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Research article

Combining GIS and FAO's crop water productivity model for the estimation of water footprinting in a temporary river catchment

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ABSTRACT

In the arid and semi-arid areas such as those in southern Europe, the correct management of water is of fundamental importance as well as the estimation of water consumption associated with human activities. Considering a temporary river catchment, the Water Footprint (WF) methodology allows direct and indirect estimation of water consumption required for the production of a given product. Furthermore, the WF estimation often involves the use of Geographic Information Systems (GIS) that allows to process climate, land use and soil type data. With the intent of strengthening existing methodologies applied at basin scale, this study deals with the estimation of WF in a temporary river catchment combining GIS and FAO's (Food and Agriculture Organization of the United Nations) crop water productivity model. In detail, with reference to each municipality in the Candelaro catchment area (2330 km^2, Southern Italy), the blue and green component of WF was calculated for the agricultural products. Additionally, the role of treated wastewater, intended as a strategy of water deficit compensation at basin scale, was addressed. Results showed a WF of 686 Mm^3/year with a greater contribution from the green than the blue component. The wheat was the cultivation that required the largest quantity of rainwater while tomato was the product that contributed to the increased demand for irrigation water, which accounted for about 50% of the blue component. The other agricultural products that contributed to the demand for blue water were grapes and olive trees. Finally, the treated wastewater can substantially contribute to covering the water deficit; results showed a contribution of 30%–40% of water savings.

1. Introduction

The increasing growth in the world's population which is expected to reach 9.2 billion by 2050 and the intensification of activities in the agricultural, industrial and tertiary sectors require an ever-increasing demand for water (WWAP (United Nations World Water Assessment Programme), 2015). The main demand comes from the agricultural sector, which uses about 70%–80% of the world's water resources (Molden, 2017). Today there are many different regions that are subject to water stress with consequent difficulties on agricultural activities. As Brown and Matlock (2011) reported, cereal imports could compensate for these shortcomings. In the arid and semi-arid areas such as those in southern Europe, the correct management of water is of fundamental importance as well as the evaluation of water consumption associated mainly with agricultural activity (Sabziparvar and Tabari, 2010; Lopez and Vurro, 2008; Ortega et al., 2004).

The estimation of global, national and local (at river basin or municipality scale) water consumption can be performed using the Water Footprint (WF) (Chapagain and Hoekstra, 2003). In general, WF makes it possible to estimate the direct and indirect consumption of fresh water required for the production of a given product (Hoekstra et al., 2011). With reference to the boundaries of a river basin, WF allows the estimation of the quantity of water used to produce one tonne of product (expressed as m^3/ton), considering each agricultural, industrial and tertiary activities as presented in the study area. For this purpose, Mekonnen and Hoekstra (2011) refer to the so-called *Virtual Water Content*. In addition, the WF calculation also takes into account several components such as the green, blue and grey water footprint. These concern, respectively, rainwater, groundwater/river water and water associated with the use of fertilizers that can cause a potential polluting load (Hoekstra et al., 2011).

In literature there are several studies on WF at basin scale (Table 1); a top-down approach that also consider the import and

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Table 1
Survey on the application of the WF methodologies at basin scale.

N.	Aim of the study	Key observations on:					References
		Methodology	Investigated sectors	Specificities of the case study			
				Name, basin classification[a]	Rainfall [mm/year]	Surface [km^2]	
1	Evaluate the WF of agriculture in the basin developing the CWU Model (a spatially-explicit water balance model to assess the green and blue water consumed by crops and the water needed to assimilate the leaching of nitrogen applied as fertilizer).	CWU Model computes in a spatially way the actual evapotranspiration of the crop in non-optimal conditions. The model was developed using Model Builder (ESRI ArcGIS 9.3).	Agricultural sector	Duero river basin (Spain and Portugal); B	400–1800	98,073	de Miguel et al. (2015)
2	Demonstrate that the WF based on the multi-regional input–output approach can differ according to the type of the model (i.e. combined or separated) used to calculate it.	Interregional input–output approach	All goods and services	Yangtze River Basin (China)	–	1.8 × 10^6	Okadera et al. (2014)
3	Analyse the WF at basin scale focusing on green and blue components. Furthermore, to present the blue WF disaggregated for both surface and groundwater.	Bottom-up approach and Crop Water requirements option for the calculation of WF in agriculture sector.	Agriculture and livestock; industry; domestic supply; energy; tourism	Guadalquivir basin (Spain); B	535	57,530	Dumont et al. (2013)
4	Quantify the net VW import and export amounts of agricultural products for the river basins of the EU28.	National WF of agricultural sectors was extrapolated to livestock and population raster data and aggregated to the river basin level.	Agricultural products	EU 28 river basin	–	>1000	Vanham and Bidoglio (2013)
5	Assess WF considering a semi-arid basin.	Bottom-up approach and Crop Water requirements option for the calculation of WF in agriculture sector.	Agricultural (crop production and livestock one); Industrial; Domestics.	Heihe River Basin (China); B	20 - 480	130,000	Zeng et al. (2012)
6	Develop a multi-regional input–output accounting framework to assess the regional virtual water flows (both green and blue water). Furthermore, to calculate WF for rural and urban households in each part of the basin.	Multi-regional input–output economic and water accounting framework.	Agriculture and livestock; industry and service.	Yellow River (China); C, B	–	795,000	Feng et al. (2012)
7	Estimate the virtual irrigation water balance (an important component of the WF that provides additional information to the basin blue water balance).	Estimation of Virtual Irrigation Water Balance as the difference between Exported and Imported Virtual Irrigation Water.	Agricultural sector	Guadalquivir River (Spain); B	550	57,000	Montesinos et al. (2011)
8	Investigate virtual water trade using an input–output model.	Input–output model based WF accounting framework.	Agriculture and livestock; industry and service.	Haihe River Basin (China)	371–771	318,000	Zhao et al. (2010)

[a] Classification of the basin: A = arid; B = semi-arid; C = perennial.

export of products was used by Okadera et al. (2014), Montesinos et al. (2011) and Zhao et al. (2010). Virtual Water trade was also evaluated at national level and between Italy and others countries for the import and export of agricultural products, considering the water saving or loss through trade (De Leo and Miglietta, 2012; De Leo et al., 2013; Lamastra et al., 2017; Miglietta and Morrone, 2018a). Instead, Dumont et al. (2013) and Zeng et al. (2012) adopted a bottom-up approach based on the number of consumers/population in the study area. Additionally, Miglietta et al. (2015) and De Leo and Miglietta (2012) estimated the WF considering the production and consumption of agricultural products, in particular olive oil and wine, while Vanham and Bidoglio (2014) conducted a WF assessment distinguished different scenarios based on the dietary habits of the population. WF was also investigated considering energy crops such as sugar beet, sugar cane, potato, cassava, maize, barley and others used for production of ethanol or rapeseed, soybean and palm oil for biofuels (Su et al., 2015; Gerbens-Leenes, 2018) or for biogas production (Pacetti et al., 2015).

In some studies, the study area was a semi-arid zone whose real problem is the estimation of water consumption and the consequent sustainable management of water resources (Dumont et al., 2013; Zeng et al., 2012; Montesinos et al., 2011). Based on the prevalent activities conducted within the catchment area, some authors have also chosen to estimate only the WF regarding agricultural production; others instead have also investigated the industrial and domestic sector (Table 1).

The WF estimation often involves the use of Geographic Information Systems (GIS); the GIS allows to process climate, land use and soil type data, both on a large and on a smaller scale. Furthermore, GIS allows to interpret the results globally (Shtull-Trauring et al., 2016).

