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Co-evolution of hydrological components under climate change scenarios in the Mediterranean area

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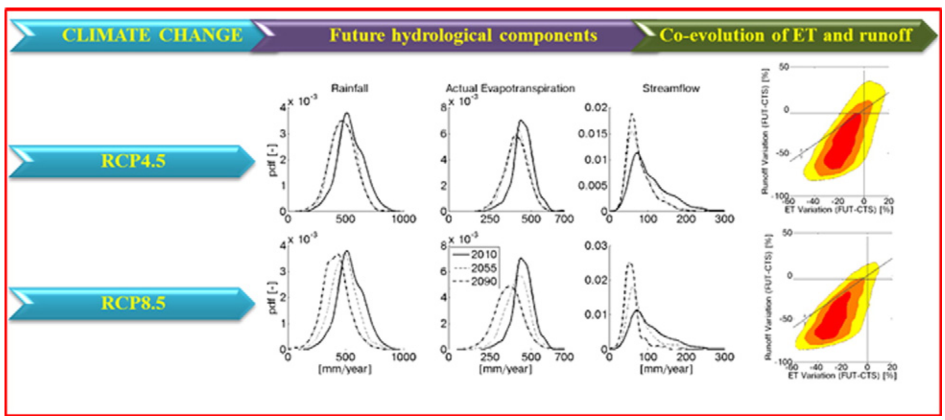
HIGHLIGHTS

- This study investigates at basin spatial scale future runoff and evapotranspiration.
- A simple conceptual hydrological model and GCMs realizations have been coupled.
- Radical shift and shape modification of the annual runoff and evapotranspiration *pdf* are foreseen.
- Future evapotranspiration will lead to similar (same sign) and more marked modifications in runoff.

GRAPHICAL ABSTRACT



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ABSTRACT

The Mediterranean area is historically characterized by high human pressure on water resources. Today, while climate is projected to be modified in the future, through precipitation decrease and temperature increase, that jointly and non-linearly may affect runoff, concerns about water availability are increasing. For these reasons, quantitative assessment of future modifications in the mean annual water availability are important; likewise, the description of the future interannual variability of some hydrological components such as runoff and evapotranspiration are highly wished for water management and ecosystems dynamics analyses.

This study investigates at basin spatial scale future runoff and evapotranspiration, exploring their probability density functions and their interdependence as functions of climatic changes. In order to do that, a parsimonious conceptual lumped model is here used. The model is forced by different future climate scenarios, generated through a weather generator based on a stochastic downscaling of an ensemble of General Circulation Models (GCMs) realizations. The use of the adopted hydrological model, under reliable stochastic future climate scenarios, allows to project future values of evapotranspiration and runoff in a probabilistic framework and, at the same time, the evaluation of their bivariate frequency distributions for changes through the Multivariate Kernel Density Estimation method.

As a case study, a benchmark Mediterranean watershed has been proposed (Imera Meridionale, Italy). Results suggest a radical shift and shape modification of the annual runoff and evapotranspiration probability density functions. Possible implications and impacts on water resources management are here addressed and discussed.

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1. Introduction

Implications of climate change for future water resources assessing, planning, and management have been the subject of several studies from the eighties (Gleick, 1989). First studies were based on perturbation scenarios and results were so wide to appear somehow useless for practical purposes (Arnell and Reynard, 1996). More reliable projections have been achieved in recent years through the use of Regional Climate Models (RCMs) and General Circulation Models (GCMs) to generate future climatic scenarios. One of the first works was carried out by Arnell (1999) who described the implications of climate change for global hydrological regimes and water resources using climate change scenarios from GCM outputs and simulating global river flows at macro scale. Results, which were also confirmed by more recent and detailed studies, stated that the average annual runoff would be increased at the high latitudes, in equatorial Africa and Asia, and Southeast Asia, and would be decreased at the mid-latitudes and most subtropical regions. Since the beginning, it was clear that possible future changes in streamflow could give rise to competition for water between different sectors, namely civil, irrigation, energy production, and recreation (Hamlet and Lettenmaier, 1999).

While several studies have been dedicated to areas where the runoff is forecasted to increase at the annual time scale, thus not generating problems for water availability but rather for flood risk (Heo et al., 2014; Middelkoop et al., 2001), most of the climate change studies have been focused on areas where the runoff trend is negative due to rainfall decrease and temperature increase. These areas, especially if highly populated, raise serious challenges for water management in the next future. Antonellini et al. (2014) evaluated the effects of climate and land use change on the water resources and the economic development of the Tahadart basin (Morocco). They argued that increased temperature could increase the risk of drought and negatively influence freshwater availability because of the increase in evaporation from open water surface bodies. Islam et al. (2014) assessed the hydrologic impact of climate change on the Murray–Hotham catchment (Australia) using a multi-model ensemble approach, for statistically downscaling GCM outputs to precipitation, coupled with a hydrological model. Downscaled and bias-corrected data were obtained from 11 GCMs, resulting in a significant rainfall reduction with respect to the observed past, depending on the emission scenarios. These changes, coupled with temperature increase, were found to cause a dramatic decrease in runoff, with percentage reductions in the order of 74% in the worst emission scenario at the end of the 21st century. A similar study was carried out in the Karkheh basin in the semiarid region of Iran (Ashraf Vaghefi et al., 2014). In particular, runoff and evapotranspiration components were modeled with uncertainty ranges for both historic and future data. Authors stated a decrease by 44% in the freshwater availability in the southern part of the country, where much of agricultural activities are located. In a very recent study, Santos et al. (2014) assessed not only the impact of climate change on stream flow components but also on aquifer properties and water table fluctuations. They found dramatic reductions in runoff, base flow and dug water levels, which anticipate negative consequences for irrigation capacity and crop productivity.

