GIS–based application of Benfratello's method to estimate the irrigation deficit and its uncertainty under different climate change scenarios

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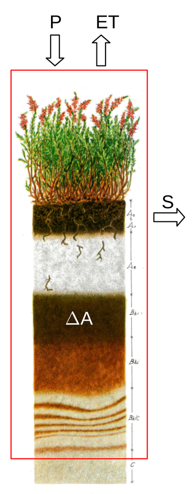
Abstract

Benfratello's *Contribution to the study of the water balance of an agricultural soil* (*Contributo allo studio del bilancio idrologico del terreno agrario*) was firstly published in 1961. The paper provides a practical conceptual and lumped method, based on climatic forcings and on the field capacity, to determine the irrigation deficit in agricultural districts. It generalizes the previous Thornthwaite (1948) and Thornthwaite & Mather (1955) water balances thanks to the application of a dimensionless approach introduced by De Varennes e Mendonça (1958), and of a power–law desiccation function. Since then, it has been used in many semi–arid areas in Southern Italy. Due to its simplicity and to the small number of required parameters, Benfratello's method could be regarded to as an effective tool to assess the effects of climatic, landuse and anthropogenic changes on the soil water balance and on the irrigation deficit, both at the climatic scale and in real time. In previous EGU–GA contributions (Barontini et al., 2021, 2022) we presented a GIS–based implementation of Benfratello's method to assess the irrigation deficit in the Capitanata plain ($4550\,\mathrm{km}^2$), and a theoretical development of the method to estimate in closed form the interannual variability of the calculated irrigation deficit, once known the variability of temperature and precipitation. In this contribution we present the results obtained by applying the GIS–based Benfratello framework to assess the irrigation deficit and its variability in the Capitanata plain under different climate change scenarios. The scenarios were generated with the following procedure: (i) evaluation of different GCMs (CNRM-CM5, CMCC-CM and IPSL-CM5A-MR) in comparison with the historical data, (ii) correction of systematic biases, (iii) application of the same biases to the corresponding IPCC RCP4.5 and RCP8.5 scenarios, (iv) statistical downscaling of the obtained models to estimate future time series for the meteorological stations of interest in the considered case study and (v) spatial interpolation with ordinary Kriging.

Benfratello's method

- Original hypotheses:
  1. No water capillary rise from the groundwater table to the soil,
  2. Runoff and percolation only after the field capacity U is reached.
- Control volume (sketched on Kubiena's *Humus podsol*):



- Simplified soil water balance for the i–th month of the j–th year:

$$\Delta A_{i,j} = P_{i,j} - ET_{i,j} - S_{i,j}\,, \quad (1)$$

$A_{i,j} \leq U\,[L]$: equivalent depth of the available stored water at the end of the month; $\Delta A_{i,j} = A_{i,j} - A_{i-1,j}$: variation of the available water; $P_{i,j}\,[L]$:monthly precipitation; $ET_{i,j}\,[L]$: monthly (actual) evapotranspiration; $S_{i,j}\,[L]$: cumulated water exceedance. D and S stand for the Latin *deficit* (*it lacks*) and *superavit* (*it exceeded*), they were early introduced by De Varennes e Mendonça (1958) and later maintained by Benfratello (1961).

- The monthly deficit $D_{i,j}$ is the water needed to fill the gap between the maximum required evapotranspiration $ET_{\max,i,j}$ and the actual one $ET_{i,j}$. The calculations are performed on a climatic basis, so that the expectation of the water balance provides the expectation of the monthly deficit:

$$\Delta A_i = P_i - ET_i - S_i\,;\; D_i = ET_{\max,i} - ET_i\,. \quad (2)$$

- The average year is divided into two seasons:
  1. wet season $P_i \geq ET_{\max,i}\,;\; ET_i = ET_{\max,i}$ where

$$\Delta A_i + S_i = P_i - ET_{\max,i}\,,\; S_i > 0 \text{ when } A_i = U \quad (3)$$

