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# Performance evaluation of integrated system to model the climate change impacts on hydro-geological hazard

*By* **Guido Rianna**
Impacts on Soil and Coasts Division, CMCC-Capua
*guido.rianna@cmcc.it*

**Renata Vezzoli**
Impacts on Soil and Coasts Division, CMCC-Capua
*renata.vezzoli@cmcc.it*

**Nicola Ciro Zollo**
Impacts on Soil and Coasts Division, CMCC-Capua
*nicola.zollo@cmcc.it*

*and* **Paola Mercogliano**
Meteo System & Instrumentation Laboratory, CIRA-Capua Impacts on Soil and Coasts Division, CMCC-Capua
*p.mercogliano@cira.it*

**SUMMARY** This paper provides the main results about the validation of the modeling chain used to estimate the variation in geo-hydrological hazard induced by Climate Changes (CC); it represents one of the milestone for year 2014 of GEMINA project within the work package A.2.17. In particular, the work package A.2.17 "Analysis of geological risk related to climate change" has as main goal the analysis of the impacts of Climate Changes on occurrence and magnitude of landslides, floods and low flows conditions on some specific contexts of the Mediterranean area. We show that the integrated system combines, in adequate way, high resolution regional climate scenarios, models of impacts and statistical downscaling techniques. In addition, this document contains a description of test cases on which the integrated system has been verified.

**Keywords:** dynamical downscaling, quantile mapping, floods, Po river basin, pyroclastic covers, flowslides

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## 1. INTRODUCTION

The report presents several findings related to the validation of the climate/impact modeling chain developed within the WP A.2.17 "Analysis of the hydro-geological risk related to climate change" of GEMINA project. By way of example, in such research paper, only main results about the validation of modeling chain, for landslides and hydrological hazards, in two very different geomorphological contexts [respectively, Cervinara (South Italy) for landslides and Po river basin for hydrological hazard] are displayed; however, as discussed in Conclusions, they are part of a much broader research carried out, in these years, by Capua unit of ISC-CMCC Division. Nonetheless, even from these ones only, it emerges how the developed modeling chain is enough flexible to be used for different hazards characterized by significantly different extension (point/slope scale for landslides, watershed for hydrological hazard).

## 2. MOTIVATION

For the next century, the majority of the climate models agree in assessing, under the effect of CC, an increase in extreme precipitation events frequency and almost unchanged intensity, and, in average, a decrease in the total precipitation over the Mediterranean area [8]. The expected partitioning of precipitation enhances the possibility of alternation between long dry and short extremely wet periods [3], causing generally an increase in the geo-hydrological hazards. In last years, several researches have investigated the potential effects of CC on geo-hydrological hazards in Italian Peninsula that is prone to them; for example, Coppola et al. (2014,[12]) Vezzoli et al. (2013, 2014 [57, 55]) focus on the Po river discharges, Camici et al. (2013, [7]) on the flood frequency of Tiber river, Gunawardhana and Kazama (2012, [22]) investigate the water availability and the low-flow of the Tagliamento River; for what concern landslide phenomena, for example, Comegna et al. (2012,[10]) and Rianna et al. (2013, 2014 [38, 39]) assess the effects of CC on slow movements on different clayey slopes respectively located in Southern (Costa della Gaveta) and Central (Orvieto) Italy while Damiano and Mercogliano (2012, [13]) hypothesize the different impact of CC on shallow fast landslides through the investigation of pyroclastic covers in Campania Region. The assessment of the magnitude of climate changes impacts on the geo-hydrological hazard is usually performed coupling climate projections with impacts models able to capture the main characteristics of phenomena of interest. Because of current constrains of physically based climate models (GCM and RCM) mostly related to current achievable horizontal resolutions, for a proper reproduction of weather forcing, several studies have pointed out the improvements associated to adoption of statistical approaches (SA) in cascade to GCM/RCM outputs while emphasizing the added value produced by regional climate simulations in comparison to short-circuited GCM/SA results [24, 37]. Starting from such findings, in the simulation chain (Fig.1) developed by ISC division (Capua unit), the Global Climate Model (GCM), CMCC-CM, is dynamically downscaled through the regional climate model (RCM),COSMO-CLM; then, the so obtained weather forcing are processed by Bias Correction Statistical Approach (BC) in order to provide reliable climate datasets constituting the input for impact models. Finally, according the considered hazard, impact tools can provide estimates of occurrence and magnitude of investigated phenomena (and their variation under the effect of CC). For a proper assessment, two different moments of analysis have to be taken into account. First, a simulation of a past/present period is performed to calibrate/validate the different elements of simulation chain against observations, then, simulations of future climate, based on emission scenarios supplied by socio-economic approaches, can be performed to estimate future trends of weather variables and their impacts Accordingly, this research paper is explicitly focused on the validation of the modeling chain; and it is so organized: first the test areas are described (Section 3); then some elements about adopted climate models (Section 4) and used BC approaches (Section 4.3) are given; then impact models are introduced (Section 5); finally, main results about validation are provided (Section 6) and Conclusions are drawn (Section 7).

## 3. TEST CASES

### 3.1 LANDSLIDE: CERVINARA TEST CASE

Cervinara slope is located 50 km North-East to Naples; on December, 16, 1999, it has been affected by a rapid flowslide (Fig.2) triggered by a total precipitation of 320 mm in about 50 h, causing huge damage and five casualties in surrounding areas. In the area, highly fractured calcareous mountains are maintained by loose unsaturated pyroclastic covers hardly thicker than 2-3 m. These morphological configurations are widespread in the Campania Region, as result of the activity of some volcanoes including Somma-Vesuvius. Thanks to the beneficial effect of suction, typically steep silty-sandy covers are stable. However, as explained through back-analysis of numerous cases in similar soils in Campania Region [34, 17], coupled effect of particularly wet periods (during which infiltration contributions largely exceed evapotranspiration losses) followed by heavy rainfall events on 1-2 days scale can induce suction (and related apparent cohesion) decreases such as to trigger landslide phenomena. On these phenomena, the potential effect of CC is currently a challenging issue: indeed, while temperature increase could lead to increase in evapotranspiration losses (supporting slope stability), the variation in expected rainfall patterns (increase of cumulative values for event and of precipitation interarrival period) could have totally different effects on actual infiltrated values and then soil water contents.

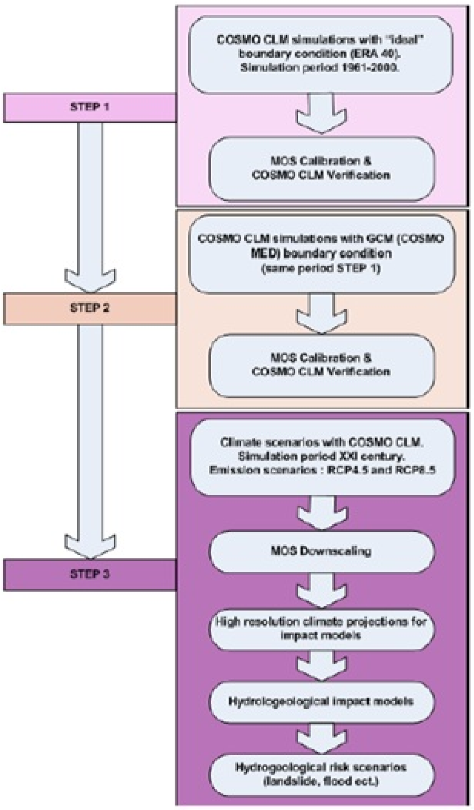

Figure 1:
Structure of the integrated system as proposed in GEMINA [61].

