Analysis of the streamflow extremes and long term water balance in Liguria Region of Italy using a cloud permitting grid spacing reanalysis dataset

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Abstract

Characterizing the hydrometeorological extremes, both in terms of rainfall and streamflow, as well as the estimation of long term water balance indicators are essential issues for the flood alert and water management services. In recent years simulations carried out with meteorological models are getting available at increasing spatial and temporal resolutions (both historical reanalysis and near real-time hindcast studies); these meteorological datasets can thus be used as input in distributed hydrological models to drive long-period hydrological reanalysis. In this work we adopted a high resolution meteorological reanalysis dataset that covers the whole Europe territory for the period between 1979 and 2008, with 4 km grid spacing and 3 hours of time resolution. This reanalysis dataset was used together with a rainfall downscaling algorithm and a rainfall bias correction technique in order to produce input to a continuous and distributed hydrological model. The resulting modelling chain allowed to produce long time series of distributed hydrological variables, inter alia streamflows and evapotranspiration, in the Liguria Region, located in the Northern part of Italy, and among the western Mediterranean areas mostly impacted by severe hydro-meteorological events.

The observations available from the local rain gauges network were compared with the rainfall estimated by the dataset, and then used to perform a bias correction with the aim of matching the observed climatology. An analysis of the annual maxima discharges derived by

simulated streamflow time series was carried out, by comparing them with observed discharge where available and using as benchmark a regional statistical analyses elsewhere. Eventually, an investigation of long term water balance was performed by comparing simulated runoff ratios with available estimations based on observations.

The study highlights both limits and potentialities of the considered framework as a methodological approach to undertake hydrological analysis in study areas mainly characterized by small basins, thus allowing to overcome the limits of observations which are punctual and in some cases not fully reliable.

1 Introduction

The estimation of the magnitude and the probability of occurrence of a certain streamflow is an important task for a number of purposes: risk assessment, design of structural protections against flooding, civil protection aims, settings of thresholds in early warning systems.

The standard approach of using streamflow observations to carry out a statistical analysis on a particular outlet (Kottegoda and Rosso, 1997), is not always possible because of lack of observations; to solve this problem a frequency regionalization approach can be used (De Michele and Rosso, 2002) even using both observations and streamflow derived by hydrological modelling (Boni et al., 2007).

On the other hand studies and methodologies regarding the management of water resources and drought also have an important role especially in the perspective of possible future changes in climate and water needs (Calanca et al., 2006; Fu et al., 2007; Döll and Müller, 2012; Asadieh and Krakauer, 2017). In this case the analysis of long-term water balance components is of primary importance, and the evaluation of total runoff and evapotranspiration becomes crucial.

In the last decades the use of Reanalysis of past weather for hydrological purposes and to study basins behaviour in different hydrological regimes became quite frequent, also because the reliability of reanalysis meteorological variables is constantly improving together with the increasing of spatial and temporal resolution. Among many others, Choi et al. (2008) investigated the applicability of temperature and precipitation data from the North American Regional Reanalysis (NARR, about 32 km grid spacing) for hydrological modelling of selected watersheds in northern Manitoba, while Bastola and Misra (2013) used reanalysis products as surrogates for large-scale observations and showed that they are superior in simulating hydrological response in respect to other four considered meteorological datasets. Furthermore, Krog et al. (2015) used ECMWF interim reanalysis (ERA-Interim, about 70 km grid spacing) as input to an hydrological model in order to better understand the processes that drive the hydrological response of one of the largest rivers in Patagonia; similarly, Nkiaka et al. (2017) investigated the potential of using global reanalysis datasets as input for hydrological modelling in the data-scarce Sudan-Sahel region.

In this work a high-resolution (Δt=3 h, Δx=4 km) regional dynamical downscaling of historical climate scenarios is used as input to a hydro-meteorological chain including a rainfall downscaling algorithm (RainFARM, Rebora et al. 2006a, 2006b) and a continuous distributed hydrological model (Continuum, Silvestro et al. 2013), producing high-resolution (Δt=1 h, Δx=< 500 m) 30 years length modelled variables history for a reference Mediterranean region.Both Continuum model and RainFARM downscaling algorithm were widely employed and tested in the study area in previous works (Gabellani et al., 2008; Silvestro et al., 2014; Laiolo et al., 2015; Davolio et al., 2017).

The CORDEX (COordinated Regional climate Downscaling Experiment, Giorgi et al. 2009) initiative is aiming at producing regional climate change projections worldwide for input into impact, adaptation and disaster risk reduction studies using regional climate models (RCM) at fine spatio-temporal resolution and forced by different GCMs from the CMIP5 (Coupled Model Intercomparison Project Phase 5, CMIP5) archive. Along these lines Kotlarski et al.

(2014) confirmed, with simulations on grid-resolutions up to about 12 km (0.11°), the capability of RCMs to correctly reproduce the main features of the European climate for the period 1979-2008. However they also exhibit relevant modeling errors concerning some metrics, certain regions and seasons: as an example precipitation biases are in the ±40% range while seasonally and regionally averaged temperature biases are generally smaller than 1.5 °C. Building on these findings, Pieri et al. (2015) moved one step further, in the framework of the EXtreme PREcipitation and Hydrological climate Scenario Simulations (EXPRESS-Hydro) project, by dynamically downscaling, at 4 km grid spacing and 3 hours time resolution, the historical climate scenarios generated by the ERA-Interim reanalysis using the state-of-the-art non-hydrostatic Weather Research and Forecasting (WRF) regional climate model.

The distributed nature of the state and output variables of the hydrological model allowed to investigate the possibility of using this kind of modelling chain for extreme streamflow statistical analysis (e.g. distribution of annual discharge maxima) and long term water balance (e.g. long term runoff ratio) in a fully distributed perspective. Furthermore, the high spatial grid spacing and time resolution of the forcings, together with the use of a rainfall downscaling model, allowed to explore the use of such high resolution reanalysis in regions characterized by the presence of small hydrological watersheds (Silvestro et al., 2011) in areas with complex topography and frequently stroke by flash floods (Altinbilek et al., 1997; Cassola et al., 2016). These latter, together with the analysis of the distribution of flood extremes, are the main novel contributions of the presented analysis in respect to other works that employ a similar modelling cascade. It is in fact mandatory using high resolution reanalysis since coarser ones can not reproduce the small-scale rainfall structures needed to correctly reproduce the hydrometeorology processes of the study region.

The study shows the capabilities and the limits of the considered modelling chain to reproduce low frequency streamflow and long term water balance as an alternative to the use of observations, in a scarce data environment or in those cases where the spatial distribution of hydro-meteorological processes results to be essential.

The manuscript is organized as follows: section 2 describes the study area, hydro-meteorological data set and models, section 3 shows the results, and in section 4 the discussion and conclusions are reported.

2 Materials and Methods

2.1 Study Area and Case study

Liguria Region is located in northern Italy (Figure 1), it is characterized by basins which have steep valleys due to their proximity to the Apennines and Alps and drainage area in the range 10^1 to 10^3 km^2. The response time to precipitation pulses of these basins is short, ranging between 0.5 to 10 hours (Maidment, 1992; Giannoni et al., 2005). The maximum elevation of mountains is around 2500 m, valleys have very steep slopes, with average values at basin scale between 10 and 20 % ; a large part of the ground surface of the region is covered with forest or other types of vegetation like meadows and shrubs with the catchments mouth often in correspondence of towns and cities densely inhabited. The hydrological regime is prevalently torrential and the entire study area is frequently stroke by flash floods (Rebora et al., 2013), as a consequence the variability of annual discharge maxima is high. Winter seasons are generally not rigid but the elevation varies from sea level to more than 2000 m, as consequences temperatures are below zero only few days/year along the coast and at low altitude but they drops even below -10 °C inland; during warm season temperature rises rarely over 31-32 °C. Snow occurs only few days during the year and it is not infrequent that near the coast it does not snow for several consecutive years.

A quite dense meteorological stations network monitors the territory of Liguria, it is named OMIRL – "Osservatorio Meteo-Idrologico della Regione Liguria" and it is managed by the Environmental Agency of Liguria Region (ARPAL). This monitoring network yields raingauge measurements with timesteps smaller than 1 hour (e.g. 5-10 minutes) for more than 150 gauges over the region; the density is averagely 1 raingauge/40 km^2. Temperature, radiation, wind, air humidity gauges are part of the system, even though their density is lower than the rain gauges one. Continuous data were collected from 2011 to 2014 for calibrating/validating the hydrological model. For a subset of 95 raingauge stations (see Figure 1), historical validated data are available from 1978 to 2010 at daily scale; in fact ARPAL built a database useful for climatic and statistical analysis which is freely available on web (http://www.arpal.gov.it/homepage/meteo/analisi-climatologiche/atlante-climatico-della-liguria.html). These data were used in the presented study for bias correction of reanalysis rainfall estimation.

For 11 level gauge stations continuous hourly data are available from 2011 to 2014 together with stage discharge curves, while annual discharge maxima (hereafter ADM) time series longer than 30 yrs are available for a set of 15 level gauges (Figure 1); these latter cover sub-periods which are not continuous from 1950 to recent years. Moreover, in the Hydrologic Annual Survey (http://www.arpal.gov.it/homepage/meteo/pubblicazioni/annali-idrologici.html), an official document published by the Regional Agency for Environment Protection, annual basin-scale runoff ratio (defined as runoff volume/precipitation) are available for 6 stations.

In Table 1 the availability of the discharge and discharge-related data is summarized together with hydro-geomorphic characteristics of the basins upstream each station.

All the described data are checked by ARPAL personnel in agreement with WMO recommendations to keep out measuring errors and evidently not valid values.

2.2 EXPRESS-Hydro reanalysis

Pieri et al. (2015) assessed the WRF regional climate model performances to reproduce observed precipitation extremes, over Europe and with a particular focus on the Greater Alpine Region; the assessment was performed by comparing the simulations results with available gridded observational datasets such as the high-resolution Alpine precipitation grid dataset (APGD) developed by MeteoSwiss in the framework of the European Reanalysis and Observations for Monitoring (EURO4M) collaborative project (Isotta et al. 2013). Overall Pieri et al. (2015) results showed that increased grid spacing together with the use of explicitly resolved convection allows to achieve a better modelling of the precipitation field spatio-temporal distribution. Furthermore, the overestimation of precipitation (around 5% on annual average over the European domain with respect to E-OBS observational data) was reduced significantly and the distribution and the statistics of the rainfall rate, particularly over the Alps and Apennines area, were better reproduced. More recent studies confirmed the need for high-resolution dynamical downscaling for extreme weather impact studies in regions with complex terrain (Pontoppidan et al. 2017, Schwitalla et al. 2017).

In this work we extended the analysis of average annual and seasonal high-resolution rainfall reanalysis for Liguria area, taking advantage of the richer climatological dataset (95 stations): results and comments are provided in section 3.1.

2.3 Bias correction of rainfall fields (B.C.)

Before being used as input for the hydrological simulations, the EXPRESS-Hydro reanalysis rainfall dataset was compared with the climatological precipitation data obtained by the Liguria raingauge dataset (Liguria climatological atlas). The observed dataset is constituted by validated time series of about 95 raingauges homogeneously distributed on the Liguria

Region territory: the time series cover the whole 1979-2008 period of the EXPRESS-Hydro dataset (even if not for all gauges) at daily timestep.

In order to provide to the hydrological model Continuum the most reliable input data possible, the EXPRESS-Hydro reanalysis precipitation data were BIAS-corrected by employing the observed data to assure an accurate reproduction of the rainfall climatology of the area in terms of monthly cumulate. No other variables were available in the Liguria climatological atlas, so no BIAS correction was applied to other variables of the EXPRESS-Hydro dataset.

Different methods are available in literature to perform a BIAS correction (hereafter B.C.) on different variables (rainfall, temperature, etc., Fang et al. 2015): in this work a CDF-matching approach was selected (Fang et al. 2015).

Given the analysis performed on the EXPRESS-Hydro reanalysis dataset (see Section 3.1), and the statistical analysis of the observed data (Liguria climatological atlas) it was evident that a strong seasonality is present in both datasets.

In order to preserve both the seasonality and the inter-annual variability of the observations, the correction was based on the monthly cumulates, that were computed for both the Express-Hydro dataset (thus producing N x 12 maps representing the average cumulate rainfall map for each month, N number of years of the Express-Hydro dataset) and the observed dataset (producing time series of N_{obs} x 12 values representing the average accumulated rainfall for each month and for each of the available raingauges, N_{obs} number of years of the observed dataset).

