Climate change effects on the hydrological regime in non perennial river basins

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Abstract

Recent years have witnessed an increasing interest on global climate change and, although we are only at the first stage of the projected trends, some signals of climate alteration are already visible. Climate change encompasses modifications in the characteristics of several interrelated climate variables, and unavoidably produces relevant effects on almost all the natural processes related to the hydrological cycle. This study focuses on the analysis of potential impacts of climate variations on the streamflow regime of small river basins in Mediterranean seasonally dry regions. Such areas, in fact, could be particularly vulnerable to climate change due to the general water scarcity and intermittence of streamflow, which are strongly controlled by the inter-annual and seasonal variability of precipitation and evapotranspiration.

This paper attempts to provide a quantitative evaluation of potential variations in the flow duration curves (FDCs) and in the partitioning between surface and subsurface contributions to streamflow, induced by climate changes projected over the next century in five different river basins, within the northwestern Sicily (Italy), representative of wide hydrological behaviors. To this aim, it is here used a recent hydrological model, the ModABa (*MODel for Annual flow duration curves assessment in ephemeral small BAsins*), which is first calibrated at each site with regard to a past period with available streamflow observations, and, then, is forced by daily precipitation and reference evapotranspiration series representative of the current climatic conditions (2003-2013) and two future temporal horizons, referring to the time windows 2045-2065 and 2081-2100 and centered around 2055 and 2090, respectively. Current and future climatic series are generated by a weather generator, the AWE-GEN (*Advanced WEather GENerator*), based on a stochastic downscaling of an ensemble of General Circulation Models (GCMs).

The results quantify how the projected reduction in precipitation and increase in temperature are reflected in the hydrological response of the selected basins through a sensible downshift of the FDCs and a significant reduction in the mean annual streamflow. Substantial alterations in streamflow seasonality and in the relative importance of the surface and subsurface components are also highlighted. Results indicate how the torrential character of Sicilian river basins could be exacerbated by climate change, with a lengthening of the dry season and a higher intensity of extreme floods due to intensive rainfall events. All this could have important implications for the water resource management and for the sustainability of many riparian Mediterranean ecosystems.

Keywords: Climate Change; FDC; ModABa; GCM; Ephemeral basins

1 Introduction

Knowledge about flow regime in river basins has a capital importance for a variety of practical applications, especially for watershed management and water sustainable use. The hydrological regime plays a crucial role in determining the biotic composition, structure and function of river basins. A full understanding of surface water availability and seasonality should drive us towards a rational use of the water resource, aimed to satisfy anthropogenic needs, warranting, at the same time, sufficient resources to support ecosystems services.

Streamflow regime in a river is highly dependent on different climatic factors, among which the most important is surely the precipitation, in terms of frequency, intensity and seasonal distribution of rainfall events. The cause-effect relationship between precipitation and discharge becomes more noticeable in non perennial rivers, where streamflow mainly relies on surface runoff. Thus, the study of the hydrological regime under transient climate conditions results particularly relevant in ephemeral river basins, such as those characterizing many arid and semi-arid regions, where the variations in streamflow characteristics strongly depend on the underlying precipitation patterns.

Climate change is projected to have significant fallout upon streamflow regimes worldwide. Since the beginning of climate change literature, researchers investigated on potential impacts on streamflow regimes, which in turns could affect water resources availability and riparian ecosystems existence in some vulnerable areas. Great attention has been recently paid on this theme as demonstrated by the huge number of investigations performed over the last decade (Arnell, 1999 and 2003; Middelkoop et al., 2001; Beyene et al., 2010; Stahl et al., 2010; Bocchiola et al., 2011; Morán-Tejeda et al., 2011; Hannaford and Buys, 2012, Confortola et al., 2013, Liuzzo et al., 2015), but there are few studies on this specific topic with regard to ephemeral rivers (e.g., Ying and Huang, 1996; Schulze, 1997; Batisani, 2011), where water scarcity frequently occur and where the effects of potential changes in the climate forcings could imply eco-hydrological alterations heavier than for perennial streams.

Future climatic projections, according to the *fifth assessment report* of the *Intergovernmental Panel on Climate Change* – IPCC-5AR (IPCC, 2013), depict a changing global water cycle, with increases in disparity between dry and wet regions. The Mediterranean region, where future projections seem to lead toward an increase in aridity, can be considered as a “hot spot” for climate change, with marked modifications of precipitation in terms of both total amount and seasonal variability (e.g. Ulbrich et al., 2006; Sheffield and Wood, 2008). In particular, in many warm Mediterranean areas, which are already characterized by a limited water resource, the continue rise in greenhouse gases emission is likely to induce a further reduction in water availability, also in the order of 20% (Mariotti et al., 2008) or more, mainly due to the combined effect of a reduction in precipitation and a simultaneous increment of temperature, with a consequent increment in the evaporation and transpiration rates.

Starting from this premise, the primary objective of the present study is to explore the climate change impact on the hydrological regime of ephemeral Mediterranean river basins. A recent parsimonious hydrological model for the probabilistic characterization of the daily streamflow in non perennial catchments, i.e. the ModABa - *MODel for Annual flow duration curves assessment in ephemeral small BAsins* (Pumo et al., 2014) is used. The model provides, for a given basin and climate forcings, the corresponding flow duration curve (FDC), also giving useful indications about the repartition between the slow, subsurface, and the fast, surface, components of streamflow. The FDC, which displays streamflow values against their relative exceedance time, probably represents the most efficient method for summarizing the hydrological features of a river, since it describes its ability in providing flows of various magnitudes. A brief overview of the use and derivation of FDCs in hydrology can be found in Vogel and Fennessey (1994, 1995). Here, an opportunely designed module of the ModABa, i.e. *Module Statistics,* is used to infer the principal characteristics of the hydrological regime from the FDCs.

To date, the ModABa has never been applied in basins different from that used for its preliminary design and validation (i.e., Eleuterio at Lupo river basin, Sicily, Italy), where, nevertheless, it has shown a relevant accuracy in reproducing the empirical FDC (Pumo et al., 2014). The present paper then also represents a first attempt to apply the model to other different basins, further testing its reliability and generality. In the previous application on the Eleuterio at Lupo river basin, the reliability of the model was also successfully tested with regard to different time periods characterized by a certain climatic variability, and this aspect encouraged us to adopt the ModABa in the present work with the aim to investigate potential modifications of the FDC under transient climate conditions.

Five river basins are here selected within the study area (i.e., northwestern Sicily, Italy); at each site, the model is first calibrated against past streamflow observations, and then it is forced by reliable stochastic current and future climatic scenarios in order to assess the impact of climate change on the hydrological response.

The future climate scenarios are generated starting from precipitation and temperature realizations obtained by General Circulation Models (GCMs). The GCM realizations here considered correspond to two of the four greenhouse gas concentration trajectories adopted by the IPCC-5AR (Moss et al., 2010; IPCC 2013): the *Representative Concentration Pathway* (RCP) 4.5 and 8.5. The GCMs typically have a temporal and spatial resolution (daily or even monthly time resolution and pixel dimension that ranges from about 100 to 300 km) inadequate to represent hydrological processes at scales smaller than the continental scale, so downscaling of GCM-based data is a key aspect in climatologically driven hydrological simulation (Chen et al., 2011). The adoption of higher spatial resolution (e.g., 25–50 km) regional climate models (RCMs) could still not provide the resolution required for robust hydrological modeling as demonstrated by difference recent studies (e.g., Milly et al., 2005). However, a wide range of statistical approaches (Wilby and Wigley, 1997), some of which explicitly focused on hydrological applications (e.g., Fowler et al. 2007), can be applied to downscale further to the local scale by relating point climate observations and climate models outputs. In this study an opportune stochastic downscaling technique is adopted (Tebaldi et al., 2004; 2005) using the Advanced WEather GENerator - AWE-GEN (Ivanov et al., 2007; Fatichi et al., 2011). The AWE-GEN is a numerical tool capable of reproducing many statistical properties of several meteorological variables from the hourly time-scale up to several years. For each considered river basin, the *Baseline* scenario, representative of the current climate (i.e., 2003-2013), is created, as well as two future climate scenarios for each emission scenarios investigated (i.e., RCP 4.5 and 8.5), namely the climate projections at *2055* and *2090*, based on an ensemble of GCMs projections over the periods 2045-2065 and 2081-2100, respectively. In particular, rainfall, temperature, solar radiation, relative humidity and wind speed are simulated by the AWE-GEN in order to obtain stationary 50 years long time series. Using the climatic series generated by the weather generator and taking also into account the possible effect of CO_2 increase on stomatal resistance, the FAO-56 Penman-Monteith method (Allen et al. 1998) is used to estimate reference evapotranspiration series for each scenario.

The paper is organized as follows. In Section 2 the study area, with the five selected river basins, and the considered databases for the hydro-climatic data are described. It is also provided a description of both the adopted hydrological model, including model calibration at each site, and the weather generator, including the used downscaling procedure. Section 3 presents the main results. More specifically, after a preliminary evaluation of the hydrological model performances for the five basins in calibration, the principal differences emerging from the comparison between the current and the future FDCs are analyzed, highlighting the projected effects of climate change on the hydrological regime at each examined site. The results achieved for the five cases here selected could be thought as representative of the majority of Sicilian basins and, thus, they may be useful in the evaluation of the major consequences of climate change at the regional level, with important implications that could interest a wide range of sectors, from hydropower generation to agriculture, from industry to domestic water use. This study may also provide a template for investigation on future water resources in non perennial river basins under a changing climate, and, finally, could be coupled with ecological models in order to furnish critical information about the conservation, or the potential evolution, of the existing ecosystems.

2 Data and methods

2.1 Study area

The study area (Figure 1) is located in the northwestern Sicily (Italy). The precipitation regime, according to the Köppen-Geiger climate classification, belongs to the warm temperate class, with summer usually hot and dry, and with a maximum of precipitation in winter. The climate and the morphology in this area concur in determining a prevalence of small river basins characterized by non perennial hydrological regimes. Among these, five natural basins with streams no subjected to regulation and representative of the entire study area, have been selected mainly on the basis of the availability of long and reliable meteorological and streamflow historical series; the sites also warrant the fulfilment of all the prerequisites for the hydrological model adopted in this study (e.g., sub-daily time of concentration).