The Mediterranean area is probably the most vulnerable to climate alterations (Lionello et al., 2006) because of the decrease in the average streamflow, changes in river regime characteristics, and hydrological changes (García-Ruiz et al., 2011; Pumo et al., 2016; Sellami et al., 2016). Climate change in the Mediterranean area can also deteriorate water quality (Sanches Fernandes et al., 2012) endangering the life of many aquatic species (Santos et al., 2015).

In particular, Sicily (Italy), which is one of the most representative area of the Mediterranean climate, because of its high population, diversified agricultural productivity and ecosystems biodiversity, is seriously threatened by several climate alteration signals (Arnone et al., 2013; Cannarozzo et al., 2006; Caracciolo et al., 2014; Pumo et al., 2016; Viola et al., 2014a). As a consequence of such alterations, Sicily will probably face, in the short term, the effects of a reduction in water availability and ecosystems shift because of the increasing in vegetation water stress (Pumo et al., 2010). Potential impacts of climate change on surface water and groundwater resources were evaluated in a Sicilian basin (Liuzzo et al., 2014a) using a conceptual hydrological model (TOPDM, Noto (2014)). Results showed that the negative trend in precipitation determines a decrease in surface and groundwater resources, which, in turns, may affect reservoirs management.

The above-mentioned premises highlight the importance of a reliable estimation of water availability in arid Mediterranean areas in order to make appropriate future water management decisions. Following this need for knowledge, this work focuses on water resources assessment in future climatic scenarios in a Mediterranean basin, which could be considered as a benchmark for this climatic area, using a lumped conceptual hydrological model. Despite their acknowledged limitations (Beven, 1989; Renard et al., 2010; Viola et al., 2009), lumped models continue to be used widely for climate-change impact assessments (Horton et al., 2006; Jiang et al., 2007; Liuzzo et al., 2014a; Menzel and Bürger, 2002; Mimikou et al., 2000; Prudhomme et al., 2003; Wilby, 2005). The model here used is the EHSM (*EcoHydrological Streamflow Model*) (Viola et al., 2014b). This model has been selected because of its proved ability to simulate daily runoff in small semiarid basins, while the conceptual hydrological scheme keeps some physical meaning. The model is forced with different stochastic future climate scenarios, downscaled from GCMs projections adopted by the *fifth assessment report* of the *Intergovernmental Panel on Climate Change*, here after IPCC-5AR (Christensen et al., 2013), in order to obtain reliable traces of runoff, evapotranspiration, and soil moisture at basin scale.

The novelty of this work lies in the attempt of estimating not only the average future value of different hydrological components of water cycle in a critical area, but also the future probability density functions of annual runoff and evapotranspiration. The former summarizes several crucial information necessary for water management purposes while the latter provides valuable basis to ecosystems dynamics analysis and allows arguing on vegetation productivity and water stress assessment. At the same time this study, while illustrating future annual runoff and evapotranspiration, focuses on their interdependence depicting a likely joint decrease, as a function of rainfall decrease.

2. Model description

The hydrological conceptual model here used has been described by Viola et al. (2014b) and is here briefly recalled in order to depict its main features and parameters. The hydrological scheme assumed for the basin description, depicted in Fig. 1, consists of three interconnected elements: a soil bucket linked with two linear reservoirs, one responsible for the fast surface runoff component, and another accounting for the slow subsurface runoff component. The fast component of streamflow is triggered by rainfall on impervious surfaces (whose fraction is called c_0) and by excess of saturation; it is transferred through the surface reservoir to the basin outlet with a transit time of few hours. Water passing through the subsurface reservoir comes from leakage pulses and is characterized by residence times in the order of several days or months.

The water input to the system is the daily rainfall depth, R [mm/day], spatially averaged over the catchment. Rain, falling through the canopy (modeled by a simple fixed threshold) on the pervious part of the soil, drives relative soil moisture dynamics. The determination of relative soil moisture variation in the permeable part of the soil bucket during a daily temporal step is achieved numerically solving a simple balance equation through a forward finite differences method. The numerical solution provides water fluxes passing through the soil bucket: specifically, the runoff over the permeable part of the basin (Q_s), occurring when rainfall exceeds the maximum soil storage capacity, the water losses due to evapotranspiration (ET), and the