To allow a direct comparison between the observed data and the modeled dataset, the monthly cumulated data from the raingauges were previously interpolated on the Express-Hydro spatial grid, by using a kriging technique with a Spherical variogram. No regression with other spatialized variables (e.g. elevation) was employed because previous tests showed that no significant correlation were present. Since the density of the rain gauge network is high and considering the fact that the interpolation was employed only for the monthly cumulates, the possible errors introduced by the interpolation can be considered acceptable. In fact, the spatial and temporal structures of the rainfall events of interest (short-period and spatially concentrated, see previous Sections and Boni et al. (2007)) are not significantly altered.

For each cell i, the empirical CDF (Cumulative Distribution Function) of observed and modeled values were computed. At the purpose of minimizing distortions of the information, these CDFs were computed separately for each month of the year (January, February, etc.).

In the CDF-matching process the observations CDF was imposed to the Expresss-Hydro time series of a given cell i in order to obtain the corrected time series of the monthly cumulate:

$$PM'_{i,m} = F_{OSS,i}{}^{-1}\left(F_{MOD,i}\left(PM_{i,m}\right)\right) \qquad (1)$$

where PM is the Express-Hydro monthly cumulate rainfall, PM' is the bias-corrected monthly cumulate rainfall, m is the index of the month of the original series, $F_{MOD,i}$ and $F_{OSS,i}$ are respectively the CDF of the modeled and observed monthly rainfalls in the cell i.

Given these corrected monthly time series, the single instantaneous value of rainfall p (3-hours cumulate) was corrected as follows:

$$p'_{i,t} = p_{i,t}\frac{PM'_{i.m}}{PM_{i,m}} \qquad (2)$$

where:

- $p_{i,t}$ is the 3-hours cumulate rainfall modeled in the cell i at instant t
- $p'_{i,t}$ is the bias-corrected 3-hours cumulate rainfall modeled in the cell i at instant t
- $PM_{i,m}$ is the monthly cumulate rainfall modeled in the cell i in month m (in which the instant t falls)
- $PM'_{i,m}$ is the monthly cumulate rainfall modeled in the cell i in month m (in which the instant t falls) corrected with the CDF-matching

The described procedure allowed obtaining a 3-hours maps dataset in which the model bias was eliminated by keeping the characteristics of the model in terms of seasonality and inter-annual variability. Furthermore, the procedure design allows to avoid alterations of possible temporal trends, at both domain and cell spatial scale.

2.4 Downscaling the rainfall with RainFARM Model

RainFARM (Rebora et al. 2006a, 2006b) is a mathematical model able to downscale rainfall fields that can be exploited for generating rainfall scenarios consistent with large scale forecasts done by the Numerical Weather Prediction Systems (NWPS) as in Laiolo et al. (2013) and/or by expert forecasters (Silvestro and Rebora, 2014). The model accounts for the variability of precipitation fields at small spatial and time scales (e.g. $L \leq 1$ km, $t \leq 1$ hour), preserving the precipitation volume at those scales where quantitative precipitation forecasts are considered reliable (L_r, t_r). RainFARM is able on one side to preserve spatial and time patterns at L_r, t_r, on the other side to produce small-scale structures of rainfall which are consistent with detailed remote sensor observations as meteorological-radar estimation.

In the model the spatial-temporal Fourier spectrum of the precipitation field is estimated using rainfall fields predicted by a meteorological model and it is mathematically described as follows:

$$\left|\hat{g}(k_x, k_y, \omega)\right|^2 \propto (k_x^2 + k_y^2)^{-\alpha/2} \omega^{-\beta} \qquad (3)$$

k_x and k_y are the x and y spatial wavenumbers, ω the temporal wavenumber (frequency), while α and β are two parameters that are calibrated fitting the power spectrum of rainfall derived by a NWPS on the frequencies that correspond to the spatial-time scales L_r, and t_r. Extending the spectrum defined by equation (3) to the larger wave numbers/frequencies it is possible to generate a spatial-time rainfall field at a high resolution (Rebora et al. 2006b). Since the Fourier phases related with the power spectrum (3) are randomly generated before the backwards transformation in real space, RainFARM can give as output an ensemble of equi-probable high-resolution fields that remain coherent at large scale with the rainfall forecast done by NWPS. RainFARM was designed to be used for flood forecast systems implemented on small and medium sized basins (drainage area < 10^3-10^4 km^2) and it was tested in various works on the study area (Rebora et al., 2006a; Silvestro et al. 2012; Silvestro and Rebora, 2014)

In this study the algorithm is used to downscale the bias-corrected EXPRESS-Hydro reanalysis; the reliable spatial and time scales are assumed as the nominal grid spacing and temporal resolution of EXPRESS-Hydro precipitation (4 km and 3 hours, Hardenberg et al. 2015 and Pieri et al. 2015). The downscaling algorithm is not used in probabilistic configuration, but to build a possible rainfall time-spatial pattern at 1 km and 1 hour resolution that is compatible with the runoff formation at small scales, since most of the catchments in the proposed study area have reduced dimensions (often <100-200 km^2) with response time in the order of 1-6 hours.

2.5 The hydrological model: Continuum

The hydrological model used in this study is *Continuum* (Silvestro et al. 2013), it is a distributed and continuous model that relies on a space-filling approach, and uses a consolidated way for the identification of the drainage network components (Giannoni et al., 2005). All of the main hydrological processes are mathematically described in a distributed way in Continuum but it was designed to be a balance solution between complex physically based models (which describe the physical phenomena with high detail often introducing complex parameterization) and models with a empirical approach (easy to implement but far from reality) (Silvestro et al., 2015). The basin or domain of interest is represented through a regular grid, derived by a Digital Elevation Model (DEM) while the flow directions are defined with an algorithm that calculates the directions of maximum slope using the DEM. An algorithm classifies each cell of the drainage network as hillslope or channel flow depending on the main flow regime; a morphologic filter defined by the expression $AS^k = C$ is used to distinguish between hillslopes and channels ; A is the drainage area upstream of each cell [L^2], S is the local slope [-], k and C are constants related to the geomorphology of the catchment (Giannoni et al., 2000). The surface flow scheme treats differently channel and hillslope flows: the overland flow (hillslopes) is described by a linear reservoir schematization, while an approach derived by kinematic wave (Wooding, 1965; Todini and Ciarapica, 2001) is used for modeling the channel flow.

Subsurface flows and infiltration are modeled using a methodology based on an adaptation of the Horton equations (Bauer, 1974; Disikin and Nazimov, 1997); it accounts for soil moisture evolution even in conditions of intermittent and low-intensity rainfall as described in Gabellani et al., (2008).

Interception of vegetation is schematized with a reservoir that has a retention capacity S_v; this latter is estimated using static informative layers of vegetation type or Leaf Area Index data; the flow in deep soil and the water table evolution are modeled with a distributed linear reservoir schematization and a simplified version of Darcy equation.

The energy balance uses the “force restore equation” (Dickinson, 1988) that allows to explicitly model the soil surface temperature.

Snow melting and accumulation is simulated with simple equations forced with air temperature and solar radiation (Maidment, 1992) as described in Silvestro et al. (2015).

Continuum needs as input the following variables: rainfall, air temperature, short-wave solar radiation, wind velocity, air relative humidity. When the ExpressHYDRO reanalysis are used as input the following variables are considered: 2 m temperature, 10 m wind, rain depth, downward short wave flux at ground surface, 2 m air relative humidity

The parameters that require calibration in Continuum model are six, they are often estimated at basin or sub-basin scale: two for the surface flow (u_h [$m^{0.5}s^{-1}$] and u_c [s^{-1}]), two for the subsurface flow (c_t [-] and c_f [-]) and two for deep flow and watertable (V_{Wmax} [mm] and R_f [-]) processes.

The parameter u_h affects those hydrograph components which are related to fast surface flow as well as u_c but the impact of this latter depends on the length of the channeled paths. c_f is related to saturated hydraulic conductivity and controls the rate of subsurface flow rate (i.e., it). c_t identifies the part of water volume in the soil that can be extracted through evapotranspiration only and is thus related to the soil field capacity, while both c_t and c_f regulate the dynamics of saturation of the root-zone. The two parameters V_{Wmax} and R_f rule the flow in the deep soil and the dynamic of watertable, they impact on recession curves and have certain influence on flood hydrographs, only when catchments of large drainage area are considered (Silvestro et al., 2013).

In the presented work, Continuum was implemented with a time resolution of 60 min and with a spatial resolution of 0.005 deg (about 480 m). The Shuttle Radar Topographic Mission (SRTM) DEM was employed.

It was possible to calibrate the model for 11 sections where streamflow observations are available; ground stations measurements were interpolated on a regular grid of 1 km resolution by using Kriging method and used as input to the model. 01/01/2013-31/12/2014 was used as validation period, and the following skill scores, used also in the calibration process, were employed to measure the model performances.

The Nash Sutcliffe (NS) coefficient (Nash and Sutcliffe, 1970):

$$NS = 1 - \sum_{t=1}^{t\max} \frac{\left(Q_m(t) - Q_o(t)\right)^2}{\left(Q_m(t) - \overline{Q_o}\right)^2} \qquad (4)$$

where $Q_m(t)$ and $Q_o(t)$ are the modelled and observed streamflows at time t. $\overline{Q_o}$ is the mean observed streamflow.

Relative Error of High Flows (REHF)

$$REHF = \frac{1}{t\max}\left[\sum_{t=1}^{t\max}\frac{\left|Q_m(t)-Q_o(t)\right|}{Q_o(t)}\right]_{Q>Qth} \qquad (5)$$

where Q_{th} is chosen as the 99 percentile of the observed hydrograph along the calibration period. While NS has the purpose of evaluating the general reproduction of streamflow, REHF score has the aim of giving high weight to high flows leading the calibration to better reproduce the flood events.

NS and REHF were combined in a multi-objective function to carry out the calibration using the approach proposed in Madsen (2000). Calibration was done analyzing the parameter space using a brute force approach on 2011-2013 period in order to find the parameter set that optimize the multi-objective function. Hourly streamflow data were used, while Curve Number map was derived by the CORINE Land Cover (http://www.sinanet.isprambiente.it/it/progetti/corine-land-cover-1). The final setting is similar to the one described in Davolio et al. (2017).

The values of the skill scores were calculated for the validation period and resulted to be satisfactory; they are reported in Table 2.

In those basins where it was not possible to make the calibration, average values of the parameters obtained by the calibration process are assumed (see Table 2). The optimal condition would be to have the chance of calibrating the model in all the study region but this was not possible for lack of data. However, the employed hydrological model (as well as similar models developed for working on same study area) demonstrated to well work in the study environment (Giannoni et al., 2000, 2005; Gabellani et al., 2008; Silvestro et al. 2013, 2015, Cenci et al 2016) giving reasonable and quite reliable results also for not calibrated sections when used for flood forecast aims (Regione Marche, 2016). This is valid when the basins have similar characteristics especially regarding the surface response to intense rainfall events and the main genesis of rainfall-runoff process; as a consequence, the parameters have often similar values moving from a catchment to another. This was also the approach adopted in Boni et al. (2007).

In order to have reduced warm up impacts on the 1979 (first year of EXPRESS-Hydro) simulation a first run was done starting from a predefined initial condition and the state variables simulated on the 31 of December of every year (from 1979 to 2008) were averaged to estimate a reasonable initial condition for 1th January 1979 to be used in the final simulation.

Once the run of hydrological model for the period 1979-2008 was done, we had available a streamflow time series for each pixel of the calculation domain; ideally this is equivalent to having a sort of gauge every Δx along the stream network. Since the spatial resolution of the hydrological model is 480 m we discarded the analysis for basins with area smaller than A_{th}=15 km^2, because we believe that the surface water motion processes are not modeled with a sufficient detail; A_{th}=15 km^2 means a number of pixel around 60-70 to represent the catchment and at least some cells classified as channel (Giannoni et al., 2005).

2.6 Distribution of the annual discharge maxima

The results of the modeling chain were firstly compared with observations using a typical station-wise comparison approach: 15 gauge stations with at least 30 years of annual discharge maxima were identified along the Ligurian territory from the eastern side to the western one.