### 3.2 FLOODS AND LOW FLOW HAZARDS: PO RIVER TEST CASE

Po river 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

Figure 2:
Cervinara test case.

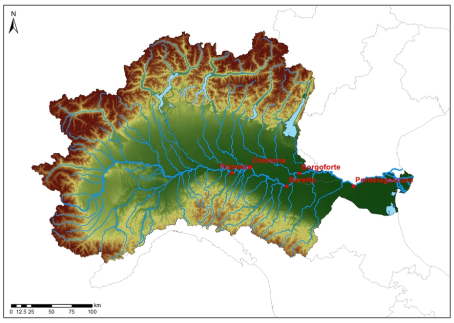

Figure 3:
Po basin: hydrological network and main closure sections.

the north of Ravenna and is the largest Italian river with an average discharge of 1540 m$^3$/s. 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 Fig.3. In the context of the Italian Law 183/1989, the Po basin is classified as being of national importance. The orography of the basin is quite complex since it is bounded by Alps, Apennines with the Po valley between them.

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, [60] and signal of changes in precipitation and temperature are present in climate observations [50, 9, 48]. Climate data analysis show, on Po river basin, an increase in annual maximum precipitation with a trend of about 0.5°C/decade since 1960. The signal is detectable in all the seasons [50], and, in particular in summer where maximum temperature are higher than the reference climate [48]. Change in precipitation, since 1980, are less evident than those in temperature, in average, there the precipitation event are more intense but less frequent, as results the annual total precipitation is reduced of 20%. At seasonal scale, the highest reduction rate are found in spring and summer (up to 50%) while autumnal precipitation are almost unvaried; in winter, snowfalls reduces as well [48]. [9] analyse time series of daily cumulated precipitation and of daily minimum and maximum temperatures in the period 1952-2002 from Piemonte and in the Valle d'Aosta regions (north-western Italy) finding a significant increase of about 1 °C on average temperatures, in particular, for maximum daily temperatures in winter and summer months; while for precipitation any significant trend is identified.

## 4. CLIMATE

### 4.1 THE GLOBAL CLIMATE MODEL: CMCC-CM

The global climate model CMCC-CM is a coupled atmosphere-ocean general circulation model, which has been implemented and developed in the framework of the European project CIRCE [20]: the atmospheric model component is ECHAM5 [40] with a T159 horizontal resolution (0.75°), while the global ocean component is OPA 8.2, in its ORCA2 global configuration, at a horizontal resolution of 2°.

ORCA2 also includes the Louvain-La-Neuve (LIM) model for the dynamics and thermodynamics of sea-ice. A performance assessment of CMCC-CM in simulating the observed Sea Surface Temperature and precipitation is reported in [43], while a comparison with other state-of-art GCMs available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) is presented in different other works e.g. [15].

## 4.2 THE REGIONAL CLIMATE MODEL: COSMO-CLM

A detailed description of the regional climate model COSMO-CLM is reported in [61, 31]. COSMO-CLM is the climate version of COSMO-LM weather model [45], developed by the CLM Community. It is a high resolution (less than 50 km) non-hydrostatic RCM able to explicitly capture small scale severe weather events and an improved representation of sub grid scale physical processes, such as clouds, aerosols, orography, land and vegetation properties. It has been already used in the framework of several European projects, such as PRUDENCE [8] and CORDEX [18], highlighting its good capability in reproducing the mean climate features of the areas under study, with a similar range of accuracy with respect to the other RCMs adopted. More details concerning the description of the main characteristics of COSMO-CLM and the configuration used to perform the simulations presented in this work are reported in [62, 32]. Climate simulations have been carried out at 0.0715° (about 8 km) of horizontal resolution using as initial and boundary conditions: (a) ERA-Interim Reanalysis [14] over the 1979-2010 period, characterized by a horizontal resolution of about 0.70°, about 79 km, to assess the performances of the regional climate model when driven by ”perfect” boundary conditions; (b) global climate model CMCC-CM (0.75°, about 85 km) to assess the uncertainties of te GCM/RCM couple before use it to climate change studies. In this case, the simulation period covers 1971-2005, an extension to 2010 of the simulation is obtained forcing the GCM with the RCP4.5 scenario. The validation over a 30 year long period of the RCM outputs used in this study, precipitation and 2 meter mean temperature, both driven by climate reanalysis and by the GCM, is available in [5, 6]. Numerical simulations over the whole Italian domain (Fig.4) were performed on a cluster of 30 IBM P575 nodes, installed at CMCC (Italy); each node has 32 Power6 (4.7GHz) cores, amounting to a total of 960 cores and an aggregate peak power of 18 TFlops. The elapsed time to simulate one climatological year using 512 cores is about 24 hours.

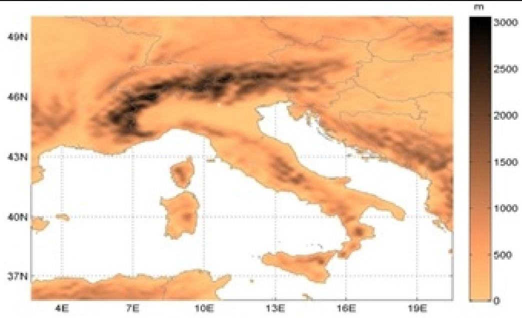

Figure 4:
COSMO-CLM domain and orography for the configuration with horizontal resolution of 8 km.

## 4.3 STATISTICAL BIAS CORRECTION

In order to reduce the bias characterizing the simulation carried out by using as driving data the output of numerical climate models, different bias correction techniques have been tested [53, 52, 51, 63, 36, 64]. The quantile mapping bias correction, that potentially corrects all the moments of the distribution function of climate variables, outperforms the other methodologies considered [46, 47, 28]. The quantile mapping technique provides an estimate of the corrected value ($X^*$) of the variable as a function of its raw value $X$ using a transfer function calculated forcing the equality between the cumulative distribution functions of the observed and simulated variable [35]:

$$F_{RCM}(X_{RCM}) = F_{OBS}(X_{OBS}) \tag{1}$$

where $F_{RCM}$ and $F_{OBS}$ are, respectively, the CDF of the simulated and observed data. So the corrected output is obtained using the following equation:

$$X^*(d) = {F_{OBS}}^{-1}(F_{RCM}(X_{RCM}(d))) \tag{2}$$

In present work, the bias correction has been applied to daily data using a different set of parameters for each month. Different approaches have been adopted for Po river basin and Cervinara; in the first case, for precipitation a Gamma distribution has been assumed for both observed and simulated data. This distribution, dependent only on two parameters, is commonly used for representing the PDF of precipitation and several studies have proved that it is effective for modelling rainfall data (see e.g. [23, 47]). For temperature, instead, the Gaussian distribution has been used, that is usually assumed to fit best temperature distribution [47]. The results of the application of quantile mapping to precipitation and 2 meter mean temperature to the simulations are presented and discussed in [53, 64] and they prove that the bias correction significantly improves the statistical similarity between observed and simulated (bias corrected) climate fields.

