stations located in the area affected by slow movements while six inclinometers stations return displacements data. Therefore, an Hellman Type pluviometer (sensitivity 0.1 mm) recorded during the same time span the rainfall depths.

CLIMATE SIMULATIONS

In the GEMINA wp 6.2.2 “high resolution climate simulations” different climate simulations with COSMO CLM will be provided. The output of these simulations will be the input for MOS statistical downscaling and then for hydrogeological impact models. Within the wp 6.2.2. will be generated:

- new high-resolution climate scenarios for the twenty-first century;
- evaluation of the present climate;
- characterization of the COSMO CLM simulation error.

As reported in the following table (figure 20), at first, will be evaluated the climatic regimes for the period 1971-2000 in two different areas:

- Mediterranean area (figure 21), with a resolution of 14 km;
- Italian area, with a resolution of 8 km, with two different configuration: Italy (figure 22) and Italy_part (figure 23).

Both simulations will use meteorological reanalysis ERA40, provided by ECMWF, as global forcing. Downstream the simulations of the future climate, the twenty-first century, will be carried out based on two different IPCC scenarios: RCP4.5 and RCP8.5. RCPs are Representative Concentration Pathways and they specify radiative forcing through the end of the 21st century. RCP4.5 is a stabilization scenario where total radiative forcing is stabilized at 4.5 W/m^2 before 2100. Under RCP8.5 scenario, instead, radiative forcing is still increasing in 2100, and emissions are still high (see figure 19). Two different areas will be simulated:

- Mediterranean area (with a resolution of 14 km) and
- Italian area (with a resolution of 8 km).

These simulations are provided by the regional climatological model COSMO-CLM. The initial and boundary conditions to the regional model will be provided by the global climate model CMCC_MED [4]; [51].

TEST CASES

CASE STUDY FOR FLOODS AND DROUGHTS SIMULATION MODELS

The Po is the longest river in Italy with a length of 652 km from its source in Cottian Alps (at Pian del Re) to its mouth in the Adriatic Sea, in the north of Ravenna and with an average discharge of 1540 m^3/s is the largest Italian river. The Po river basin is the widest in Italy and it covers an area of about 71000 km^2 including six regions: Lombardia, Piemonte, Liguria, Emilia-Romagna, Veneto, Valle d'Aosta and the autonomous province of Trento and about 3000 km^2 in Switzerland and France, see figure 24. In the context of the Italian Law 183/1989, the Po basin is classified as being of national importance. In terms of orography, it is possible to identify the following areas: the ranges of the Ligurian, Maritime, Cottian, Graian and Pennine Alps encircling the basin to the west, the Apennines to the south, the high plateau including the morainal strip and the large fluvial cones, and the plain itself. Mountains cover about one half of the area. The Po tributaries have different characteristics according to their alpine or apennine origin. The alpine tributaries regime is ruled by snow accumulation-melting processes and are characterised by broadly meandering courses over the low plains. The apennine tributaries are mainly fed by rainfall. The Po basin is affected by landslides and erosive phenomena depending on local climate, lithological and structural conditions. Overexploitation of the aquifers and the extraction of gaseous hydrocarbons caused subsidence phenomena in the inhabited area and the watercourses in the plain [10]. During the last centuries, flooding events, due to extreme meteorological conditions, of the Po or of its tributaries have caused numerous natural catastrophes, two of them, characterized by extraordinary large scale, occurred in the last 10 years. Simulations will be aimed to evaluate the effects of climate change on droughts frequency, duration and severity; and on floods frequency and peak. A set of simulations will be performed feeding with the climate scenarios provided by RCM and MOS downscaling activities the hydrological-hydraulic chains implemented in FEWS. A comparison between floods and droughts statistics from observed data (current climate) and scenarios generated data (climate