It was not possible to ensure a perfect overlapping between the simulation period and the observed data availability, in many cases observed data are not temporally continuous and they may cover longer periods (in some case 50-60 years) with large time windows of missing data. However on the basis of the conclusions drawn in the framework of Liguria climatological atlas, major climate change related trends for temperature, precipitation, and so forth are not evident, thus supporting the database usage despite these data gaps.

The comparison between observed and reanalysis driven annual discharge maxima (ADM) is firstly based on the analysis of the respective cumulative density function distributions.

The reanalysis driven ADM were fitted with a General Extreme Value (GEV) distribution (see e.g., Hoskin and Wallis, 1993; Piras et al., 2015) that represents a good compromise between flexibility and robustness. Other works based extreme statistical analysis on the Two Components Extreme Value (TCEV) model (Rossi et al., 1984), nevertheless we decided to use GEV since it has a smaller number of parameters and it was successfully applied for a wide number of applications (CIMA Research Foundation, 2015; Piras et al., 2015).

2.7 Regional analysis of the annual discharge maxima

In order to carry out a comparison following a distributed approach we referred to the work done in Boni et al. (2007) which is one of the methods operationally used in Liguria Region (by public authorities and private engineer) to estimate the ADM quantiles (Provincial Authority of Genoa, 2001; Silvestro et al., 2012). The method was conceived and tested especially for the Tyrrhenian catchments of Liguria Region, so the presented analysis was carried out only for this area. The method defines a hierarchical approach based on the analysis of the non-dimensional random variable $X_0 = X/\mu_x$, obtained by grouping together all available data, and making them non-dimensional with respect to each local (gauging station) sample mean, μ_x, taken as the index flood for gauged sites. Index flood is estimated even where observations were not available with support of rainfall regional frequency analysis and rainfall-runoff modelling in order to allow quantile estimation in each point of the region.

The final result is a methodology to estimate the index flood that can be formalized as it follows:

$$Q_{index} = f(Area, longitude) \quad (6)$$

While the quantile is:

$$Q(T) = K(T) \cdot Q_{index} \quad (7)$$

where T is the return period and K(T) is defined by the non-dimensional regional growth curve. Boni et al. 2007 defined a unique K(T) applicable to all the studied region.

In the case of the modelling chain analyzed in this work there is the availability of a large number of reanalysis driven time series because we can pick the 30 years long ADM series for each pixel of the model grid where drainage area is larger than A_{th}. In practice, the fact that we are using a distributed hydrological model, on one side allows the index flood estimation as a simple mean of a time series in each point of the domain, on the other side provides a large number of data to build the non-dimensional regional curve.

3 Results

3.1 Precipitation analysis

The comparison between precipitation climatology over Liguria from observational data and Pieri et al (2015) results has been undertaken at the annual and seasonal scales.

Pieri et al. (2015), using EURO4M-APGD reference observational dataset (Isotta et al. 2013, with about 50 daily raingauge stations over Liguria), already showed an overall underestimation of the WRF rainfall depths on annual basis in Liguria, more evident on the eastern side of the region (Figure 3, panels e-f of Pieri et al. 2015), with differences in the range between -2 and -1 mm on the coastal eastern Liguria portion and between -1 and 0 mm/day on the eastern Appennine side.

The same analysis was repeated in this study, using 95 raingauge stations over Liguria: the total annual rainfall depth results are largely confirmed both on eastern and western Liguria sides (Figure 2).

Concerning the seasonal temporal scales results, EXPRESS-Hydro tends to underestimate average observed rainfall depths during DJF (Figure 3) on eastern Liguria portion (between -1 and 0 mm/d) while overall it overestimates them on central-western Liguria (0-1 mm/d). Similar argument holds also for the MAM period (Figure 3), even if the EXPRESS-Hydro overestimation tends to get larger on the western side. During the JJA period (Figure 3), instead, EXPRESS-Hydro exhibits an overestimation of observed average rainfall depths between 0 and 1 mm/d over the western and eastern sides, while it is increasing to 1-2 mm/day over central Liguria. The underestimation gets worse over eastern Liguria during SON (Figure 3), with values between -2 and -1 mm/d over the inland portions and up to -3 and -2 mm/d over the coastal one. Conversely, on the rest of the region the underestimation falls between -1 and 0 mm/d. In Figure 4 the comparison between observations and EXPRESS-Hydro at seasonal scale is also presented in terms of scatter plots exhibiting a good correlation between reanalysis and observations, while in Table 3 we reported the BIAS and the Root Mean Square Error (RMSE).

Figure 5 shows the box plot of monthly precipitation averaged at regional scale for both EXPRESS-Hydro and observations. For each month we have two time series, observed and modeled, of rainfall cumulated values obtained averaging the maps. The comparison highlights that EXPRESS-Hydro reproduces quite well the variability along the 30 years but often underestimates the rainfall amount; this is particularly evident in January, September and October.

Figure 6 shows the same analysis of Figure 5 but performed at catchment scale on 4 basins whose characteristics are reported in Table 1; this Figure gives an idea of the performance of EXPRESS hydro at basin scale. It is interesting to evidence that in Entella closed at Panesi and Vara closed at Nasceto, which are located in central-east part of the study region, there is a general underestimation of rainfall during autumnal period, which is not present in the other 2 test basins. On the contrary, the box plots on Argentina closed at Merelli and Arroscia closed at Pogli show an overestimation during spring especially on April and May.

3.2 Distribution of the annual discharge maxima

In Figures 7 to 9 a series of graphs are presented where a selection of observed and reanalysis driven ADM CDF distributions are compared, together with the GEV obtained by reanalysis driven ADM and the corresponding 95% confidence intervals. For each station both the results obtained with and without rainfall B.C. are reported. The comparisons correspond to six hydrological gauging stations where reliable and long-time series of observed ADM are available.

The cases in Figure 7 show a shift of the observed distribution with respect to the modeled one especially without B.C. Low ADM observed values lay out of the confidence intervals of the reanalysis driven ADM GEV distribution, while the most extreme values are inside the confidence intervals. The distributions without bias correction show underestimation of ADM; B.C. leads to very good results for Entella closed at Panesi case and to an overestimation on Bisagno closed at La Presa case.

Magra closed at Piccatello (Figure 8) shows an overestimation in both cases, which is getting higher after the B.C; Argentina closed at Merelli benefits of B.C. especially regarding the extreme ADM values.

Arroscia closed at Pogli shows an improvement of reanalysis driven ADM, once B.C. is performed, while Nervia ADM without B.C. fits well observations and B.C. leads to an overestimation (Figure 9).

The Kolmogorov-Smirnov test with 5% significance level was applied to all the selected stations and corresponding results are summarized in Table 4. It is interesting that BIAS correction does not allow to increase the number of null-hypothesis (data belong to the same distribution) but for both the cases, with and without B.C., we have 9 stations on 15 that pass the test. In some stations B.C. worsens the results while in some other an improvement is observed. Changing the significance level does not change the final findings in a significant way: with 1% 12 stations pass the test with B.C. and 11 without B.C., with 10% 7 stations pass the test with B.C. and 7 without B.C.. This fact could derive on how the B.C., that acts on the monthly volume, affects short and severe rainfall events in different parts of the study area; these intense and short events are often the ones that in many cases cause the ADM.

The poor reproduction of ADM in some sections can be due to various causes; on one side it was not possible to calibrate the model all over the study region, on the other side in some periods and in some subregions the rainfall reanalysis is probably poorly representative of actual rainfall and B.C. does not correct it enough. Moreover observed peaks and simulated peaks are often referred to different time periods; this fact, together with the hydro-climatic regime typical of the study region (flash flood regime with high variability of ADM), could have a significant impact on final results.

We would like also to highlight the fact that simulated ADM distributions have often similar shapes to the observed ones and suffer of a sort of bias (for example Bisagno closed at La Presa, Figure 7), while in other cases the simulated ADM distribution is only partially out of the confidence intervals (example Argentina closed at Merelli, Figure 8). The average hydrologic regime on the study region could be only partially affected by the local bad fittings, and this is confirmed by the analysis of the regional growing curve in section 3.3.

3.3 Regional analysis of the annual discharge maxima

Figure 10 shows the comparison between the non dimensional regional growth curve obtained fitting a GEV on simulated ADM obtained with and without B.C., the observations (available ADM on Liguria Region) and the Simulated ADM; results are quite good even if it seems that modeling chain without B.C. leads to a small underestimation of high frequency events (low T) and a small overestimation of low frequency events (high T) in respect to the observations. Anyway both observed and modeled ADM lay inside the confidence intervals (95 %) for a large part of the curve.

In the Figure we reported the curves built using simulations of all the sections with drainage area larger than A_{th} together with those obtained using only the sections where the hydrological model was calibrated. The curves that used only calibrated sections are really similar to those built using all the sections, this proves that this latter option enhances the robustness of the regional curve estimation without introducing evident errors.

The main differences in the case of B.C. configuration are that observations lay always inside the confidence intervals and there is a better matching between simulated and observed sample curves. This is a significant finding in fact the regional curve is an important ingredient to deal with quantile estimation in ungauged sections.

To compare the quantiles estimated using the modelling chain with those obtained in Boni et al. (2007) the following ratio was considered:

$$Ratio(T) = \frac{Q(T)_{Model}}{Q(T)_{Reg}} \qquad (8)$$

where Model and Reg stand for modelling chain and regional analysis, T is the return period, Q is the ADM. Ideally, if modelling chain provided exactly the same results of the benchmark regional analysis, the Ratio(T) value should be around 1; Ratio(T) > 1 means overestimation in respect to the benchmark, Ratio(T)<1 means underestimation.

Figure 11 shows Ratio(T) for T=2.9 years (Index Flow) as function of the drainage area (A in km^2), while Figure 12 shows the maps of Ratio(T) for T=2.9 years and T=50 years.

The first consideration is that it appears to exist a relation between Ratio(T) and A, probably the chain cannot reproduce in detail meteorological and hydrologic processes at very small time and spatial scales, that produces sufficient runoff for extreme flow estimation (Siccardi et al., 2005). In fact for A < 30-50 km^2 the underestimation seems quite systematic even if B.C. improves results. Ratio(T) shows a general underestimation also for A>30-50 km^2 but B.C. generally leads to a better distribution between over- and underestimation. From Figure 12 is noticeable that there is a general improvement driven by B.C. especially in those areas where the model chain without B.C. underestimates Q(T). Ratio(T) for T= 50 years and T=2.9 years (Figure 12) have a similar pattern.

In the centre of Liguria Region the Ratio(T) obtained by using EXPRESS-Hydro leads to results which are comparable with findings of Boni et al. (2007) even without B.C., while simulations with B.C. apparently seem affected by overestimation. This could be due to different causes: i) it is possible that EXPRESS-Hydro well reproduces the events at small time and spatial scales (3-6 hours, 10-100 km^2) in that part of the region but generally underestimates monthly cumulates, in this case B.C. could lead to streamflow overestimation; ii) hydrological model could need a better calibration, but this is in our opinion not the case since in a calibrated basin B.C. leads to overestimation even in the site comparison (Bisagno creek, section 3.2) iii) we could also consider the possibility that maybe Boni et al. (2007) underestimates quantiles in this area. It has to be noticed that overestimation for T=2.9 years is larger than that for T=50 years, this is probably due by the fact that the shape of the growing curve in the B.C. case leads to a reduction of the overestimation when T increases; western part of Liguria has similar behaviour even if less stressed and mainly evident for larger basins only.

The underestimation on smaller catchments (A < 30-50 km^2) could be partially due by a not optimal parameterization of hydrological model (especially where calibration was not possible), but it appears more reasonable that the errors related to parameterization would lead to a uniform-like distribution between over and underestimation. However, the model spatial resolution could play a role since the representativeness of catchment morphology degrades for small drainage areas with a general smoothing effect that affects results; it is true that we put a threshold for the analysis (basins with Area<16 km^2 are neglected) but the degradation effect is clearly continuous from large to small drainage areas.

A further cause is presumably the fact that EXPRESS-Hydro cannot always adequately reproduce the rainfall structures at fine spatial and temporal scale, and the downscaling procedure can only partially correct this lack. Moreover the employed time resolution (1 hour after downscaling) could be not sufficient in some cases when drainage area is small (Silvestro et al., 2016; Rebora et al., 2013); as a consequence, the runoff processes needed to trigger such very small catchments in these cases are not properly modelled (Siccardi et al., 2005).