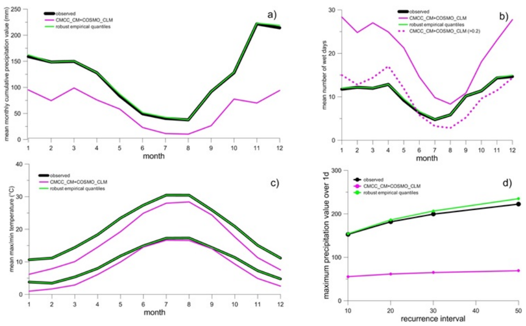

Figure 5:
a) Monthly cumulative values. b) Mean monthly number of wet days. c) Maximum and minimum temperature. d) Recurrence interval for maximum yearly values of daily precipitation (GEV statistical distribution). Black line: observed values; magenta line: simulated through climate models GCM/RCM; green line: simulated values through bias corrected (BC) climate models GCM/RCM.

Concerning Cervinara case study, an empirical quantile mapping approach (also known as RQuant; [21] was preferred; indeed, from a wide comparison with several other quantile mapping approaches, it showed much greater capability to reproduce weather forcing on current period (both in terms of average and extreme values) representing the “minimum requirement” for a climate simulation chain [59]. However, for application to future climate, the empirical approaches require additional assumptions to infer values beyond the observed range, while methods based on continuous distribution function may be directly applied. For Cervinara test case a constant correction is implemented following [4]. An overview about the improvements achieved through BC approach is reported in Fig.5 where cumulative precipitation values (a), wet days (b), maximum and minimum temperature (c) (on monthly scale) and estimated recurrence interval of yearly maximum 1 day precipitation (through GEV fitting distribution) are displayed for observed or provided by raw/BC RCMs values. For control period 1981-2010, the nearest available station is located in San Martino Valle Caudina town (SMVC) located less than 5 km from investigated slope and characterized by similar orographic features (altitude and exposure). Finally, it worth to recall that, due to aliasing effects and parameterizations associated to advection dynamics, the effective resolution of RCM do not correspond to nominal resolution (in this case, about equal to 8 km). Similarly to Skamarock (2004, [44]) and Bierdel et al., (2012, [2]), Kapper et al. (2010, [26]) adopting as RCM COSMO-CLM propose effective resolution values ranging from $3\Delta x$ to $7\Delta x$, depending on the investigated parameter and its model representation. Based on such findings, following also [30], reference RCM precipitation/temperature values have been supplied as average modeled value on 5x5 grid points surrounding the investigated slope. Further investigations on subsequent inflation problems associated to such assumption [29] are still in progress.

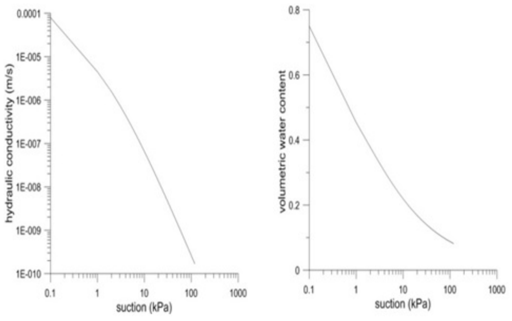

Figure 6:
Hydraulic properties of the cover [19].

## 5. IMPACT TOOLS

### 5.1 LANDSLIDE HAZARD

The response of the groundwater regime to atmospheric forcings has been investigated via 1D numerical simulations assuming, on the basis of field investigations, an homogeneous cover thickness of 1.9 m. To this aim, the adopted tool is SEEP/W FEM code [27] solving in 2D conditions the Richards' equation (1951) that regulates, in unsaturated soils, under isothermal conditions, soil water fluxes and water contents. However, to roughly estimate losses associated to atmospheric demand, at the top the net flux has been computed as the algebraic sum of daily precipitation and actual evaporation obtained by FAO dual approach [1]. Since only temperature values were available, the empirical relationships proposed by FAO guidelines to retrieve the other forcing factors governing evapotranspiration processes are employed. Natural grassland has been assumed as land cover in situ. At the cover bottom, based on the monitoring results, an outgoing flow has been imposed as function of local suction values. Although this condition allows satisfactorily returning the observed suction trends, a deep analysis about the factors by which the flux depends at the bottom has still been carrying out [11]. Soil hydraulic properties, reported in Fig.6 in term of hydraulic conductivity and soil-water characteristic curve, are retrieved by [19] according the main findings of monitoring and laboratory tests. Then, since pyroclastic covers can be assumed cohesionless, a landslide might take place when suction at the base of the cover (e.g. at 1.9 m) practically vanishes. In fact, the angle of the slope (40°), that has the features of an infinite slope, is very close to the soil friction angle (38-39°). Estimated and observed suction evolutions at depths of 0.6 and 1.7 m in time interval 2011-2012 are then shown in Fig.7. The first year has been used for parameter calibration and the second one for validation. The available period for assessing the predictive capabilities of slope hydrological component of modeling chain is rather limited; however, because of the significant time and resource effort required for an effective slope monitoring, often prerogative of individual research teams, such condition is unfortunately usual in Italy. In this regard, the long slope monitoring started in 1982 and still going on Northern clayey slopes of Orvieto af-

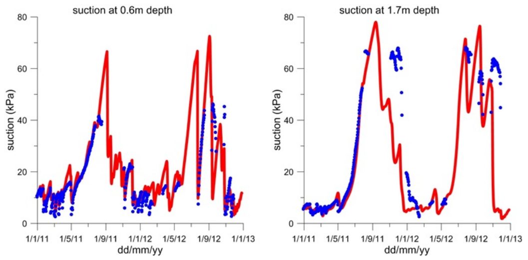

Figure 7:
Observed (blue dots) and estimated suction (continuous red line)in the calibration time window 2011-2012.

fected by slow movements is a unique example. On this slope, seven monitoring stations provide pore water pressures and slope displacements; with a consistent dataset of daily weather observations (since 1923) supplied by a weather station located very close to investigated slopes, such measurements have been used, within GEMINA project, to assess ongoing and future effect of CC on slow slope movements [38, 39, 63]. Analysis provide reliable estimates especially during the wet season while, during the dry season and fall, an higher bias between observed and calculated values arises (in special way, during the autumnal suction decrease phase). These discrepancies can be mainly induced to the adopted simplifying assumptions regarding both the flow direction (1D) and the boundary conditions at the uppermost and lowermost interfaces but, at the same time, they can be assumed totally bearable considering the high uncertainties related to the whole simulation chain.

