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Frequency variation of geo-hydrological hazards under climate change conditions in Italy

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SUMMARY This document is the product P94 of GEMINA project. It represents the milestone for year 2015 of GEMINA project within the Work Package A.2.17 "Analysis of geological risk related to climate change" which main goal is the analysis of the impacts of climate change on occurrence and magnitude of landslides, floods and low flows conditions on some specific contexts of the Mediterranean area. In particular, this document summarises the main results achieved in the analysis of geo-hydrological hazards frequency under future climate projections forcing the modelling chain presented in [56] and validated in [32] with the outputs of the climate simulation illustrated in [22] before and after the application of the bias correction techniques explained in [23].

Keywords: Climate projections, bias correction, floods, droughts, landslides

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1. INTRODUCTION

The report presents several findings related to the estimated climate change impacts on geo-hydrological hazards using the climate/impact modelling 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 this research paper, only main results about the climate change impacts on geo-hydrological hazards in four very different geomorphological contexts are displayed: Cervinara (South Italy) and Orvieto (Central Italy) for landslides and Po River (North Italy) and Calore Irpino River (South Italy) basins for hydrological hazards are displayed.

2. MOTIVATION

The majority of the climate models agree in assessing for 2100, under the effect of climate change, an increase in extreme precipitation events frequency and almost unchanged intensity, and, in average, a decrease in the total precipitation over the Mediterranean area [7]. The expected partitioning of precipitation enhances the possibility of alternation between long dry and short extremely wet periods [2], causing generally an increase in the geo-hydrological hazards. In last years, REMHI Division [48, 44, 49, 9, 28, 31, 33, 12] among others [11, 6, 17, 29], have investigated the potential effects of CC on geo-hydrological hazards in Italian Peninsula that is already prone to them and the main results achieved will be presented in next Sections. As described in [56] a climate-impact modelling chain (Fig.1) has been developed and validated [48, 32, 53, 52] to reproduce the main characteristics of geo-hydrological hazards of interest. The modelling chain accounts for the current constrains of physically based climate models both global and regional (GCM and RCM) due to the current achievable horizontal resolutions by adopting statistical approaches in cascade to GCM/RCM outputs [23]. Starting from such findings the GCM CMCC-CM [15, 35], is driven by two IPCC representative concentration pathways [21]: RCP4.5 and RCP8.5 and dynamically downscaled through the RCM COSMO-CLM [34]; then, the so obtained weather forcing are processed by one or more bias correction statistical approaches [23, 53, 52] 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 climate change).

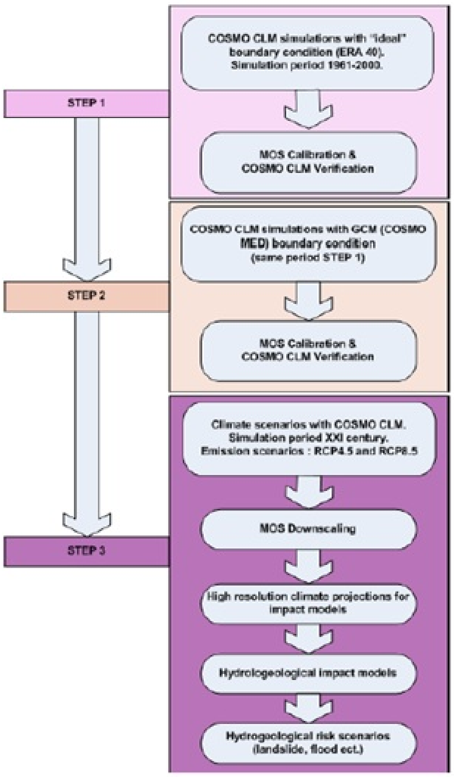


Figure 1:
Structure of the integrated system as proposed in GEMINA [56].

This research paper is explicitly focused on the variation induced by climate change in geo-hydrological hazards; and it is so organized: first the test areas are described (Section 3); then some elements about adopted RCPs, climate models and used bias correction approaches are given (Section 4); then impacts models are introduced (Section 5); finally, main results about expected climate change impacts are provided (Section 6) and Conclusions are drawn (Section 7).

3. TEST CASES

Four test cases are considered in this report, in particular, the test case of Cervinara and Po River basin has been used to illustrate the performances of the modelling chain in [32], while Orvieto, Po River and Calore Irpino basins have been used to illustrated the performances of different statistical downscaling techniques in [23].

3.1 GEO-HYDROLOGICAL HAZARD: 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 [26, 13], coupled effect of particularly wet periods (during which infiltration contributions largely exceed

Figure 2:
Cervinara test case.

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.