Among the studies reported in Table 1, Zeng et al. (2012) is one of the most interesting; it was assumed as a reference point for our investigation. However, differently from Zeng et al., WF's estimation included, in addition to the GIS spatial analysis as well as statistical data processing, the definition of two scenarios termed "full irrigation" and "deficit irrigation". The first scenario was characterized by the absence of water scarcity with the use of default values of CROP WAT tool (Hoekstra et al., 2011); the second scenario, site-specific, was based on the indications provided by the Irrigation Authority (*Ente di Irrigazione*, in italian) regarding the best available techniques for specific crops (i.e., quantity of water required per crop, frequency of irrigation). Furthermore, the role of treated wastewater in reducing basin-wide water shortages was also analysed.

Thus, the aim of the study was to combine the GIS and FAO's (Food and Agriculture Organization of the United Nations) crop water productivity model for the WF estimation in a temporary river catchment. In particular, with reference to each municipality in the catchment area, where the blue and green component of WF was calculated for the cultivated agricultural products. Furthermore, the possibility of reuse the effluents from the wastewater treatment plants (WWTPs) of the study area was addressed for a more sustainable management of water resources. For the scope, the case study of the Candelaro temporary river catchment (Southern Italy) was considered.

2. Methods

2.1. Study area

The Candelaro river catchment is located in the Apulia Region, in the southern Italy. The basin (Fig. 1) covers an area of more than 2330 km^2 in the northern part of the region, along the *Tavoliere of Apulia*, the main alluvial plain in southern Italy. The Candelaro catchment is characterized by an intermittent flow, typical of the Mediterranean river, with periodical droughts during the hottest seasons and flash flood in the rain seasons. The climate is typically Mediterranean with low precipitation, temperate winters and hot summers. Furthermore, the Candelaro river catchment were the case study of some projects about the collection and the modelling of river basin data for assessments in water management (FLOOD-MED, AQUATER, MIRAGE).

2.2. GIS

ESRI's ArcGIS software was used to develop three thematic river basin maps. The first map was developed by creating a layer outlining the surface and boundaries of the river basin. A second layer was created on this layer using the "clip" function and spatial analysis for the surface and boundaries of the municipalities that fall totally and partially within the basin. Data on the river basin and municipalities were obtained from the Italian national cartography (http://www.pcn.minambiente.it/mattm/).

Within the map of Fig. 1, the weather stations for climatic data, whose codes and geographical coordinates are listed in Table 2 (Assocodipuglia, http://www.agrometeopuglia.it), and the WWTPs, whose characteristics are listed in Table 3 (Water Information System for Europe, WISE EU), were geolocalized.

The map of land use and soil texture (Fig. 2) was elaborated on the layer of the river basin and municipalities. The data on land use (Table A.1, Appendix) were downloaded from the National Environmental Information System Network (http://www.sinanet.isprambiente.it/it) on the basis of information from the CORINE and Cover 2012 project.

Soil texture data were found on the Puglia Region website (http://www.sit.puglia.it/). Through the ArcGIS software, the surfaces of the nine soil weaving classes were developed for each individual communal area in the basin (Table A.2, Appendix). To facilitate processing in the CROP WAT program, classes were divided into three groups: low (a), medium (b) and high (c).

2.3. Climate data

A data set of daily climatic information for the period 2010–2011 was obtained from Assocodipuglia (2015) for the thirteen weather stations. The data set were composed of maximum (M) and minimum (m) temperature, relative humidity (RH), wind speed (ws) and rainfall (R). The lack of data in some stations was solved by a non-parametric regression afterwards the evaluation of the stations similarities (threshold = 0.95) by a Spearman non parametric rank-order correlation, as reported in Presti et al. (2010). Daily values were used to elaborate the average monthly values for all the parameters, as reported in Fig. 3. Data elaboration was made using XLstat 2016.

2.4. Crops

The typical representative crops cultivated in the Candelaro river basin were selected for the WF calculation: wheat, sunflower, sugarbeet, tomatoes, olives, wine grapes, and peaches (Steduto and Todorovic, 2001). Crops surfaces of olives, wine grapes, and peaches (in hectares, ha) were directly extracted from the land use map by GIS tools. On the other hand, the tomatoes, that were included in the code "arable lands" of the land use map, were extracted using the data set of ISTAT - Italian National Institute of Statistics (2010).

The planting and the harvest date of each crop are listed in Table 4, based on the information reported in Allen et al. (1998) and Rinaldi and Vonella (2006) for tomatoes and sugarbeet, respectively.

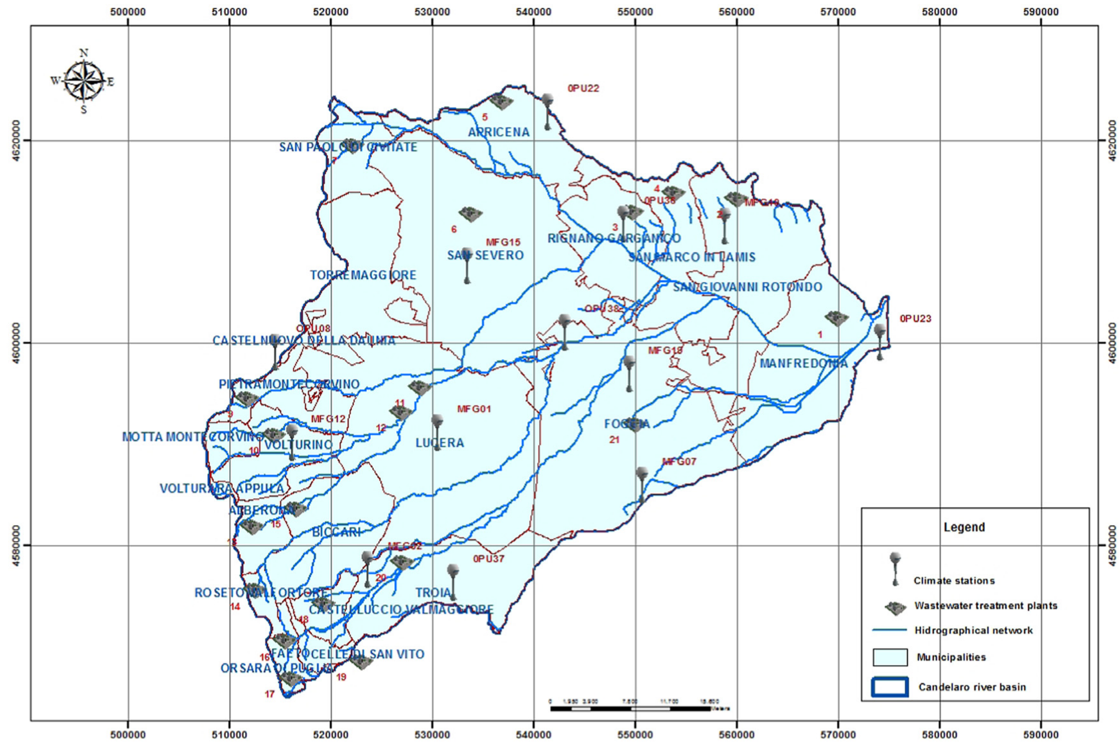


Fig. 1. Candelaro river basin, municipalities, climatic stations and wastewater treatment plants (WWTPs).

Table 2
Climatic station located in Candelaro river, geographic coordinates and elevation, latitude and longitude data.