## 5.2 FLOOD AND LOW FLOW HAZARD

To study the climate change impacts on the hydrological cycle of Po river, the integrated system has been specialised as in Fig.8, coupling the climate model with a physically based and spatially distributed hydrological model (TOPKAPI) and a basin water balance (RIBASIM) running at daily time step. Note that in [58, 55] a different version of the integrated system has been presented, i.e. the bias correction was applied to discharges instead of to climate inputs. The TOPKAPI (TOPographic Kinematic APproximation and Integration) model is a physically based distributed rainfall-runoff model, [49]. It 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 impeperious soils and the third represents the channel flows. The integration of the fundamental equations is performed for each of the cells discretizing the basin. The TOPKAPI model is structured around five modules that represent: evapotranspiration, snowmelt, soil water, surface water and channel water components respectively. 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 water balance, [49]. The RIBASIM (RIver BAsin SIMulation) model is developed by DELTARES on the basis of MITSIM model from Massachussets Istitute of Technology is usually used for support the water resource management during a drought period. The model is based on water balance

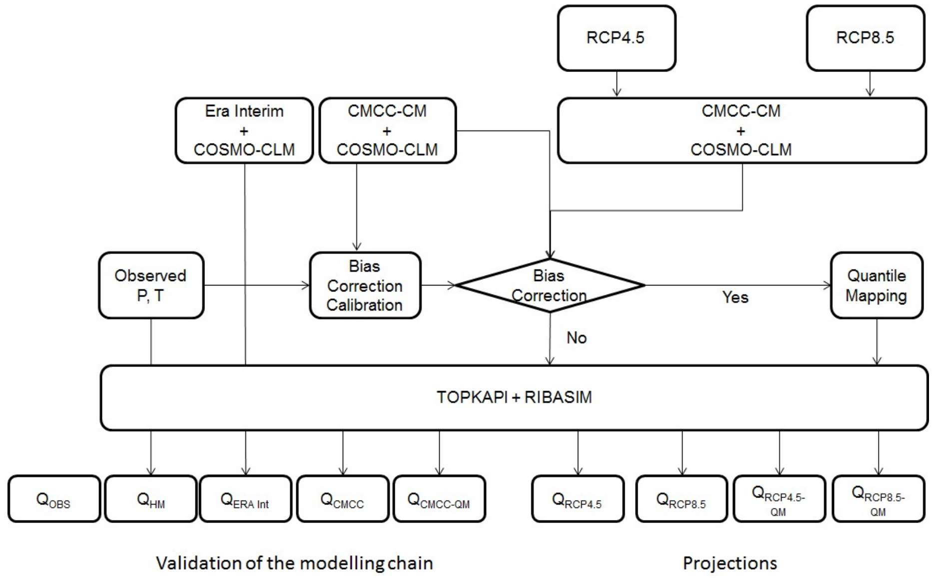

Figure 8:
Specialization of the integrated system for Po river basin.

at basin scale, and the available water is distributed within rivers, open channels, reservoir (natural and artificial), pipelines, etc in all the river basin, [25]. TOPKAPI input to RIBASIM are provided at daily time step, while the operative rules for water abstractions and reservoir are fixed at weekly time scale according to the observed behaviour in the last years, that implies that the simulation may fail in reproducing observed values if the water demand strongly differs from the recently observed one. According to the demand rules implemented in RIBASIM, the river discharge is obtained as result of the optimal distribution of the available water. For the Po river basin, the RIBASIM model accounts for the natural hydrological network, the exchange with the groundwater, and all the hydraulic works distributed in the basin that can in any way modify the natural discharge. This activity has been conducted in collaboration with Hydro-Meteo-Climate Service of the Regional Agency for Prevention and Environment (ARPA SIMC) of the Emilia Romagna Region.

## 6. VALIDATION OF THE ENTIRE SIMULATION CHAIN

### 6.1 LANDSLIDE HAZARD

In order to verify if the developed model, Section(5.1), is able to return reliable estimates of potential triggering flowslide conditions and to validate the entire modeling chain, it has been run on the control period 1981-2010 adopting as weather forcing values observed or provided by GCM/RCM/SD climate simulation chain (Section 4). When the model is forced by observed data, the proper timing in detecting potential trigger conditions can be also assessed while, in the second case, the performance evaluation can be carried out essentially in terms of the number of occurrences on time periods for which climate modeling can provide reliable statistics (30 years, according WMO

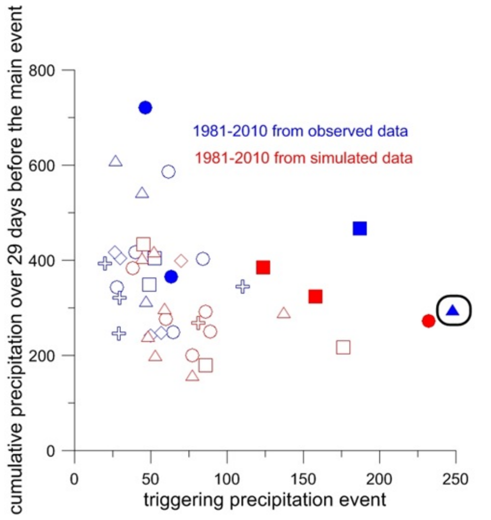

Figure 9:
Cervinara: rainfall history governing potential landslide triggering; $P_{1d}$: daily triggering precipitation; $P_{29d}$: cumulated precipitation over 29 consecutive days before the event; blue dots: critical rainfall history from observed data; red dots: critical rainfall history from simulated data in the control period. Filled indicators identify critical events; empty indicators identify pre-alert conditions (circles: January; diamond: February; cross: March; square: November; triangle: December).