The selected river basins, whose elevation distribution and main river channels are depicted in Figure 1, are: *Forgia at Lentina*, *Baiata at Sapone*, *Fastaia at La Chinea*, *Nocella at Zucco* and *Senore at Finocchiara*. The main characteristics of each basin are synthesized in Table 1, where it is reported the total area (ranging from 29 to 76 km^2), the main river channel length (from 7 to 24 km), the mean elevation (from 111 to 527 m a.s.l.) and the percentage of impervious area (from 4.3 to 8.4%).

The topographic features have been derived by a DEM (*Digital Elevation Model*) with 100 m spatial resolution, while for the characterization of the soils and vegetations of each basin and for the determination of the impervious portion, different sources have been selected and crossed: the *Corinne Land Cover Map of Sicily* of 2006 (De Jacher, 2012), the *Soil Map of Italy and Soil Data Base* of Italy's Soil Information System (SISI, *www.soilmaps.it*, Costantini et al., 2012 and 2013) and the *Land Use Map of Sicily* at 1:250,000 scale (Regione Siciliana, 1994).

The impervious part of the basins includes all the areas classified as urban, industrial and infrastructural areas, roads and rural buildings, as well as very low permeable soils, with outcrops and compact rocks. The spatial vegetation patterns for each basin (Figure 2a) have been mainly derived from the *Corinne Land Cover Map*, distinguishing between three different vegetational macro-classes, whose parameters are typical literature values used for ecohydrological applications (e.g. Cuenca et al., 1997; Caylor et al., 2005; Pumo et al., 2014). The adopted classification is essentially based on the rooting depth of vegetation; the three classes correspond to areas mainly covered by deep roots plants, referred as trees (such as broad-leaved, coniferous and mixed forests, woods and partially wooded land), medium deep roots plants, referred as shrubs (e.g., shrubland and arable lands with small size tree crops such as citrus groves, fruit trees or vineyard), and, finally, shallow roots plants, referred as grasses (e.g., arable lands with herbaceous crop associations, grassland and sparsely vegetated areas). The spatial soil patterns (Figure 2b), mainly derived through the *Soil Map of Italy*, show the presence of seven different soil textural classes (according to USDA classification) within the considered basins: sandy clay loam, sandy loam, silty clay, loam, silty loam, silty clay loam and clay loam. Soil parameters for each textural class have been estimated using data from the open source database of the National Centre for Soil Mapping - CNCP (*Research Centre for Agrobiology and Pedology* – CRA-ABP, *www.soilmaps.it*) through opportune pedotranfer functions suitable for Sicilian soils (Antinoro et al., 2008).

The relative percent cover of each vegetation and soil type present within the permeable portion of the five basins and the corresponding characteristics, useful for the successive application of the hydrological model here adopted, are listed in Tables 2a and 2b, respectively; the reported values demonstrate how the choice of the case studies allows this study to account for a good heterogeneity in terms of both vegetation coverage and soil type.

2.2 Historical database

Two different sources of data have been used, providing low (i.e. daily) and high (i.e. hourly) frequencies climatic records which are necessary for the ModABa calibration and for the weather generator set up, respectively.

The low frequency data have been provided by the OA-ARRA Regional Agency (*Agenzia Regionale per i Rifiuti e le Acque*). The OA-ARRA archive provides daily streamflow series and monthly areal precipitation for most of the Sicilian river basins, and, at the same time, furnishes daily rainfall and temperature data collected by a dense network of gauging stations over the territory. The five river basins selected for this study are indeed characterized by a streamflow OA-ARRA gauge at the outlet and by the absence of human induced modifications (e.g., dams, water diversions, etc.). Among the considered basins, the longest available daily streamflow series is that relative to *Nocella at Zucco* (42 year, from 1958 to 2003, with 4 years gap) while the shortest series is that relative to *Senore at Finocchiara* (25 years from 1961 to 1986 with only 1 year gap). Because of the discontinuities, only a limited part of the available dataset at each site has been considered, selecting the longest period with continuous data as calibration period (Table 3). Thus, the size of the resulting calibration periods ranges from 15 years (i.e., *Forgia at Lentina*) to 23 year (i.e., *Nocella at Zucco*) and, for all the cases, it results sufficiently long to allow model calibration (Pumo et al., 2014). At each site, areal estimates of daily rainfall and temperature relative to the calibration period have been derived starting from the data collected by the OA-ARRA in 35 climatic stations over the whole study area and using opportune spatial interpolation techniques. In particular, algorithms analogous to those adopted by Di Piazza et al. (2011) and based on a distance weighting scheme, which also take into account the elevation, have been here used at the daily time scale. The reliability of such a procedure has been also successfully tested with regard to rainfall by aggregating the daily areal estimates at the monthly scale and comparing the resulting values with the monthly areal precipitation for each basin, separately retrieved from the OA-ARRA dataset. Table 3 reports a list of all the raingauge (P) and thermometric (T) stations considered in this study for the reconstruction of the historical series used in calibration, while their locations are represented in Figure 1.

The weather generator here adopted needs different meteorological data at higher temporal resolution (i.e., hourly) and relative to a recent and sufficient long period (e.g., about 10 years or more) representative of the current climate conditions. The high frequency data have been provided by the SIAS Regional Agency (*Servizio Informativo Agrometeorologico Siciliano*), which furnishes hourly series of several climatic variables recorded since 2003 within the Sicily. An internal (or the closest to the basin) station of the SIAS monitoring network has been first selected for each river basin (Figure 1 and Table 3); the entire available hourly series of precipitation, temperature, solar radiation, wind speed, air relative humidity and pressure, recorded by each station until 2013, have been then retrieved and assumed as representative of the entire basin.

2.3 Hydrological model

The adopted hydrological model is the ModABa - *MODel for Annual flow duration curves assessment in ephemeral BAsins*, a model aimed to the reconstruction of the annual FDC of the daily total streamflow (baseflow plus surface runoff) in catchments with sub-daily time of concentration. One of the peculiarities of the model is that it can be also applied to cases of non perennial hydrological regime, where streamflow seasonally becomes null for a significant period of the year. The model, introduced in Pumo et al. (2014), has the great advantage to be not computationally intensive, with few parameters that can be easily derived from commonly available information about the soil and vegetation of a basin, and, moreover, it can be applied simply using daily series of precipitation and temperature (or, in alternative, reference evapotranspiration) as external forcings. The calibration procedure proposed by Pumo et al. (2014) guarantees relevant model elasticity, meant as model ability in reproducing, for the same basin, the empirical FDCs relative to different time periods and, thus, characterized by a certain climatic variability. This aspect makes the model particularly suitable for the purposes of this work. In what follows only the main features of the model are recalled, while interested readers are referred to the original paper (Pumo et al., 2014) for a more comprehensive discussion about some aspects here neglected or deeply synthesized.

The ModABa is a spatially lumped model and accounts for a different hydrological behavior between the impervious (whose fraction is denoted as c_0) and the permeable (fraction equal to 1-c_0) portions of the basin. The total streamflow is assumed to be formed by two contributions differently modelled: the slow subsurface contribution and the fast surface contribution. The model conceptualizes the basin as a linear reservoir characterized by the mean residence time of the basin with regard to the transferring process related to the slow subsurface contribution, while, with regard to the surface contribution transferring process, the basin is modeled as a linear channel which instantaneously transfers the generated fast runoff towards the basin outlet.

The ModABa has a modular structure, which, in the original formulation (Pumo et al., 2014), was essentially constituted by three interconnected modules:

1) *Module 1*: it identifies the *dry season*, i.e. part of the year with null streamflow, and the *non-zero season*, i.e. remaining part of the year, and empirically provides the probability of zero-flow within the considered basin as a function of the underlying precipitation regime;
2) *Module 2*: it derives the non-zero FDC (FDC_{nz}, i.e. duration curve of the total streamflow relative to the *non-zero season*), first separately estimating and then overlapping the non-zero FDCs relative to the subsurface and the surface component of streamflow ($SSFDC_{nz}$ and $SFDC_{nz}$, respectively);
3) *Module 3*: it combines the outputs of the previous two modules (i.e. the probability of null streamflow and the FDC_{nz}) to obtain the annual FDC.

In view of the objectives of the present work, it has been here implemented and added a new module, named *Module Statistics*, which computes: 1- the streamflow values (l/s) for a set of characteristic percent durations; 2- the mean annual discharge, Q_m (l/s) and the mean discharge over the only *non-zero season*, $Q_{m,nz}$ (l/s); 3- the mean durations in days of the *non-*

zero season (d_{nz}); 4- the mean annual runoff coefficient, (ϕ); 5- the mean annual runoff R (mm/yr); 6- the surface component percent contribution to the mean annual runoff (*SFC*).

A schematic representation of the ModABa structure is provided in Figure 3 (from Pumo et al., 2014). The first operational step consists in the separation of the hydrological year into the *dry* and the *non-zero season*. This task is assigned to *Module 1* that, following an approach analogous to that used in Croker et al. (2003), derives the probability that the streamflow is null (p_{dry}) and, consequently, the mean duration of the *dry seasons* (d_{dry}). The value of p_{dry} is estimated as a function of the mean annual values of precipitation (*MAP*) and fraction of no rainy days (f_{NR}) by a multiple linear regressive model applied to log-transformed data, according to the following power law:

$$p_{dry} = m_0 \cdot MAP^{m_1} \cdot f_{NR}{}^{m_2} \tag{1}$$

where m_0 [year/mm], m_1 and m_2 are site-specific regression parameters. The *dry season* is the driest period of the year of duration d_{dry} (Pumo et al., 2014); it is then assumed to be constant in length, while its beginning and ending days can vary year by year.

Rainfall occurring over the *dry season* is assumed to form no significant streamflow and it is therefore neglected by the model, while rainfall occurring during the remaining part of the year can feed the two different contributions to total streamflow. The mechanisms of streamflow generation are modelled by *Module 2*, which is, in turn, constituted by three sub-modules, synthetically described below: *Sub-Module 2.1*, *2.2* and *2.3*.