Code	Location	Elevation (m)	Latitude	Longitude
0PU08	Pietramontecorvino (FG) - Torretta	261	41°32’32” N	15°10’27” E
0PU22	Apricena (FG) - canale	51	41°46’24” N	15°26’20” E
0PU23	Manfredonia (FG) – Daunia Risi	−1	41°32’29” N	15°53’10” E
0PU36	Rignano Garganico (FG) - Villanova	18	41°39’16” N	15°35’13” E
0PU37	Troia (FG) - Colazze - Giardinetto	233	41°20’12” N	15°22’59” E
0PU38	Foggia (FG) – Borgo La Rocca	50	41°33’31” N	15°30’58” E
MFG01	Lucera (FG) - S. Lucia	149	41°28’11” N	15°21’54” E
MFG02	Troia (FG) - Serra Dei Bisi	391	41°20’53” N	15°16’58” E
MFG07	Foggia (FG) - Coppa Doro	63	41°25’19” N	15°36’26” E
MFG10	San Giovanni Rotondo (FG) - Matine - Carne Salata	155	41°39’07” N	15°42’25” E
MFG12	Alberona (FG) - Serrone	370	41°27’43” N	15°11’36” E
MFG15	San Severo (FG) – Casa Lorda	61	41°37’06” N	15°24’04” E
MFG19	Foggia (FG) - Monterozzi	46	41°31’16” N	15°35’31” E

The yield was expressed in ton/ha for wheat as reported by Mekonnen and Hoekstra (2011), considering also the regional yield reported by Tarantino and Disciglio (2009) and by AGRIT (2012). The yield of sunflower and peaches were selected following the study reported in Moutonnet (2000); Dichio et al. (2003); Ayars et al. (2003). Wine grapes yield was selected as reported in others works (Intrigliolo et al., 2012; Intrigliolo and Castel, 2011) taking into account also the production reported by Miglietta and Morrone (2018b). The yield of tomatoes, sugar beet and olives were selected respectively from Giuliani et al. (2016), Supit et al. (2012) and Pellegrini et al. (2016).

2.5. Water footprint (WF)

The WF of cultivated crops in the river basin was calculated according to the methodological approach reported in Hoekstra et al. (2011). In detail, crop evapotranspiration (ETc) was assessed following Eq. (1):

$$ET_c = K_c \times ET_0 \tag{1}$$

In Eq. (1), K_c was the crop coefficient that is correlated to the characteristic of the crops; Instead, ET_0 was the reference evapotranspiration calculated in relation to the climatic condition. This study focused only on the green and blue components although the grey component is an important indicator of the amount of water required to dilute pollutants in agriculture such as nitrogen-rich fertilizers, which can exceed water quality standards (Miglietta et al., 2017, 2018; Serio et al., 2018). The FAO model, CROPWAT 8.0, was used to calculate the reference (ET_0) and the crop evapotranspiration (ET_c) following the indications reported in FAO (2010) and Allen et al. (1998). ET_c was calculated using the approach of the dual crop coefficient (Eq. (2)), and forecasting of the rain events on the K_c value as reported in Allen et al. (1998):

$$ET_c = (K_{cb} + K_e) \times ET_0 \tag{2}$$

where, $K_c = K_{cb} + K_e$, K_{cb} = basal crop coefficient and K_e = soil water coefficient.

The basal crop coefficient (K_{cb}) estimated in the study area was extracted from previous researches for some cultivations such as peaches, sunflower, sugarbeet, tomato and wheat (Garofalo and Rinaldi, 2014). For the others crops (olive and wine grapes), K_{cb}

Table 3
WWTPs characteristics and geographic coordinates[a].

N.	ID	Name	PE[b] (inhabitants)	Geographic coordinates			
				System 1		System 2 (DMS)	
				Longitude	Latitude	Longitude	Latitude
1	IT160000000028	Manfredonia	77.000	15.875113	41.600446	15°52'30"	41°36'1"
2	IT16Q13000000001	San Giovanni Rotondo	45.600	15.719974	41.680722	15°43'11"	41°40'50"
3	IT160000000040	Rignano Garganico	3.200	15.596721	41.669567	15°35'48"	41°40'10"
4	IT160000000046	San Marco in Lamis Vecchio	10.937	15.645988	41.709242	15°38'45"	41°42'33"
5	IT160000000004	Apricena	13.800	15.442312	41.768196	15°26'32"	41°46'5"
6	IT160000000050	San Severo	88.000	15.405919	41.668188	15°24'21"	41°40'5"
7	IT160000000049	San Paolo di Civitate	7.500	15.265114	41.729934	15°15'54"	41°43'47"
8	IT16Q11000000000	Castelnuovo della Daunia Nuova	4.509	15.125210	41.581413	15°7'30"	41°34'53"
9	IT160000000039	Pietra Montecorvino	3.479	15.129158	41.537226	15°7'44"	41°32'14"
10	IT16Q90000000438	Volturino	1.979	15.129330	41.478093	15°7'45"	41°28'41"
11	IT160000000026	Lucera A - località Macello	18.750	15.344250	41.514479	15°20'39"	41°30'52"
12	IT160000000027	Lucera B – Valle Crusca	12.500	15.322428	41.492270	15°19'20"	41°29'32"
13	IT160000000002	Alberona	1.500	15.126262	41.436570	15°7'34"	41°26'11"
14	IT160000000043	Roseto Val Fortore	2.700	15.087981	41.369616	15°5'16"	41°22'10"
15	IT160000000007	Biccari	4.500	15.196428	41.406288	15°11'47"	41°24'22"
16	IT160000000019	Faeto 1	3.000	15.164156	41.320160	15°9'50"	41°19'12"
17	IT160000000020	Faeto 2	1.500	15.163126	41.290501	15°9'47"	41°17'25"
18	IT16Q90000000391	Castelluccio Valmaggiore	3.449	15.209818	41.348517	15°12'35"	41°20'54"
19	IT160000000035	Orsara di Puglia	3.261	15.258913	41.275279	15°15'32"	41°16'31"
20	IT160000000056	Troia	7.800	15.322428	41.359083	15°19'20"	41°21'32"
21	IT160000000021	Foggia	208.000	15.597515	41.480681	15°35'51"	41°28'50"

[a] Source, Urban Waste Water Treatment maps (http://www.eea.europa.eu/data-and-maps/uwwtd/interactive-maps/urban-waste-water-treatment-maps-1).
[b] PE = Population equivalent corresponding to a five-day biodegradable organic load of 60 g BOD_5/d (De Feo et al., 2013).

Table 4
Crop data, harvesting period and yield.

Crops	Planting period	Harvest period	Yield (ton/ha)[a]	Yield (ton/ha)[b]
Grapes	April 2011	October 2011	8.3	16.3
Olives	March 2011	November 2011	2.5	10.0
Peaches	March 2011	November 2011	19.3	19.3
Sugarbeet	October 2010	July 2011	51.1	17.2
Sunflower	April 2011	July 2011	0.70	–
Tomato	April 2011	August 2011	45.5	82.8
Wheat	November 2010	June 2011	2.20	–

[a] Rain fed.
[b] Irrigated.

assumed the values reported by Allen et al. (1998). The K_{cb} was calculated as daily values for all the crops and for the elaboration of the coefficient curve that is represented in Fig. 4.

Furthermore, the lengths of growth stages measured in the Foggia district (Garofalo and Rinaldi, 2014) and in the Mediterranean region (Ghrab et al., 2013) were used to obtain more site-specific K_c values.

The soil water coefficient (K_e), that described the evaporation component of ET_c, was calculated following Eq. (3):

$$K_e = \min(K_r \times (K_{c\,max} - K_{cb});\ f_{ew} K_{c\,max}) \tag{3}$$

where, min = minimum value between the parameters in the rounded bracket; K_r = evaporation reduction coefficient (dimensionless); $K_{c\,max}$ = maximum value of K_c following rain or irrigation; f_{ew} = fraction of soil exposed and wetted following to rain events.

The K_r coefficient reported in a previous study, was used for water stressed crops such as vegetables, olives, wine grapes, and fruit trees (Daccache et al., 2016). The $K_{c\,max}$ was calculated with Eq. (4):

$$K_{c\,max} = \max(\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](h/3)^{0.3}\};\ \{K_{cb} + 0.05\}) \tag{4}$$

where, max = maximum value between the parameters in the rounded bracket; u_2 = wind speed (in m/s); RH_{min} = relative minimum humidity; h = mean maximum plant height during the total period of calculation.