indications). In Fig.9, the assessment is reported in terms of potential critical precipitation events. Here are shown (filled indicators) the combinations $P_{1d}$-$P_{29d}$ ($P_{29d}$ is the cumulated precipitation over 29 consecutive days before the present one) that led, in numerical simulation, to the attaining of the zero suction value at the bottom of pyroclastic cover, above assumed as trigger mechanism; moreover, empty indicators indicate combinations $P_{1d}$-$P_{29d}$ for which 1 kPa suction value (equivalent to a pre-alert condition) is reached at bottom. The blue filled indicators indicate critical events estimated through observed data in the control period. The circled triangle corresponds to the December, 16, 1999 flowslide. This means that the further three blue dots do represent sort of missed landslide events. It is worth to mention that the corresponding precipitations caused landslides in nearby areas in similar geomorphological contexts (in Palma Campania, 1986; in Alfaterna, 2003; in the same Cervinara area, 2010); moving to filled red indicators representing the critical events returned forcing the physical model with simulated data, the number of estimated occurrences is quite comparable (3 vs 4; “rough mean recurrence interval” about equal to 10 years); again, it allows to recognize how the weather variables patterns provided by the GCM/RCM/BC chain are adequate at reproducing those actually observed (in terms of both timing and values). Actually, for an event, reproduced rainfall history potentially inducing the event is very similar to that verified for Cervinara landslide; instead, the other two returned simulated critical events are characterized by significant (but not extremely high) both values of $P_{1d}$ and $P_{29d}$. Differentiating the events according to the occurrence month (see captions for details), it can be noted that, for both, the events are concentrated in the time window ranging from November to January. Indeed, it may be actually due to the specific stratigraphic features (mantles thick less than 2 meters) and hydraulic properties of the investigated covers (particularly pervious, see Fig.6) similarly determining also the limited extent assumed for significant antecedent precipitations (29 days), main function of eruptive events (number and magnitude) that have affected the slopes. For these reasons, in other areas of Campania Region, in fact, the pyroclastic covers have experienced flowslide events in previous periods (September-October) or following (March-May) under similar main events but different length (and so cumulated values) of the significant antecedent rainfalls. For what regard the attainment of pre-alert conditions, during the 30 years, 18 and 16 events (again a very similar number of expected occurrences), about equal to a potential event every two years, are returned for analysis respectively forced by observed and simulated climate datasets; in all cases, it can be assumed that zero is not (numerically) reached as the main event or antecedent precipitations are "insufficient"; as evidence of such hypothesis, the domain formed by “pre-alert” conditions is almost totally encompassed (unless a point) in threshold curve detected by other red and blue “critical events” points. In such cases, the "close to trigger" conditions have been estimated to occur in a larger time span between November and March; in specific, analysis driven by observed data return a high number of expected “pre-alert” events in second part of wet season (February-March) while using simulated data, almost all events continue to be concentrated on November-January period. Finally, an additional interesting remark is the potential use of such data for early warning. In fact, the domain occupied by blue and red filled points represent sort of threshold. Based on that, in the examined geomorphological context cumulated precipitations $P_{29d}$ less than 200 mm and $P_{1d}$ less than 50 mm should not cause any slope failure. For higher values, the critical conditions should be regulated by the combination of $P_{29d}$-$P_{1d}$.

## 6.2 FLOOD AND LOW FLOW HAZARDS

In order to assess, on control period, the predictive capabilities of entire climate/hydrological/hydraulic water balance modeling chain, impact tools (Section 5.2) estimating $Q$ discharges values have been driven by weather forcing observed or provided by different configurations of climate components of modeling chain according the framework displayed in Fig.8. All the simulations are validated over the common period 1991-2010. The first of the validation simulations,$Q_{HM}$, is aimed to assess the uncertainties related to TOPKAPI/RIBASIM models and to estimate the overall error associated to them. The climate input for this simulation is a dataset of precipitation and 2 meter mean temperature provided by ARPA SIMC built on the observed meteorological data published in the Hydrological Yearbooks and integrated with observations, validated and quality checked, collected by the stations network in Po river catchment and gridded on the same grid of COSMO-CLM. The interpolation method used to generate the dataset is the inverse of the distance; for temperature the orographic effect is considered using a fixed gradient. Figure 10 shows the annual cycle of precipitation (a,b) and temperature (c,d) on Po river basin closed at Piacenza (a,c) and Pontelagoscuro (b,d). The good agreement between $Q_{OBS}$ and $Q_{HM}$, is confirmed by the high value of the correlation coefficient between $Q_{OBS}$ and $Q_{HM}$, 0.90. The monthly variability of discharges is properly reproduced but winter and spring streamflows are underestimated (Fig.11(a,b)). For winter, a partial justification may lay in errors in precipitation measurements, due to shading effects caused by the accumulation of a snow pillow on the rain gauges or by the freezing of the water collected inside, so that precipitation is not correctly measured. To assess the error in winter precipitation measurements, an activity to estimate the snow cover from MODIS Snow Covered Area (SCA) product has been carried on [41, 42]. Results of this analysis are functional to (a) estimate the snow water equivalent, i.e. the regional snow resource, and (b) validate the snow component in COSMO-CLM. Underestimation of spring discharges is partially explainable by the calibration of RIBASIM that is more oriented to reproduce droughts than floods like those occurring in spring. For summer discharges, we have to point out that RIBASIM simulates an excessive water abstraction, probably because it has been calibrated and validated on the period 2000-2010 that is drier

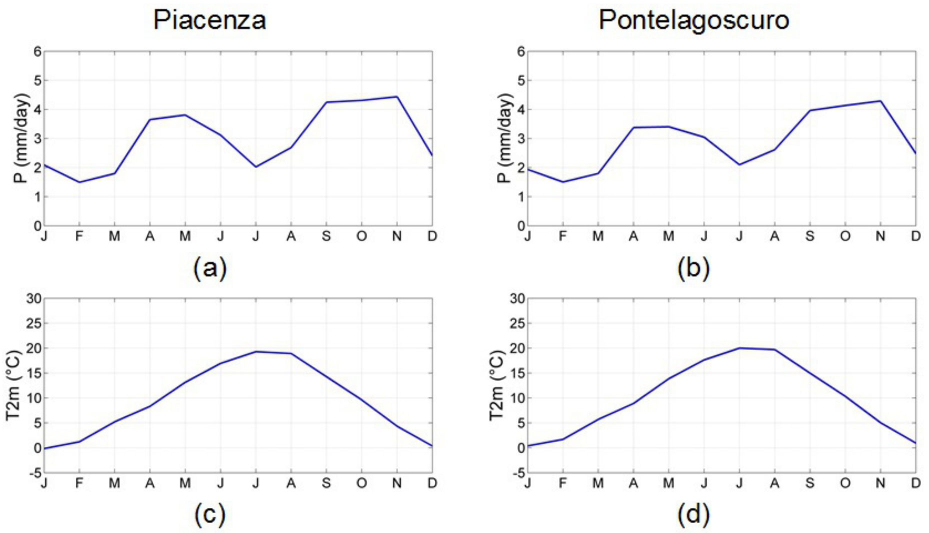

Figure 10:
Observed precipitation (a,b) and temperature (c,d) monthly averaged over Po river basin close at Piacenza (a,c) and Pontelagoscuro (b,d). The period considered is 1991-2010.