Sub-Module 2.1 is based on an ecohydrological model, originally introduced by Botter et al. (2007 and 2008) and further extended by Pumo et al. (2013 and 2014), which is applied to the permeable portion of the basin. Once the fraction of impervious area c_0 is derived, the model requires the following spatially averaged parameters characterizing the mean soil and vegetation of the permeable areas: the rooting depth, Z_r; the threshold for canopy interception, δ_{veg}; the porosity, n; the saturated hydraulic conductivity, k_s; the relative soil moisture contents at the wilting point (s_w) and at the field capacity (s_{fc}); the β coefficient used to describe the hydraulic conductivity power law (Laio et al. 2001). The sub-module is based on the analytical solution of a stochastic soil moisture balance equation. Water losses from the soil, contributing to the baseflow, depend on the relative soil moisture content, whose dynamics are, in turn, driven by external climatic forcings relative to the *non-zero season*. Evapotranspiration is assumed to vanish below s_w and to increases linearly as the soil moisture increases up to a maximum, potential, rate (ET_{max}) that is reached in correspondence of s_{fc}. Field capacity is assumed as a threshold soil moisture content whose upcrossing determines the triggering mechanism for subsurface runoff generation. Rainfall interarrival process is simulated as a stationary marked Poisson process with rate λ_p (1/day) while the daily rainfall depths are assumed to be distributed according to an exponential distribution with mean $1/\gamma'_p$ (γ'_p in mm^{-1}). The process of rainfall interception by vegetation is also taken into account by a censoring process on the rainfall series that modifies the mean rainfall frequency in an apparent rate (λ'_p) on the basis of the canopy interception threshold, δ_{veg}.

The mean daily potential evapotranspiration, ET_{max} (mm/day) is derived from the reference evapotranspiration, ET_0, as $ET_{max}= k_v \cdot ET_0$, where k_v is a constant referred as vegetational coefficient. Despite this procedure implies the introduction of a further parameter that has to be calibrated (i.e., k_v), it allows for the use of simple procedures, such as the Thornthwaite (1949) or the Hargreaves et al. (1985) methods, which offer the great advantage of being based only on the temperature information, which is often the only available climatic data.

The transport model (i.e., linear reservoir) adopted for *Sub-Module 2.1* assumes the residence times as exponentially distributed with parameter k, which is the inverse of the mean residence time of the basin. The $SSFDC_{nz}$ is finally obtained as the complement of the cumulative exceeding probability of the subsurface streamflow, which is, in turn, derived from the steady state pdf of the specific subsurface streamflow, where this last is assumed as a Gamma-distribution (Pumo et al., 2014).

Relevant empirical relationships between the two calibration parameters of *Sub-Module 2.1* (i.e., k and k_v) and the underlying climatic forcings were found in Pumo et al. (2013), where it was also demonstrated how the use of such relationships considerably improves model elasticity to climate variability. For this reason the model adopts two multiple linear regression models to assess such parameters as a function of λ'_p and ET_0:

$$\begin{cases} k = a_1 + b_1 \cdot \lambda'_p + c_1 \cdot ET_0 \\ k_v = a_2 + b_2 \cdot \lambda'_p + c_2 \cdot ET_0 \end{cases} \tag{2}$$

where a_1 [*1/day*], b_1, c_1 [*1/mm*], a_2, b_2 [*day*], c_2 [*day/mm*] are site-specific regression parameters.

Sub-Module 2.2 follows the same conceptualization of Yokoo and Sivapalan (2011). The surface component of streamflow is assumed to be formed by two different contributions: the *impervious runoff* and the *direct surface runoff*. The first is simply given by the entire amount of rain fallen onto the impervious portion of the basin during the *non-zero seasons*. The second contribution derives from the permeable areas of the basin and accounts for a Hortonian infiltration-excess mechanism that could occur in presence of very intense rainfall events (heavy rains), when rainfall intensity is likely to exceed the soil infiltration capacity. The *direct surface runoff* is assumed to be formed by the excess of rainfall with respect to a critical heavy rain threshold, referred as *HRT* [mm/day]. *Sub-Module 2.2* computationally derives the $\mathrm{SFDC_{nz}}$ directly from the non-zero precipitation duration curve ($\mathrm{PDC_{nz}}$), through a not linear filter for the precipitation, whose parameters are c_0 and *HRT*. It is possible to obtain the surface contribution to the specific daily streamflow at the generic *i*-th day of the *non-zero seasons*, $Q_s(i)$, as a function of the precipitation at the same day, $R(i)$ (Pumo et al., 2014). Computing Q_s for each day of the *non-zero seasons*, the $\mathrm{SFDC_{nz}}$ is finally derived as the complement of the cumulative "frequency of exceedance" distribution of Q_s.

In *Sub-Module 2.3*, the $\mathrm{SSFDC_{nz}}$, resulting by *Sub-Module 2.1*, and the $\mathrm{SFDC_{nz}}$, resulting by *Sub-Module 2.2*, are overlapped, deriving the non-zero total streamflow flow duration curve ($\mathrm{FDC_{nz}}$). This last represents streamflow values occurring between 0 and p_{nz}, with p_{nz}= 1 - p_{dry}. In order to obtain the annual FDC, it is necessary to rescale the interval [0, p_{nz}] into the entire relative duration interval [0, 1] by transforming the component flows of the $\mathrm{FDC_{nz}}$. This task is assigned to *Module 3*, which is based on the theory of total probability. In particular, for the generic *i*-th streamflow Q_i, the transformed exceedance probability $P(Q_i)$ over the interval [0,1] is computed by the following equation:

$$P(Q_i) = P(Q_i)_{nz} \cdot p_{nz} \tag{3}$$

where $P(Q_i)_{nz}$ is the exceedance probability of the streamflow Q_i derived by the $\mathrm{FDC_{nz}}$.

2.4 Model calibration

The ModABa calibration at each basin has been performed, with regard to the calibration period previously selected (Sect. 2.2 and Table 3), adopting the same procedure used in Pumo et al. (2014). The first step is the determination of the impervious fraction of each basin and the estimation of the parameters representative of the mean vegetation and soil of the permeable portion of the basins. The information already discussed in Sect. 2.1 and synthesized by Tables 1 and 2 has been used to this aim, and, more specifically, the characteristics of the mean vegetation and soil have been obtained for each basin as weighted averages of the parameters relative to each type of vegetation and soil present within the basin, with weights given by the relative cover fractions. The estimated values for the five considered case studies are reported in Table 4.

The procedure for the assessment of the other calibration parameters can be summarized in three sequential phases: 1. calibration of *Module 1* and, more specifically, of the regression parameters of Eq. (1); 2. calibration of *Sub-Module 2.1* and, more specifically, of the regression parameters of Eq. (2), considering a preliminary, empirically fixed, value of *HRT*; 3. optimization procedure for deriving the calibration parameter *HRT* of *Sub-Module 2.2*.

An opportune model performance index is required for the last two phases. To this aim it is used the distance index Δ (Pumo et al., 2013; 2014), which is a measure of (dis)similarity between corresponding empirical and theoretical FDCs whose value, ranging between 0 and 1, decreases as the matching between the two curves improves. The estimation of Δ follows a simple distance-based procedure, with distances evaluated in fixed points (i.e., comparison points) of the two compared curves.

The parameters of Eqs. (1) and (2) are estimated through a regression analysis that considers different subperiods over the entire available dataset (i.e., calibration period). The regression analysis for Eq. (1) explores the cause-effect relation between precipitation and percentage of no-flow days. The empirical values of *MAP* and f_{NR}, and the corresponding empirical mean annual percentage of days with null streamflow are first derived for all the considered subperiods, and, then, interpolated by the power law of Eq. (1), assessing the regression parameters m_0, m_1 and m_2 by the least square method.

The regression analysis for Eq. (2) explores the relationships for each subperiod between the underlying climatic parameters λ'_p and ET_0, and two “optimal” values for k and k_v. Such “optimal” parameters are values corresponding to the best model reproduction of the empirical FDC at the level of each subperiod (i.e., minimum Δ). They are derived as best solutions for each subperiod by a Monte Carlo procedure, after 200,000 simulations, each one associated to a different combination of k and k_v randomly generated (i.e., randomly extracted by a uniform distribution of each parameter within a wide range opportunely fixed). The regression parameters of Eq. (2) between the “optimal” parameters k and k_v and the climatic parameters λ'_p and ET_0, are finally assessed, also in this case, by the least square method.

Regression analysis methods, such as those used for Eqs. (1) and (2), require to consider an adequate number of sufficiently long subperiods within the entire calibration period; their performances are, in fact, related to the explored variability of the independent variables (i.e., climatic forcings). The minimum size of the subperiods for Eqs. (1) and (2) calibration is identified (Table 4) following the same approach adopted by Pumo et al. (2014), based on Cochran’s formula (Cochran, 1077); all the continue subperiods within the calibration period of each basin having size equal or longer than the minimum size found for Eq. (1) are considered to calibrate *Module 1*, while for *Sub-Module 2.1*, the considered subperiods are those generated by a moving time-slot over the calibration period with fixed size, coincident with the minimum size found for Eq. (2).

The procedure adopted to calibrate Eq. (2) parameters requires to set a preliminary value for the parameter *HRT* of *Sub-Module 2.2*, which also conditions the parameter γ'_p of *Sub-Module 2.1*, representing an upper bound for infiltrating rainfall. The critical threshold *HRT* [mm/day] defines the precipitation events that can be classified as “heavy rain”. In general, the threshold value is related to the processes under analysis and the specific objectives of the analysis and it depends on several basin characteristics (Pumo et al., 2014). It is often derived from the cumulative frequency distribution of daily precipitation (PDC) as the daily precipitation associated to a critical *i*-th percentile (Kunkel et al., 2007). Following the same approach used in Pumo et al. (2014), the precipitation value corresponding to the *5*-th percentile of the $\mathrm{PDC}_{\mathrm{nz}}$ (i.e., precipitation duration curve of the *non-zero season*) for each investigated basin is here assumed as “first guess” value for *HRT* to be used in the Eq. (2) calibration procedure. Nevertheless, the preliminary empirical estimation of *HRT* is successively refined by an appropriate optimization procedure that represents the last ModABa calibration phase. This is performed iteratively applying the model to the entire calibration period with progressively increasing values of *HRT* and computing as final value for *HRT* that associated to the minimum value of Δ (best model performances). In particular, for each river basin, it has been considered a value of *HRT* ranging from the precipitation value associated to the *20*-th percentile of the $\mathrm{PDC}_{\mathrm{nz}}$ (minimum *HRT*) to the value associated to the *0.01*-th percentile (maximum *HRT*).