The exposed and wetted soil fraction (f_{ew}) was calculated following Eq. (5):

$$f_{ew} = \min(1 - f_c;\ f_w) \tag{5}$$

where, (1 - f_c) was the average exposed soil fraction not covered by vegetation (0.01–1) and f_w the average fraction of soil surface wetted by irrigation or precipitation (0.01–1).

The average exposed soil fraction (1 - f_c), was estimated using the following Eq. (6):

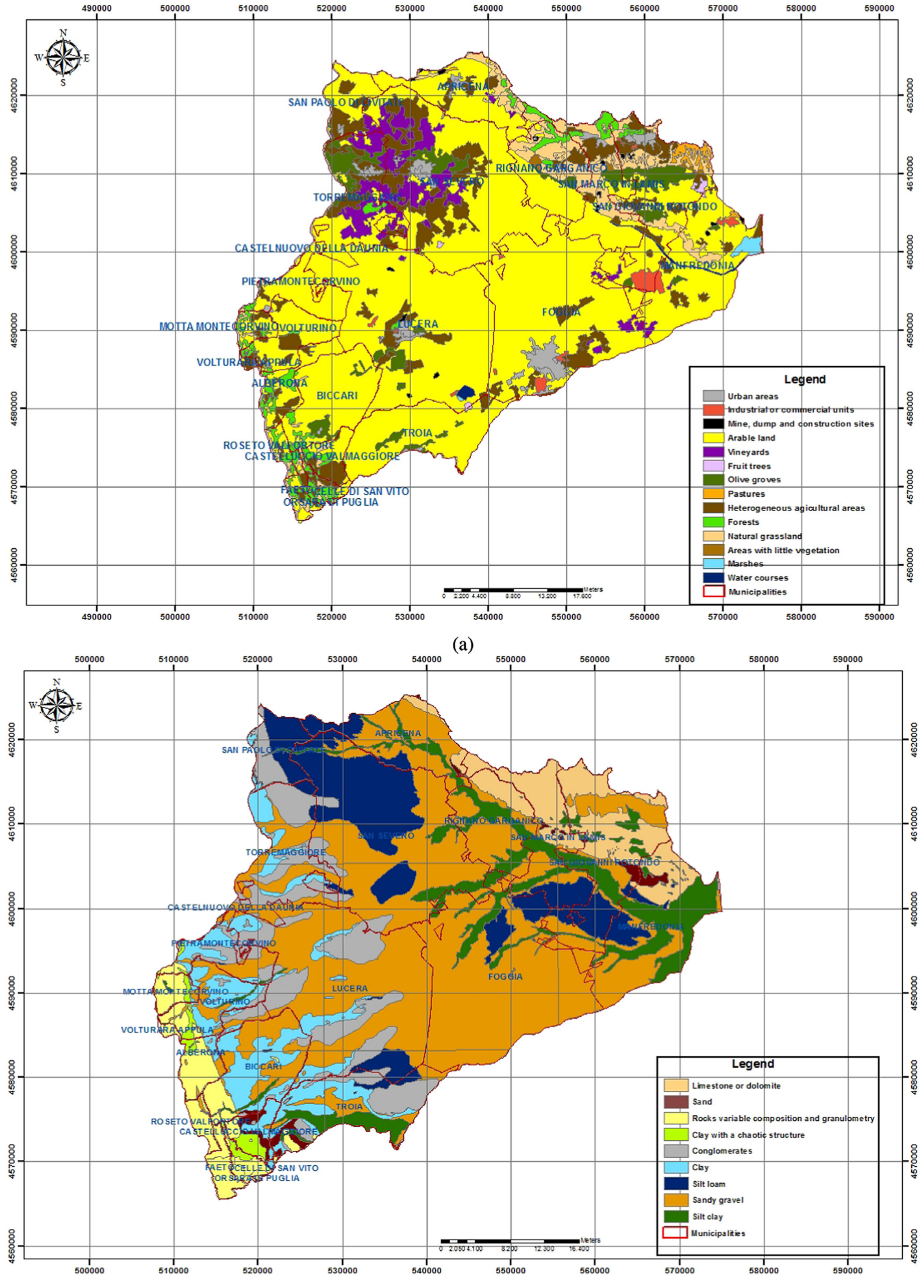
$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}}\right)^{(1+0.5h)} \tag{6}$$

In which $K_{c\,min}$ was the minimum K_c value for dry bare soil with no ground cover (0.15 - 0.20).

The final daily values of K_c were calculated using the previous Eqs. (2)–(6)), and as observed in Fig. 4, the coefficient curve (in red) was reported for all the crops.

After the appropriate adjustments, the K_c values were used for the calculation in CROPWAT. ET_0 was estimated by mean of CROPWAT FAO model, using the monthly climatic data (max and min temperature, humidity, wind speed, sun hours, rain).

For the soil parameters, total available soil moisture values, maximum infiltration rate, and the initial soil moisture depletion were inserted for three categories: light, medium and heavy (See also Table A.2, Appendix). The values of total available soil



(a)

(b)

Fig. 2. Candelaro River Basin (a) land use and (b) soil texture.

moisture were extracted from Global map maximum soil moisture (Batjes, 1997). The maximum rooting depth values reported in Allen et al. (1998) were used in CROPWAT model for each crops.

For the estimation of ET_c values, the irrigation schedule options were used as reported in Hoekstra et al. (2011). The irrigation at fixed stages of growth were selected as reported on irrigational recommendation of the local (Capitanata's) consortium (http://consorzio.fg.it).

Firstly, the Virtual Water Content (VWC) was elaborated and expressed as m^3/ton. The WF was calculated multiplying the VWC