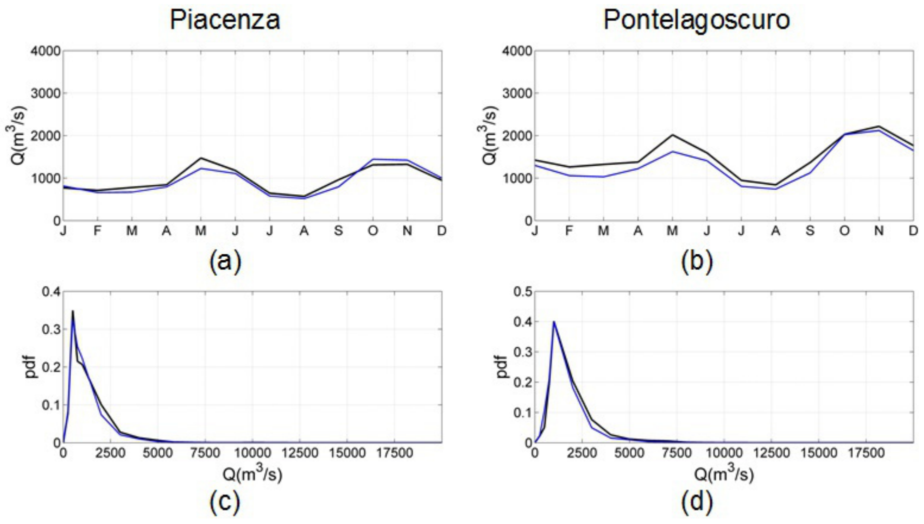

Figure 11:
Comparison between observed ($Q_{OBS}$, in black) and TOPKAPI/RIBASIM simulated ($Q_{HM}$, in blue) discharges in the 1991-2010 period for Piacenza (a,c) and Pontelagoscuro (b,d) periods as monthly average (a,b) and relative frequency (c,d).

than 1991-1999 and, consequently, the real water demand on the whole 1991-2010 is lower than the modelled one. The overall error on the average discharge is 4% for Piacenza and 12% for Pontelagoscuro closure section. In terms of probability density function, the agreement between observed and simulated discharges is quite good, Fig.11(c,d), with an underestimation of the modal value.

The second simulation is aimed to evidence the additional error introduced by COSMO-CLM, forced by ERA-Interim reanalysis, in the Po river discharges ($Q_{ERAInt}$). The comparison between observed and simulated climate shows an excess in the simulated precipitation from January to July and an underestimation from July to December, the bias in precipitation is about 2.5% (Fig.12(a,b)). The temperature field is correctly reproduced with a bias in the $\pm 1°$C range (Fig.12(c,d)). For discharges at Piacenza, Fig.13(a), the average error between $Q_{OBS}$ and $Q_{ERAInt}$ is 2%, the maximum errors are in summer: 62% in June (1915 vs 1179 m$^3$/s) and 52% in July (977 vs 644 m$^3$/s) and the minimum -20% in September (768 vs 963 m$^3$/s) and -19% in November (1077 vs 1324 m$^3$/s) and February (577 vs 712 m$^3$/s). At the Pontelagoscuro closure section, Fig.13(b), the distribution of the error is similar to Piacenza: the error in the average annual discharge is about 8% with maxima of 54% in June (2458 vs 1595 m$^3$/s) and 49% in July (1406 vs 947 m$^3$/s) and minima in November (-28% , 1601 vs 2218 m$^3$/s) and February (-29% 891 vs 1263 m$^3$/s). The probability density functions at both closure sections (Fig.13(c,d)) show a substantial agreement between $Q_{OBS}$ and $Q_{ERAInt}$ leading the idea that the error is more on the timing than in the discharges magnitude.

The third simulation, producing the $Q_{CMCC}$ time series, is aimed to evaluate the uncertainties introduced by the GCM/RCM couple, in the modelling chain output. Under the CMCC-CM boundary conditions, the COSMO-CLM tendency to overestimate the precipitation is boosted (Fig.14(a,b)) and temperature are, in average, underestimated (Fig.14(c,d)) of -1.8 °C. The variability of $Q_{CMCC}$ series across the year is similar, in shape, to the one of $Q_{ERAInt}$ but amplified, similarly to the precipitation behaviour, Fig.15(a,b). The delay of one month in the occurrence of the spring peak is retrieved and the autumnal peak occurs in October while in observed time series the maximum is reached in November, this is more evident for Pontelagoscuro discharges than for Piacenza. In both sections, the excessive precipitation in summer result in a overestimation of discharges with errors ranging between 97 and 234% for Piacenza and 94 and 207% for Pontelagoscuro. The maximum underestimation, about 30%, occur in November in both sections. The substantial overestimation of discharges is retrieved in the probability density function where the modal value is shifted toward right Fig.15(c,d), this is more evident for Piacenza discharges than for Pontelagoscuro ones.

The fourth simulation, producing the $Q_{CMCC-QM}$ time series, is aimed to evaluate the capability of the distribution derived quantile mapping to remove the systematic error and some of the uncertainties associated to the GCM/RCM climate. Figure 16 reports the monthly precipitation and temperature after the bias correction. The bias in precipitation ranges, for Piacenza, between 27% (March) and -18% (September) and, for Pontelagoscuro, between 21% and -18% in the same months. The bias in temperature is almost null. The good fitting of simulated and bias corrected climate data with the observation is proved by the limited differences between $Q_{OBS}$ and $Q_{CMCC-QM}$ either in magnitude

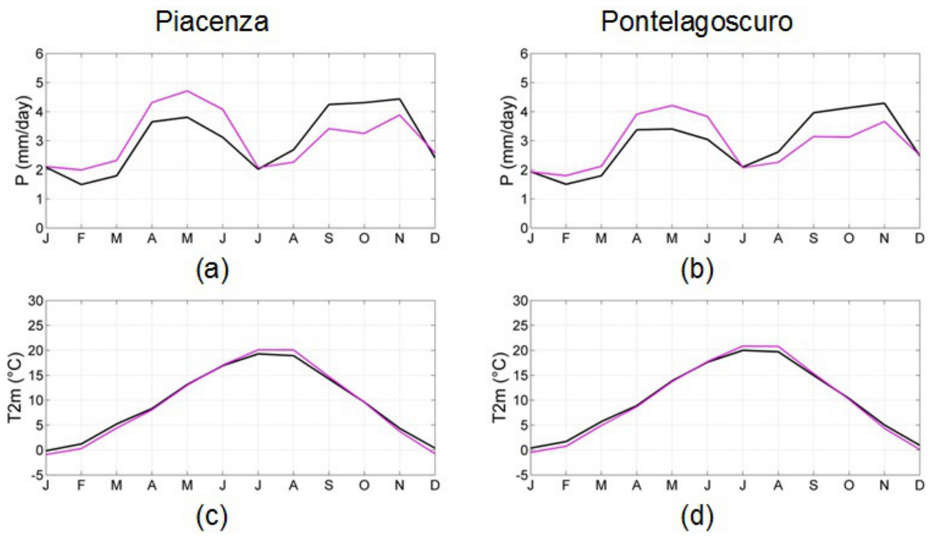

Figure 12:
Observed (in black) versus ERA-Interim/COSMO-CLM (in magenta) precipitation (a,b) and temperature (c,d) monthly averaged over Po river basin close at Piacenza (a,c) and Pontelagoscuro (b,d). The period considered is 1991-2010.