The combination of the aforementioned factors leads us to consider that the underestimation of quantiles for very small catchments (i.e. A < 30-50 km^2) is a structural problem of the modelling chain.

This fact is corroborated by the analysis shown in Figure 13, left panel. The Ratio(T) averaged on the target area is plotted as a function of T for all the sections with drainage Area ≥ 16 km^2. Ratio increases with T especially for the B. C. case, this means that growth curve values (K(T)) obtained by EXPRESS-Hydro partially balance the underestimation of average ADM (used as Index Flow) in the estimation of higher quantiles. Ratio(T=2.9 years) changes from 0.47 to 0.71, Ratio(T=50 years) changes from 0.45 to 0.66. If we increase the threshold area from 16 to 50 km^2 (Figure 13, right panel) results improve with a reduction of the underestimation for both cases (with and without B.C.).

As already shown the general underestimation of Ratio(T) for small catchments is not completely confirmed for all the region, in the central part of Liguria Region there is an area where results are quite good even for basins with Area < 50 km^2; bias correction leads to an overestimation of Ratio(T) in some cases. Apparently in this area EXPRESS-Hydro can produce rainfall spatial-temporal structures able to trigger flood events compatible with the hydro-climatology of small basins. This is also the area of the study region that previous studies demonstrated to be characterized by highest values of rainfall maxima for 1, 3, 6, 12 and hours (Boni et al., 2008).

3.4 Effects of the rainfall downscaling on simulated ADM

In order to assess the influence of the rainfall downscaling, the modelling cascade was applied without using the rainfall downscaling. In this way for each pixel of the domain a 30 years length time series of ADM was obtained by the hydrological model driven with the bias corrected rainfall reanalysis which has not a spatial and temporal pattern below the native EXPRESS-Hydro resolution. The rainfall field was considered with constant intensity over 3 hours and simply gridded from 4 km to 1 km.

We computed the average ADM over 30 years and we compared it with the one obtained by the complete chain on each pixel by estimating the following ratio:

$$RatioDS = \frac{Q_{MeanNoDS}}{Q_{MeanDS}} \qquad (9)$$

The RatioDS was then plot versus the drainage area obtaining the graph in Figure 14.

It is evident how the downscaling affects the results, the impact generally increases when drainage area decreases, it is crucial to simulate the ADM on small catchment when drainage area is lower than 100-150 km^2. The analysis evidences how the underestimation of quantiles shown in section 3.3 would be enhanced without using the rainfall downscaling procedure.

3.5 Water balance and runoff ratio

In this section some considerations about the long-term water balance are shown in order to evaluate how the applied system can reproduce hydrological cycle and some variables interesting for water balance and water management purposes.

Since among the model' output there are maps of evapotranspiration, we estimated the distributed runoff ratio (RR) at cell scale as:

$$RR(x,y) = \frac{Rain(x,y) - Evt(x,y)}{Rain(x,y)} \quad (10)$$

Where Rain(x,y) and Evt(x,y) are the total modeled rainfall and evapotranspiration in the cell which has coordinates (x,y) over the 30 years of simulation: this is interesting to have an idea of the pattern of RR over the region. The maps of RR are shown in Figure 15, together with maps of annual mean rainfall for both cases: with and without B.C..

Spatial pattern of RR is strongly correlated to spatial pattern of precipitation, and this latter is evidently related with orography especially for the case without B.C..

When a single cell has a large number of upstream cells, it tends to be frequently saturated because of the contributions of subsurface flow of the upstream cells. As a consequence we decided to not show the values in the cells that belong channel network as modeled by the hydrological model (Giannoni et al., 2005), because they are poorly representative (generally the values are very low and even negative).

B.C. produces an increasing of precipitation all over the entire region and a reduction of differences between coastal and inland areas. Even the runoff ratio increases with rainfall B.C.

In order to estimate how the modeling chain reproduces the available observations we calculated the runoff ratio at basin scale on a target section s with:

$$RRs(s) = \frac{VQ(s)}{Rain(s)} \quad (11)$$

where Rain(s) is the accumulated rainfall over the basin upstream the section s and VQ(s) is the integral on time of streamflow volume passed through section s. We considered some closure sections where runoff ratio estimated by observations (rainfall and streamflow) is available (see Table 1). They can be found in the Hydrologic Annual Survey (http://www.arpal.gov.it/homepage/meteo/pubblicazioni/annali-idrologici.html), which is an official document published by the Regional Agency for Environment Protection. The observed runoff ratios are not available for the simulation period (1979-2008) but they are estimated as an average of values available on non-continuous periods since about 1940 to nowadays, thus they are a possible benchmark to assess the performance of the modeling chain.

Results are reported in table 5. Modeled RRs are compatible with the hydro-climatology of the target area (Barazzuoli and Rigati, 2004; Provincia di Imperia, 2017) but at the same time it is evident a general underestimation in the western part of the region (basins 4,5,6). B.C. improves results and RRs are more similar to the benchmark.

The rainfall B.C. introduces only small variations in terms of runoff ratio, this means that considering the long term water balance, the increasing or decreasing of rainfall lead on similar percentage variation on both runoff and evapotranspiration.

For example, in the center and eastern parts of Liguria, B.C. leads to a general increasing of precipitation and to a reduction of the orographic features of the spatial pattern, but at the same time the evapotranspiration increases, consequently RRs have a small increase considering B.C. case. As shown in sections 3.2 and 3.3 the increasing of rainfall leads to larger values of ADM, but the RRs do not change significantly.

This result could be due to the fact that even other EXPRESS-Hydro variables would need correction, we refer for example to the solar radiation or to wind speed which are important forcings for energy balance (and so for long term water balance), but no reliable and dense data are available for the entire simulation period. Another reason could be found in the hydrological model, since a calibration more devoted to preserve long term runoff could lead to better results. In any case we could say that generally the results are good and they highlight the potentialities of using such modeling chain even for water balance purposes.

4 Discussion and conclusions

This work explores the possibility of using EXPRESS-Hydro, a high-resolution regional dynamical downscaling of ERA-Interim reanalysis meteorological dataset with the state-of-the-art non-hydrostatic Weather Research and Forecasting (WRF) regional climate model, for hydrological purposes on small catchments. This was done using a subset of EXPRESS-Hydro meteorological variables as input to a distributed continuous hydrological model to produce streamflow simulations. The rainfall fields were downscaled from the original spatial-time resolution (4km, 3 hours) to a finer one (1km, 1 hours). All the analysis was conducted with and without applying a bias correction to rainfall fields. The study area is the Liguria Region in Italy with a particular focus on Tyrrhenian coast.

Firstly we evaluated the performance of the presented modelling chain in reproducing extreme streamflow statistics. This was done following two approaches: i) comparing statistical distribution of ADM with observations in some measurement points ii) using as benchmark the regional analysis presented in Boni et al. (2007) that allows a comparison with a distributed perspective.

Secondly we evaluated how the modeling chain reproduces the long term water balance analyzing the modeled runoff ratios and using estimations based on observations as benchmark.

The results are encouraging even if the modelling chain cannot always reproduce with high accuracy the considered benchmarks. The ADM statistic is reproduced quite well in various parts of the target region but there are sub-regions where there is alternatively a general underestimation or overestimation of the quantiles. Rainfall B.C. leads to a general improvement reducing the underestimation but introducing an overestimation in some basins especially in the central part of the region.

Comparison of modelled and observed ADM on single sites shows that for a large number of the measurement sites the time series belong to the same distribution with significance 5%; the fitting of modelled ADM with GEV distributions are generally good and often the observations lay inside the confidence intervals at 95% of significance, especially for low frequent quantiles. Anyway B.C. sometimes worsen the results, there are sites where the GEV fitting without B.C. is better than that with B.C.

Comparison with regional analysis shows interesting results with different behaviour in different parts of the region depending on how EXPRESS-Hydro generates the spatial-temporal patterns of precipitation and how rainfall bias correction corrects the quantitative amounts.

Both punctual and distributed analysis show that there is a general underestimation for basins with drainage area smaller than 30-50 km^2 but B.C. considerably corrects this underestimation. This is probably due to structural problems of the modelling chain under the aforementioned drainage area; for this class of basins it is necessary to further go down with time and spatial scales in generating meteorological input, especially precipitation (Siccardi at al., 2006; Silvestro et al., 2016), and presumably even in hydrological modelling (Yang et al., 2001). A possibility to deal with very small basins is study a way to better exploit the potentialities of the downscaling algorithm (RainFARM), that is here used in a deterministic way only to generate a possible temporal-spatial pattern with 1h and 1 km spatial resolution but maintaining the precipitation volumes and structures generated by EXPRESS-Hydro at its native resolution (3 hours, 4 km).

Runoff ratio RR was used as indicator to evaluate long term water balance. The RR coefficient evaluated on 30 years length simulation period at cell scale, has reasonable values for the climatology of the region (Barazzuoli and Rigati, 2004; Provincia di Imperia 2017) and its pattern is highly correlated with annual mean rainfall pattern. RR at basin scale was compared with estimations based on observations for some measurement points, the values are quite good as order of magnitude but generally the modelling chain underestimates in both analyzed configurations even if B.C. improves the results. This could be due to the fact that also the variables related to energy balance (for example the solar radiation and wind) modelled by EXPRESS-Hydro probably need correction, this opportunity is not developed in the presented work, mainly for lack of reliable and sufficiently dense data.

To summarize the results of the presented investigation, we could state that the perspective of using the present modelling chain to produce hydro-meteorological statistical analysis in the study area is good, even if some difficulties and lacks were emphasized by the study. The fully distributed approach allows to reproduce the hydro-climatic characteristics and features in a continuous way along the territory. Rainfall B.C. contributes in a relevant way to improve the results, helping the system to better model some rainfall characteristics not completely captured even by a high-resolution meteorological reanalysis. Very small basins (Area < 30-50 km^2) generally suffer of a structural underestimation partially corrected by B.C..

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5 Tables

Basin	Section	ADM 30 years time series	Hourly discharge data	Runoff ratio	Area [km^2]	Mean Slope [%]	Mean heght [m]
Magra	Calamazza	X	X		1650	18	503
Magra	Piccatello	X		X	78	21	590
Vara	Nasceto	X	X	X	202	23	651
Petronio	Riva Trigoso	X			55	19	401
Graveglia	Caminata	X			43	24	590
Entella	Panesi	X	X	X	364	21	535
Lavagna	San Martino	X			163	23	570
Bisagno	Passerella Firpo		X		92	20	398
Bisagno	La Presa	X			34	25	520
Sansobbia	Ponte Poggi	X			33	21	470
Neva	Cisano	X	X	X	123	25	670
Arroscia	Pogli	X	X	X	204	27	650
Impero	Rugge	X			73	19	480
Argentina	Merelli	X	X	X	188	26	883
Nervia	Isolabona	X			123	22	690
Tanaro	Ponte Nava	X			147	23	1350

Bormida	Murialdo		X		134	19	820
Bormida	Piana Crixia		X		273	15	550
Orba	Tiglieto		X		76	21	560
Aveto	Cabanne		X		33	23	1130

Table 1: availability of discharge data used for model validation, ADM analysis, long term mass balance analysis. The characteristics of the basins upstream each measurement station are reported.

Basin	Section	u_c [$m^{0.5}s^{-1}$]	u_h [s^{-1}]	c_t [-]	c_f [-]	NS	REHF
Magra	Calamazza	127	0.000194	0.3	0.05	0.81	0.14
Vara	Nasceto	125	0.000191	0.5	0.035	0.83	0.10
Entella	Panesi	64	0.000192	0.3	0.05	0.77	0.18
Bisagno	Passerella Firpo	110	0.000556	0.5	0.05	0.26	0.16
Neva	Cisano	63	0.000194	0.3	0.05	0.71	0.25
Arroscia	Pogli	65	0.000192	0.3	0.02	0.74	0.31
Argentina	Merelli	62	0.000185	0.3	0.035	0.84	0.21
Bormida	Murialdo	85	0.000174	0.3	0.05	0.35	0.51
Bormida	Piana Crixia	66	0.000200	0.5	0.02	0.76	0.41
Orba	Tiglieto	114	0.000278	0.5	0.02	0.88	0.21
Aveto	Cabanne	69	0.000520	0.5	0.02	0.73	0.41

Table 2: hydrological model validation; skill score values obtained for the calibrated. The calibrated parameters are also reported. V_{Wmax} [mm] and R_f [-] have values 500 mm and 1 for all the basins.