All the results of the calibration procedure for each river basin, together with the climatic variables representative of each calibration period, are synthesized in Table 4. The calibration procedure has led to model parameters whose values are coherent with the values found in Pumo et al. (2014). Only the parameter m_0 for the case of the *Nocella at Zucco* river basin results significantly different from those computed for the other basins; this is due to the fact that the *Nocella* basin exhibits an hydrological behavior rather different from the other basins, being it characterized by a higher precipitation and a lower temperature, and, consequently, a less ephemeral response in term of streamflow. Nevertheless, the resulting values of m_0 for this site is consistent with the analogue value ($=21\cdot10^8$) found by Croker et al. (2003), where a different formulation (i.e. only related to the *MAP*) to estimate p_{dry} at the regional level was used; in fact, the application of the formulation by Croker et al. (2003), calibrated for Portuguese catchments, to the case of *Nocella at Zucco* river basin would provide a value of p_{dry} for the calibration period practically coincident with the value obtained by Eq. (1) with the parameters provided in Table 4.

2.5 Weather generator and downscaling procedure

The future climatic scenarios here analyzed are generated by the hourly *Advanced WEather GENerator,* AWE-GEN, (Ivanov et al 2007; Fatichi et al., 2011) adopting an opportune downscaling procedure based on a stochastic downscaling of GCMs realizations (Tebaldi et al., 2004 and 2005; Fatichi et al., 2011 and 2013). Since the hydrological model calibration has been carried out using a database (i.e., OA-ARRA dataset) different from that used to train the weather generator (i.e., SIAS dataset) and considering at each site a past period not representative of the current conditions, the selected calibration periods are scarcely suitable as reference scenarios to evaluate potential future changes in the hydro-climatic variables. To this aim, a *Baseline* scenario, representative of the current conditions, has been opportunely generated for each basin by the same AWE-GEN.

The stochastic downscaling method uses a Bayesian approach to weight climate model realizations (Tebaldi et al., 2004; 2005; Fatichi et al., 2011), which allows the derivation of the probability distributions of factors of change (FOCs) representative of an ensemble of GCM projections. FOCs from single climate models can be calculated as “ratios” for precipitation and “delta” for temperature (i.e., ratios and differences between climate statistics of GCMs historical and future scenarios). More specifically, a set of factors of change is computed to adjust mean monthly air temperature and several statistics of precipitation (e.g., mean, variance, skewness, frequency of no-precipitation) at different aggregation periods (24, 48, 72, 96 h), as a result of comparing historical and projected climate model outputs. The factors of change derived from the ensemble of GCM realizations are successively used to obtain statistics representative of future climate scenarios. Using such statistical properties, an updated set of AWE-GEN parameters can be estimated. Each parameters set is calculated assuming stationary climate for any considered period. Finally, the re-parameterized weather generator is used to simulate hourly time series of climatic variables that are considered to be representative of the future climate. For a more detailed description of the model and procedures, see original papers by Ivanov et al. (2007) and Fatichi et al. (2011 and 2013), and the model guidelines, publically available at the website: *http://www-personal.umich.edu/~ivanov/HYDROWIT/Models.html*.

In this study, realizations from a subset of thirty two GCMs, used by the IPCC-5AR (Moss et al., 2010; IPCC 2013), have been considered. The IPCC-AR5 analyzed four greenhouse gas concentration trajectories (*Representative Concentration Pathways*: RCPs), corresponding to four possible hypotheses about the rise of greenhouse gases emission in the years to come. The four RCPs (i.e., RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5) are related to the possible radiative values increase in the year 2100 with respect to the pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively). The GCM realizations corresponding to a “moderately optimistic”, i.e. RCP 4.5, and the most “pessimistic”, i.e. RCP 8.5, IPPC-AR5 greenhouse gas concentration trajectory have been considered in this study.

The GCMs outputs exhibit a large spread, underlining inherent uncertainties in climate model predictions. This is particularly evident for precipitation where factors of change are substantially different among the models, while the discrepancies relative to the detected changes in air temperature results generally more restrained.

The method is here applied starting from hourly data from 2003 to 2013 derived from the SIAS meteorological stations selected as representative of the five investigated case studies (i.e., one station for each basin, see Table 3). Five climate scenarios have been created and investigated for each selected case study: namely the *Baseline* and two climate projections, at *2055* and *2090*, for both the RCPs 4.5 and 8.5, based on GCM projections over the periods 2045-2065 and 2081-2100, respectively. The downscaling procedure uses the GCMs outputs of the grid cells containing the SIAS weather station selected as representative for each study basin. Rainfall, temperature, solar radiation, relative humidity and wind speed have been simulated in order to obtain stationary 50 years long time series for each climatic scenario. For the generation at each site of the various scenarios, the weather generator has been re-parameterized using only the median of each FOC, creating just one realization of the GCMs ensemble. Only FOCs for precipitation and air temperature have been evaluated; therefore, changes of the other required variables, i.e., solar radiation, relative humidity and wind speed, are not a direct consequence of the calculated factors of change, but are only due to the internal relationships embedded in the weather generator. The FOCs have been used to re-estimate climate statistics for the central years (*2055* and *2090*) of the periods 2046-2065 and 2081-2100, while the *Baseline* scenario, assumed as the control scenario period for which

GCMs data and SIAS data are available, has been generated considering the same statistical properties derived from the observation period (i.e., 2003-2013).

3 Results and discussion

3.1 Hydrological model performances

The ModABa performances are here evaluated at each basin in terms of ability in reproducing the main characteristics of the hydrological regime during the calibration period. Empirical and theoretical FDCs relative to the calibration period are compared evaluating the distance index Δ, and it is also shown a comparison between some results arising from the *Module Statistics* and the corresponding data empirically computed.

Figure 4 shows the comparison between model (black curves) and empirical (red points) FDCs for the five basins, also reporting the associated value of Δ. Each curve, represented in a semi-log plot, describes the various durations (days) associated to different specific streamflow values (mm/day). Despite the five considered basins exhibit marked differences in the main topographic characteristics (Table 1), in vegetation and soil covers (Table 2) and in the main climatic forcings (Table 4), model performances in terms of Δ are comparable for all the cases and consistent with the performances exhibited for the case of the *Eleuterio at Lupo* in Pumo et al. (2014). For two basins (i.e., *Forgia at Lentina* and *Baiata at Sapone*) the distance indexes are significantly lower than that shown for the case of *Eleuterio at Lupo* (i.e., Δ=0.0089) denoting a better reproduction of the empirical FDC, and only a case (i.e., *Nocella at Zucco*) has provided a slight higher value of Δ (i.e., Δ=0.0129).

Most of the evidences arising from the previous application by Pumo et al. (2014) have been here confirmed; for instance, model reproduction of the lower and more frequent streamflow values has been extremely accurate for all the investigated cases, with near coincident lower tails for the model and the corresponding empirical FDCs, while, in some cases, a slight underestimation of the frequencies can be noticed in the part of the FDCs representing the transient zone in which subsurface contribution becomes prevalent with respect to the surface contribution (i.e., durations from about 3 to 9 days). Moreover, the model often shows some difficulties in reproducing streamflow values relative to extremely rare event, i.e. associated frequencies in the FDC corresponding to sub-daily durations. This general behavior is highlighted in the example reported in Figure 5, relative to the case of the *Forgia at Lentina*, where specific streamflow values are not log-transformed and the duration domain is separated in two parts. In the same figure, the representation of also the SSFDC and SFDC highlights the prevalence of the subsurface contribution to streamflow for the middle and lower part of the FDC (right panel), while the surface contribution essentially controls the upper tail (left panel).

Table 5 shows a comparison between some descriptors (i.e., values of the discharges for fixed percent durations, mean discharge over the year and over the *non-zero season*, mean durations of the *non-zero season*) of the hydrological regime simulated by the ModABa and observed for the same period. Also such results confirm the general good accuracy of the model in reproducing the observed hydrological behaviors of the investigated basins during the calibration period. The model reproduces the discharge of various magnitudes with acceptable discrepancies. Also in terms of mean discharge over the year (Q_m) and the *non-zero season* ($Q_{m,nz}$), the differences between theoretical and empirical values are rather moderate with an exception for the *Nocella at Zucco* river basins, where a significative overestimation of about 120 l/s for both the values can be noticed. This outcome is affected by a consistent overestimation of the streamflow values associated to very rare events (durations lower than 7 days). Model reproduction of the *non-zero season* mean duration is extremely accurate for the case of *Fastaia at La Chinea*, while, for the other considered basins, the ModABa provides a systematic overestimation on the order of 20 days (on average, about the 10% of the season). This could be also due to the fact that the model simulates also very low discharges, i.e. lower than streamflow gauge accuracy.

3.2 Projected changes in precipitation and temperature

Predicted climatic scenarios are similar in all the selected basins (Table 6), with a decrease in precipitation and a simultaneous increase in temperature in the order of about the 10% for both the considered temporal horizons under the RCP 4.5 and for the *2055* scenario under the RCP 8.5, and about twofold percent variations for the *2090* under the RCP 8.5. Rainfall events are projected to be, on average, less frequent and more intense over the year. The mean annual precipitation percent reduction from *Baseline* to *2090* ranges, among the five basins, from the 10.9% to the 12.4%, under the RCP 4.5, and from the 21.6% to the 23.8%, under the RCP 8.5, while the temperature percent increment ranges from the 9.7% to the 12.4% under the RCP 4.5, and from the 20.9% to the 25.3% under the RCP 8.5.

For instance, in the case of *Senore at Finocchiara*, the mean annual precipitation decreases, under the RCP 4.5, from 659 mm, in *Baseline*, to 598 mm in *2055* and 583 mm in

2090 (about -76 mm in a century) while the mean annual temperature increases from 16.7 °C to 18.2 °C in *2055* and 18.8 °C in *2090* (i.e. about +2°C in a century). Analogous and more marked trends can be noticed for the same basin under the RCP 8.5, corresponding to a greater increase in greenhouse gas concentration: in this case, the mean annual precipitation decreases down to 587 mm in *2055* and 503 mm in *2090* (i.e. -156 mm), while the mean temperature increases up to 18.9°C in *2055* and 20.8 °C in *2090* (i.e. about +4 °C).

