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Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation

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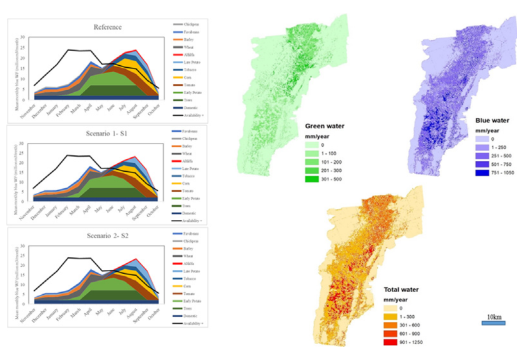
HIGHLIGHTS

- This is the first study on the water saving effect of mulching and drip irrigation at catchment scale.
- Mulching and drip irrigation will reduce the blue water footprint in Upper Litani Basin (ULB) by 5%.
- Additional measures will be needed to lower the water footprint in the ULB to sustainable level.
- Mulching reduces the water footprint of crops more than drip irrigation, but combining is the best.

GRAPHICAL ABSTRACT



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ABSTRACT

Water scarcity has received global attention in the last decade as it challenges food security in arid and semi-arid regions, particularly in the Middle East and North Africa. This research assesses the possible alleviation of water scarcity by reducing the water footprint in crop production through the application of soil mulching and drip irrigation. The study is the first to do so at catchment scale, taking into account various crops, multi-cropping, cropping patterns, and spatial differences in climate, soil, and field management factors, using field survey and local data. The AquaCrop-OS model and the global water footprint assessment (WFA) standard were used to assess the green and blue water footprint (WF) of ten major crops in the Upper Litani Basin (ULB) in Lebanon. The blue water saving and blue water scarcity reduction under these two alternative practices were compared to the current situation. The results show that the WF of crop production is more sensitive to climate than soil type. The annual blue WF of summer crops was largest when water availability was lowest. Mulching reduced the blue WF by 3.6% and mulching combined with drip irrigation reduced it by 4.7%. The blue water saving from mulching was estimated about 6.3 million m^3/y and from mulching combined with drip irrigation about 8.3 million m^3/y. This is substantial but by far not sufficient to reduce the overall blue WF in summer to a sustainable level at catchment scale.

1. Introduction

Growing numbers of people in the world are facing severe freshwater scarcity (Mekonnen and Hoekstra, 2016; Wada et al., 2011). Since about 92% of all water consumption in the world relates to agriculture

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(Hoekstra et al., 2012), there is increasing interest in the question how to reduce water use and vulnerability to water shortage in agriculture, particularly in irrigated crop production (Jägermeyr et al., 2015; Brauman et al., 2013). Possibilities for reducing water use in cop production vary widely, from soil mulching to reduce unproductive soil evaporation (Pi et al., 2017), drip irrigation to maximize the fraction of irrigation water that reaches the plant (Postel et al., 2001), deficit irrigation to increase water productivity in terms of crop per drop (Chai et al., 2016), conservation tillage to improve soil properties and water holding capacity (Azimzadeh, 2012), crop diversification and rotation to enhance resilience under water scarcity (EIP-AGRI, 2016), cultivation of drought resistant crops or crop varieties to reduce vulnerability to water shortages (Hu and Xiong, 2014) to changing spatial cropping patterns to match crop choice to local growing conditions (Schyns and Hoekstra, 2014; Davis et al., 2017).

Here, we focus on soil mulching and drip irrigation as two of the promising agricultural practices that may contribute to increasing water productivity. Whereas most studies focus on field scale, we focus on the catchment level in order to estimate the aggregate water saving and water scarcity alleviation that can be achieved when these practices are applied throughout a catchment. To quantify water consumption of a crop we use the concept of the water footprint, an indicator of freshwater appropriation in a certain place and time. We consider two components: the green water footprint that refers to evapotranspiration of rainwater and the blue water footprint that refers to evapotranspiration of irrigation water (Hoekstra, 2017; Hoekstra et al., 2011). We further use the concept of blue water scarcity, defined as the ratio of the total blue water footprint in a catchment to the blue water availability, whereby the latter equals natural runoff in the catchment minus the flow that needs to be maintained in support of local ecosystems and communities (Hoekstra et al., 2011).