	BIAS [mm]	RMSE [mm]
DJF	-10.47	60.21
MAM	-0.71	56.13
JJA	-47.71	59.58
SON	-89.55	120.73

Table 3: Comparison between observations and EXPRESS-Hydro. Skill scores estimated on seasonal time scale.

Basin	Section	P value	K-S test	P value (B.C.)	K-S test (B.C.)
Magra	Calamazza	0.008	NO	0.855	Yes
Magra	Piccatello	0.036	NO	0.021	NO
Vara	Nasceto	0.632	Yes	0.012	NO
Petronio	Riva Trigoso	0.780	Yes	0.023	NO
Graveglia	Caminata	0.030	NO	0.065	Yes
Entella	Panesi	0.002	NO	0.990	Yes
Lavagna	San Martino	0.062	Yes	0.701	Yes
Bisagno	La Presa	0.056	Yes	0.022	NO
Sansobbia	Ponte Poggi	0.350	Yes	0.005	NO
Neva	Cisano	0.420	Yes	0.110	Yes
Arroscia	Pogli	0.172	Yes	0.820	Yes
Impero	Rugge	0.003	NO	0.860	Yes
Argentina	Merelli	0.078	Yes	0.218	Yes
Nervia	Isolabona	0.206	Yes	0.449	Yes
Tanaro	Ponte Nava	0.001	NO	0.034	NO

Table 4: Kolmogorov-Smirnov test with 5% significance. P values are reported together with verification of null-hypothesis (data belong or not to the same distribution).

Basin	Section	N. Progr	Area [km^2]	Obs. RR.	Model RR	Model RR (B.C.)
Magra	Piccatello	1	78	0.61	0.62	0.63
Vara	Nasceto	2	202	0.7	0.64	0.66
Entella	Panesi	3	364	0.73	0.64	0.67
Neva	Cisano	4	123	0.59	0.47	0.49
Arroscia	Pogli	5	204	0.55	0.48	0.51
Argentina	Merelli	6	188	0.65	0.51	0.53

Table 5. Runoff ratios (RR) obtained by the modeling chain (with and without the rainfall bias correction) compared to those estimated by observations.

6 Figures

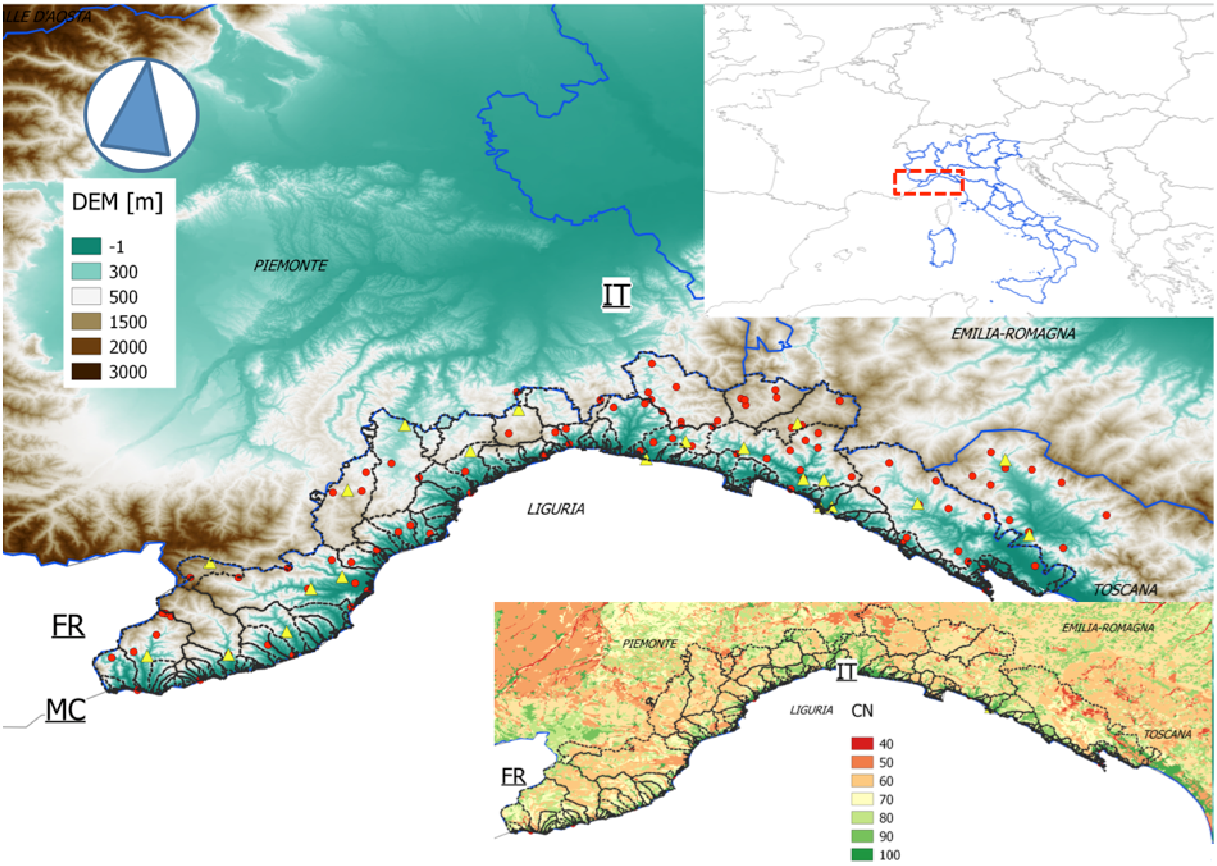

Figure 1. Study area. Blue lines represent the regional boundaries of Italy, dashed line shows the main catchments of the study region, red dots represent the meteorological rain-gauge station of Liguria region of Italy where 32 years (1978-2010) of daily data are available, yellow triangles are the level gauge sections. Digital elevation model highlights the morphology of the region. In the bottom right corner the curve number map is reported to show synthetically the usage of soil.

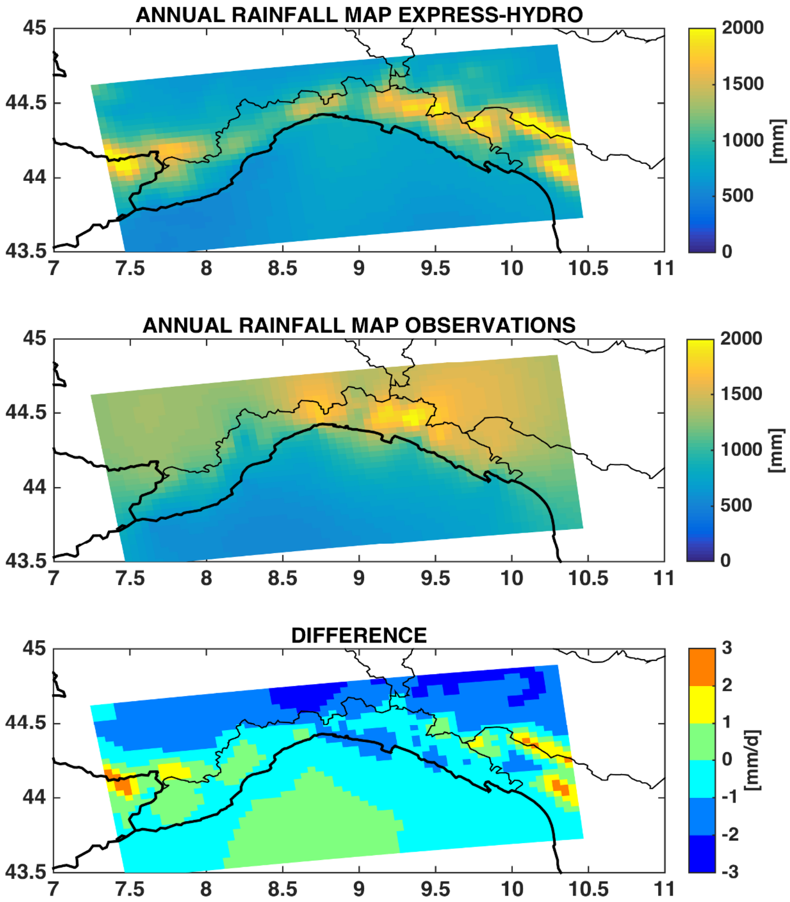

Figure 2. Upper panel shows the average annual rainfall map over Liguria area, the middle panel shows the average observed annual rainfall map, while the bottom one shows their difference in mm/d.

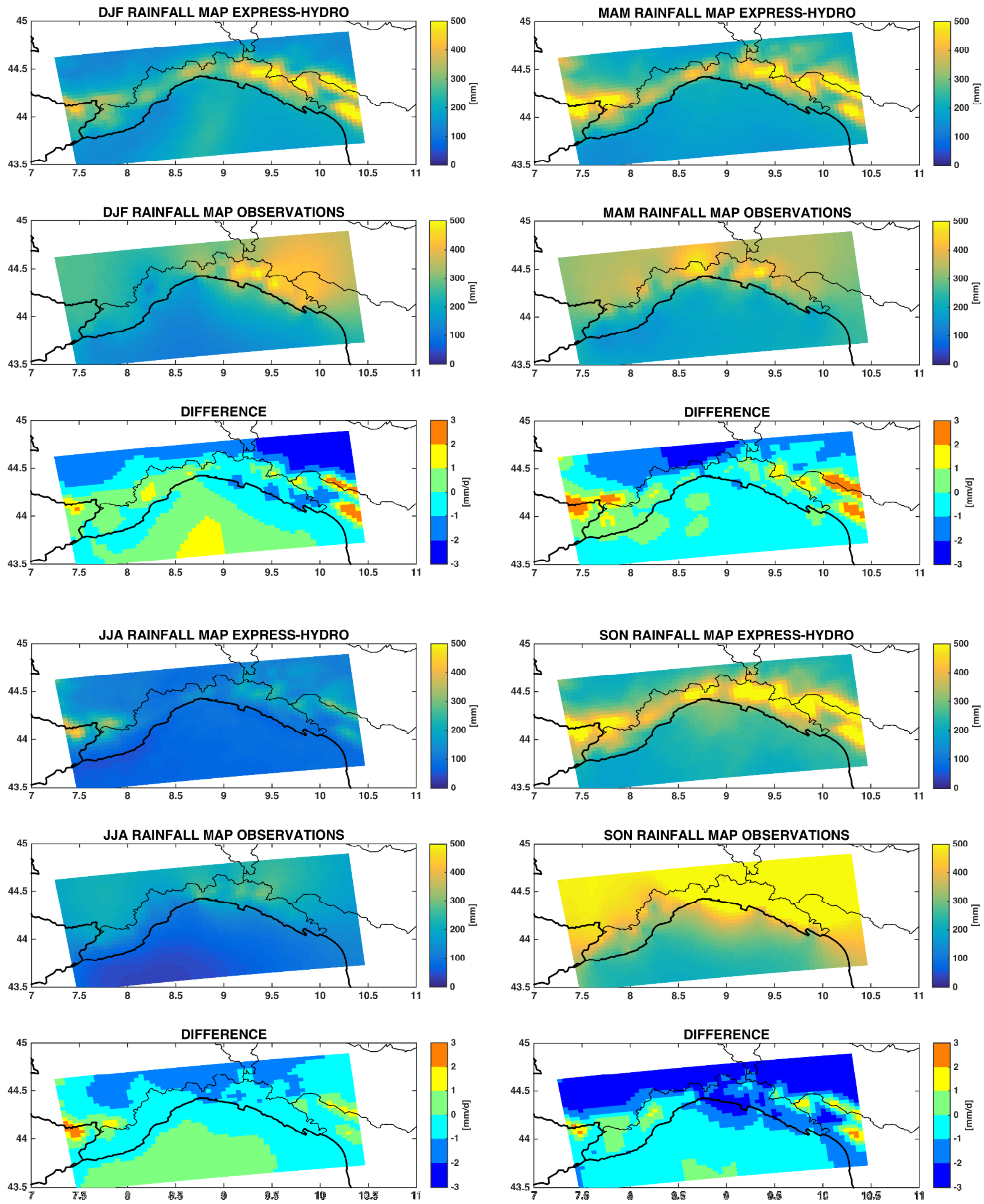

Figure 3. Upper panel shows the average DJF, MAM, JJA, SON rainfall maps over Liguria. For each season 3 maps are shown: EXPRESS-Hydro rainfall map, observed rainfall map, difference map in mm/d.