A representation of the projected climatic changes at the monthly level is provided in Figure 6 for the same case (*Senore at Finocchiara*), which shows, for each scenario (different colors) generated by the AWE-GEN, the median and the 10th-90th percentile values of the monthly precipitation *P* (Figures 6a and 6b) and temperature *T* (Figures 6c and 6d) under both the RCPs 4.5 (left panels) and 8.5 (right panels). With respect to the *Baseline* scenario, significant decreases in monthly precipitation are predicted under the RCP 4.5 (Figures 8a and 8c) especially for the winter months (about -44 mm in precipitation from December to March in *2090*), while the higher increases in temperature are mainly predicted during the summer months (e.g., +2.7°C in August for the *2090* versus a minimum monthly increase of +1.6 °C in February). The same behavior is projected also under the RCP 8.5 (Figures 6b and 6d), with the most relevant decrements in monthly precipitation during wintry months (e.g., -25 mm in December for the *2090* scenario), and maximum temperature increments during the summer (e.g., almost +5 °C in July and August in *2090* scenario).

3.3 Projected changes in evapotranspiration

Climate change may alter the entire energy balance at the basin scale, inducing significative changes in the evapotranspiration processes. The increase in the air concentration of CO_2, on the one hand, induces a temperature increase, which implies an increment also in the atmospheric evaporative demand, while, on the other hand, it is expected to induce a reduction in plants stomatal conductance to water vapor (Long et al., 2004, Moratiel et al., 2011). Alterations of the leaf stomatal conductance with increasing CO_2, could potentially reduce the energy used in evaporating processes, also modifying the mechanism of stomatal regulation. This anticipated phenomenon could partially counterbalance the effects on evapotranspiration induced by the temperature increment.

The coupled effect of climatic forcings and vegetation response is here taken into account through the evaluation of the current and the future reference evapotranspiration series by the FAO-56 Penman-Monteith formulation (Allen et al., 1998) and hypothesizing an opportune function relating the stomatal conductance and the air CO_2 concentration. In particular, starting from the estimation of the stomatal conductance of the standard vegetation associated to the current atmospheric CO_2 concentration (i.e., 390 ppm), we referred to the results of Long et al. (2004), which observed decreased stomatal conductance by about the 20%, on average, for C3 plants grown in elevated CO_2 concentration (about 550 ppm) in *FACE* (*Free-Air* CO_2 *Enrichment*) experiments, based on more than 200 independent measurements.

Given the overall uncertainty of the CO_2 effects in reducing stomatal conductance, especially in the long-term when plants might undergo acclimation effects (Ainsworth and Long, 2005), it has been here assumed a stepwise formulation, the same adopted in Caracciolo et al. (2014), assuming a linear decrease of stomatal conductance from the current value to a value reduced by the 20%, in accordance with Longo et al. (2004), for CO_2 concentration increasing from the current value to 550 ppm and assuming a constant stomatal conductance for higher values of carbon dioxide concentration.

More specifically, the current stomatal conductance, referred to a hypothetical well-watered grass with standardized characteristics (canopy height of 0.12 m, bulk surface resistance of 70 s/m, albedo equal to 0.23, LAI_{max} equal to 2.88 $m^2 \cdot m^{-2}$) and equal to 0.0144 m/s according to Allen et al. (1998), has been assumed for the *Baseline* scenarios. According to the projections of the IPCC (2013), the expected CO_2 concentrations for the projections *2055* are 535 ppm and 675 ppm under the RCPs 4.5 and 8.5, respectively, while for the projections *2090* are 575 ppm and 1090 ppm under the RCPs 4.5 and 8.5, respectively. Thus, for the scenarios *2055* of the RCP 4.5 the estimated stomatal conductance was 0.0118 m/s, while, for all the other future scenarios, it was assumed the value of 0.0115 m/s (i.e., -20%, corresponding to atmospheric CO_2 concentrations $\geq$ 550 ppm).

A daily reference evapotranspiration series has been finally derived by FAO-56 Penman-Monteith equation for each considered basin and climatic scenario, using, after daily aggregation, the climatic series generated by the AWE-GEN for all the required climatic data (i.e., temperature, solar radiation, wind speed, air relative humidity and air pressure).

The reference evapotranspiration values at the averaged monthly time-scale, ET_0, obtained for the case of *Senore at Finocchiara* are also represented in Figures 6e and 6f, while the mean annual values for each basin are reported in Table 6. The monthly increments of reference evapotranspiration follow those in temperature, with a maximum in summer months (July and August) and a minimum in February. The variations predicted under the RCP 8.5 scenario are much more relevant than those relative to the RCP 4.5, especially with regards to the summer months. At the annual level, it can be noticed how the induced percent variations in the reference evapotranspiration values are rather dissimilar among the various basins, differently from what observed with regard to the changes in both temperature and precipitation. The projected reference evapotranspiration increments range from about the 0.35% (i.e., *Fastaia at La Chinea*, *2055*, RCP 4.5) to the 8.2% (i.e., *Fastaia at La Chinea*, *2090*, RCP 8.5). Finally, it is worth emphasizing that reference evapotranspiration have been here obtained implicitly neglecting possible non-stationarity in solar net radiation, wind speed and vapor pressure deficit time series.

3.4 Projected changes in the hydrological regime

The hydrological model has been forced by the daily series of precipitation and reference evapotranspiration generated for each considered climatic scenarios, using the calibration parameters given in Table 4. The five climatic scenarios generated for each basin (i.e., *Baseline*, and the future scenarios *2050* and *2090* for both the RCPs 4.5 and 8.5) account for alterations induced by climate change on precipitation, temperature, and stomatal conductance. Although the consideration of time invariant soil and vegetation patterns is barely realistic, no hypotheses have been made about changes in land use during all the analyzed temporal horizons, focusing in this manner on the potential alterations in the hydrological regime only due to the predictions of the climate change models.

Prospective shifts in the hydrological regime of each basin are here investigated through the analysis and the comparison of the FDCs and the different data provided by the *Module Statistics* for each climatic scenario. The shape of the FDC, especially in its upper and lower parts, could be particularly significant in characterizing the type of flow regime and the basin ability to sustain low flows during the dry seasons. The evaluation of the mean annual streamflow is directly related to the water resource availability assessment, while the analysis of potential variations in the mean duration of the flow (*non-zero*) season could suggest different strategies towards a more rational and sustainable use of the rivers and the underlying ecosystems.

3.4.1 The Baseline scenarios

A first analysis consists in a qualitative comparison, for each basin, between the FDC relative to the current *Baseline* scenario and the empirical FDC relative to the calibration period (Figure 4). An Italian classification, according to the Legislative Decree n.131/2008, distinguishes the non perennial rivers into three different classes: 1- *intermittent*, with flow conditions during more than 8 months per year; 2- *ephemeral rivers*, with flow conditions during less than 8 months per year; 3- *episodic*, usually dry and with flow conditions after intense rainfall events. According to this classification and analyzing the empirical FDCs for the calibration periods, all the selected case studies were in recent past belonging to the *ephemeral rivers* class, with the exception of the *Nocella at Zucco*, where the past hydrological regime can be classified as *intermittent*. The same classification results maintained for all the basins also for the current scenarios, reproduced by the ModABa.

In all the cases, precipitation, temperature and evapotranspiration regime estimated for the *Baseline* scenarios results rather similar to that observed during the calibration period: slight differences can be mainly attributable to the different datasets used (OA-ARRA database in calibration and SIAS database for the *Baseline* scenarios generation).

The model FDCs relative to the various climatic scenarios are shown in Figure 7. As a consequence of the rather moderate difference in climatic forcings, the FDCs relative to the *Baseline* scenarios (black curves) are almost coincident with the empirical FDCs for each basin (red points in Figure 4). The most evident discrepancies between current-simulated and past-observed FDCs can be noticed for the case of *Forgia at Lentina*, which, among the five investigated basins, is that characterized by the highest distance between calibration and *Baseline* climate; for this case, the *Baseline* FDC denotes a significative reduction of streamflow over the entire durations domain with respect to the calibration period (i.e., 1971-1985), while the shape of the curve remains essentially unaltered.

3.4.2 Projections under the RCP 4.5

The first considered emission scenario, namely the RCP 4.5, considers a greenhouse gas concentration trajectory with a relevant initial increase of CO_2 up to about the 2060 and then a sort of “plateau” for successive years. This obviously implies relevant changes on all the hydro-climatic variables passing from the *Baseline* to the *2055* projection, and significantly smoothed alterations passing from the scenario *2055* to the *2090*. All this is actually here confirmed by the analysis of both the climatic forcing and the resulting FDCs for all the case studies. Dashed and solid gray curves in Figure 7 show the projected FDCs in *2055* and *2090*, respectively, under the RCP 4.5. It can be noticed how the curves approximately preserve the *Baseline* FDCs shape, resulting significantly downshifted with respect to the *Baseline*, especially in the middle-low part, while the upper tails of the FDCs result approximately unaltered. The differences between the *2055* and *2090* FDCs are much less marked than those between the *Baseline* and *2055* FDCs; for the case of *Baiata at Sapone* the two future FDCs are practically coincident, while for the case of *Fastaia at La Chinea,* the *2055* curve is even lower (i.e., reduced streamflow) than that relative to the *2090*. This is due to the fact that, for both the cases, the two climatic projections (i.e. *2055* and *2090*) are almost identical (Table 6), especially with regard to the only *non-zero season*, and the modifications induced in the streamflow regime are essentially driven by changes in the characteristics of rainfall events, that are projected more intense and less frequent in *2090*.

The general behavior in terms of changes in the FDCs is also highlighted in Figure 8, relative to two cases (i.e., *Nocella at Zucco* and *Senore at Finocchiara*), where the specific streamflow values are not log-transformed and the duration domain is represented in a fragmented version, separately representing the highest and rarest streamflow values (i.e., with duration under 14 days), and the middle-low part of the FDC, with the most frequently overcome streamflow values (i.e., durations over 14 days).