We take the Upper Litani Basin (ULB) in Lebanon as study area, which may be a representative case for the region of the Middle East and North Africa (MENA). Over the last forty years, the per capita availability of fresh water in the MENA region has dropped by two-thirds; currently it is one-tenth of the world average (FAO, 2014a). The region is the most water-scarce part of the world, with a high dependency on transboundary water resources; by 2050, freshwater availability per capita in the MENA region will have declined another 50% compared to the present (FAO, 2014a). The low water availability combined with a 2% annual population growth (FAO, 2015b) puts water and food security on top of the agenda for most governments in the MENA region. Since agriculture is the primary user of freshwater resources in all countries, alternative agricultural practices are required to reduce water use in the agricultural sector (Bastiaanssen and Steduto, 2017; le Roux et al., 2017). Lebanon is one of the most water-stressed countries in the region, with a water availability below the critical threshold of 1000 m^3 per year (FAO, 2015a; United Nations, 2001).

In order to assess how mulching and drip irrigation can reduce water consumption and alleviate water scarcity at catchment level we employ the AquaCrop-OS model, the open-source MATLAB version of FAO's crop water productivity model AquaCrop (FAO, 2017). We assess the green and blue WF of the major crops in the ULB catchment under both current conditions and with mulching and drip irrigation, both separately and combined. We account for the spatial heterogeneity in soils and climate and for inter-annual variability by considering a multi-year period (2009–2016).

2. Method and data

2.1. Study area

The Upper Litani Basin is Lebanon's largest surface water source, situated between the Lebanon Mountains and the Anti-Lebanon Mountains, with an area of 1500 km^2. The Litani River originates from the fertile Bekaa valley. The climate of the interior zone of Litani Basin varies from sub-humid in the south to arid in the north within <100 km (Dixit and Telleria, 2015; Ramadan et al., 2012). By the construction of the Albert Naqash dam and Qaraoun reservoir in 1959, the Litani basin is divided into the Upper Litani Basin (ULB) and the Lower Litani Basin (LLB) (Fig. 1). The ULB faces wet winters (November–May) and dry summers (April–October). The three main cropping schemes are perennial crops, high-value summer crops and a rotation of winter and summer crops. Inappropriate water management has caused severe water shortage and widespread water pollution (USAID, 2014). Lebanon's water consumption has increased due to the expansion of the irrigated area from 23,000 ha in 1956 to 90,000 ha in 2000. Governmental implementation of pumping wells and irrigation schemes in the 1990s resulted in increasing pressure on groundwater resources. Since the 2000s, interest in water management and water use efficiency in Lebanon has grown (Alcon et al., 2019; Shaban and Houhou, 2015).

The ULB is the main agricultural area in Lebanon, having 42% of the country's farmlands and 50% of the irrigated lands (FAO, 2012a, 2012b). USAID (2014) observed a significant increase in groundwater abstractions and decrease in river flows, and found that annual water demand exceeds the physical water availability, resulting in a groundwater decline of 0.5–2.0 m per year. Climate change projections for the basin show an increase in the temperature and impact studies expect a reduction in runoff in dry months of the year, which will lead to greater competition over the limited water resources (EIP-AGRI, 2016; Ramadan et al., 2013a; Ramadan et al., 2013b; USAID, 2014). Since the Syrian crisis, the arrival of approximately 275,000 refugees in Lebanon substantially increased annual water consumption in the ULB, reaching a total of 392 million m^3 per annum (Jaafar and King-Okumu, 2016).

2.2. Estimation of the blue and green water footprint of crop production

The annual WFs of crop production for ten major crops in the ULB during the period 2009–2016 were estimated on a daily basis following