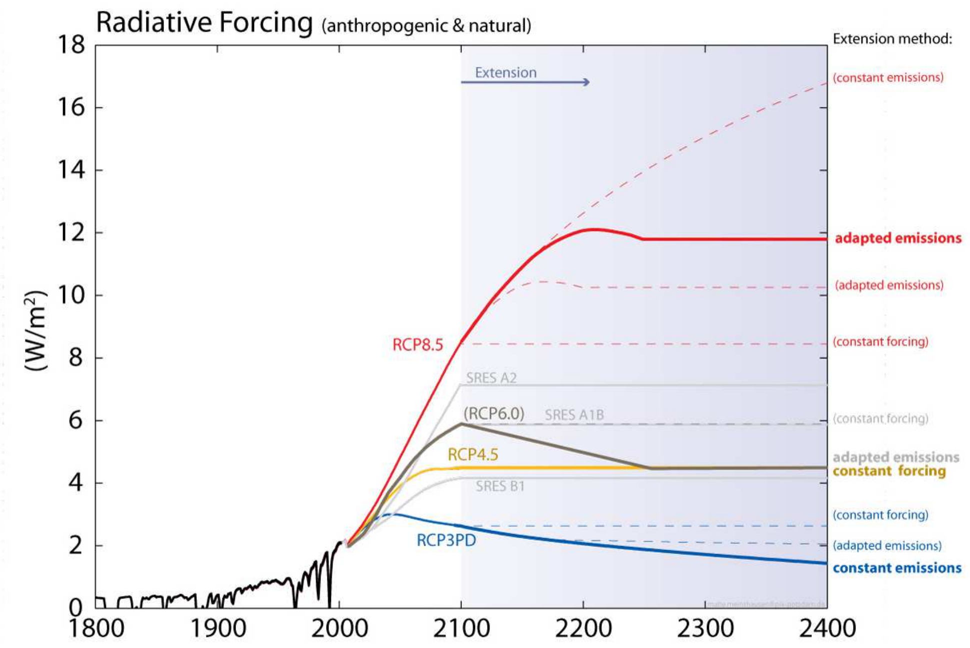


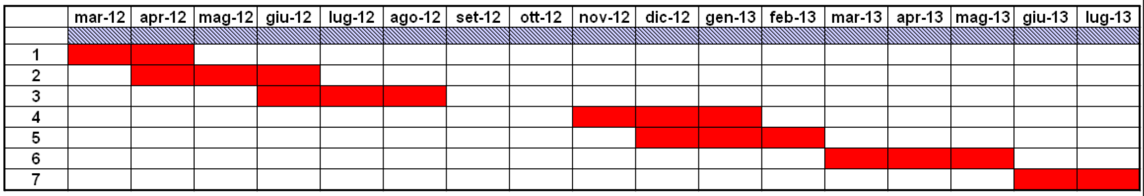
Figure 19:
Schematic illustration of radiative forcing scenarios.

change) will allow to qualify and quantify the climate change effects on flood and drought risks with respect to the scenarios considered.

CASE STUDY FOR LANDSLIDES SIMULATION MODEL

Three case studies are selected to evaluate the climate changes effects on slope stability in the Mediterranean area:

Orvieto located in Central Italy, Umbria Region, 105 km north of Rome [58]. The slope extends over 600 metres with a slope angle equal to about 12 degrees. From the bottom to the soil surface, within the slope, it is possible to recognize an in situ formation of overconsolidated clays; at depth, it is stiff and intact while, proceeding upwards, the material softens and significant fissures appear. The clay formation is overlain by a slide debris cover. It is formed in the shallower part by pyroclastic and clayey material while the first component results absent in the deepest part of the cover. The softened clay shows a maximum depth of 23 m while, for the debris cover, it is 17.5 m. Three kinds of movements are identifiable: slow translational movements within the softened clay layer; slope failures characterized by progressive dynamics due to man-made changes in slope geometry and hydrological system; very slow (according the Cruden-Varnes classification) translational movements at the contact between softened clay layer and debris cover. The first and the third type of slope movements appear strongly related to the piezometric levels and hence to the