  2. dry season $P_i < ET_{\max,i}$ where

$$\Delta A_i = P_i - ET_i\,,\; S_i = 0 \quad (4)$$

With $t = 0$ at the beginning of the dry season (when $A = A_{\max} \leq U$), the fundamental hypothesis of the method is

$$\frac{\frac{\mathrm{d}B}{\mathrm{d}t}}{-\frac{\mathrm{d}L}{\mathrm{d}t}} = \frac{\mathrm{d}A}{\mathrm{d}L} = \left(\frac{A}{U}\right)^m \quad (5)$$

in which $-L(t) = ET_{\max}(t) - P(t)$ is the potential soil water loss and $B(t) = ET(t) - P(t)$ the actual soil water loss. The power $m \geq 0$ accounts for the different attitude of the crop to react to a water stress and it generalizes the Thornthwaite and Mather's approach in which $m = 1$.

- Following the dimensionless approach by De Varennes e Mendonça (1958) we define $-\lambda_{\min}$, $\alpha_{\min}$, $\alpha_{\max}$ and $\sigma_{w,\max}$ as the dimensionless forms of the maximum potential loss during the dry season, of the minimum available soil water at the end of the dry season, of the maximum available soil water at the beginning of the dry season, and of the maximum soil water gain at the end of the wet season, respectively, so that the annual water balance is written as
  1. $\alpha_{\min} = \alpha(\lambda_{\min})$ in the dry season
  2. $\alpha_{\max} = \alpha_{\min} + \sigma_{w,\max}$ in the wet season, with $\alpha_{\max} \leq 1$
- Finally the dimensionless annual deficit at the end of the dry season is

$$\delta = -\lambda_{\min} + \alpha_{\min} - \alpha_{\max} \quad (6)$$

Uncertainty estimation

In order to use the Benfratello's method output as design input for irrigation purposes we need to determine also the uncertainty of the irrigation deficit, as a consequence of the interannual variability of the climatic variables, viz temperature and precipitation.

1. Define the interannual variabilities $\sigma(\lambda_{\min})$ and $\sigma(\sigma_{w,\max})$ for the dry and wet season respectively, by composing the monthly variabilities $\sigma(\lambda_i)$ and $\sigma(\sigma_{w,i})$:

$$\sigma(x) = \frac{1}{U}\sqrt{\Sigma_i\left[\left(\frac{\mathrm{d}ET_{\max}}{\mathrm{d}T}\right)^2\Bigg|_{T=T_i}\sigma^2(T_i) + \sigma^2(P_i)\right]} \quad (7)$$

with $x = \lambda_{\min}$ and $x = \sigma_{w,\max}$ in the dry and wet season respectively

2. Determine the deficit uncertainty $\sigma(D)$ according to the soil water state at the end of the wet season:

(a) $A_{\max} < U$ ($\alpha_{\max} < 1$):

$$\sigma(\delta) = \sqrt{\sigma^2(\lambda_{\min}) + \sigma^2(\sigma_{w,\max})} \quad (8)$$

(b) $A_{\max} = U$ ($\alpha_{\max} = 1$):

$$\sigma(\delta) = |-1 + \alpha_{\min}^m|\;\sigma(\lambda_{\min}) \quad (9)$$

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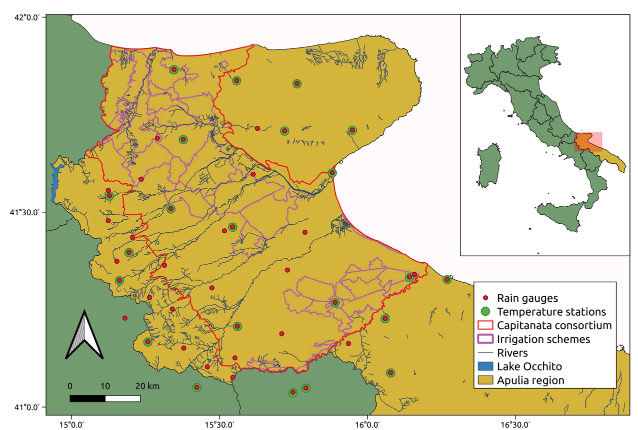
$$\sigma(D(t_w)) = U\,\sigma(\delta(t_w)) \quad (10)$$