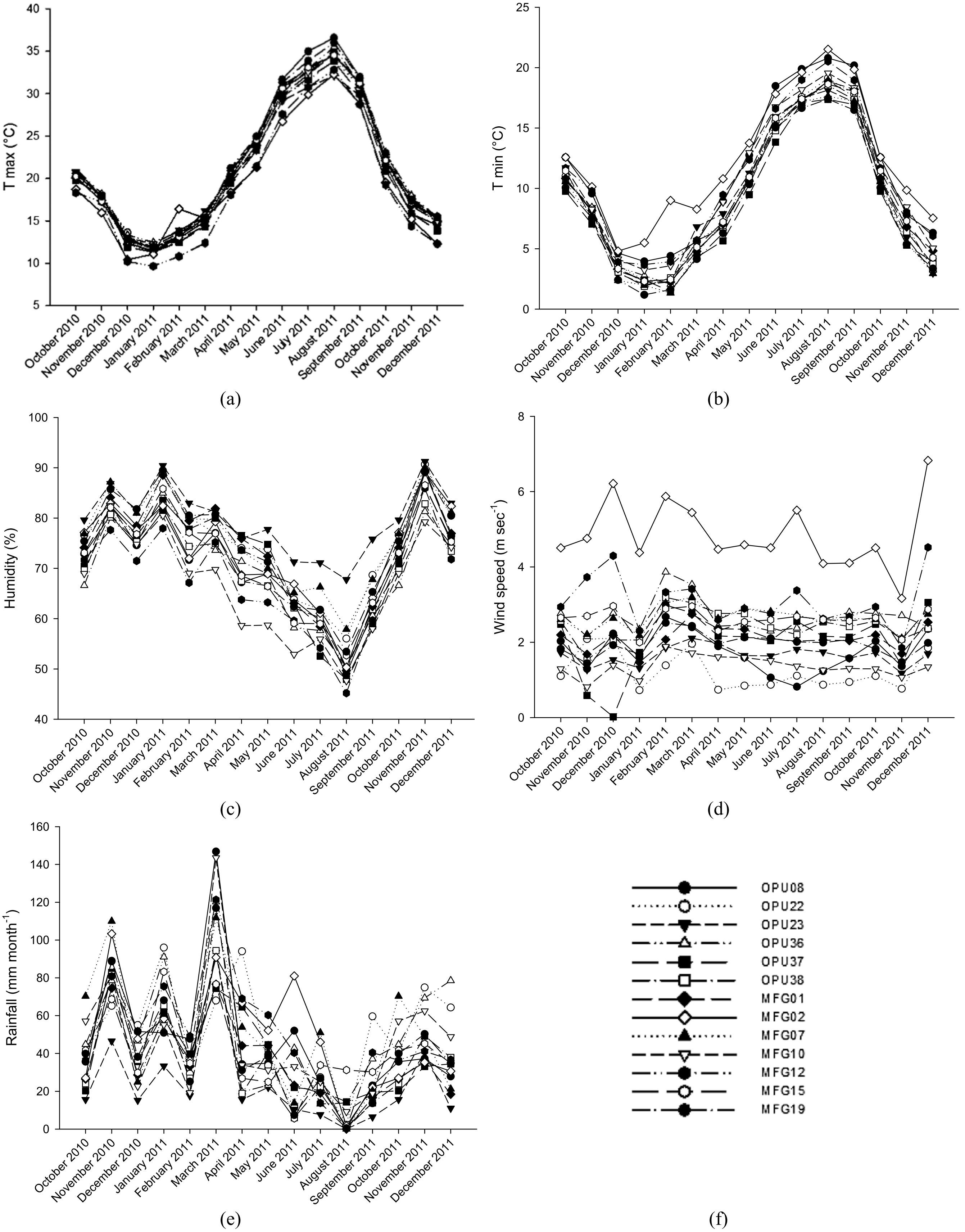


Fig. 3. Data extrapolated from climatic station: (a) Maximum temperature; (b) Minimum temperature; (c) Humidity; (d) Wind speed; (e) Rainfall; (f) Nomenclature.

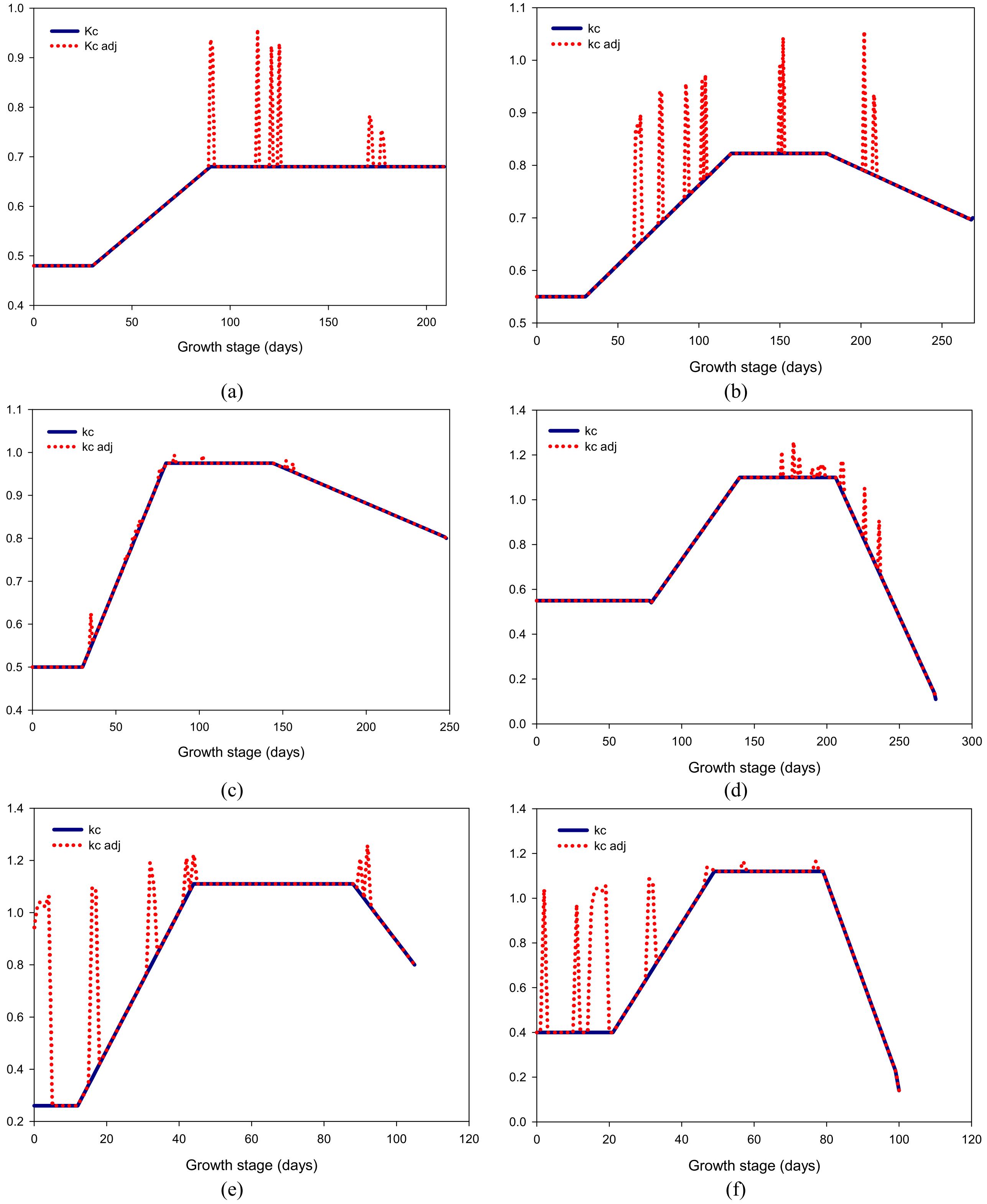


Fig. 4. Coefficient curve for K_{cb} daily values for: (a) Grapes; (b) Olives; (c) Peaches; (d) Sugar beet; (e) Tomato; (f) Sunflower. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for the crops production (ton), and it was expressed as m^3/year (Hoekstra et al., 2011).

2.6. Irrigation strategies

All crops were considered irrigated except for wheat and the sunflower. Two scenarios were planned for the calculation of the

WF: Scenario 1, full irrigation (Full-IRR); Scenario 2, deficit irrigation (Def-IRR).

In the Scenario 1, it was considered that the whole area of irrigated crops was irrigated. In the Scenario 2, it was considered 36% of the area under all irrigated crops as an irrigation percentage (Daccache et al., 2016). In addition, it was considered the contribution that the reuse of treated wastewater could make to the amount of water required for crops. For this purpose, a reuse of 80% of the wastewater inlet to the WWTPs was assumed. The remaining 20% was used to maintain the minimum flow of receptor bodies.

3. Results and discussion

The total Virtual Water Content (VWC) and the green and blue components were elaborated at basin scale. The green component was the largest respect to the blue that represents the 40% and the 27% of the total VWC respectively for the two scenarios (Full-Irr and Def-IRR) and the deficit irrigation (Def-Irr).

In Fig. 5, the average values of the VWC green and blue were reported for the single cultivated crops.

For all crops, except for wheat and sunflowers were reported green and blue components expressed as m^3/ton in Full-Irr and Def-Irr scenarios.

The VWC values observed for wheat and sunflowers, respectively 4040 and 1655 m^3/ton, were comparable with these estimated at the global level, because of wheat had a great contribution to the total WF of the global crop production (Mekonnen and Hoekstra, 2011).

Among the irrigated crops, olives showed the highest VWC, that decreased from full (632 m^3/ton) to deficit irrigation (559 m^3/ton). Grapes and peaches showed a similar VWC values, in the range (277–317) m^3/ton.