Under the RCP 4.5 scenario, the *Nocella at Zucco* basin has shown the lowest variations among the five analyzed cases, with an almost unaltered hydrological regime in *205*5 and a slight reduction, for fixed duration, of almost all the streamflow values in *2090* projection. A quantitative analysis can be performed also through the value reported in Table 7a. With regard to the case of *Nocella at Zucco,* comparing the various discharges of equal percent duration for the *2055* with the corresponding *Baseline* values, it can be noticed how higher streamflow values for extremely rare events (with duration lower than about 4 days) partially compensate for the reduction in discharges over almost all the years, keeping unaltered the annual water availability of the river (i.e., almost constant mean annual runoff). This effect, related to the modelling structure of the ModABa, also concerns the *2090* projection, where the mean annual discharge is reduced by only the 6.4% despite a percent reduction in precipitation and a percent increment in temperature of almost the 13%. In this basin, moreover, both the mean duration of the *non-zero season* and the annual runoff coefficient remain almost unchanged.

The second case reported in Figure 8 (i.e., the *Senore at Finocchiara*) can be assumed as representative of the behavior of all the other basins. With respect to the previously discussed case, the modifications on the FDCs induced by climate change under the RCP 4.5 are here much more relevant, especially for what concerns the middle-low part of the curves, while, also in this case, the upper tails remain almost unaltered with higher streamflow values associated to the lowest frequencies (i.e., durations lower than about 2 days). As it can be noticed by Table 7a, the *non-zero season* of the *Senore at Finocchiara* basin is projected to be significantly shorter in the future and, on average, characterized by a higher discharge (i.e., higher $Q_{m,nz}$). At the annual level, it can be observed a significative decrement of the available water resource, with the mean annual runoff reduced about by the 10% and the 20% for the projections at *2055* and *2090*, respectively.

3.4.3 Projections under the RCP 8.5

The RCP 8.5 considers an exponential increase of the atmospheric CO_2 with a projected concentration in 2100 over three times the current value. In all the basins here examined, the variations from the *Baseline* to the *2055* in both precipitation and temperature under the RCP 8.5 results only slightly higher than under the RCP 4.5, while much more marked differences can be noticed comparing the *2090* climatic scenarios of the two different concentration trajectories (Table 6). Moreover, the *2055* precipitation, temperature and reference evapotranspiration under the RCP 8.5 result quite similar to the corresponding forcings obtained for the scenario *2090* under the RCP 4.5.

Under the RCP 8.5, the percent variations in both precipitation and temperature from the *Baseline* to the *2090* temporal horizon are about two times those projected passing from the *Baseline* to the *2055*, and even more accentuated differences can be noticed with regard to the reference evapotranspiration. Such a behavior is also reflected in the hydrological response of the various basins to the different climatic scenarios. From the observation of the FDCs (Figures 7 and 8), one can notice that the FDCs projected in *2055* under the RCP 8.5 (red dashed curves) are quite close to those relative to the *2090* under the RCP 4.5 (black solid curves), while the FDCs projected in *2090* under the RCP 8.5 show a deep modification in the hydrological regime of the analyzed basins; actually, in some of the basins previously classified as *ephemerals*, the flow conditions in the future could mainly (or totally) rely on the precipitation regime, approaching to hydrological conditions typical of *episodic* river basins.

Some basic statistics obtained for the RCP 8.5 and synthesized in Table 7b, project, on average, a reduction of about the 13% in the annual water availability in *2055*, while, for the *2090*, the projected percent reduction results, on average, of about the 32%, with a maximum of almost the 39% for *Baiata at Sapone*. A very important aspect is the relevant shortening of the *non-zero season*, which in some cases (i.e., *Forgia at Lentina* and *Senore at Finocchiara*) is projected to be almost halved for the *2090*. Despite a mean annual runoff coefficient only slightly reduced with respect to the *Baseline*, the hydrological regime for the *2090* projections appear significantly modified. Although streamflow values in *2090* are projected to be lower than the current values over almost all the year (i.e., for more than the 99% of the year), the mean discharge over the *non-zero season* is projected to increase; this behavior, observed for all the cases with the exception of the *Nocella at Zucco*, is again related to the hydrological model structure and is the result of the projected higher occurrence of extreme streamflow values with very low associated frequencies (i.e., durations in the order of 1 day or less), probably due to heavy rain events that are projected to occurs more frequently and with a higher intensity in the future. Although this last aspect may reflect the uncertainties of GCMs in reproducing rainfall extremes, it is worth mentioning that a good capability in reproducing historical trends by GCMs was recently recognized (e.g., Tebaldi et al., 2006).

3.4.4 Projected changes in streamflow components

The adopted hydrological model allows for the evaluation of the relative importance of the two streamflow components (i.e., surface and subsurface) in contributing to the runoff both at the annual and the daily level. For each analyzed climatic scenario, the percent contribution of the surface flow component (*SFC*) to the mean annual runoff (*R*) has been evaluated. Unfortunately no direct observations are available for such a kind of analysis and, therefore, the respective results, discussed in this section, should be interpreted with some degree of uncertainty given the impossibility to perform a rigorous validation.

With regard to the *Baseline*, despite the daily discharge during the most part of the year is mainly formed by the subsurface component, the surface contribution to the mean annual runoff results prevalent in all the basins (Table 7), with the only exception of the *Fastaia at La Chinea* river basin (*SFC*= 41.3%); this behavior actually reflects the typical torrential nature of most of the Sicilian rivers. The *Baiata at Sapone* is the basin showing the highest value of *SFC* (=77.6%), while for the other cases the surface component weights on the total annual runoff for about the 60%.

According to our results (Table 7), potential effects of climate change on the analyzed basins could entail also the repartition between the two streamflow components; for both the considered temporal horizon (*2055* and *2090*), the relative weight of the surface component is predicted to significantly increase, especially with regard to the RCP 8.5 scenario, further enhancing the torrential character of the considered basins. For the case of the *Senore at Finocchiara*, the value of *SFC* could even increase from the 58% to almost the 86% in the next 80 years, under the prospective of the RCP 8.5. The projected surface (*SFC*) and subsurface (*SSFC*) percent contributions to the mean annual runoff, *R*, under the RCP 8.5 are also represented in Figure 9, where it is also possible to compare the different value of *R* provided by the five basins. It can be noticed that the *R* reduction over the two analyzed temporal horizons, especially for the cases of *Fastaia at La Chinea* and *Senore at Finocchiara*, is mainly due to a reduction in the *SSFC* contribution, probably attributable to heavier evapotranspiration processes, while the projected increases in *SFC* imply only a moderate reduction of the surface component volumetric contribution to the mean annual flow volume, mainly attributable to changes in the rainfall structure and seasonal distribution.

The discharge partitioning, at the daily level, between the surface flow component and the subsurface flow component over the *non-zero season* is represented in Figure 10 for three basins, which represents the cases with the highest and the lowest current value of *SFC* (*Baiata at Sapone* and *Fastaia at La Chinea*, respectively) and the case showing the highest projected variations in terms of *SFC* (i.e. *Senore at Finocchiara*). The figure compares the *Baseline* with the *2090* curves under both the RCPs 4.5 and 8.5. Each curve represents the surface component percent contribution relative to the various streamflow values as a function of the corresponding frequency (i.e. percent durations) in the $\mathrm{FDC}_{\mathrm{nz}}$; thus, each point of the curves provides the streamflow component repartition as a function of the percentage of the *non-zero season* for which the corresponding total streamflow is exceeded. Only the portion of the *non-zero season* where the surface contribution weights on the daily streamflow for more than the 10%, corresponding to the streamflow values associated to the lower durations (i.e., higher streamflow values), is represented.

Under the current conditions (i.e., *Baseline*) the percent contribution of surface component at the daily level (SFC_i) is significative (>10%) for streamflow values that are exceeded over about the 20% of the *non-zero season* at the *Baiata at Sapone* and *Fastaia at Finocchiara* basins, and about the 24% at the *Senore at Finocchiara* basin. Significative future modifications on this aspect result only for the case of *Senore at Finocchiara*, where the portion of the *non-zero season* with streamflow values having SFC_i >10% could increase up to the 33%. The surface contribution is dominant (SFC_i >90%) for streamflow values that are currently exceeded only for an extremely limited part of the flow season (less than the 2% for all the cases) and no relevant future variations are projected on this aspect.

Substantial changes are, conversely, projected for the *2090* scenario under the RCP 8.5 with regard to the portion of the *non-zero season* characterized by streamflow values mainly formed by the surface component. In fact, form Figure 10, it can be noticed how, passing from the *Baseline* to *2090* scenario of the RCP 8.5, the percentage of the *non-zero season* characterized by streamflow with SFC_i >50% increases from the 4% to almost the 26% for the case of *Senore at Finocchiara*, and from the 12% to the 17% for the *Baiata at Sapone* basin, while it is almost unaltered for the case of *Fastaia at La Chinea*.

4 Conclusions

The analyses here performed has highlighted potential impact of climate change upon freshwater resource in five small basins within the northwestern Sicily, investigating possible modifications in the respective flow duration curve (FDC). In this paper, a recent hydrological model, the ModABa, and a weather generator, the AWE-GEN, have been coupled to analyze the effects of some generated future climate scenarios on the mean annual runoff and on the daily streamflow amount and composition (in terms of reparation between surface and subsurface components) for the selected case studies.

An opportune calibration procedure makes the adopted hydrological model particularly suitable to work under variable climatic conditions. The model has been first calibrated at each site with regard to a past “known” period, testing its performances that have been revealed, for all the cases here investigated, coherent and comparable with the performances previously shown in Pumo et al. (2014). For each basin, a *Baseline* scenario representative of the current conditions, which maintains the statistical properties of recently (i.e., from 2003 to 2013) observed series of precipitation, wind speed, air temperature, relative humidity and pressure, has been generated by the AWE-GEN. The future scenarios generated by the same model refer to two different temporal horizons, in order to investigate potential changes induced in about half century (projection at *2055*) and in about a century (projection at *2090*) under two possible different greenhouse gases emission scenarios (i.e., RCPs 4.5 and 8.5 by the IPCC, 2013).