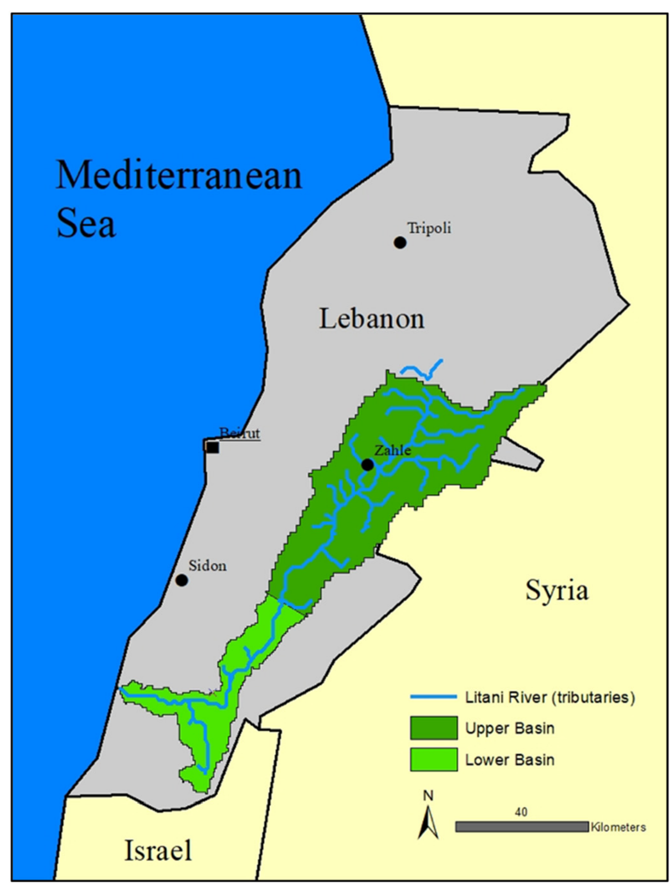

Fig. 1. Upper and Lower Litani Basin in Lebanon.

the global water footprint assessment standard (Hoekstra et al., 2011). These crops include wheat, potato (early and late), alfalfa, barley, chickpea, corn, fava bean, tobacco and tomato, which together account for about 94% of the total harvested area in the ULB (USAID, 2014).

The AquaCrop model was employed to estimate evapotranspiration (ET) and crop yield for each land unit (LU) by simulating the dynamic soil water balance and biomass growth on a daily basis. The soil water balance is as follows:

$$S_i = P_i + I_i + C_i - SO_i - D_i - E_i - T_i \tag{1}$$

where S is soil water content (mm) on day i, P is precipitation (mm), I is irrigation (mm), C is capillary rise (mm) depending on the soil type and availability of the shallow groundwater table, SO is the surface runoff (mm), D is deep percolation (mm), E is soil evaporation (mm), and T is crop transpiration (mm). Evaporation and transpiration were simulated separately from the soil moisture balance. Surface runoff is simulated using the Curve Number (CN) method (Rallison, 1980):

$$RO_i = \frac{(P_i - 0.2 * Si)^2}{P_i + S - 0.2Si} \tag{2}$$

We partitioned daily soil moisture into a green and blue component using the method by Chukalla et al. (2015):

$$Sg_t = Sg_{t-1} + P_t - RO_t\left(\frac{P_t}{P_t + I_t}\right) - (D_t + ET_t)\left(\frac{Sg_{t-1}}{S_{t-1}}\right) \tag{3}$$

$$Sb_t = Sb_{t-1} + I_t - RO_t\left(\frac{I_t}{P_t + I_t}\right) - (D_t + ET_t)\left(\frac{Sb_{t-1}}{S_{t-1}}\right) \tag{4}$$

where S_g is the green soil water content (mm) and S_b the blue soil water content (mm). The green and blue parts of the crop water use (CWU) over the season were calculated by aggregating, respectively, the green and blue evapotranspiration (ET) over the growing period:

$$CWU_g = \sum_{t=1}^{T} \frac{Sg_t}{S_t} ET_t \times 10 \tag{5}$$

$$CWU_b = \sum_{t=1}^{T} \frac{Sb_t}{S_t} ET_t \times 10 \tag{6}$$

whereby CWU_g is the green water consumption (m^3) over the growing season, CWU_b the blue water consumption (m^3), and the factor 10 the conversion factor from mm to m^3. The green and blue fractions of ET on a certain day depend on the green and blue fractions in the soil water on the same day. The green water footprint (WF_g) and blue water footprint (WF_b), both in m^3/t, were obtained by dividing CWU over the season by the crop yield (Y):

$$WF_g = \frac{CWU_g}{Y} \tag{7}$$

$$WF_b = \frac{CWU_b}{Y} \tag{8}$$

The average WF of each crop in ULB was obtained by averaging the WFs for all representing LUs, accounting for their relative contributions.

We used AquaCrop – a more advanced model than the CropWat model that has been employed in many previous WF studies (Mekonnen and Hoekstra, 2011) – for its good performance in estimating crop water use across various agronomic and environmental conditions (Ran et al., 2018). Among the four AquaCrop model versions, standard, plug-in, GIS and OS (FAO, 2017; Foster et al., 2017; Lorite et al., 2013), we found AquaCrop-OS (Open Source, in Matlab software) the most suitable one to meet our purpose, because it supports parallel execution and cut simulation times when applying the model in a large geospatial framework. This model enabled multiple point simulations while other versions of AquaCrop can only simulate one crop and one soil type per simulation run.