3.2 GEO-HYDROLOGICAL HAZARD: ORVIETO TEST CASE

Orvieto is located on top of a mesa, consisting of a rock slab overlying a tronco-conical base with gentle slopes (12° to 15°), formed by stiff clays. The clay formation (a silt and clay of medium plasticity) is intact and very stiff at depth (undrained strength higher than 1 MPa at 30 m of depth) but proceeding upwards it shows an increase in void ratio caused by softening processes and the appearance of fissures and joints, which at the top of the formation are opened and oxidized, as well as the clay matrix is. Most of the slope is covered by a landslide debris resulting from remoulding of the underlying clay formation mixed to a slight coarse grained fraction, deriving from the disruption of the pyroclastic rock slab, which increases in the top soil (up to 15%). Slope movements and pore pressure have being monitored since 1982 by the Institute for Environmental Geology and Geo-Engineering of the National Research Council through inclinometers and piezometers (both Casagrande and vibrating-wire cells) in a sample area located on the northern part of the hill. Twenty-five to thirty year-long datasets (depending on the measuring location) of displacements and pore pressure measurements at various depths have been collected. Measurement frequency is monthly up to the 2002 and bimonthly from 2002 to 2013, Fig.3. Daily rainfall and temperature data are provided by a meteorological station of the Hydrological Service of Region Umbria, which is active since 1920 with few short periods of incompleteness. Monitoring indicates that the slope is affected by slow translational movements along pre-existing slip surfaces/shear bands located within the upper part of the overconsolidated clays, down to a depth of 30 m, and within the overlying debris cover, usually at a depth lower than 10 m. Deep movements occur at an average displacement rate of 2 to 6 mm/year with yearly re-activation excepting for particularly dry years, when negligible displacements are recorded. Shallow slides, often superimposed on the deep movements, show higher average displacement rates (40-50 mm/year) and reactivate even more than once in a hydrological year.

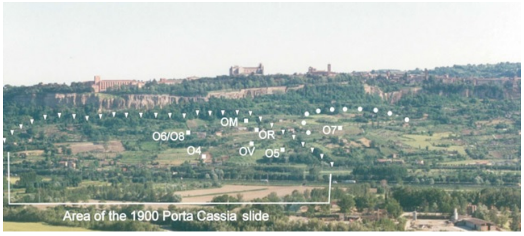


Figure 3:
Location of monitoring stations on Northern slope of Orvieto from [41].

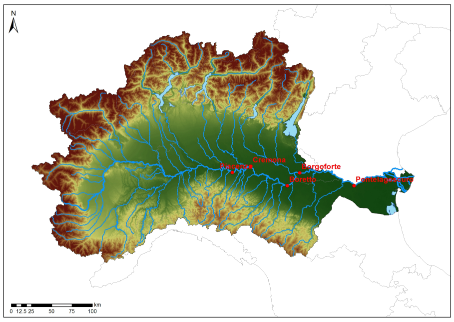


Figure 4:
Po basin: hydrological network and main closure sections.

3.3 HYDROLOGICAL HAZARD: 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 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.4. 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, [55] and signal of changes in precipitation and temperature are present in climate observations [42, 8, 39]. Climate data analysis show, on Po river basin, an increase in annual maximum precipitation with a trend of about 0.5Â°C/decade since 1960. The signal is detectable in all the seasons [42], and, in particular in summer where maximum temperature are higher than the reference climate [39]. 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 [39]. [8] 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 dÁosta regions (north-western Italy) finding a significant increase of about 1Â°C on average temperatures, in particular, for maximum daily temperatures in winter and summer months; while for precipitation any significant trend is identified.

3.4 HYDROLOGICAL HAZARD: CALORE IRPINO RIVER TEST CASE

The Calore Irpino River basin covers an area of about 3058 km^2 in Campania, Fig.5. The River length is about 108 km long and the average discharge is 31.8 m^3/s at its outlet in the Volturno River. The Calore Irpino River basin is characterised by a micro-climate that, together with the water availability guarantee by the River itself, foster the cultivation of vegetables, vineyard and olive trees. The occurrence of climate change may alter the equilibrium of this ecosystem with impacts on the local economy. The test case is a limited portion of the basin, i.e. the basin closed at the Montella section due to the availability of meteorological and hydrological data.

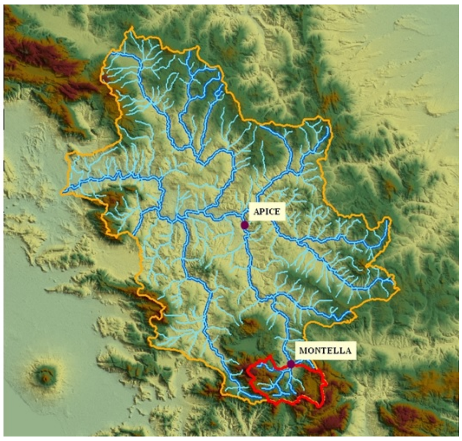


Figure 5:
Calore Irpino basin and sub-basin closed at Montella.

4. CLIMATE SIMULATIONS

Climate projections are the results of numerical simulations performed by climate models under different scenarios. Among the IPCC scenarios we focus on RCP4.5 and RCP8.5. The first is a stabilization scenario leading the radiative forcing at about 4.5W/m^2 in 2100, while the latter is a more extreme scenario, leading radiative forcing up to 8.5W/m^2 in 2100 compared to pre-industrial era [21]. Such scenarios are used to drive the global climate model CMCC-CM [35, 15] that is dynamically downscaled by the regional climate model COSMO-CLM [34] that provide climate variables at an horizontal resolution, i.e. 0.0715Â° (about 8 km), comparable with the one of the geo-hydrological hazard model. The behavior of climate projections over the test case areas has been illustrated in [5, 22]. Unfortunately, RCM outputs are affected by systematic biases caused by, e.g., uncertainty in the GCM/RCM parametrizations or assumptions, and which have to be removed before performing quantitative evaluations on hydrological or other impacts [36]; to this aim bias correction techniques have been proposed in recent years [57, 16, 27]; among these ones, quantile mapping approaches have been proved outperforming the other ones. In considered cases, this method is implemented albeit with some theoretical differences. Concerning Cervinara case study, an empirical quantile mapping approach (also known as RQuant); [16] 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 [54]. 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 beyond the "observed" range a constant correction is implemented following [3]. Concerning Po river basin test case, the distribution derived method is applied: both observed and simulated precipitation has been assumed to follow a Gamma distribution [18, 37], temperature data have been assumed to be normally distributed [37].