	mar-12	apr-12	mag-12	giu-12	lug-12	ago-12	set-12	ott-12	nov-12	dic-12	gen-13	feb-13	mar-13	apr-13	mag-13	giu-13	lug-13
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1	🟥	🟥															
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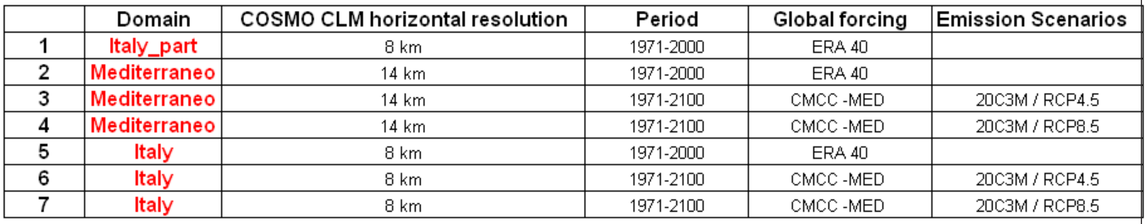
(a)



	Domain	COSMO CLM horizontal resolution	Period	Global forcing	Emission Scenarios
1	Italy_part	8 km	1971-2000	ERA 40	
2	Mediterraneo	14 km	1971-2000	ERA 40	
3	Mediterraneo	14 km	1971-2100	CMCC -MED	20C3M / RCP4.5
4	Mediterraneo	14 km	1971-2100	CMCC -MED	20C3M / RCP8.5
5	Italy	8 km	1971-2000	ERA 40	
6	Italy	8 km	1971-2100	CMCC -MED	20C3M / RCP4.5
7	Italy	8 km	1971-2100	CMCC -MED	20C3M / RCP8.5

(b)

Figure 20:
Scheduled climate simulations within GEMINA wp 6.2.2 (a) and characteristics of runs (b). The 20C3M scenario use historical greenhouse gasses concentrations through the 20th century.

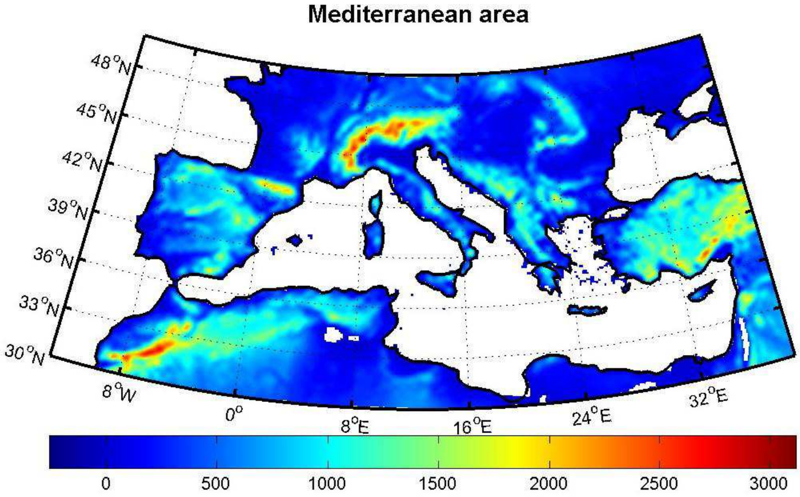


Figure 21:
Domain of simulations on Mediterranean area and orografy.