A considerable decrease of the total VWC was observed for sugarbeet and tomatoes, that reached values of 92 and 64 m^3/ton, respectively. Tomatoes showed higher values of blue component that corresponded to 56 and 49 m^3/ton in the two scenarios respect to green component, that were 8 and 15 m^3/ton respectively, due to the seasonality of tomatoes crops, that grew especially during summer periods.

From the comparison between the values of the VWC obtained in this study and those reported by Mekonnen and Hoekstra (2011), the VWC was lower for some crops such as tomatoes, olives, grapefruits and peaches. This variability was principally due to the different yield at national and regional level, and to the different geographical location. Furthermore, in this study, the same yield was considered between the two irrigation strategies because of the lack of information. Previous investigations demonstrated that principally irrigation deficit (rain fed) could decrease yields (Giuliani et al., 2016; Pellegrini et al., 2016), so site-specific information are very important to find.

The assessment of the amount of water required for the total agricultural production in the river basin was calculated by means of WF, and expressed in Mm^3/year. Green and blue component percentage within the two scenarios were reported in Fig. 6.

In the first scenario, the total WF was 686 Mm^3/year; WF green constituted the 80.4% (551 Mm^3/year) while WF blue the 20% (135 Mm^3/year). In the second scenario, WF was 676 Mm^3/year and under the deficit irrigation, it was observed a decrease of WF blue (−17%) and an increase of WF green (+83%). The increase and decrease of green and blue components were principally due to the irrigation scenarios that moved from full and deficit irrigation, as reported in Chukalla et al. (2015).

The WF evaluation in the Candelaro river basin resulted in line with the results of Vanham and Bidoglio (2014, 2013), that estimated a value of WF >582 Mm^3/year.

The detailed evaluation of the WF green, described in left pie chart (Fig. 6), showed that wheat contributed to the higher part of WF green with 83.1% and 81.3% from full to deficit irrigation, respectively, confirming the VWC results. On average, olives and grapes accounted for the 6.5% and 5.6% of WF green. Sugarbeet and peaches accounted for 2.2% and 0.2%, respectively. Tomatoes accounted for 1.2% in the first scenario; this percentage increased until to 2.4% for the deficit irrigation scenario. In this regard, tomatoes were the crop that required the highest percentages of WF blue, 57.0% and 61.7%, respectively from full to deficit irrigation (Fig. 6). Grapes accounted for around the 19.0% in both scenarios. Olives required 17.0% and 2.9% WF blue in full and deficit scenarios, respectively. Sugarbeet accounted for 6.4% and 5.5% and no variation was observed for peaches (1%) in the both scenarios.

The Candelaro river basin was located in the Consortium of “Bonifica della Capitanata”, that is one of the most important irrigation consortium in the Mediterranean area. The consortium was divided in two districts (Fortore and Sinistra Ofanto) that supplied water from the Fortore watershed and the Occhito dam by mean of their water distribution system (Lamaddalena et al., 2004). As reported in Daccache et al. (2016) and in Lamaddalena et al. (2004), the consortium was unable to meet the entire demand of water due to intensive agricultural activities.

In this regard, Table 5 showed the amount of water provided by the Consortium that was calculated on the basis of the percentages reported by Daccache et al. (2016) and Lamaddalena et al. (2004). On average, the consortium helped to provide the 41% of the required amount of water for irrigation. Remaining water was often withdrawn by the private well with an uncontrolled manner. The water supplied from groundwater, that constituted the higher contribution to irrigation, was also showed in Table 5.

The potential reclaimed water reused for agricultural irrigation in the river basin was considered in our investigation as a possible solution to help the water demand. The potential reclaimed water resulted of 47 Mm^3/year as output from the WWTPs located in the Candelaro catchment, that could contribute to 35 and 41% of water saving in case of full irrigation and deficit irrigation, respectively. These results were absolutely in line with the planning policy of the Apulia Region (Water Protection Plan); as the first region in Italy, it has always included the reuse of wastewater among the possible strategies of water management (Lopez and Vurro, 2008).

The WF assessment was recently evaluated at river basin scale for single catchment (Feng et al., 2012; Zeng et al., 2012; Zhao et al., 2010) and for the European rivers basins (Vanham and Bidoglio, 2014, 2013). Differently from them, in our study WF was evaluated only for crops in a semi-arid basin, neglecting the WF of others goods and services (because this area was intensely cultivated). As previously described, WF assessment considered in detail the river basin dividing the study area on the basis of municipalities. For each municipality, the crops area and the soil texture characteristics were extracted using GIS tools. The obtained results highlighted how a detailed analysis at basin level is important in order to identify possible spatial differences within the basin such as climatic conditions, use of the soil as well as lithology factors that may affect WF, in line with what highlighted by Zeng et al. (2012). The local evaluation of the WF of our study resulted principally influenced by the climatic conditions as well as by the size of the agricultural crops area. The WF values resulted higher in the municipalities with the biggest size in which WF green, WF blue and agricultural areas were correlated for the 23 municipalities (Fig. 7).

The municipalities were grouped in four cluster based on the size of circles that were referred to the agricultural areas. The municipalities that had an agricultural surface area > 20.000 ha were included in the first group, as Lucera, Foggia and San Severo, listed in descending order, except for Foggia. The first group showed the highest WF green and blue, that were included in the range 72–87 Mm^3/year (WF green), and 16–41 Mm^3/year (WF blue), considering both scenarios. San Severo was absolutely the municipality

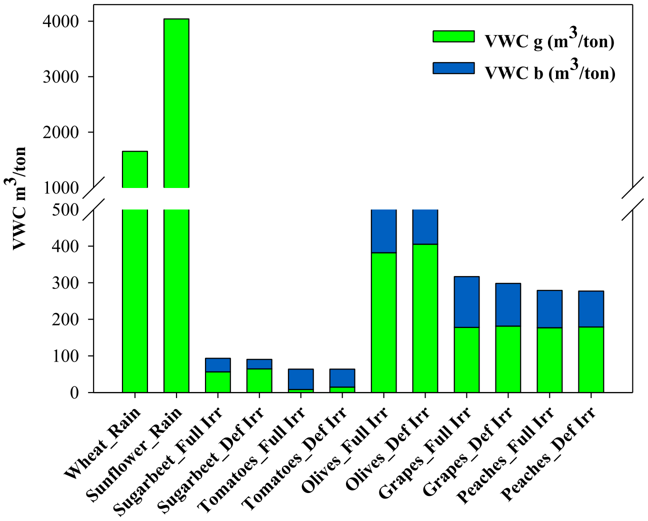


Fig. 5. Virtual Water Content green (VWC g) and blue (VWC b), expressed as m^3/ton, are reported for crops in the first scenario (Full-Irr) and in the second scenario (Def-Irr). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