5. IMPACT TOOLS

A description of the impacts models used for the four different test cases is reported below.

5.1 GEO-HYDROLOGICAL HAZARD: CERVINARA TEST CASE

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

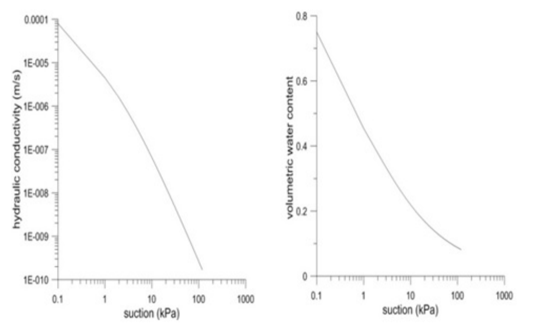


Figure 6:
Hydraulic properties of the cover [14].

adopted tool is SEEP/W FEM code [20] 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 [10]. Soil hydraulic properties, reported in Fig.6 in term of hydraulic conductivity and soil-water characteristic curve, are retrieved by [14] 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°).

5.2 GEO-HYDROLOGICAL HAZARD: ORVIETO TEST CASE

The exceptionally long time-history allows a view on both short- and mid-term variations in displacement rates which are strikingly linked to changes in pore pressures and rainfall cumulated over long periods. Attention is focused on deep movements, which involve larger volumes, are less dependent on local geotechnical conditions and ensure a long life to in-depth monitoring instrumentation, thus providing long time series of displacements. In particular, the analyses concern data from the OR monitoring station (probe inclinometer and Casagrande piezometer) installed in the central part of the slope, which is characterized by the longest monitoring history. To this aim, Fig.7 shows the relationship between maximum yearly cumulative rainfall over 120 days, P_{120M}, and observed annual displacement. Although characterized by significant dispersion, a clear linkage between the two variables is detectable. However, it reveals how landslide body mobilizes, every year, regardless of corresponding precipitation pattern. To investigate the effect of climate change on landslide activity, the main ingredients of the adopted simulation chain are essentially two: weather input (namely, precipitation) on current (beyond the observed ones) and future time spans are provided by climate modelling chain and a simple impact tool allowing to "translate" the effect of cumulative precipitation values in slope displacements: to this aim, having verified a rather good agreement between the evolutions of maximum values, P_{120M}, for hydrological year and the yearly displacement, y_d, Fig.7, we considered the op-

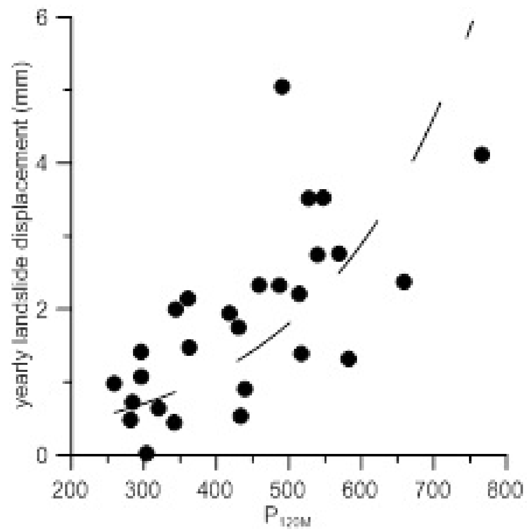


Figure 7:
Annual landslide displacement measured by inclinometer OR at the depth z = 20 m, as a function of the maximum cumulative rainfall over 120 days, P_{120M}.

portunity of adopting such parameter as proxy variable for landslide activity. In particular, the following exponential relationship

$$y_d = 0.17 \times \exp\left(4.7 \times 10^{-3} P_{120M}\right) \qquad (1)$$

can suitably fit the observed data preserving the minimum displacement rate also for low P_{120M} values. Even though the correlation index R2 slightly exceeds 0.4, adopting the relationship over the monitoring period returns a cumulative displacement equal to about 55 mm, that slightly underestimates the actual value (58.6 mm).

5.3 HYDROLOGICAL HAZARD: PO RIVER TEST CASE

To study the climate change impacts on the hydrological cycle of Po river, the integrated system has been specialised coupling the bias corrected precipitation and temperature time series from the regional 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 [48, 44] 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, [40]. 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 impervious 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, [40]. 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 at basin scale, and the available water is distributed within rivers, open channels, reservoir (natural and artificial), pipelines, etc in all the river basin, [19]. 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.

5.4 HYDROLOGICAL HAZARD: CALORE IRPINO RIVER TEST CASE

The assessment of climate change impacts on Calore Irpino River has been performed following the approach described for Po river basin with the exception that, due to the limited size and to the low anthropogenic pressure on the test case area, the basin water balance model is not implemented; for the same reasons it has been possible to test the effects of several bias correction methods on the components of the hydrological cycle and river discharge [23, 46]. For Calore Irpino area, on the contrary of Po River, the climate observations at Montella station are assumed to be representaive of the whole domain and as simulated climate variables the average values on a 3×3, i.e. the effective resolution of the RCM, grid centred on Montella site have been used.