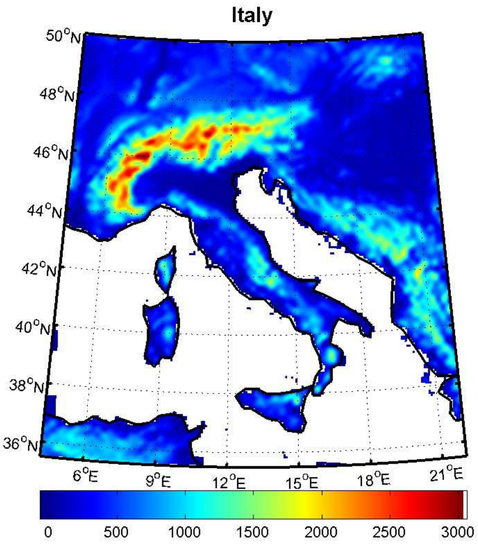


Figure 22:
Domain of simulations on Italian area and orografy.

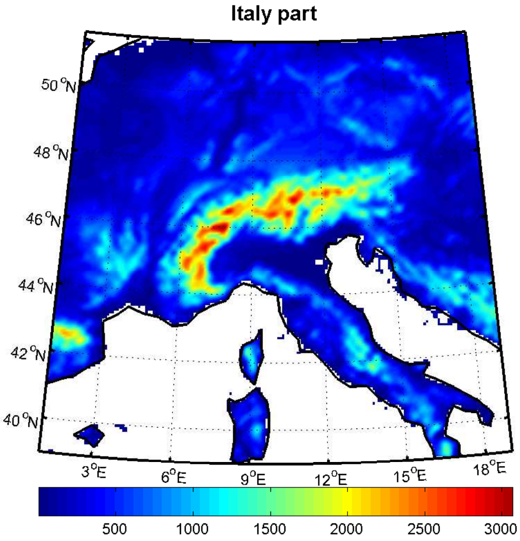


Figure 23:
Domain of simulation on Italian area (Italy_part) and orografy.

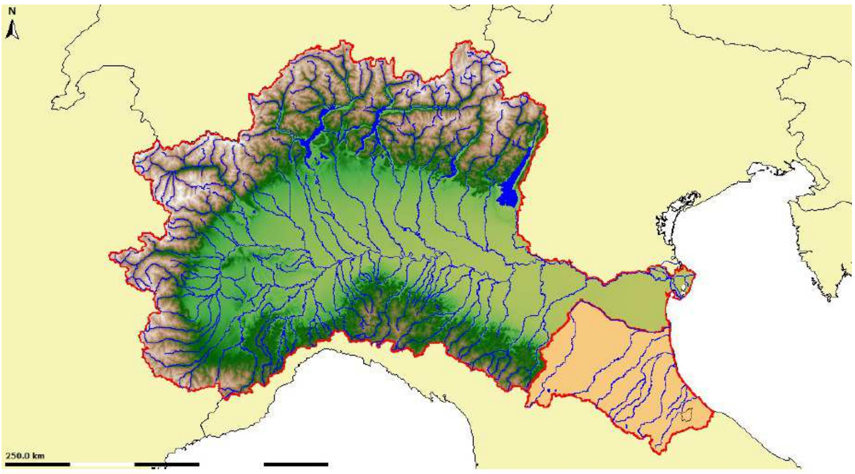


Figure 24:
Po river basin in FEWS

rainfalls regime (cumulated values over the entire wet season, October-April).

Cervinara located in the South-Italy at north-east of Naples [17]. The slope object of analysis shows a maximum slope angle of 40°; above a fractured limestone bedrock, is recognizable a pyroclastic cover with average thickness of about 2.4 m. Proceeding downwards, for what concern the pyroclastic cover, the following layers are identifiable: top soil cover formed by remoulded volcanic ashes (thickness about 60 cm), an upper layer (20 cm) of coarse pumices; a layer (100 cm) of volcanic ashes; a lens (20 cm) of finer pumices mixed with ash; a bottom layer (40 cm) of weathered ash. On December 1999, in the area several rainfall-induced landslides occurred; the movements were characterized by very high velocities; during the post failure one of these had a post failure evolution in flowslide . For the Cervinara pyroclastic soils, the high saturated permeability values and the simultaneous condition of partial saturation make significant, because a landslide is triggered, recent and antecedent precipitations; for similar soils, the effective meteorological window for antecedent conditions was estimated equal to 4 months [43].