Our findings have demonstrated that climate change is likely to have substantial effects on the hydrological regime of typical non perennial small basins of the southern Mediterranean region. For all the selected basins, all climate change scenarios project a significative reduction in the mean annual discharge, which mainly reflects the changes in precipitation, as it is demonstrated by the scarcely altered annual runoff coefficient. The results show a different response to climate change across the basins here considered, in consideration of the different geomorphologic characteristics, basin size, vegetational and soil patterns; the strongest changes have been found for the basin of *Senore at Finocchiara*, which is the largest considered basin, with the highest fraction of clayey soils and grass vegetation.

Beside the future water resources reduction, which is a common outcome for Mediterranean case studies, the novelty of this work consists in the analysis of future streamflow seasonality and distinction between surface and subsurface components. In fact, large alterations to streamflow seasonality are projected so that in the future we may expect, according to our predictions, more intense winter flood and more prolonged droughts in summer. The season usually dry could be subject to a general lengthening, also in the order of about three months in a century, under the most “pessimistic” emission scenario (RCP 8.5), and the hydrologic regime could be shifted from the current conditions (classified as *ephemeral*) towards conditions typical of *episodical* torrential rivers, where discharge totally relies on precipitation. This prevision is also strengthened by the simulated projected changes in the repartition between the two main components of streamflow, both at the annual and the daily level. The relative importance of the surface component in contributing to the mean annual runoff is projected to significantly increase. Flow conditions during the *non-zero season* are projected to be characterized by higher streamflow values, on average, with respect to the current conditions, with a more frequency of intensive floods due to more frequent and intense heavy rains.

This study also demonstrates that the change induced in the hydrological response of the basin is strongly related to the considered rate of growth in carbon dioxide concentrations in the atmosphere; in fact, the projected changes in *2090* under the RCP 4.5 are comparable with those predicted for the *2055* under the RCP 8.5, while the previsions for *2090* under the RCP 8.5 depict, for the analyzed basins, an alarming future scenario, with important and potentially dramatic implications for the biotic component of the underlying ecosystems and for which opportune counter-measures should be thought by local authorities.

Our outcomes, arising from an integrated approach linking climate, hydrological and ecosystem models, could be affected by different sources of uncertainty mainly associated with the hydrological model structure and parameters, with the observations used to drive and evaluate the two models (ModABa and AWE-GEN), and with the climate scenarios generation. Although an adequate ModABa reliability and accuracy in the reproduction of the FDC and water availability has been proved by both the past (Pumo et al., 2014) and the five here presented model applications to real cases, the assessment of model reliability in terms of evaluation of the streamflow component repartition would need further analysis. Furthermore, different techniques in the GCMs downscaling might give different estimates of the climatic variables changes and, consequently, of the induced variations in the hydrological regime of the investigated river basins. In spite of the uncertainties, common to many other studies on this topic, this work may be considered as a benchmark for studies aimed to future water resources assessment and could provide a sound basis for supporting decision making on water resources management in the analyzed region.

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Table 1. Main features of the five case studies: A = Total area [km^2]; L = main river channel length [km]; H_m = mean elevation [m a.s.l.]; c_0 = fraction of impervious area [%].

River Basin	A [km^2]	L [km]	H_m [m a.s.l.]	c_0 [%]
Forgia at Lentina	50.06	23.9	287	7.22
Baiata at Sapone	29.06	11.5	111	7.14
Fastaia at La Chinea	23.94	7.1	327	8.35
Nocella at Zucco	61.57	14.7	527	4.29
Senore at Finocchiara	75.92	23.6	407	7.37

Table 2. Parameters and relative percent cover relative to each vegetation (*a*) and soil (*b*) type present within the permeable portion of the five study basins. $\boldsymbol{Z_r}$= mean rooting depth; $\boldsymbol{\delta_{veg}}$= canopy interception threshold; $\boldsymbol{K_s}$= saturated hydraulic conductivity; $\boldsymbol{\beta}$= coefficient of the hydraulic conductivity power law; $\boldsymbol{n}$= porosity; $\boldsymbol{s_w}$= wilting point; $\boldsymbol{s_{fc}}$= field capacity.

(a)	***Parameters***		***Relative Percentage***				
	Z_r	δ_{veg}	*[%]*				
VEGETATION	*(mm)*	*(mm)*	*Forgia*	*Baiata*	*Fastaia*	*Nocella*	*Senore*
Trees	1000	2.0	*63.6*	*34.8*	*51.3*	*5.9*	*29.9*
Shrubs	400	1.0	*12.8*	*51.3*	*8.3*	*70.0*	*16.6*
Grasses	150	0.5	*23.6*	*13.9*	*40.4*	*24.1*	*53.5*

(b)	***Parameters***					***Relative Percentage***				
	K_s	β	n	s_w	s_{fc}	*[%]*				
SOIL	*(mm/day)*					*Forgia*	*Baiata*	*Fastaia*	*Nocella*	*Senore*
Sandy loam	607	13.8	0.415	0.22	0.47	*7.0*	-	*15.7*	*46.9*	-
silty loam	473	11.7	0.462	0.23	0.61	*1.2*	-	*0.5*	*1.3*	*13.1*
loam	227	14.2	0.465	0.26	0.55	*15.6*	*52.8*	*12.7*	*0.7*	*1.4*
silty clay loam	101	15.9	0.518	0.36	0.69	-	*44.3*	-	-	*4.2*
clay loam	90	16.3	0.504	0.35	0.65	*31.6*	*2.9*	-	*4.1*	*20.0*
Silty clay	65	19.2	0.532	0.47	0.77	*22.7*	-	*25.0*	*36.9*	-
Sandy clay loam	43	17.4	0.527	0.51	0.77	*21.8*	-	*46.1*	*10.2*	*61.4*

Table 3. Historical database by OA-ARRA used to derive historical series of daily streamflow, rainfall and temperature for the hydrological model calibration and database by

SIAS used to generate recent series of meteorological hourly data needed for the Weather Generator. For each case study the name (with ID-code and coordinates), the available and the considered dataset for both the hydrometric and the meteorological stations are listed. Name and typology of each station by OA-ARRA considered to estimate areal rainfall and temperature historical series at each basin are also reported (*P= Pluviometric station; T= Thermometric station*).

	measured variables		***Forgia***	***Baiata***	***Fastaia***	***Nocella***	***Senore***
Historical series (Hydrological Model) **source:** OA-ARRA	streamflow *(daily)*	*Name*	Forgia at Lentina	Baiata at Sapone	Fastaia at La Chinea	Nocella at Zucco	Senore at Finocchiara
		ID code	*3710*	*3720*	*3730*	*3680*	*3795*
		Coordinates	*38.05N 12.67E*	*37.97N 12.60E*	*37.93N 12.75E*	*38.08N 13.11E*	*37.74N 13.03E*
		av. dataset (size/from/to)	29 years (3 miss.)	27 years (7 miss.)	35 years (2 miss.)	42 years (4 miss.)	25 years (1 miss.)
			1971 2002	*1968 2001*	*1962 1998*	*1958 2003*	*1961 1986*
	Selected dataset (Calibration Period)	*(size/from/to)*	**15 years**	**17 years**	**18 years**	**23 years**	**18 years**
			1971 1985	***1974 1990***	***1967 1984***	***1977 1999***	***1969 1986***
	Areal rainfall and temperature *(daily)*	*Considered stations:*	*Erice (P); Lentina (P); Trapani (PT); Diga Paceco (PT); Calatafimi (P); Brogo Fazio (PT); Diga Rubino (PT); Fastaia (P); Specchia (P); Pioppo (PT); Partinico (PT); Montelepre (PT); Romitello (P); Montevago (P); Contessa Entellina (P); P.te Belice (PT); Vaccarizzo (P); Sambuca di Sicilia (PT); Giuliana (P); Chiusa Sclafani (P); Bisaquino (P); Diga Arancio (P); Corleone (PT); S.Margherita Belice (PT); S.Giuseppe Jato (PT); S.Giorgio C.C.(P); Vita (P); Segesta (P); Cuddia C.C. (P); Capo S.Vito (P); Dammusi (P); Carini (P); Salaparuta (P); Ginestra (P); Poggio S.Francesco (P)*				
Recent series (Weather Generator) **source:** SIAS	rainfall, temperature, solar radiation, wind speed, air relative humidity and air pressure *(hourly)*	*Name*	Erice	Trapani Fulgatore	Calatafimi	Partinico	Contessa Entellina
		ID code	303	308	300	277	267
		Coordinates	*38.03N 12.59E*	*37.95N 12.66E*	*37.85N 12.88E*	*38.07N 13.09E*	*37.72N 13.04E*
	Selected dataset *(size/from/to)*		**11 years**				
			from 2003 to 2013				

Table 4. Hydrological model calibration parameters and climate variables representative of the calibration period for the five river basins. Fraction of impervious areas (c_0); mean soil

and vegetation parameters (symbols are the same used for Table 2); regression parameters for Eqs.(1) and (2); number and size of the subperiods considered in the regression analyses; mean annual values of precipitation (*MAP*), rainfall events frequency (λ) and depth (α), fraction of no-rainy days (f_{NR}), temperature (*T*) and daily reference evapotranspiration (ET_0).