6. CLIMATE AND GEO-HYDROLOGICAL HAZARDS PROJECTIONS

This section is devoted to present the effects of climate change on severity/frequency of future geo-hydrological hazards on the test cases illustrated in Section 5.

6.1 LANDSLIDE HAZARD: CERVINARA TEST CASE

In this section, we present the results of the modelling chain for Cervinara test case at 2071-2100. A detailed description of the modelling chain specialized for Cervinara test case is available in [53, 52, 32, 28] togheter with the validation of the modelling chain itself in the control period 1981-2010. The first analysis performed is on the climate signal, in particular, Fig.8 reports the comparison between the annual cycle of average precipitation and temperature within the control period and the expected values at 2071-2100 under the RCP8.5. The results show a substantial decrease in cumulative precipitation for March-October period, but in the "wet" season an increase in precipitation is detected. At the same time, a reduction in average number of rainy days is estimated (Fig.8(b)): if, in the drier months it could be partly due to the reduction of total values, in the wet season this corresponds to an increase of the intensity of precipitation events.

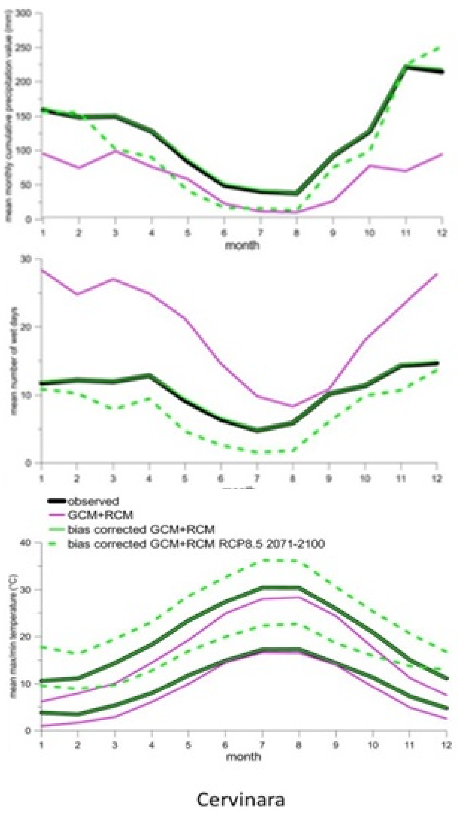


Figure 8:
From top to bottom: average monthly precipitation, wet days and temperature for Cervinara site. Comparison among observations, raw and bias corrected control period and bias corrected RCP8.5 2071-2100 data.

While changes in the average behaviour of climate variables allows understanding the general features of potential future climate conditions, the assessment of slope response requires the analysis of extreme precipitation val-

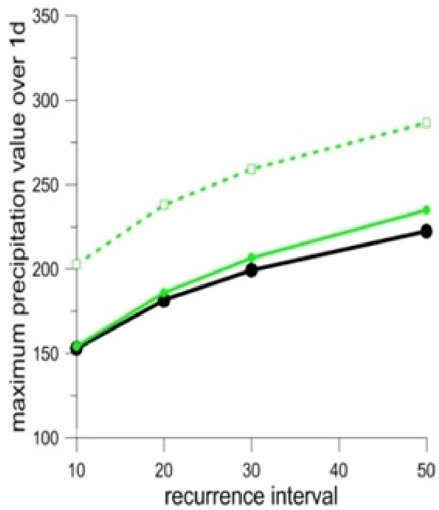


Figure 9:
Recurrence interval for maximum yearly values of cumulated daily precipitation (GEV statistical distribution). Black line: observed values; continuous green line: simulated values over the same time interval; dashed green line: simulated values over the time interval 2071-2100

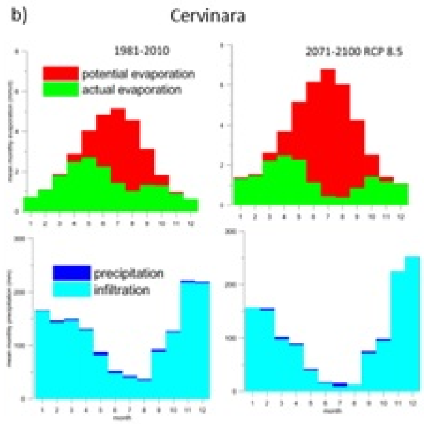


Figure 10:
Comparison between monthly potential and actual evaporation and monthly total and infiltrated rainfall for the control period and the 2071-2100 time window (RCP8.5 scenario)

ues. Following [41] and taking in mind the results previously achieved [53, 52, 32] the maximum daily precipitation P_1d is assumed as control variable to estimate climate change impacts on Cervinara landislide. For both control and projection period the timeseries of such maxima have been fitted through the General Extreme Value (GEV) distribution, Fig.9 to evaluate changes in the frequency of precipitation events able to trigger the landslide. As shown in Fig. 9 a not negligible increase of the maximum is estimated or, conversely, a reduction in their recurrence period.

The next step has been the assessment of the hydraulic slope response to climate change and to the induced variations in the soil water balance. In Fig.10, the main components of soil surface water balance are displayed: the evaporative loss increases in spring and winter seasons thanks to water availability determined by precipitations in the wet season, while in Summer and, partly, in Autumn, the greater evaporative demand could not lead to greater water losses because of the reduction in cumulative precipitation during these months. However, thanks to the higher soil hydraulic conductivity, the fallen water could totally infiltrate also during heavy precipitations. Then, the estimated increase in intense rainfall events on daily scale might significantly affect the slope behaviour.