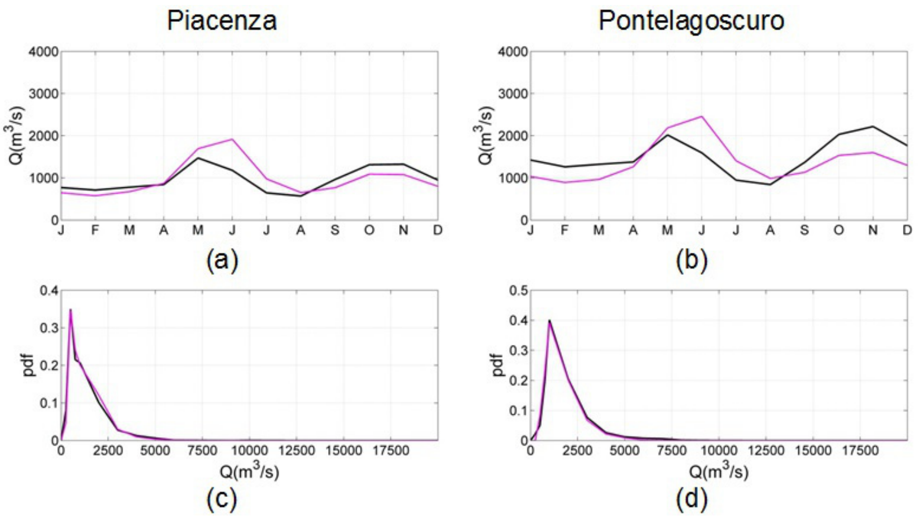

Figure 13:
Comparison between observed ($Q_{OBS}$, in black) and $Q_{ERA}$ (in magenta) discharges in the 1991-2010 period for Piacenza (a,c) and Pontelagoscuro (b,d) periods as monthly average (a,b) and relative frequency (c,d).

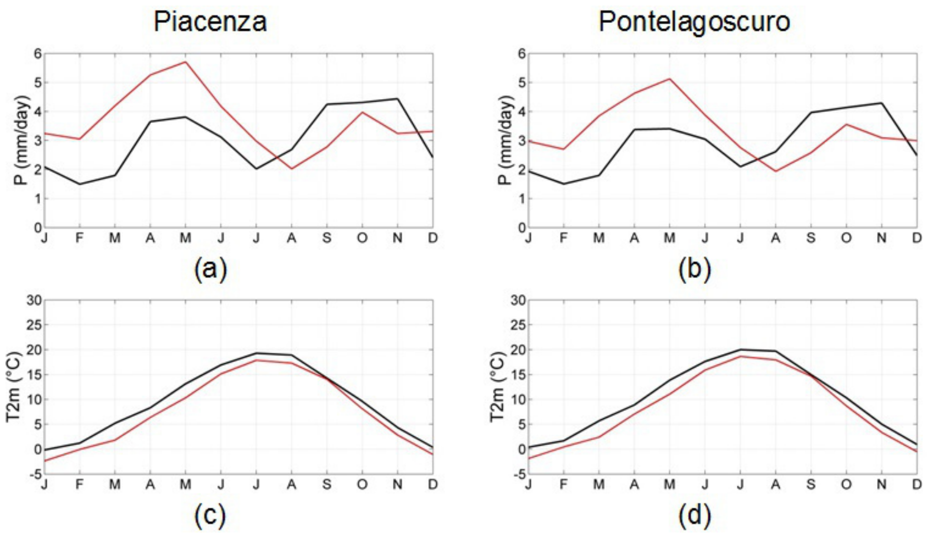

Figure 14:
Observed (in black) versus CMCC-CM/COSMO-CLM (in red) precipitation (a,b) and temperature (c,d) monthly averaged over Po river basin close at Piacenza (a,c) and Pontelagoscuro (b,d). The period considered is 1991-2010.

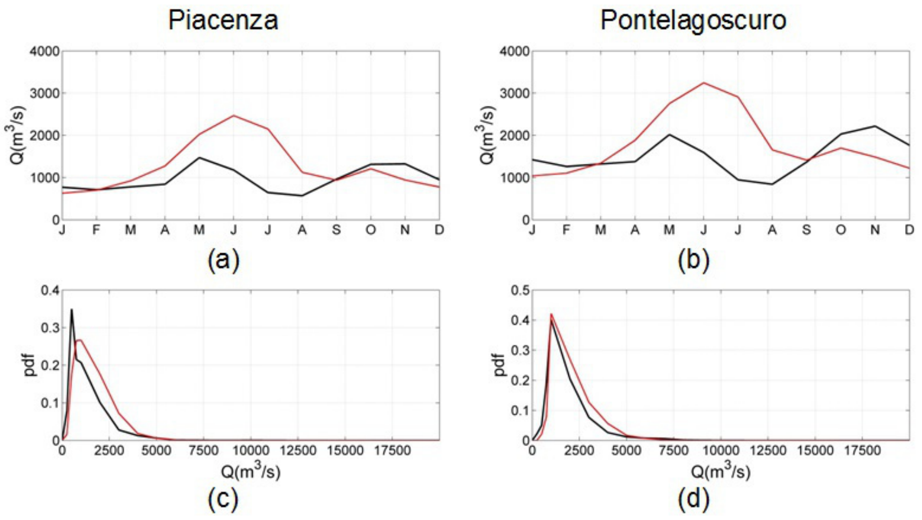

Figure 15:
Comparison between observed ($Q_{OBS}$, in black) and $Q_{CMCC}$ (in red) discharges in the 1991-2010 period for Piacenza (a,c) and Pontelagoscuro (b,d) periods as monthly average (a,b) and relative frequency (c,d).

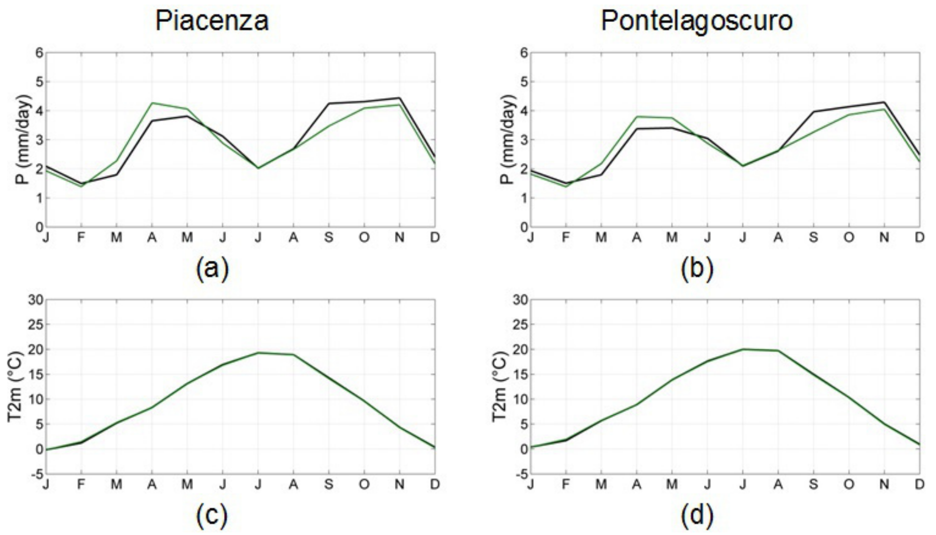

Figure 16:
Observed (in black) versus CMCC-CM/COSMO-CLM/QM (in green) precipitation (a,b) and temperature (c,d) monthly averaged over Po river basin close at Piacenza (a,c) and Pontelagoscuro (b,d). The period considered is 1991-2010.