Fosso san Martino located in the Central-Italy in Abruzzo Region [6]. The drainage basin of San Martino stream extends over 2.6 km^2. For what concern the stratigraphy of the slopes forming the valley sides, their soil profile can be reduced to 4 overlying layers; from bottom to the top, are recognizable: an overconsolidated very stiff saturated marly clay (clayey silt) forming the bedrock, a weathered band of the bedrock (it appears heavily softened and destructered in the upper area which thickness is about 3 meters); an overconsolidated (due to erosion processes) clayey silty colluvial cover and a oxidized and highly fissured thin crust characterized by very high hydraulic conductivity. In this case, the instability phenomena can be classified as very slow movements (cm/year); the colluvial cover moves a rigid body while the displacements are concentrated within the weathered clay stratum. As for the Orvieto case-history, the displacements result strictly related to the piezometric levels; in turn, due to very low hydraulic conductivity of the involved soils, they are sensitive to cumulated rainfalls values over the entire wet season.

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INTRODUCTION

This report is aimed to define the general objectives of GEMINA wp 6.2.17 “Analysis of the hydrogeological risk related to climate change” and to describe the work plan to achieve these objectives. This document defines the architecture of the simulation system, the main features of the tools adopted and the strategy for the verification of the integrated system. The main goal of the wp 6.2.17 is to provide an evaluation, qualitative and quantitative, of the hydrogeological risk in some typical contexts of the Mediterranean area. In particular, the focus will be on landslides, floods and droughts risks. The research activity will also analyse the role of the uncertainties of the complex relationship between “climate change and hydrogeology” at regional scale on risks evaluation.

MOTIVATION

The warming of the climate system in recent decades is evident from observations showing an increase in global average air and ocean temperatures, a widespread melting of snow and ice, and a global rising of sea level. Several studies show that most of the observed increase in global temperatures since the mid-20th century is related to the observed increase in anthropogenic greenhouse gas concentrations. This climate warming may cause an intensification of the water cycle, which is strongly dependent on the atmospheric temperature, and may determine a change in many components of the hydrological cycle such as: precipitation patterns, intensity and extremes; atmospheric water vapour; evapotranspiration; soil moisture and runoff. However, it is difficult to identify long-term trends for the components of hydrological systems as they are often masked by their significant natural variability, on time-scales from interannual to decadal. This variability, together with limitations in the spatial and temporal coverage of monitoring networks, can explain the current substantial uncertainty in trends identification of hydrological variables [3]. Many hydrological simulations predict a change in the hydrological cycle, but these projections are typically affected by several sources of uncertainty, in fact, in addition to the uncertainty of the considered hydrological model, there is also the uncertainty related to the fact that these models use, as input, the results of climate simulations, which in turn are characterized by a certain uncertainty. A further problem is related to the different spatial scales of climate models and hydrological models. A number of methods have been used to handle these scale differences, ranging from the simple interpolation of climate model results to dynamic or statistical downscaling methods, but all these methods introduce other uncertainties into the projections [3]. This work is aimed to evaluate variations in the hydrogeological risks (in particular floods and landslides) due to climate change and the main goal of this research activity is to correctly model the link between hydrological and climate models. In particular the focus will be on the Mediterranean area. In this region, according to Christensen et al. (2007) [14], annual mean temperatures will rise more than the global average and the warming is likely to be largest in summer (figure 1). Moreover, in the Mediterranean area the majority of the models foresee summers characterised by an increase, in frequency, of extreme daily precipitation despite a decrease in average precipitation. Thus this tendency can lead to longer dry periods, increasing the risks of droughts, interrupted by extreme intense precipitation, enhancing the risk of floods [3]. This scenario of hydrologic and climatic variability is also associated with an increase in the vulnerability of the territory. This increased environmental vulnerability is mainly related to anthropogenic effects and is caused by exces-