The potential effects of soil water balance changes in Cervinara are shown in Fig. 11 taking into account the joint effects of precipitation cumulated in the 29 days (P_{29d}) before the event represented by P_{1d} datum. The red dots represent the critical events during the control period obtained from simulated data; in turn, the green dots critical events in the future 2071-2100 period. In addition, the blue dots indicate critical events estimated through observed data in the control period. The comparison between the clusters of red and green dots clearly shows that future extreme precipitation events could produce an increase of the probability of landslide occurrence.

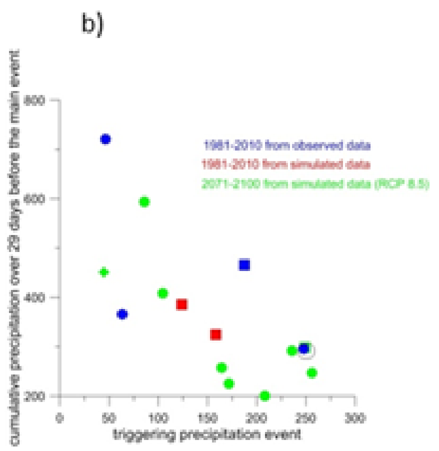


Figure 11:
Precipitation history governing potential landslide triggering; P_{1d}: daily triggering precipitation; P_{29d}: cumulated precipitation over 29 consecutive days before the event; blue dots: critical rainfall history from observed data; red dots: critical rainfall history from simulated data in the control period; green dots: critical rainfall history from simulated data in the future time window.

6.2 GEO-HYDROLOGICAL HAZARD: ORVIETO TEST CASE

As described in Section 5.2, for Orvieto test case it is possible to identify a relationship between cumulative precipitation P_{120M} and slope displacements on the basis of which the assessment of climate change impacts on Orvieto slope displacements can be performed. In particular, Fig.12(a) compares the P_{120M} trends related to observations (1921-2013), to the control period (1981-2010) and to the future (2011-2100) according to RCP4.5 and RCP8.5 scenarios. Moreover, in Fig.12(b) the relationship retrieved between yearly displacement and P_{120M} is used to perform a first attempt to evaluate the future evolution of deep movements detected on Northern slope of Orvieto. The simulation chain is able to reproduce the P_{120M} values observed during the control period, even partly underestimating the inter annual variability [33].

For the future period, the trend detected by RCP4.5 follows the observed decreasing trend under comparable amounts of seasonal precipitation, while the evaluated decrease of P120M becomes less pronounced according to the one provided by RCP8.5, because of estimated increase of Winter precipitation. Anyway, for both concentration scenarios the inter- annual variability shows values that are comparable to those observed for the area. For what concern the displacement evolutions, Fig.12(b), also adopting P_{120M} values estimated through the simulation chain, the evaluated displacement over the monitoring period is quite similar to observed amount; . For the future period, the trends seem to accommodate the current evolution at decreasing slope [33]; in this case, the choice of a determined concentration scenario only marginally affects the total displacements. Finally, the comparison between such evolutions and the trend at 2100, under steady state conditions, obtained by assuming a mean yearly displacement equal to that monitored (continuous black line in Fig.12(b) corresponding to a rate equal to 1.89 mm/year) allows us to evaluate a substantial deceleration (the forecasted rate of movement is about 1.67 mm/year). The displacement field of this active deep landslide in overconsolidated clays shown by a long-lasting monitoring, points out an evident reducing trend in the rate of movement. Such a behaviour could be directly related to the recognized decreasing trend in the maximum yearly cumulative rainfall over four months, that is induced by weather modifications in the landslide area. Since the actual knowledge allows us to depict reliable scenarios of the incoming climate change, the likely landslide response to the future rainfall regime can be in turn estimated by a simulation chain based on the expected increase in radiative forcing over the 21st century. The results of our analyses point out that local climate change should be respon-

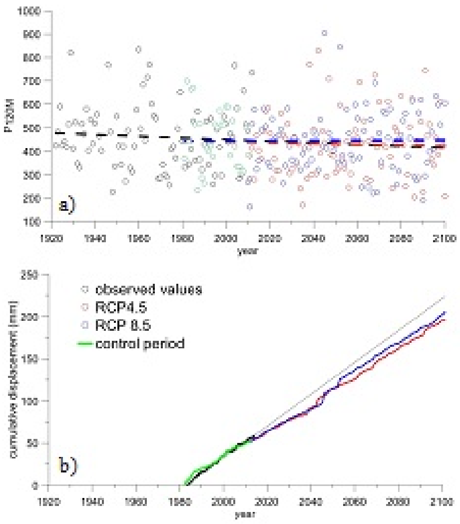


Figure 12:
(a) observed and simulated precipitation P_{120M}, considering control period (1981-2010) and future period (2071-2100), for both RCP4.5 and RCP8.5 scenarios; (b) observed and simulated cumulative displacement.

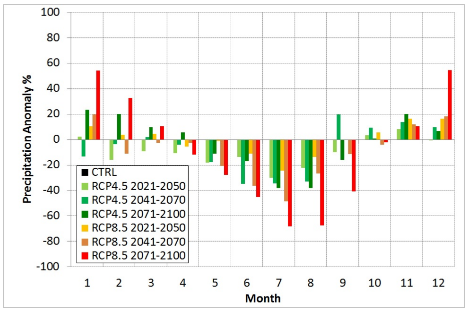
sible for a substantial slow deceleration of the landslide movement. The evaluation of the effects induced by the ongoing weather changes could represent an important issue to evaluate the long-term landslide risk assessment for infrastructures having high vulnerability to this type of slope movements.