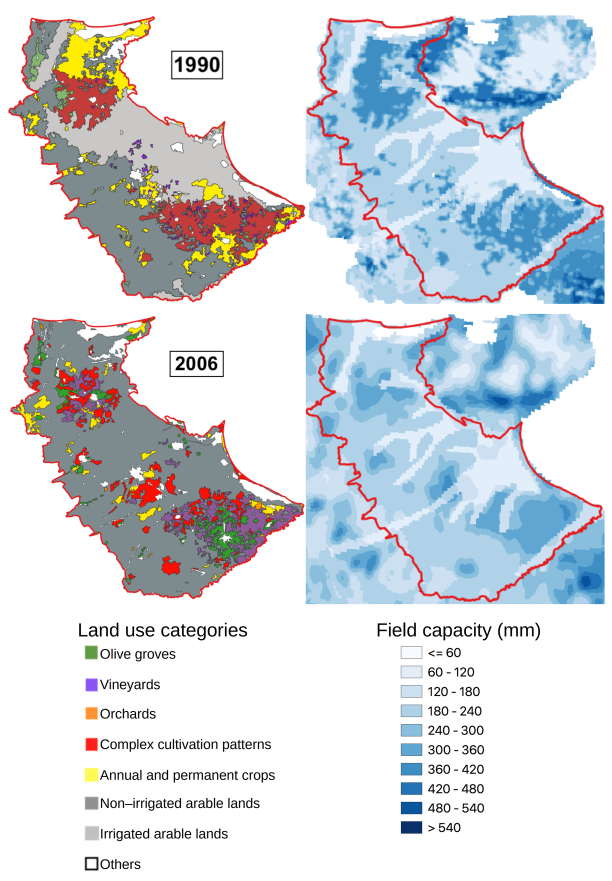
Case study

- The Bonifica della Capitanata district in the Northern part of Apulia region, Southern Italy

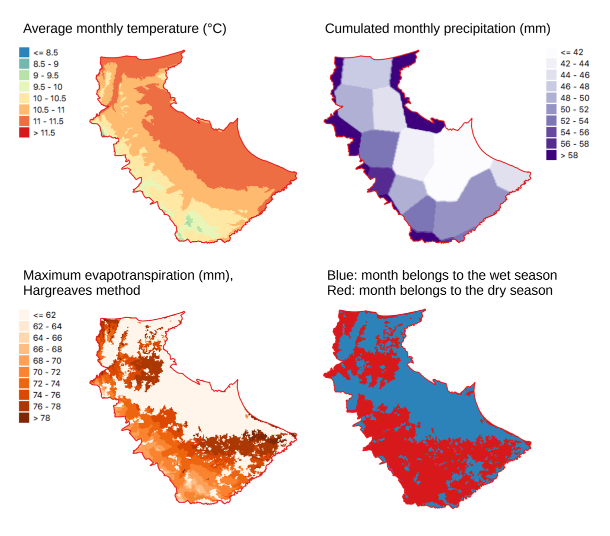


GIS–based application

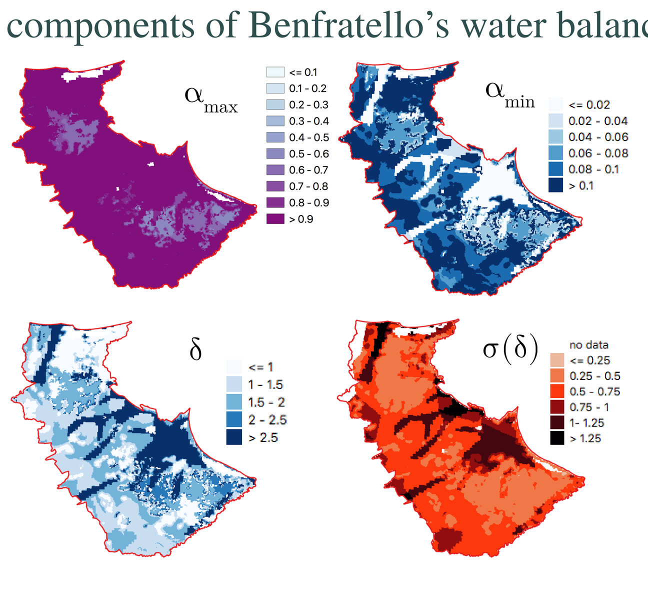
- First input data: land-cover and field capacity