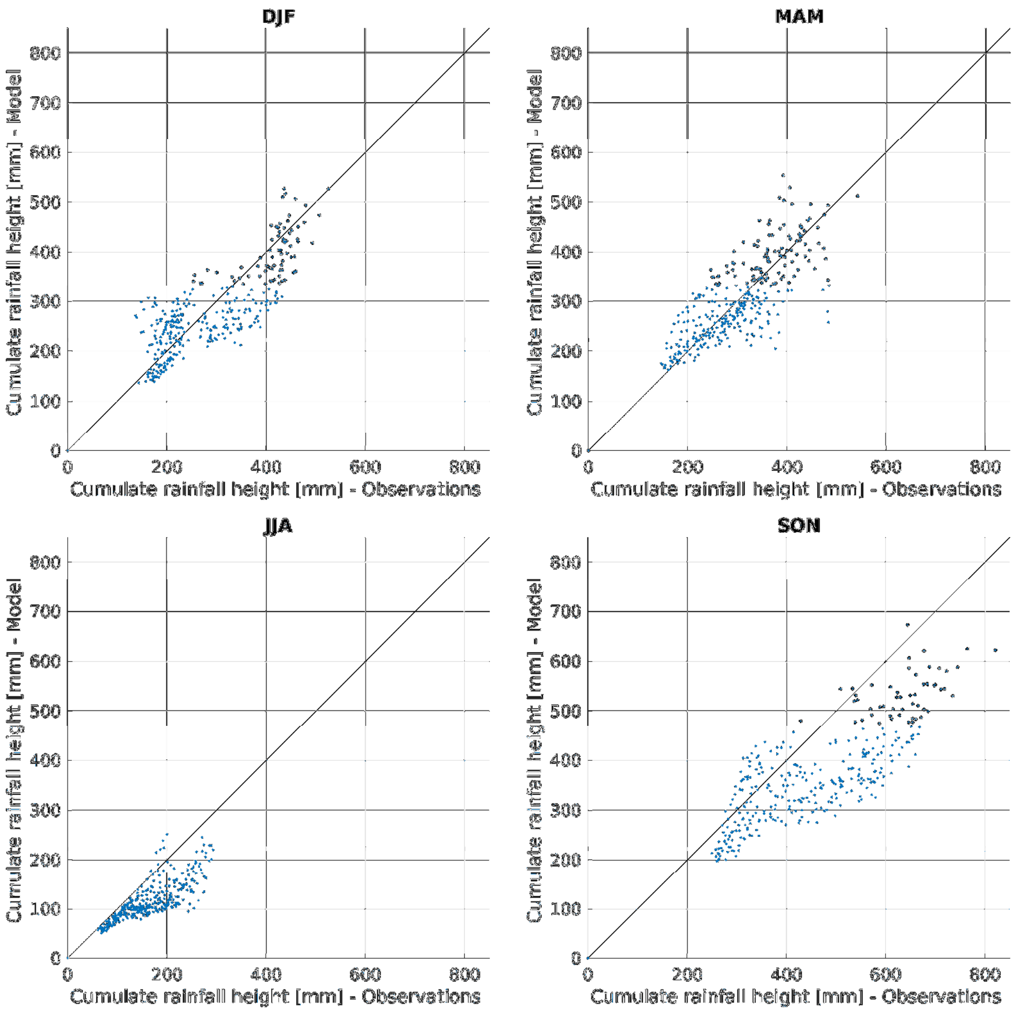

Figure 4: Scatter plots of seasonal precipitation built used data on EXPRESS-Hydro spatial resolution (pixel to pixel comparison). X axis reports observed interpolated rainfall, Y axis reports EXPRESS-Hydro estimation.

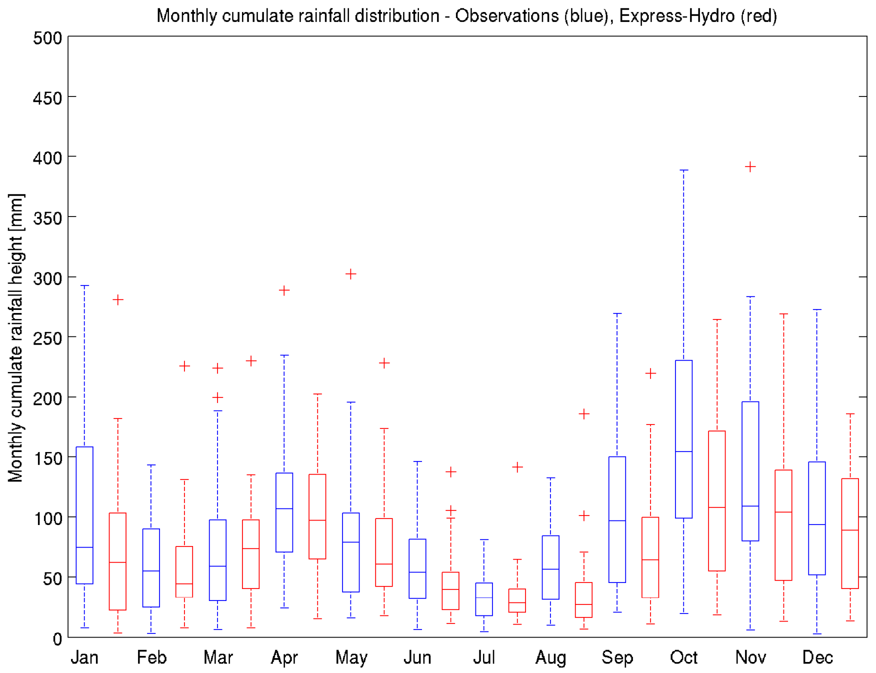

Figure 5: Box plot of monthly precipitation averaged at regional scale. Blue box plots are built with observations while red ones with EXPRESS-Hydro reanalysis.

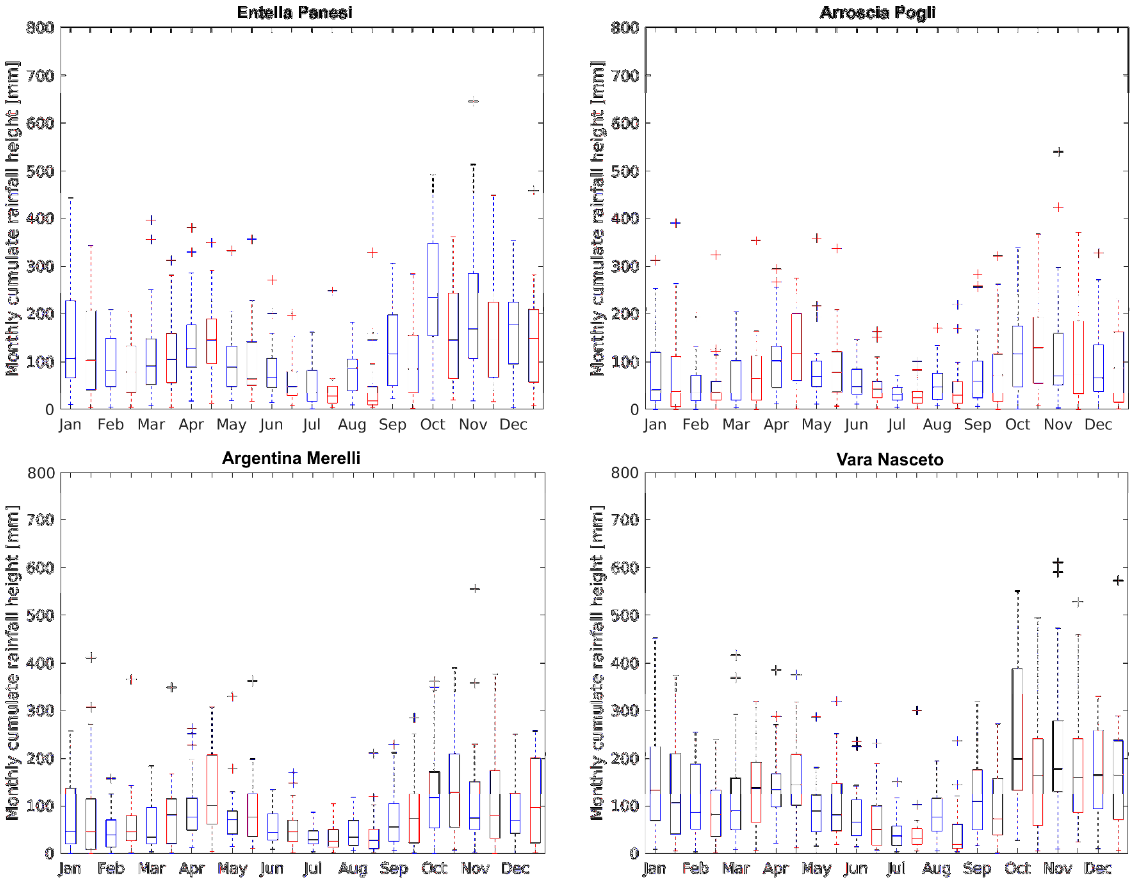

Figure 6: Box plot of monthly precipitation averaged at basin scale for 4 test catchments. Blue box plots are built with observations while red ones with EXPRESS-Hydro reanalysis.

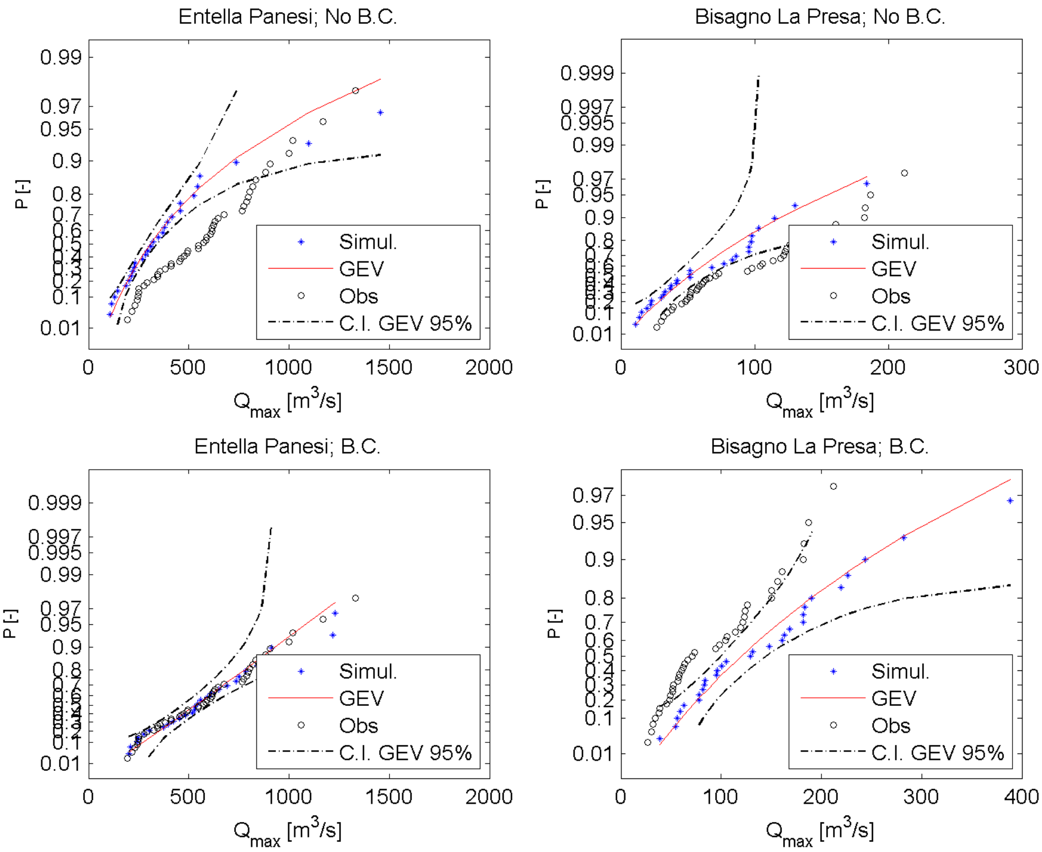

Figure 7. Distribution of ADM for Entella closed at Panesi (364 km^2) and Bisagno closed at La Presa (34 km^2). Blue dots are the simulated ADM, black dots are observed ADM, red line is the GEV fitted on simulated ADM while dotted lines are confidence intervals with 95% significance. Upper panels show results without rainfall bias correction, bottom panels show results with rainfall bias correction.