6.3 HYDROLOGICAL HAZARD: PO RIVER

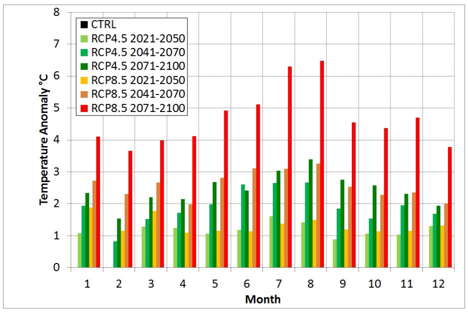
In this section, we present the results of the modelling chain for the 2021-2050, 2041-2070 and 2071-2100 periods compared to the control period 1982-2011 [44, 49, 47]. The variables analysed are daily precipitation, 2 m mean temperature and Po River discharges at Pontelagoscuro providing an integral measure in space and time of Po River response to climate inputs. Climate inputs considered are those bias corrected. Figure 13(a) reports the precipitation anomaly estimated over the whole Po river basin under both scenarios for the three time slices considered. Projections show a marked seasonality in precipitation changes, in general, precipitation is expected to reduce in spring and summer and increase in autumn and winter. In particular, for RCP4.5, the "wetter" season duration ranges between 4 months (2021-2050: Oct-Jan; 2041-2070: Sep-Dec) and 7 months (2071-2100: Oct-Apr) while, for RCP8.5 the "wetter" season is 3 (2041-2070: Nov-Jan) to 6 (2021-2050: Oct-Mar) months. Considering temperatures, Fig. 13(b), the anomaly is always positive, with RCP8.5 values that, at 2071-2100, are almost the double of those of RCP4.5, while in the 2021-2050 the two scenarios are comparable. A more detailed analysis on seasonal climate anomalies and their spatial distribution over Po river basin is reported in [47].

As consequence of the alteration of precipitation distribution and of the increased water demand from the atmosphere ruled by temperature, changes in discharges are found, Fig.13(c). The discharge anomaly is strongly influenced by precipitation distribution; for RCP4.5 positive anomalies are detected between November and January (2021-2050), October-January (2041-2070), November-May (2071-2100), for RCP8.5 the discharge increases between November and May (2021-2050), December-April (2041-2070) and December-April (2071-2100).

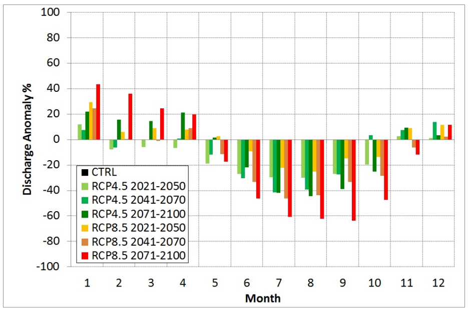
Since changes in the precipitation seasonality may affect the occurrence of prolonged low flows (droughts) and of high flows (floods) we try to quantify the occurrence and severity of both extremes under climate change conditions. As threshold value to define a low (high) flow we use the $Q_{300}(Q_7)$ threshold, i.e. the discharge that in the control period is exceeded, on average, for 300 (7) days at year. Figure 14 reports for both low (a,c) and high (b,d) flows the



(a)



(b)



(c)

Figure 13:
Precipitation, temperature and discharge anomalies under RCP4.5 and RCP8.5 for the periods 2021-2050, 2041-2070, 2071-2100

average number of days (a,b) the threshold is exceeded and the average volume associated (c,d).

In the control period (and in observation, [24, 49]) low flows mostly occur in summer while in winter the phenomenon is less marked in terms of both average volume deficit (V_D) and number of day (D_D) during which $Q < Q_{300}$, Fig.14(a) and (b). The average volume deficit $V_{D,i}$ for the $i-$month is estimated as

$$V_{D,i} = 86400 \times \sum_{j=1}^{N_i} \max\left(0, Q_{300} - Q_j\right) \qquad (2)$$

where N_j is the number of day for the $i-$month of the year. Under RCP4.5 scenario the drought volume is estimate to double (as minimum) in summer, while variation in the remaining season are negligible; coherently the average number of low flows days increases and it is likely the persistence of low flow regime during the whole summer season. Under RCP8.5 scenario the situation is even more extreme, at 2071-2100 the estimated drought volume is almost three times the one in the control period and low flows become the “standard” river regime in summer, conversely winter droughts show a limited variability with respect to the control period. Under both scenarios the severity and the duration of low flow in summer are exacerbated by the precipitation reduction and temperature increase, that bring the water balance model to estimate a higher water uptake from rivers and groundwater.