- Second input data: climatic variables T, P, $ET_{\max}$ (calculated as the crop evapotranspiration in standard condition according to the FAO56 procedure) and dry/wet season



- Dimensionless components of Benfratello's water balance



Climate change scenarios

The scenarios were generated with the following procedure:

1. Combination of different GCMs (CNRM-CM5, CMCC-CM and IPSL-CM5A-MR) with the IPCC RCP4.5 and RCP8.5 scenarios as well as with historical data
2. Statistical downscaling of the obtained models to estimate future time series of air temperature and precipitation for the meteorological stations of interest in the considered case study
3. Spatial interpolation with ordinary kriging.

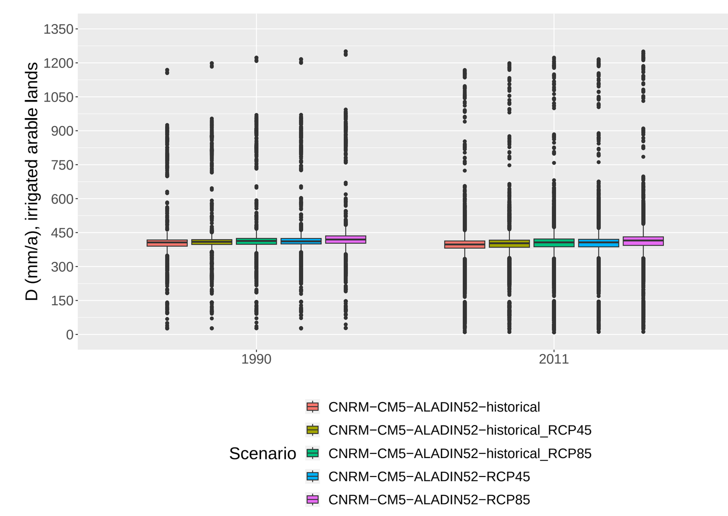
See Guyennon et al. (2017) for the extended treatment of this topic.

These interpolations have a spatial definition of $1\,\mathrm{km}$ and are based on a 9413–points grid in which every point is identified by a triad of values (X and Y in WGS84–UTM33 and altitude). Monthly values of P and T are available for each point.

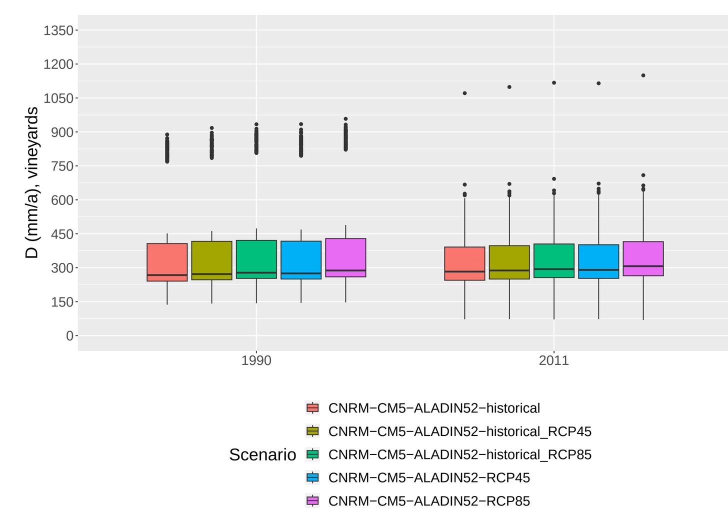
Preliminary results

The obtained P and T maps were then used as input data for the already developed GIS–based application of Benfratello's method. Here we show a land–use–specific comparison between the combination of two land–cover and five climatic scenarios

- Irrigated arable lands



- Vineyards



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Link to the extended paper

For further material please refer to our recently published paper *Application of Benfratello's method to estimate the spatio–temporal variability of the irrigation deficit in a Mediterranean semiarid climate*:

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