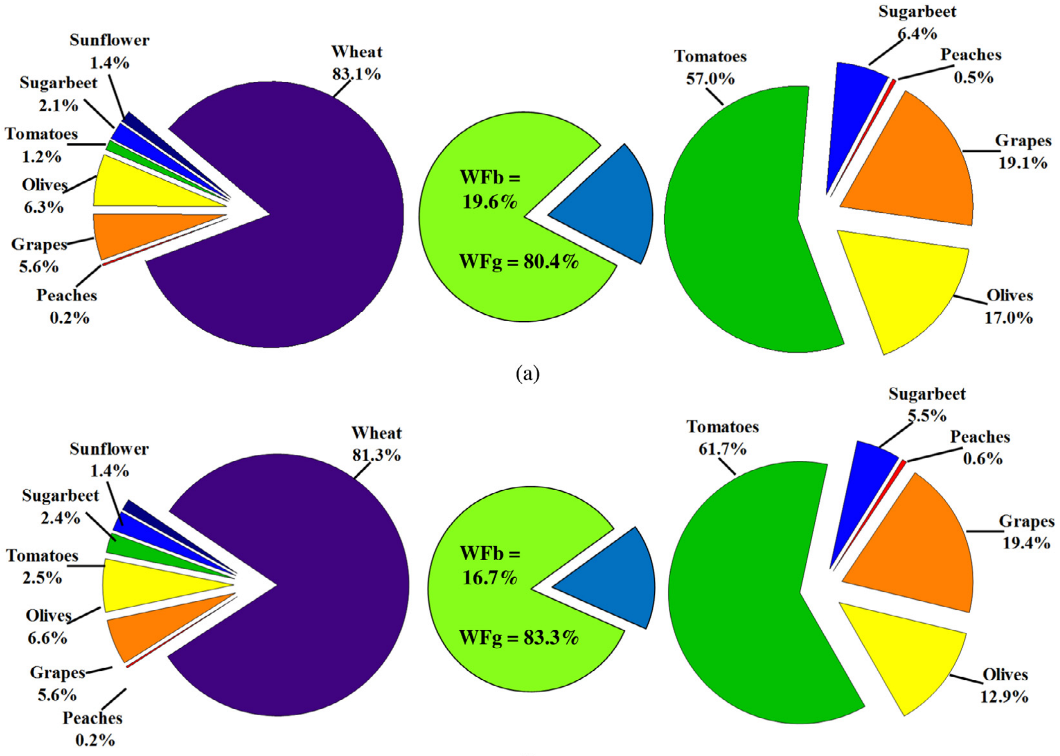
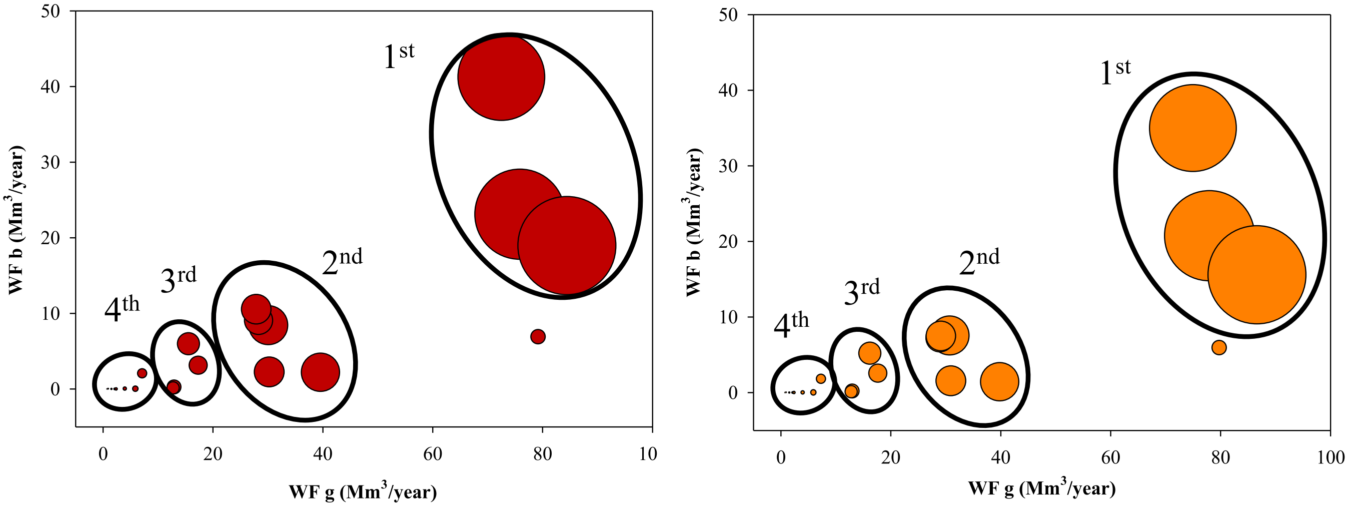


Fig. 6. WF green and blue percentage in the full irrigated (a) and deficit irrigated (b) scenarios. A central pie chart described green and blue component percentage; on the right, the percentage of blue water required by the irrigated crops; on the left the percentage of the rain fed crops. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Consortium supply and water saving.

Scenario	WF blue	Consortium Water supply			Groundwater supply			Potential water saving
	Mm^3/year	Mm^3/year[a]	Mm^3/year[b]	Mm^3/year[c]	Mm^3/year[a]	Mm^3/year[b]	Mm^3/year[c]	%
Scenario 1	135	50	61	55	85	74	80	35
Scenario 2	113	42	51	46	71	62	67	42

[a] The percentage reported by Daccache et al. (2016) was used.
[b] The percentage reported by Lamaddalena et al. (2004) was used.
[c] Average value.



(a) (b)

Fig. 7. Each bubble plot represented the first (a) and the second scenario (b). The position of the circle in plots is related to the WF green and blue values correlation, the size of bubbles is correlated to the agricultural areas in the municipalities that were grouped in four groups.

that requires the greater amount of blue water, requiring about of 30% of the total WF blue. Instead, the municipalities of Foggia and Lucera showed a greater contribution of the WF green. These elaborations highlighted how a local WF assessment was highly dependent on climatic conditions; furthermore, it required a much broader time interval.

4. On the applicability of the methodological proposal

There were a number of difficulties in applying the proposal. The former was related to the lack of data at basin level on agricultural production considering the quantity and yields. The experience gained during the development of our proposal suggested the need to develop a new data acquisition mechanism for the scope. For instance, based on the previous experience of De Gisi et al. (2015, 2014) in the field of wastewater treatment, it could be interesting to develop a mechanism based on the interaction “Farmer-Irrigation Authority- ISTAT. The frequency of data acquisition was another fundamental aspect; following the experience of the wastewater sector mentioned above, a biennial frequency could be considered. The latter shall be generally compatible with the rotation cycles adopted by farmers.

A further difficulty was the calculation phase of the K_c coefficient, which depends on many factors such as the plant’s growth phase and climatic conditions. Since WF’s assessment is sensitive to errors in the calculation of evapotranspiration (Et_0), K_c coefficient and crop planting date (Zhuo et al., 2014), it is convenient to reduce uncertainty in the estimation of green and blue water footprints at river basin.

Finally, the results of the WF as calculated with the proposed approach could provide useful information to the consumer of the product who became aware of the quantity of water needed for the production of the vegetables purchased (Galli et al., 2017). In this respect, information on labelling may emphasize the sustainability of the product.

However, consumers are not the only receivers of the problems of sustainable water management and consumption for the production of agricultural products. Other important stakeholders are farmers, whose attitudes are not entirely positive towards water saving measures. This their negative attitude is due to their thinking about influence of water saving on productivity and yields of their crops (Pino et al., 2017). Moreover, according to some authors, the WF would have a negative impact on farmers who are not aware of the pressure and impact of agriculture on water resources. Therefore, their attitudes can be positively influenced by specific communication policies managed by ministries or associations.

5. Conclusions and future outlook

The WF is an approach widely used at national and/or regional level while it is little implemented at basin level. The methodology proposed in this work aims not only to estimate the WF at basin scale but also to combine the contribution of the reuse of treated wastewater as possible solution for water saving and less utilization of water resources in the aquifer.

The WF calculated for the entire Candelaro river (2330 km^2) is equal to 686 Mm^3/year, certainly higher than the one evaluated for its tributary, Celone river, which is equal to 79.9 Mm^3/year (D’Ambrosio et al., 2018). The largest contribution to WF was found in the green component compared to the blue component. The wheat was by far the cultivation that required the largest quantity of rainwater, contributing about 80% to the green component and tomato, on the other hand, was the agricultural product that contributed to the increased demand for irrigation water, which accounted for about 50% of the blue component. The other agricultural products that contributed to the demand for blue water were grapes and olive trees, respectively. Furthermore, in the area under study, the results obtained from the calculation of the blue component of the WF and the data on the availability of water for irrigation have highlighted the typical problems of a semi-arid area in which, the use of treated wastewater, could contribute about 30%–40% of water savings.