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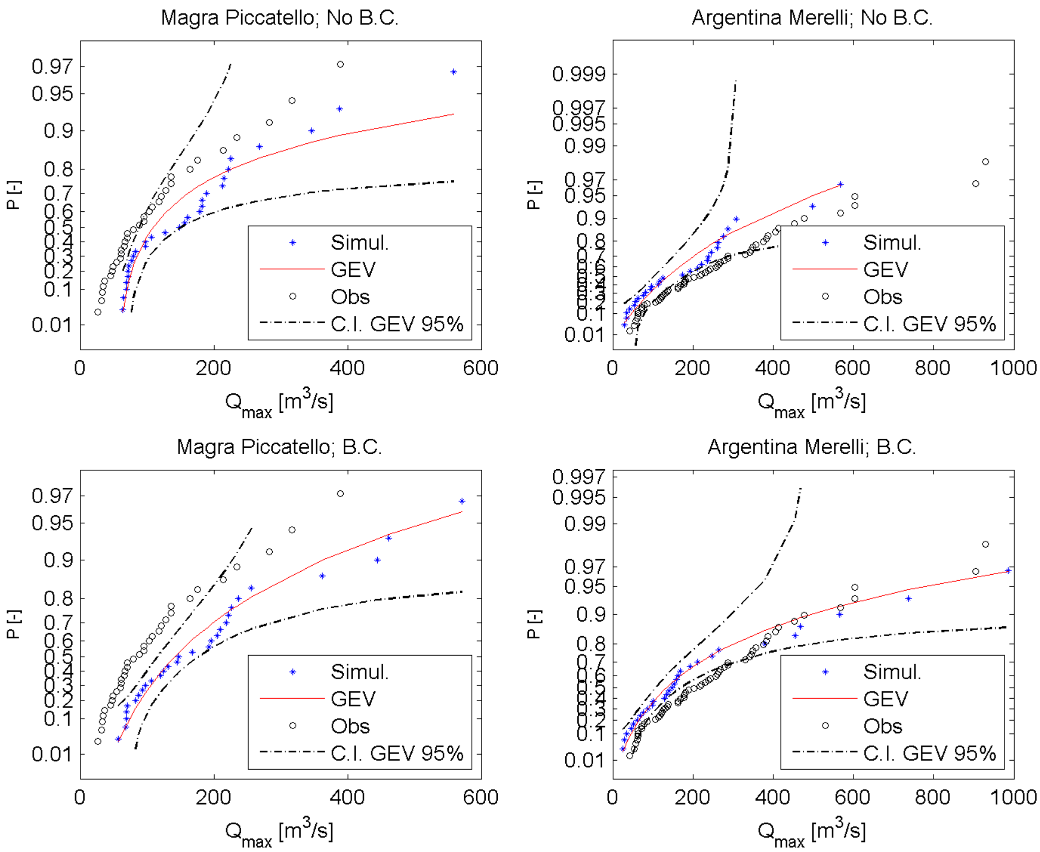

Figure 8. Same as figure 6 but for Magra closed at Piccatello (78 km^2) and Argentina closed at Merelli (188 km^2).

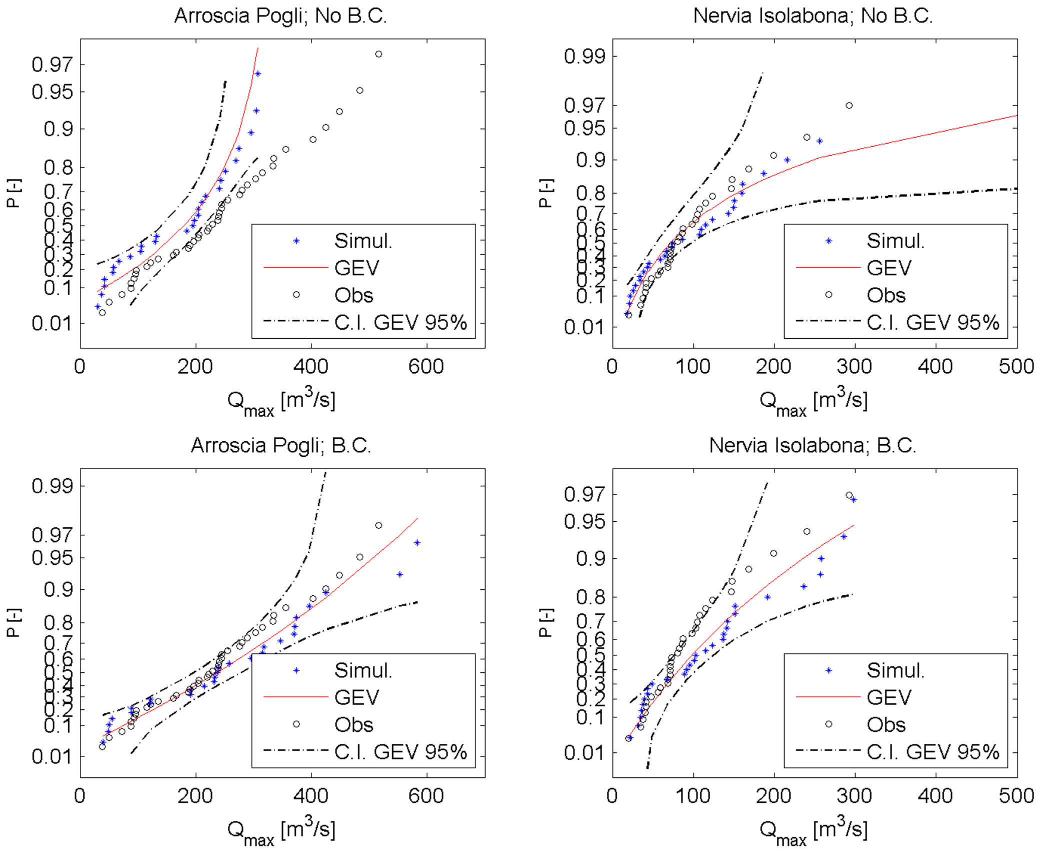

Figure 9: Same as figure 6 but for Neva closed at Cisano (123 km^2) and Nervia closed at Isolabona (122 km^2).

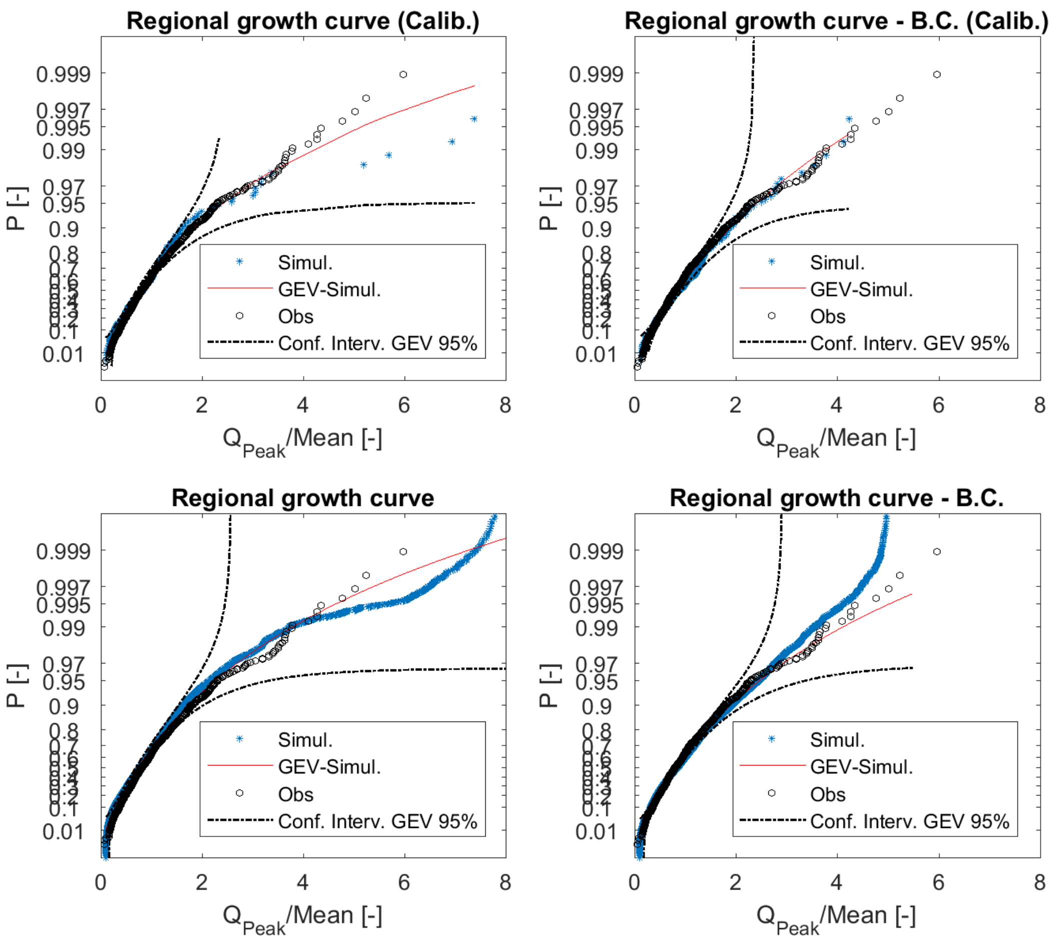

Figure 10. Sample growth curve obtained by model chain (blue dots) compared with observations (black dots). Red line is the GEV distribution fitted on modeled values while dotted lines are the confidence intervals with significance 95%. Top panels: results without and with rainfall bias correction using the sections where hydrological model was calibrated.

Bottom panels: results without and with rainfall bias correction using all the closure section with drainage area larger than A_{th}.

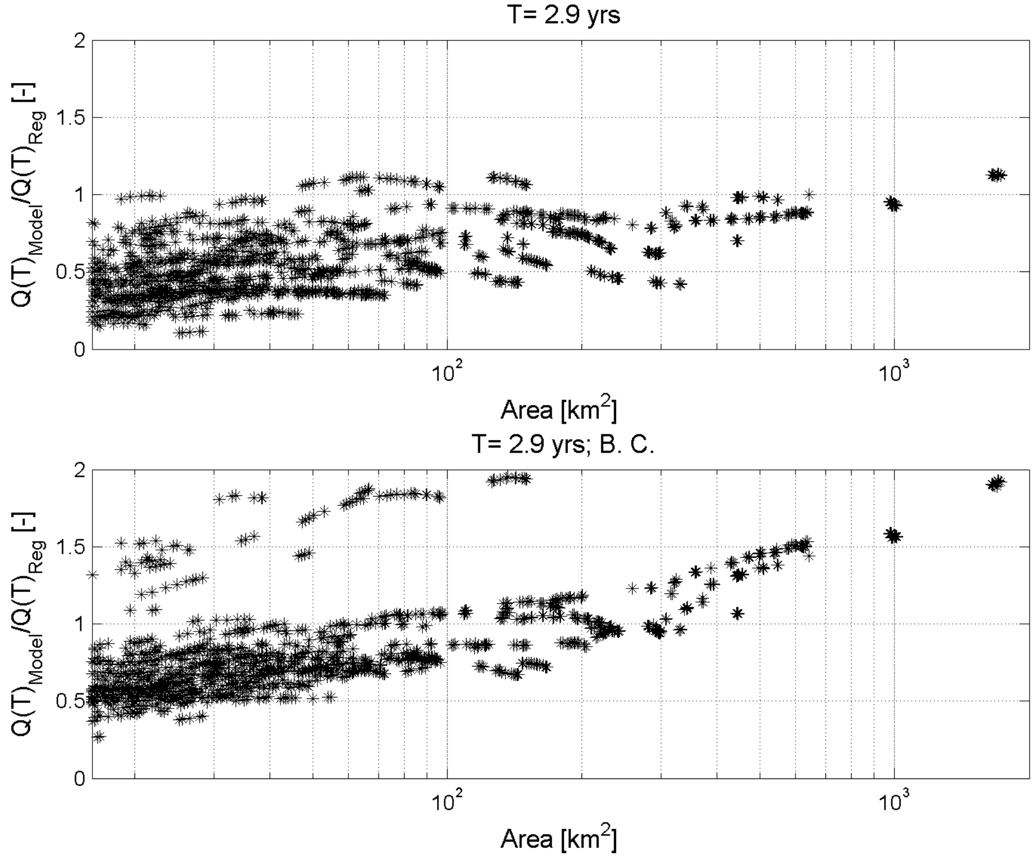

Figure 11. Ratio(T) as a function of drainage area. T=2.9 years which correspond to index flow. Upper panel shows results without rainfall bias correction, lower panel (B.C.) with rainfall bias correction.