				Forgia	***Baiata***	***Fastaia***	***Nocella***	***Senore***
impervious fraction		c_0	-	0.072	0.071	0.084	0.043	0.074
mean vegetation parameters		Z_r	*(mm)*	722.5	574.2	606.7	375.3	445.5
		δ_{veg}	*(mm)*	1.52	1.28	1.31	0.94	1.03
mean soil parameters		K_s	*(mm/day)*	136.6	167.2	162.8	324.2	113.7
		β	-	16.65	14.99	16.85	16.25	16.32
		n	-	0.503	0.490	0.503	0.474	0.513
		s_w	-	0.39	0.31	0.42	0.35	0.43
		s_{fc}	-	0.67	0.62	0.69	0.62	0.72
Regression parameters of Eq.(1)	***Subperiods for Eq.(1)***		*number*	*10*	*15*	*45*	*45*	*21*
			size (years)	*≥12*	*≥13*	*≥10*	*≥15*	*≥13*
	estimate of p_{dry}	m_0	*(year/mm)*	0.5	13.3	747.2	39270527	12.6
		m_1	-	-0.18	-0.41	-1.29	-2.91	-0.64
		m_2	-	-3.20	2.08	-2.99	0.43	-1.95
Regression parameters of Eq.(2)	***Subperiods for Eq.(2)***		*number*	*4*	*4*	*5*	*9*	*5*
			size (years)	*12*	*14*	*14*	*15*	*14*
	estimate of k	a_1	*(1/day)*	0.048	0.165	-0.321	0.173	0.113
		b_1	-	1.083	0.114	-5.519	0.207	0.663
		c_1	*(1/mm)*	-0.250	-0.139	2.106	-0.088	-0.232
	estimate of k_v	a_2	-	2.642	7.802	-1.740	-6.381	-0.641
		b_2	*(day)*	0.396	2.762	22.364	8.440	-1.838
		c_2	*(day/mm)*	-0.958	-4.909	-3.894	2.693	2.781
heavy rain threshold		***HRT***	*(mm/day)*	21.2	19.8	18.2	34.0	19.4
Climate conditions for the calibration period		***MAP***	*(mm/year)*	674	650	686	974	654
		λ	*(1/day)*	0.304	0.283	0.302	0.299	0.318
		α	*(mm)*	6.10	6.29	6.21	8.93	5.62
		f_{NR}	-	0.696	0.717	0.698	0.701	0.682
		T	*(°C)*	18.1	18.7	17.6	17.3	16.4
		ET_0	*(mm/day)*	2.43	2.52	2.38	2.36	2.24

Table 5. Comparison between model and empirical values relative to the calibration period for: various discharges (l/s) of equal percent duration; mean annual discharge (Q_m) and mean discharge over the *non-zero season* ($Q_{m,nz}$) in l/s; mean durations of the *non-zero season* (d_{nz}) in days.

Discharge of equal percent duration (l/s)

		Forgia		**Baiata**		**Fastaia**		**Nocella**		**Senore**	
		Emp.	Theo.	*Emp.*	Theo.	*Emp.*	Theo.	*Emp.*	Theo.	*Emp.*	Theo.
Percent duration	***80%***	*0*	**0**	*0*	**0**	*0*	**0**	*10*	**17**	*0*	**0**
	40%	*30*	**35**	*10*	**11**	*5*	**7**	*120*	**128**	*40*	**40**
	20%	*170*	**176**	*30*	**38**	*77*	**69**	*290*	**295**	*180*	**198**
	10%	*410*	**383**	*80*	**72**	*150*	**163**	*550*	**619**	*490*	**454**
	5%	*750*	**766**	*180*	**203**	*325*	**357**	*950*	**978**	*1020*	**951**
	1%	*3650*	**1860**	*740*	**652**	*2120*	**923**	*2890*	**3662**	*5540*	**2763**
Q_m	***(l/s)***	*202*	**201**	*42*	**71**	*101*	**97**	*243*	**365**	*302*	**315**
$Q_{m,nz}$	***(l/s)***	*415*	**377**	*100*	**138**	*221*	**208**	*284*	**398**	*611*	**571**
d_{nz}	***(day)***	*178*	**195**	*152*	**189**	*166*	**169**	*312*	**334**	*180*	**201**

Table 6. Mean characteristics representative of the five climatic scenarios (current or *Baseline* scenario and future scenarios: *2055* and *2090* for both the *RCP 4.5* and *RCP 8.5*) generated by the AWE-GEN for each considered river basin. Symbols are the same used in Table 4.

	river basin:	***Forgia***					***Baiata***				
	scenario:	***Baseline***	***RCP 4.5***		***RCP 8.5***		***Baseline***	***RCP 4.5***		***RCP 8.5***	
			2055	***2090***	***2055***	***2090***		***2055***	***2090***	***2055***	***2090***
MAP	*(mm/year)*	**649**	589	*571*	579	*501*	**649**	593	*578*	578	*509*
λ	*(1/day)*	**0.293**	0.234	*0.228*	0.221	*0.186*	**0.277**	0.252	*0.229*	0.230	*0.194*
α	*(mm)*	**6.07**	6.90	*6.87*	7.18	*7.37*	**6.40**	6.44	*6.92*	6.87	*7.20*
f_{NR}	-	**0.707**	0.766	*0.772*	0.779	*0.814*	**0.723**	0.748	*0.771*	0.770	*0.806*
T	*(°C)*	**17.8**	19.4	*20.0*	20.0	*21.9*	**19.1**	20.6	*20.9*	21.0	*23.1*
ET_0	*(mm/day)*	**2.40**	2.45	*2.47*	2.46	*2.56*	**2.55**	2.59	*2.59*	2.59	*2.69*

	river basin:	***Fastaia***					***Nocella***				
	scenario:	***Baseline***	***RCP 4.5***		***RCP 8.5***		***Baseline***	***RCP 4.5***		***RCP 8.5***	
			2055	***2090***	***2055***	***2090***		***2055***	***2090***	***2055***	***2090***
MAP	*(mm/year)*	**664**	606	*590*	593	*517*	**944**	850	*827*	837	*719*
λ	*(1/day)*	**0.336**	0.287	*0.275*	0.275	*0.231*	**0.333**	0.267	*0.269*	0.268	*0.232*
α	*(mm)*	**5.42**	5.80	*5.88*	5.90	*6.13*	**7.76**	8.72	*8.44*	8.55	*8.48*
f_{NR}	-	**0.664**	0.713	*0.725*	0.725	*0.769*	**0.667**	0.733	*0.731*	0.732	*0.768*
T	*(°C)*	**17.3**	19.0	*19.3*	19.6	*21.3*	**16.8**	18.3	*18.8*	19.1	*21.0*
ET_0	*(mm/day)*	**2.40**	2.41	*2.41*	2.43	*2.59*	**2.33**	2.36	*2.38*	2.39	*2.48*

	river basin:	***Senore***				
	scenario:	***Baseline***	***RCP 4.5***		***RCP 8.5***	
			2055	***2090***	***2055***	***2090***
MAP	*(mm/year)*	**659**	598	*583*	587	*503*
λ	*(1/day)*	**0.303**	0.250	*0.245*	0.256	*0.214*
α	*(mm)*	**5.95**	6.54	*6.51*	6.28	*6.46*
f_{NR}	-	**0.697**	0.750	*0.755*	0.744	*0.786*
T	*(°C)*	**16.7**	18.2	*18.8*	18.9	*20.8*
ET_0	*(mm/day)*	**2.27**	2.28	*2.30*	2.31	*2.41*

Table 7. Results from *Module Statistics* under the RCP 4.5 (*a*) and the RCP 8.5 (*b*). Discharges (l/s) of various percent duration; mean annual discharge (Q_m) and mean discharge over the *non-zero season* ($Q_{m,nz}$) in l/s; mean durations of the *non-zero season* (d_{nz}) in days; mean annual runoff coefficient (ϕ); mean annual runoff in mm/yr (R); mean percent contribution of the surface component to the annual runoff (*SFC*).

a) **Discharge of equal percent duration (l/s)**

RCP 4.5		Forgia			Baiata			Fastaia			Nocella			Senore		
		Baseline	2055	2090	Baseline	2055	2090	Baseline	2055	2090	Baseline	2055	2090	Baseline	2055	2090
Percent duration	80%	0	0	0	0	0	0	0	0	0	9	9	5	0	0	0
	40%	12	4	0	7	2	2	2	0	0	101	98	77	33	9	3
	20%	92	58	34	30	15	15	57	21	27	285	236	201	166	91	53
	10%	270	193	142	67	39	33	130	69	100	575	502	457	461	303	228
	5%	585	506	436	186	144	134	273	197	263	903	838	753	918	742	623
	1%	1562	1534	1400	597	506	531	713	617	799	1750	2263	1672	2251	2316	1934
Q_m	(l/s)	167	151	131	75	55	61	64	53	63	304	303	285	252	227	203
$Q_{m,nz}$	(l/s)	334	340	335	150	130	143	156	145	175	340	343	328	451	457	463
d_{nz}	(day)	183	162	142	182	156	156	150	132	132	327	322	317	204	181	160
ϕ	(–)	0.16	0.16	0.14	0.12	0.10	0.11	0.13	0.11	0.14	0.17	0.18	0.18	0.16	0.16	0.14
R	(mm/yr)	105	95	82	81	60	66	84	69	83	156	155	146	105	94	84
MAC_{sc}	(%)	60.1	64.9	68.8	77.6	82.4	83.5	41.3	59.7	49.2	57.5	59.6	64.0	58.0	68.0	73.6

b) **Discharge of equal percent duration (l/s)**

RCP 8.5		Forgia			Baiata			Fastaia			Nocella			Senore		
		Baseline	2055	2090	Baseline	2055	2090	Baseline	2055	2090	Baseline	2055	2090	Baseline	2055	2090
Percent duration	80%	0	0	0	0	0	0	0	0	0	9	7	0	0	0	0
	40%	12	0	0	7	0	0	2	0	0	101	89	30	33	3	0
	20%	92	36	5	30	12	4	57	27	9	285	219	101	166	54	6
	10%	270	145	44	67	30	14	130	96	55	575	480	309	461	235	80
	5%	585	441	282	186	130	94	273	259	190	903	805	600	918	633	401
	1%	1562	1459	1214	597	538	465	713	789	703	1750	1709	1454	2251	1963	1595
Q_m	(l/s)	167	137	103	75	61	46	64	63	50	304	270	216	252	205	167
$Q_{m,nz}$	(l/s)	334	346	407	150	154	163	156	175	173	340	308	285	451	465	632
d_{nz}	(day)	183	144	93	182	145	102	150	132	106	327	321	276	204	161	97
ϕ	(–)	0.16	0.15	0.13	0.12	0.12	0.10	0.13	0.14	0.13	0.17	0.17	0.15	0.16	0.14	0.14
R	(mm/yr)	105	86	65	81	67	49	84	83	66	156	139	110	105	85	70
MAC_{sc}	(%)	60.1	69.0	78.7	77.6	86.1	89.3	41.3	49.7	56.6	57.5	58.3	72.9	58.0	73.8	85.7