We estimated the WF of the ten major crops in the ULB considering the existing multi-cropping patterns and crop rotations in combination with four soil types and six climate zones within the basin. We used AquaCrop-OS batch run script and Matlab's Parallel Computing Toolbox to execute multiple individual simulations as a batch run. For each simulation, we prepared 16 input files (18 for multi-crops in rotation with corresponding irrigation management).

The simulation period was from January 2009 to December 2016. The first two calendar years were used for initializing the model. This means that the accounting period (over which we consider the results) starts with the second winter crop season and the third summer crop season (Table 1). For all cropping patterns, we thus have simulation results for six years for analysis and presentation. We assumed soil moisture at field capacity at the start of the summer cropping season in 2009.

Parametrization was done following the steps recommended by FAO (2014b). The simulation was started using estimated parameters. By iteration, parameters were adjusted to match the simulated yields with the observed data. The Root Mean Square Error (RMSE) was used to evaluate the model performance of simulated yield for each crop. The observed data were derived from our survey and FAOSTAT (2018). The performance per crop is summarised in Table 2.

2.3. Blue water scarcity

The blue water scarcity in a catchment is defined as the ratio of total blue WF to the blue water availability in the catchment (Hoekstra et al., 2011). To assess the blue water scarcity in the ULB, the blue WF in the ULB and blue water availability were calculated on a monthly basis. The monthly blue WF of major crops were estimated using AquaCrop-OS. The blue WF of the domestic, industrial and forestry sectors were obtained from USAID (2014). The combined domestic and industrial consumption was estimated 25 million m^3/y, assumed constant over time, and irrigation water consumption of the forestry sector was estimated about 5 million m^3 per month over the summer period (April–August), i.e. an annual irrigation water consumption of 25 million m^3/y. No earlier water footprint study at catchment level ever before included the blue WF of forestry, but it is no more than reasonable to do so given that also this sector can have a substantial footprint (Schyns et al., 2017).

To calculate water availability, defined as natural runoff minus environmental flow requirements (EFR), an initial rate of 80% was considered for EFR (Hoekstra et al., 2011). Due to unavailability of data for natural runoff in the catchment, the historical runoff record for the period 1938–1962 was used as a basis for estimating the annual natural runoff, adding the irrigation water use in that specific period to compensate for the fact that runoff was already partially depleted. Monthly water availability and blue WFs of the domestic, industrial and forestry sectors are summarised in Table 3. The aggregated blue WF of the domestic, industrial and forestry sectors exceeds water availability during May–August while the blue WF of the biggest water-using sector, agriculture, has not been included yet.

To increase the water availability, we examined three options:

- Lowering EFR. An EFR of 80% of natural runoff could be too strict (Zhuo et al., 2016), so we also considered a scenario with an EFR of 60% of natural runoff.

Table 1
Counting of the summer and winter crop harvests during the simulation period.

	2009	2010	2011	2012	2013	2014	2015	2016
Summer	1	2	3	4	5	6	7	8
Winter		1	2	3	4	5	6	7
Period	Initialization period		Water accounting period					

Table 2
The model performance regarding yield simulation per crop type.

Crop	Barley	Chickpeas	Corn	Fava beans	Potato[a]	Tobacco	Tomato	Wheat	Alfalfa
RMSE (%)	2.93	5.53	3.46	5.81	6.25	7.12	4.35	17.25	n.a.

[a] Sum of early potato (58%) and late potato (42%) corrected for their relevant areas.

Table 3
Variables in the water availability assessment for the Upper Litani Basin.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Hist. runoff[a]	63	79	78	55	33	17	11	9	10	13	16	28	411
Natural runoff[b]	67.4	84.6	83.5	58.9	35.3	18.2	11.8	9.6	10.7	13.9	17.1	30	441
EFR80[c]	54.0	67.7	66.8	47.1	28.3	14.6	9.4	7.7	8.6	11.1	13.7	24.0	353
Availability[d]	13.5	16.9	16.7	11.8	7.1	3.6	2.4	1.9	2.1	2.8	3.4	6.0	88
Blue WF D&I[e]	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	25
Blue WF trees[f]	0	0	0	5	5	5	5	5	0	0	0	0	25
EFR60[g]	40.4	50.8	50.1	35.3	21.2	10.9	7.1	5.8	6.4	8.3	10.3	18.0	265
Fossil water use[h]					2	2	2	2	2				10
C900[i]	−10	−10	−10		1	8	9	9	3				30
Availability+ [j]	17.0	23.8	23.4	23.6	17.1	17.3	15.7	14.8	9.3	5.6	6.8	12.0	186