In the control period (and in observation) high flows ($Q > Q_7$) mostly occur in spring (driven by snow-melting and precipitation) and autumn (driven by precipitation only) with autumnal events more severe than the spring ones. The average volume associated to high flow (V_F) is estimated as

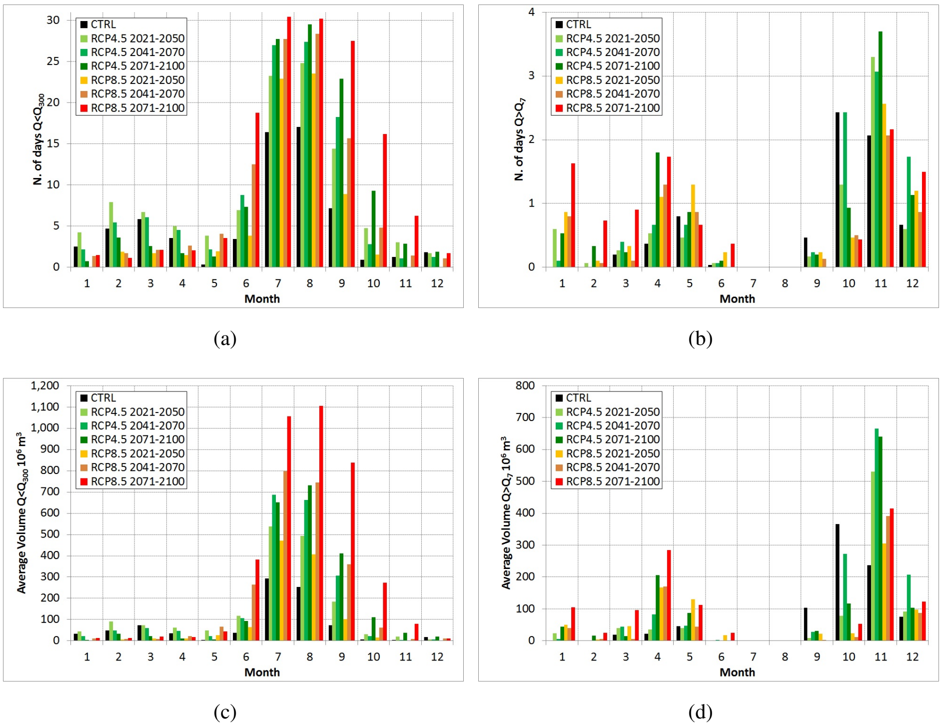


Figure 14:
Low and high flow occurrence and severity analysis under climate change conditions. Average number of days (a,b) the threshold is exceeded and the average volume associated (c,d)

$$V_{F,i} = 86400 \times \sum_{j=1}^{N_i} \max\left(0, Q_j - Q_7\right) \quad (3)$$

while D_F is the average number of days such as $Q > Q_7$, Fig.14(c) and (d). Under RCP4.5 scenario the drought volume is estimate to double (as minimum) in summer, while variation in the remaining season are negligible; coherently the average number of low flows days increases and it is likely the persistence of low flow regime during the whole summer season. Under RCP8.5 scenario the situation is even more extreme, at 2071-2100 the estimated drought volume is almost three times the one in the control period and low flows become the "standard" river regime in summer, conversely winter droughts show a limited variability with respect to the control period. According to the simulations performed, in the future, discharges will exceed Q_7 more often from November to June and less often in September and October. In terms of high flow volumes; in spring, projections at 2071-2100 are both characterised by a significant increase in the volume, and in autumn, both projections show less frequent and lower volumes than the control period and RCP4.5 projections are more severe than RCP8.5.

6.4 HYDROLOGICAL HAZARD: CALORE IRPINO RIVER

As illustrated in Section 5.4 Calore Irpino River due to its limited dimensions and the reduced anthropogenic pressure is an ideal test case to evaluate the effects of the different components of the modelling chain adopted on both input and output variables, in particular, a detailed description of the impacts of different bias correction methods tested is reported in [51] together with the analysis of their impacts on the hydrological cycle, while [46] provides the step by step implementation and analysis of the results achieved. Within this Section, the main findings in terms precipitation, temperature and discharge under RCP4.5 and RCP8.5 on the near (2021-2050), medium (2041-2070) and long (2071-2100) term are summarised. Figure 15 reports the results for the simulations driven by RQUANT bias corrected precipitation and temperature time series, but these results are analogue to those of the other simulations driven by bias corrected and not climate variables. On the left side are reported the projections under RCP4.5 and on the right side those under RCP8.5.

At 2021-2050, the average precipitation is expected to reduce, with the exception of February, August and November under RCP4.5 conditions and of February and August only under RCP8.5 scenario. It is worth to note that the about 40% increase in August corresponds an increase in daily precipitation of about 0.5-0.6 mm/day. On the same period, the temperature is expected to increase with the highest anomaly in winter: 2.0°C for RCP4.5 and 2.4°C for RCP8.5 and the lowest in summer: about 1.4°C for both scenarios. As result, the simulated discharges are, on average, reduced of 15.9% (RCP4.5) and -18.4% (RCP8.5), under RCP4.5 scenario the maximum reductions are simulated between spring and winter, while for RCP8.5 the highest reduction rates are in autumn and winter.

At 2041-2070, the average precipitation is expected to reduce, with the exception of February (+3.9% under RCP4.5) and November (+0.3% under RCP8.5), as result the yearly precipitation is about 17.8% (RCP4.5) and 28.1% (RCP8.5) less than in control period. For temperature, a positive annual anomaly of 2.3°C for RCP4.5 and 3.0°C for RCP8.5. As for 2021-2050 period, the winter anomalies are the highest: 2.7°C for RCP4.5 and 3.5°C for RCP8.5 while the lowest are for RCP4.5 in spring (1.9°C) and for RCP8.5 in autumn (2.8°). Discharges show a yearly decrease of about 22.7% under RCP4.5 scenario and of 33.5% under RCP8.5; for RCP4.5 the discharge anomaly ranges between -32.3% (December) and -11.8% (March), the anomaly, under RCP8.5, is more severe and it varies between -45.2% (October) and -18.6% (March).