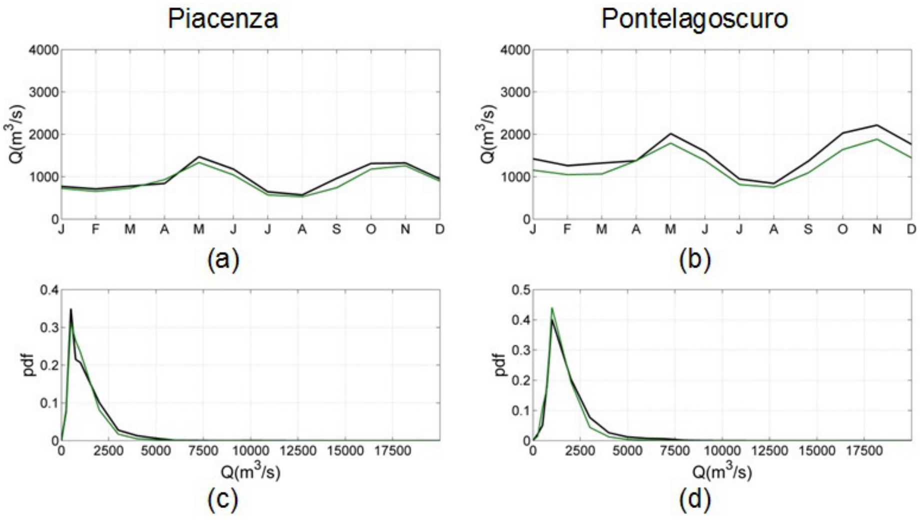

Figure 17:
Comparison between observed ($Q_{OBS}$, in black) and $Q_{CMCC-QM}$ (in green) discharges in the 1991-2010 period for Piacenza (a,c) and Pontelagoscuro (b,d) periods as monthly average (a,b) and relative frequency (c,d).

and timing, Fig.17.

The maximum (minimum) error for discharges at Piacenza is 11% (-23%) in April (September) and, for Pontelagoscuro, the error ranges between 0.2% (April) and -20% (March and September). In Tab.1 are reported some of the main statistics characterizing the observed and simulated discharges. The results confirm that bias corrected climate simulations are aboslutely more suitable for hydrological study purposes than the raw RCM outputs [16, 47].

## 7. CONCLUSIONS

The paper briefly introduces some results about the validation performed on different geo-hydrological hazards; however, a much more extended work has been carried out on such issue within GEMINA project. In particular, concerning floods and low flow hazards, Po river basin surely represent a challenging test case because of its extent and geo-morphological complexity; on the other hand, it may be regarded as fully illustrative of the variations in, hydrological cycle, potentially occurring in the Mediterranean area. As above recalled, on the same test case, also other configurations of modeling chain (in the specific, subjecting to bias correction approach not weather variables but directly the discharge output) have been tested [55, 57]. In addition, a stochastic approach to derive flood peaks from extreme precipitations under present and future climate has been developed and tested over small basin [54, 56]. The stochastic approach is complementary to the results presented here, since it refers to fast phenomena induced by intense precipitation that may not be caught at the daily time scale at which the modeling chain works. For what regard the assessment of the effect of CC on landslide activity, in this report, the main results about shallow and fast landslide test case are reported; however, through the same approach above introduced, deep analysis have been carried out also on Orvieto clayey slope affected, instead, by slow/very slow movements [63, 38, 39]. This demonstrates how the chain can be indifferently adopted for both fast (and shallow) and slow (and deep) slope movements characterized by infrequent trigger or yearly reactivations. On control periods, for all investigated case histories, the developed simulation chain proves to be a reliable tool allowing to adopt more confidently it on future time span for which the emission scenarios represent a further substantial source of uncertainty. Moreover, it should be noted as the actual limiting factor in the application of the chain to further test cases is unfortunately linked to the difficulty of finding reliable set of observed data for validation of the climate chain and/or the calibration of the impact tools. A key issue arisen by work regards the confirming about the current need of correcting, through statistical approaches, GCM/RCM outputs when involved in impact studies [37, 46, 63]. The adoption and development of bias correction approaches adequate for the specific geo-hydrological hazards have extensively been investigated within GEMINA project [63, 64, 52]; the investigations have confirmed how quantile mapping tools outperform the other methods; however, two distinct procedures have been selected for analysis at watershed (distribution derived gamma approach) or slope scale (empirical quantile approach). The developed framework involving single models for each component of the simulation chain could be easily expand allowing the adoption of model ensembles whose benefits are widely shown in last years [47, 33]. Although the intrinsic differences between the investigated cases, the validation procedure carried out is substantially able to quantify (or, at least, identify the relative weight of) uncertainties associated to

**Table 1**

Main statistics of discharge timeseries analysed at Piacenza and Pontelagoscuro for the 1991-2010 period, units are m$^3$/s.

| | Piacenza | | | | | Pontelagoscuro | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $Q_{OBS}$ | $Q_{HM}$ | $Q_{ERAInt}$ | $Q_{CMCC}$ | $Q_{CMCC-QM}$ | $Q_{OBS}$ | $Q_{HM}$ | $Q_{ERAInt}$ | $Q_{CMCC}$ | $Q_{CMCC-QM}$ |
| $Q_{0.05}$ | 338 | 341 | 381 | 462 | 338 | 566 | 501 | 576 | 743 | 468 |
| $Q_{0.10}$ | 398 | 392 | 429 | 548 | 393 | 680 | 596 | 649 | 876 | 573 |
| $Q_{0.25}$ | 502 | 499 | 525 | 672 | 514 | 860 | 777 | 816 | 1075 | 807 |
| $Q_{0.50}$ | 697 | 698 | 713 | 944 | 707 | 1172 | 1078 | 1130 | 1457 | 1118 |
| $Q_{0.75}$ | 1087 | 1038 | 1142 | 1594 | 1017 | 1767 | 1546 | 1683 | 2292 | 1522 |
| $Q_{0.90}$ | 1863 | 1611 | 1898 | 2487 | 1555 | 2831 | 2319 | 2514 | 3325 | 2143 |
| $Q_{0.95}$ | 2494 | 2244 | 2435 | 3033 | 2034 | 3609 | 3045 | 3135 | 3967 | 2712 |
| average | 961 | 921 | 980 | 1266 | 883 | 1518 | 1343 | 1398 | 1817 | 1289 |
| std. dev. | 802 | 819 | 744 | 889 | 673 | 1097 | 1005 | 871 | 1075 | 805 |

each element of modeling chain.

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