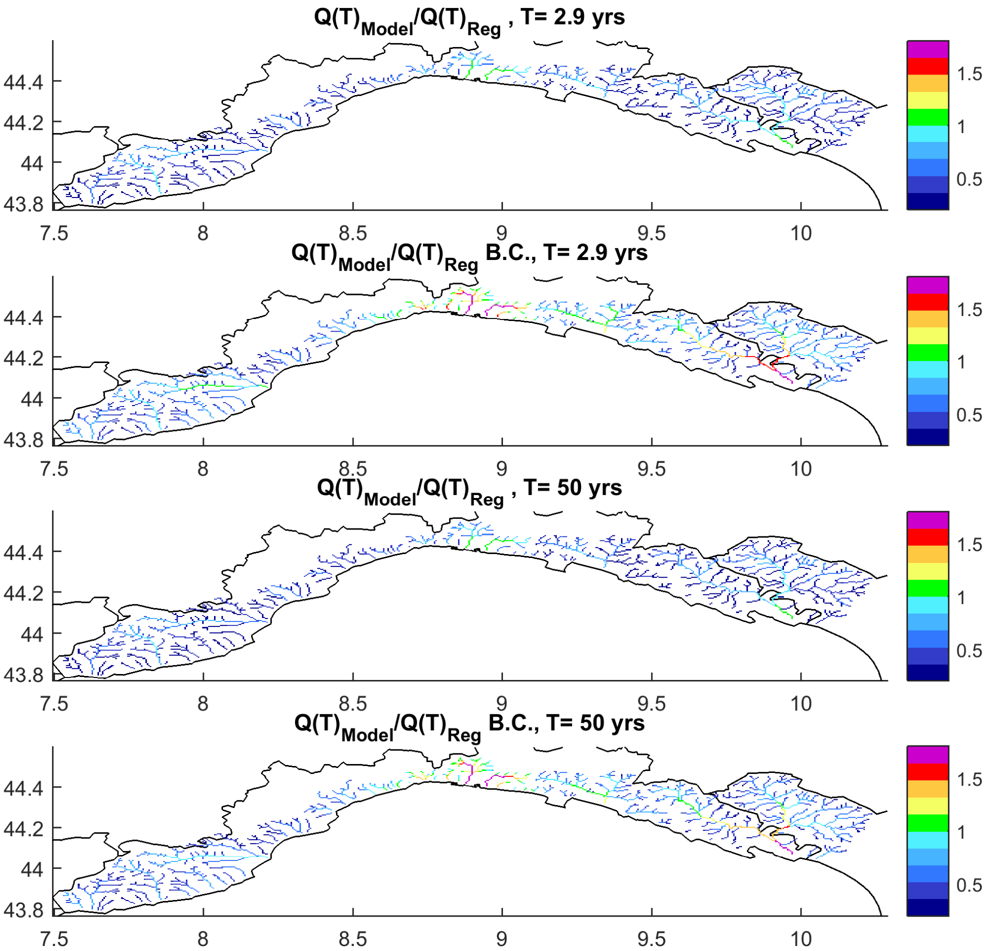

Figure 12. Maps of Ratio(T) for T=2.9 and 50 years. Upper panel shows results without rainfall bias correction, lower panel (B.C.) with rainfall bias correction. The B.C. increases the percentage of drainage network points that have values around 1.

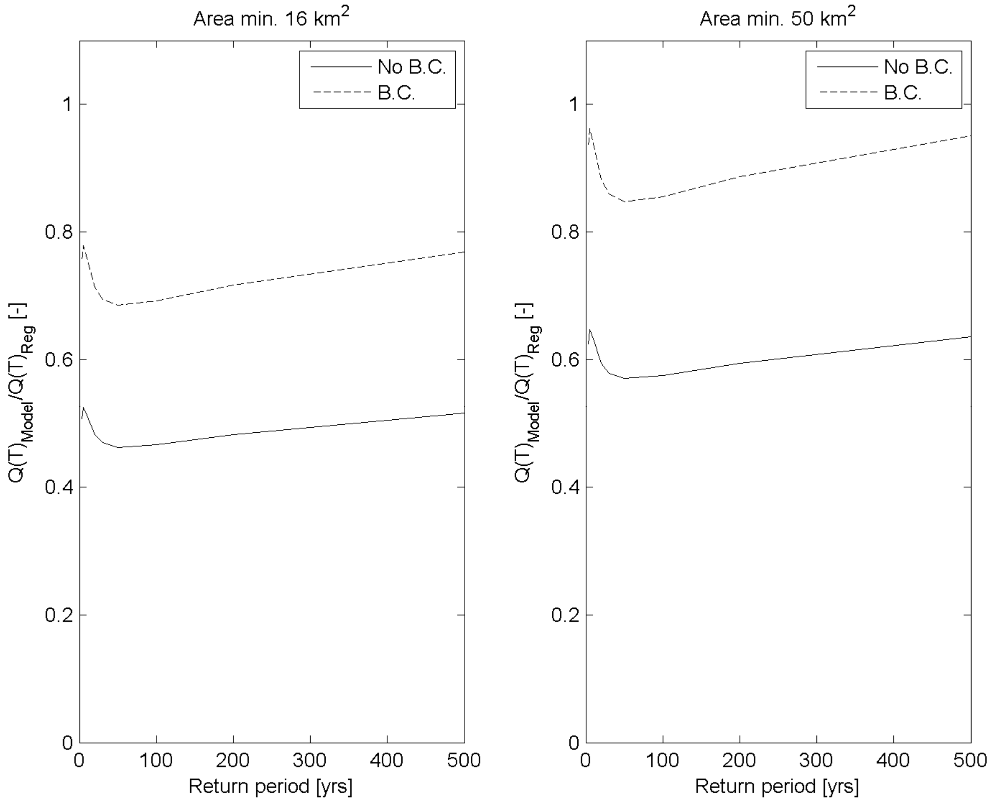

Figure 13. Mean Ratio(T) over the considered domain as a function of T. Continuous line (no B.C.) is the case without rainfall bias correction, dotted line (B.C.) is the case with rainfall bias correction. Left panel is the case where points with drainage area lower than 16 km^2 are discarded; right panel is the case where points with drainage area lower than 50 km^2 are discarded.

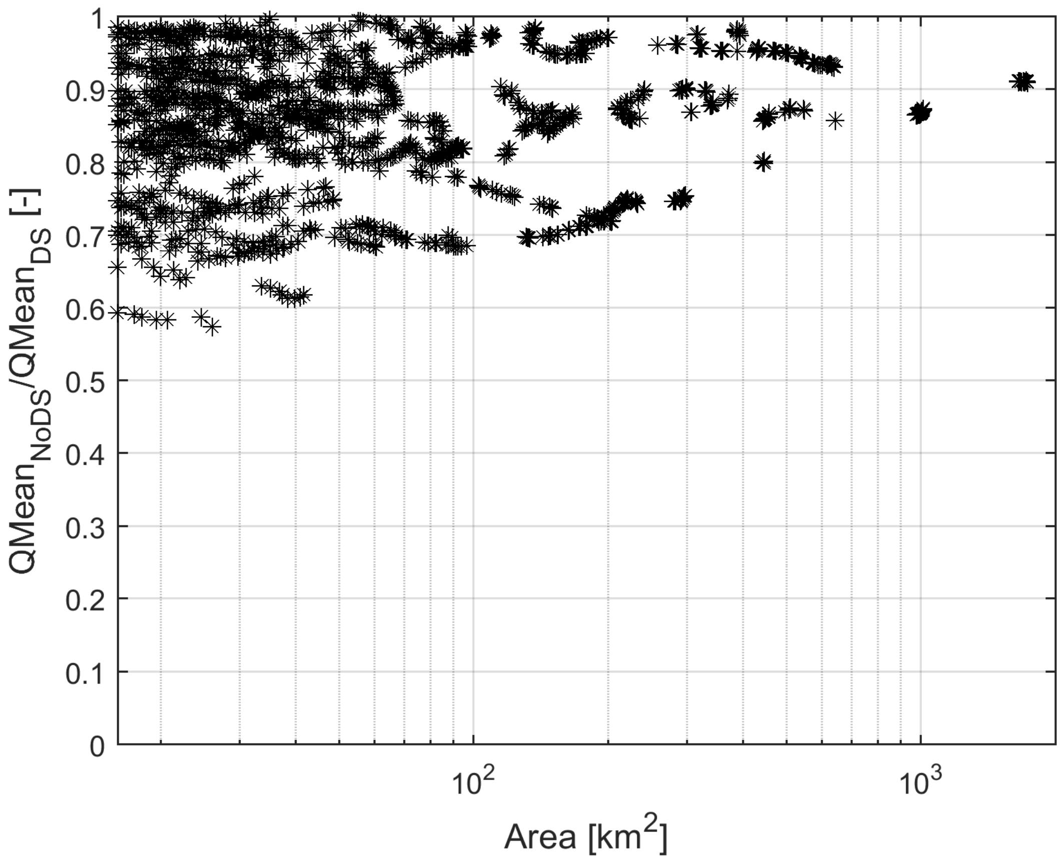

Figure 14. Ratio between mean flow estimated without and with downscaling as a function of drainage Area. The graph shows that the impact of rainfall downscaling increases when basin drainage area decreases.

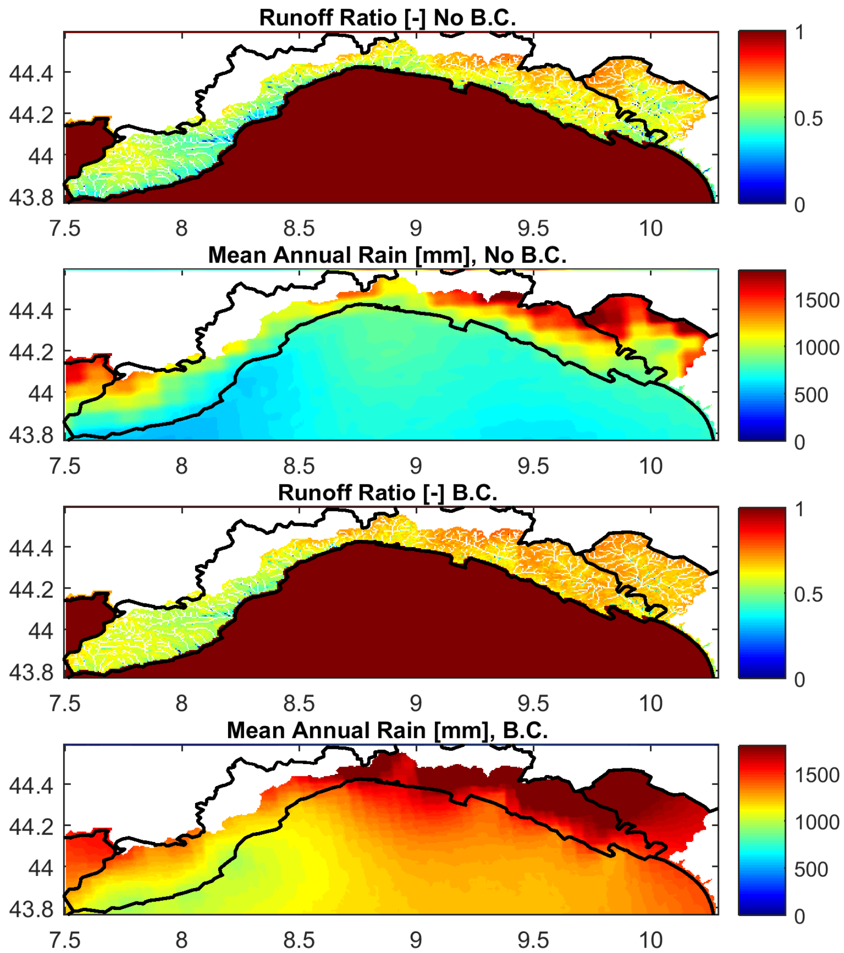

Figure 15. Distributed runoff ratio and mean annual rainfall. Upper panels show the model estimation without B.C. while lower panels with B.C. .