At 2071-2100, the average precipitation is about 19.1% (RCP4.5) and 35.4% (RCP8.5) less than in the control period with a decrease of about 40% between May and September (RCP4.5) and between 50% and 70% from May to August (RCP8.5). Only under RCP4.5 scenario, positive anomalies are projected in February (8.2%), March (7.6%) and November (21.5%). For temperature, the positive anomaly persists and it is estimated in 2.9°C for RCP4.5 and 5.2°C for RCP8.5 on annual scale. In particular, under RCP4.5 the temperature anomaly varies between 2.7°C in summer and 3.4°C in winter, while under RCP8.5 it ranges between 4.8°C both in spring and autumn and 6.2°C in winter. The projected discharges, due to the projected precipitation reduction and temperature raise, reduce of 21.2% under RCP4.5 and 42.6% under RCP8.5 scenario. Under RCP4.5, to the positive anomaly of precipitation in February, March and November does not correspond a positive value in discharge anomaly (only February shows a negligible +0.2%) meaning that the precipitation increase is not sufficient to compensate the soil, vegetation and atmosphere water demand. Under RCP8.5, the discharge anomaly is always negative and it ranges between -19.6% in February to -64.4% in November, on average, the seasonal anomaly varies between -34.8% in spring and -56.8% in winter.

According to the simulations performed, in the future, Calore Irpino River is expected to be

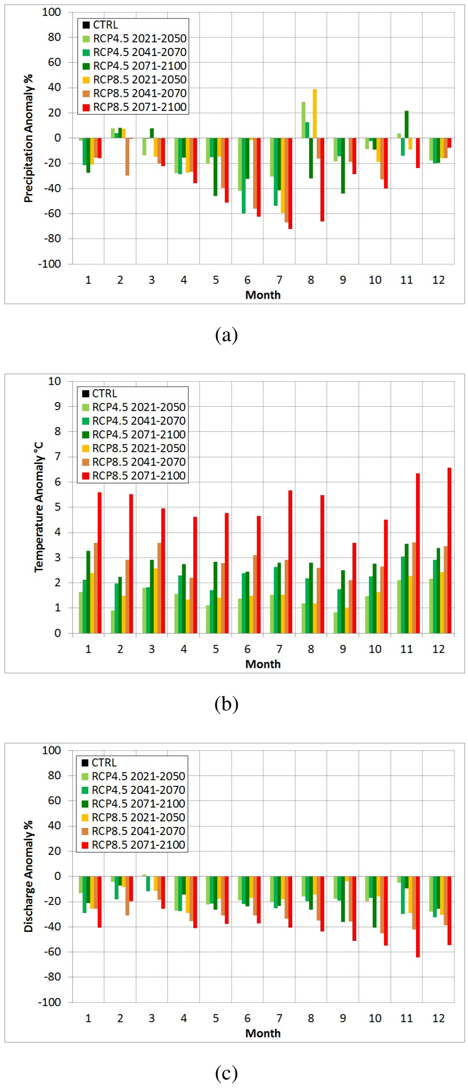


Figure 15:
Precipitation, temperature and discharge anomalies under RCP4.5 and RCP8.5 for the periods 2021-2050, 2041-2070, 2071-2100

more prone to prolonged low flows periods that may cause problem to the agricultural production of this area.

7. CONCLUSIONS

The paper briefly summarized some of the results achieved by REMHI Division [5, 25, 28, 31, 33, 30, 44, 50, 49, 47, 53, 52, 57, 58, 43, 45, 32, 22], within the Work Package A.2.17 of GEMINA project, on four different test case areas, on climate change and weather-induced geo-hydrological hazards.

In particular, concerning the assessment of the effect of climate change on landslide activity, the main results about shallow and fast landslide test case are reported; however, through the same approach above described, deep analysis have been carried out also on Orvieto clayey slope affected, instead, by slow/very slow movements [57, 31, 33]. 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.

It is worth noting that both the reported landslide case histories have extensively analysed also in Chapter 3 of recent Italian contribution for "Slope Safety preparedness for Effects of Climate Change" [28] held in Naples (co-organized by REMHI-CMCC) last November where reports from about 20 countries have been discussed by researchers of different disciplines.

Concerning floods and low flow hazards, Po river basin surely represent a challenging test case because of its extent and geomorphological complexity; on the other hand, it may be regarded as fully illustrative of the variations in, hydrological cycle, potentially occurring in the Mediterranean area. In terms of discharges, the simulations performed show an average decrease, under both RCPs considered. The magnitude of this reduction is a function either of the scenario and the projection period considered. The exceedance analysis on low flows shows that, in summer, Po River these events are expected to become more common and the water deficit associated with them is not negligible. In terms of high flow, on average, the threshold would be exceeded more frequently and the associated volumes are higher, especially in November. Similar analysis have been carried on over a the Calore Irpino river basin in Campania [46], in this case, also impacts on hydrological cycle components have been investigated, see e.g. [23].

Although, all the findings shown here are affected by the overall uncertainty of the modelling chain chosen [38, 4], they provide a clear picture of the fragility of Italian territory to climate change. A final consideration concerns the current constraints of climate change simulations which can capture only statistical distributions of precipitation at daily scale, preventing the analysis of the effects of sub-daily precipitation patterns.

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