In methodological terms, the WF assessment resulted a good indicator of water amount required for the crops production of a river basin. At basin and municipal scale, this methodology highlighted the use of WF in combination with GIS that allowed to represent and elaborate data at double scale. WF was also a measure of the potential water demand that could be combined with the potential water reuse calculation. The weak points of this methodological proposal are lack of some local information about agricultural practices in small farms and about in-stream monitoring activities that was demonstrated very important to evaluated WF in temporary river as reported by D’Ambrosio et al. (2018). Notwithstanding the weak points, the approach of evaluating WF combining GIS tool, and water saving evaluation considering wastewater treated use is an interesting approach for the future water management in semi-arid river basin to prevent water scarcity.

Table A.1
Land use data.

N°	Municipalities	Total Area (ha)	Urban areas (ha)	Industrial or commercial units (ha)	Arable land					Vineyards	Fruit trees	Olive groves	Pastures	Heterogeneous agricultural areas	Forests	Natural grassland	Total Agri-cultural Area (ha)	Crops Area/Total Agricultural Area (%)
					Total (ha)	Wheat (ha)	Sunflower (ha)	Sugar beet (ha)	Tomatoes (ha)									
1	Alberona	4363.0	–	–	2328.8	1560.7	7.7	13.4	2.3	–	–	–	–	750.8	1252.9	30.4	3079.7	75.6
2	Apricena	9849.5	281.9	–	6708.7	4311.1	63.9	381.9	1215.3	139.0	–	–	55.2	768.0	212.5	1583.9	7670.9	90.0
3	Biccari	10714.0	32.1	–	9335.8	6899.4	445.4	114.3	84.3	–	–	727.6	–	20.5	51-	88.1	10083.8	99.8
4	Castelluccio Valmaggiore	2596.1	–	–	1135.8	792.3	142.8	–	2.7	–	–	23.6	–	928.5	406.2	102.1	2087.8	55.5
5	Castelnuovo della Daunia	339.3	–	–	338.5	241.7	4.7	12.4	5.4	–	–	–	–	0.3	–	0.5	338.8	99.9
6	Celle di San Vito	1593.3	–	–	265.6	160.7	14.8	–	2.3	–	–	–	–	420.7	696.1	210.9	686.3	38.7
7	Faeto	1786.6	–	–	633.5	433.9	86.4	–	–	–	–	–	–	306.4	537.7	309.0	939.9	67.4
8	Foggia	31442.1	1944.5	407.7	26090.3	19759.6	98.6	196.2	4273.2	582.7	–	–	–	2417.0	–	–	29090.0	91.7
9	Lucera	34080.8	537.0	130.4	29935.7	21231.7	330.4	2071.7	2534.1	64.8	48.9	808.5	–	2022.1	70.7	–	32880.0	93.9
10	Manfredonia	16027.8	26.6	461.8	12295.0	8634.3	10.5	198.1	1536.1	218.0	21.7	202.1	89.1	1101.9	2.3	701.6	13928.0	92.1
11	Motta Montecorvino	1779.1	5.8	–	1012.2	637.8	33.2	–	2.7	–	–	–	–	299.2	339.9	122.0	1311.4	77.2
12	Orsara di Puglia	67.6	–	–	45.4	37.1	0.3	–	1.0	–	–	–	–	–	20.7	1.5	45.4	100.0
13	Pietramontecorvino	5276.8	63.0	–	4496.1	3124.7	685.5	52.3	39.3	–	–	–	–	559.5	102.5	55.7	5018.0	89.6
14	Rignano Garganico	8956.0	45.7	–	3898.1	2394.5	1.9	28.3	1177.9	–	–	370.4	–	533.2	637.1	3235.3	4801.7	88.9
15	RosetoValfortore	1174.3	–	–	515.9	352.7	16.5	–	0.1	–	–	–	–	86.0	413.1	159.2	601.9	85.7
16	San Giovanni Rotondo	16668.7	458.4	749.8	6025.0	4729.3	4.6	17.3	356.2	128.9	208.5	2425.2	807.7	2474.7	340.5	2798.8	12069.9	79.5
17	San Marco in Lamis	11246.3	216.1	33.7	5157.6	4085.8	–	27.7	332.9	10.5	–	562.4	–	1124.1	811.6	3103.6	6854.6	83.6
18	San Paolo di Civitate	4503.5	89.2	–	2630.2	1769.8	12.7	64.1	318.5	330.6	–	42.7	–	1410.7	–	–	4414.2	68.0
19	San Severo	33524.7	737.5	–	19097.9	12973.1	77.7	1152.0	3320.8	5259.3	49.0	1207.5	–	7163.2	–	10.3	32776.9	78.1
20	Torremaggiore	11492.0	311.8	–	3815.2	2922.9	76.3	175.3	176.0	3146.3	–	1754.4	–	2464.4	–	–	11180.2	78.0
21	Troia	12416.4	65.5	–	11448.3	9422.1	346.8	21.7	154.8	–	32.4	622.5	–	247.7	–	–	12350.9	98.0
22	Voturara Appula	275.4	–	–	57.9	41.9	1.2	–	0.5	–	–	–	–	215.9	1.7	–	273.8	21.1
23	Volturino	5830.7	63.1	–	4474.3	3173.7	227.9	29.3	18.5	–	–	–	–	1026.7	266.6	–	5501.0	81.3

Table A.2
Soil texture data.

Municipalities	Limestone or dolomite[b]	Sand[a]	Rocks with variable composition and granulometry[b]	Clay with a chaotic structure[c]	Conglomerates[a]	Clay[c]	Silt loam[b]	Sandy gravel[a]	Silt clay[c]
Alberona	–	–	50.9	5.7	15.9	13.0	–	13.8	0.8
Apricena	7.9	1.1	–	–	–	–	16.9	61.0	13.2
Biccari	–	0.8	12.8	0.1	2.8	42.8	0.2	37.6	2.7
Castelluccio Valmaggiore	–	23.7	15.7	27.4	1.5	30.1	–	1.2	0.5
Castelnuovo della Daunia	–	–	–	–	23.0	5.9	–	71.2	–
Celle di San Vito	–	2.8	73.1	20.3	0.1	3.7	–	–	–
Faeto	–	–	100.0	–	–	–	–	–	–
Foggia	–	–	–	–	–	–	7.1	85.6	7.3
Lucera	–	–	–	–	26.4	8.9	4.5	60.0	0.1
Manfredonia	17.9	2.7	–	–	–	–	9.3	31.0	39.1
Motta Montecorvino	–	–	73.8	11.0	–	4.5	–	8.0	2.7
Orsara di Puglia	–	6.0	79.4	–	1.5	–	–	7.1	5.9
Pietramontecorvino	–	–	6.3	2.6	29.0	33.2	0.4	27.7	0.8
Rignano Garganico	20.0	–	–	–	–	–	–	54.3	25.7
RosetoValfortore	–	–	92.1	–	–	–	–	6.9	0.9
San Giovanni Rotondo	39.5	2.1	–	–	–	–	13.4	29.1	15.9
San Marco in Lamis	42.1	1.6	–	–	–	–	17.9	25.1	13.4
San Paolo di Civitate	–	–	–	–	36.4	4.5	57.6	–	1.5
San Severo	–	–	–	–	5.7	0.6	39.9	48.5	5.3
Torremaggiore	–	–	–	–	41.2	18.2	4.6	36.1	–
Troia	–	4.6	2.2	–	27.4	24.9	5.2	16.3	19.4
Voturara Appula	–	–	96.3	–	–	–	–	1.8	1.9
Volturino	–	–	15.5	5.5	6.4	47.3	–	22.7	2.7
Total	–	–	50.9	5.7	15.9	13.0	–	13.8	0.8

[a] Low.
[b] Medium.
[c] High.

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Appendix

See Tables A.1 and A.2.

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