All variables are presented in million m^3/y.
[a] Historical runoff record for the period 1938–1962 (USAID, 2014).
[b] Natural runoff = historical runoff + irrigation (1938–1962).
[c] Environmental flow requirements taken as 80% of natural runoff.
[d] Water availability = natural flow – EFR80.
[e] Blue WF of the domestic and industrial sectors.
[f] Blue WF of trees.
[g] Environmental flow requirements when taken as 60% of natural runoff.
[h] Fossil water extraction.
[i] Storage of water in the wet period and release in the dry period through the new irrigation scheme of canal C900.
[j] Adjusted water availability (availability$^+$) = natural runoff – EFR60 + fossil water extraction + C900.

- Extracting fossil water. Currently, the fossil water abstraction in the basin is about 80 million m^3/y on average (USAID, 2014). The Litani River Authority, in collaboration with USAID, formulated a future scenario where they suggest to reduce this to 30 million m^3/y. For this study, an abstraction of 10 million m^3/y from fossil groundwater was assumed acceptable.
- Storage of water. A new irrigation canal called C900 has been planned to abstract water from Lake Qaraoun (located at the downstream point of ULB). This new canal can deliver water stored in the wet period in Lake Qaraoun to upstream areas in the ULB in the dry period; this canal will increase water availability up to 30 million m^3/y.

An adjusted water availability rate (Availability+) for the ULB was calculated by combining these three options (see Table 3):

$$\text{Availability}^{+} = \text{Natural runoff} - \text{EFR60} + \text{Fossil water use} + \text{C900} \quad (10)$$

The blue WFs of the domestic, industrial and forestry sector, natural runoff and the two indicators for water availability are shown in Fig. 2,

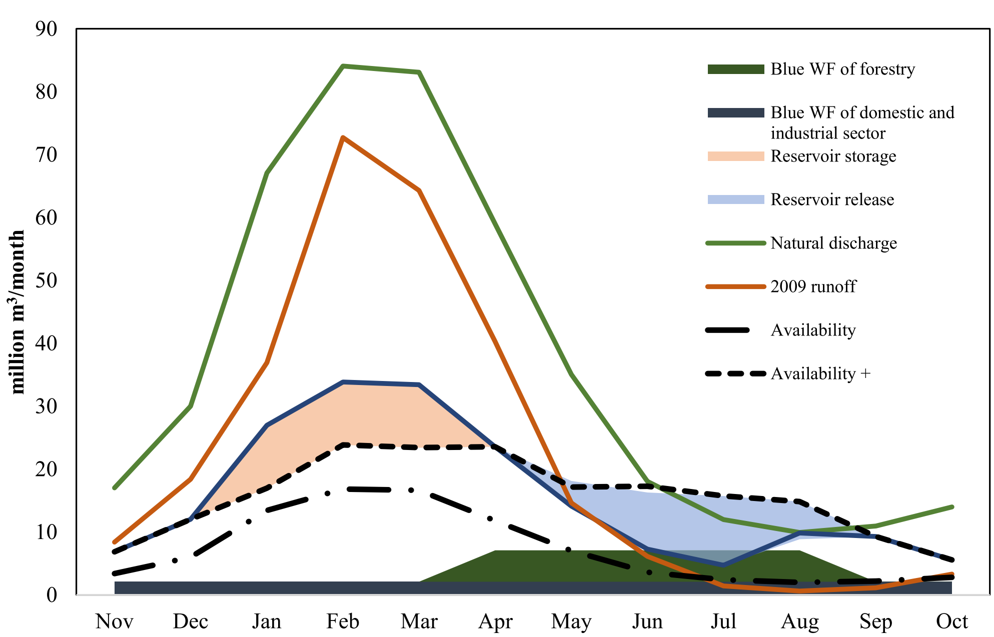

Fig. 2. Blue water availability and blue water footprint in the Upper Litani Basin (2011–2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

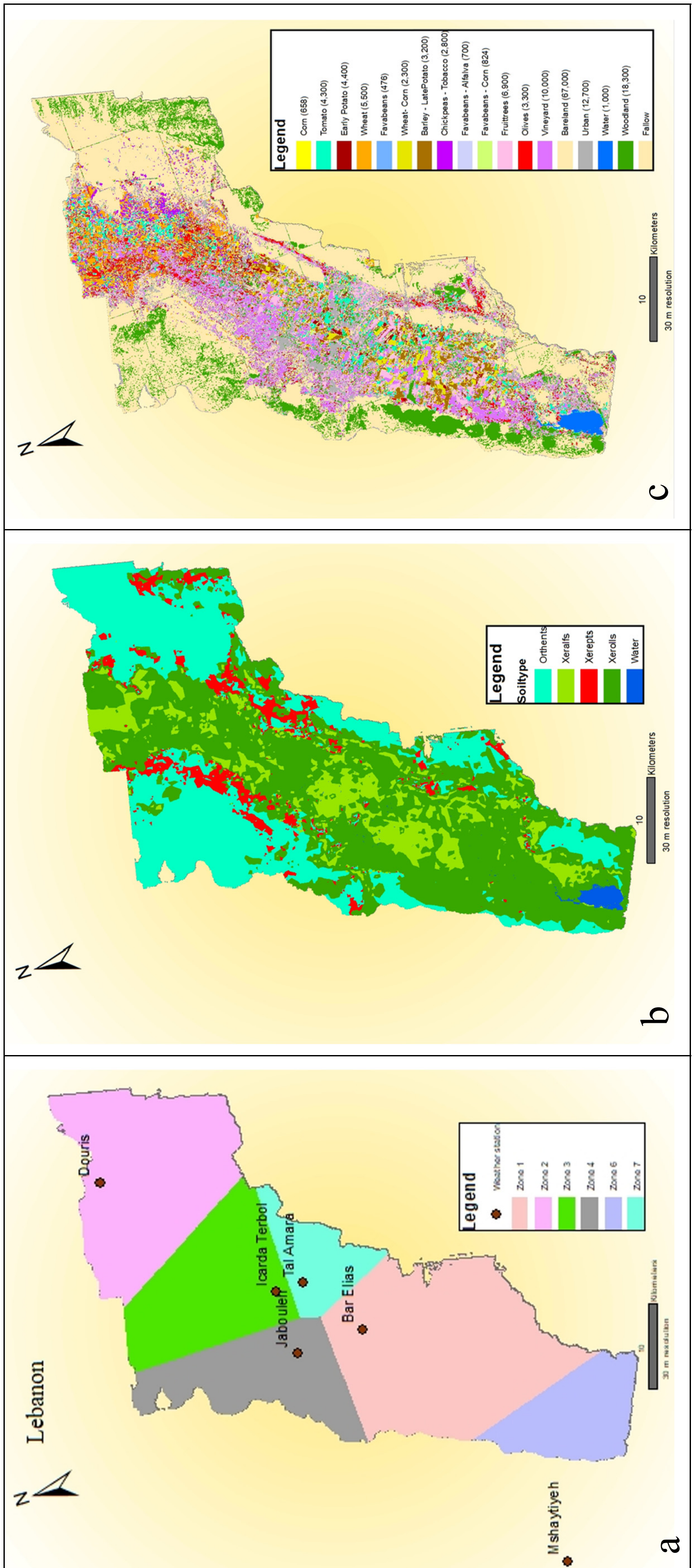

Fig. 3. Climate zones (a), soil types (b), and land use including ten major crops (c) in the Upper Litani Basin.

which also shows the actual runoff measured in 2009. Annual natural and actual runoff were used to estimate the abstraction from fossil groundwater. Current runoff is around 300 million m^3 (USAID, 2014), while natural runoff was estimated to be around 440 million m^3 (see Table 3). The part of the blue WF that was higher than this difference must have been extracted from fossil groundwater reserves. The annual fossil groundwater extraction is calculated as the blue WF minus the difference between the natural and current runoff (assuming that the difference between natural and current runoff refers to the water consumption from renewable water resources).

Following (Hoekstra et al., 2012), monthly rates of water scarcity were categorized into four levels of water scarcity: low (<1.0), moderate (1.0–1.5), significant (1.5–2.0) and severe (>2.0).

2.4. Alternative agricultural practices

We developed two alternative management scenarios compared to current field and irrigation management practices in the ULB. To reduce soil evaporation and soil compaction, control weeds and their transpiration, and nutrient management, the first scenario differs from the reference scenario by applying mulching for all crops. The second scenario also applies mulching for all crops and, in addition, replaces available irrigation by drip irrigation for summer crops.

2.5. Data

To account for different combinations of crop, soil and climate in water use calculations, we divided the study area into different land units (LUs). Each LU represents a homogeneous area with one specific crop in a specific soil type under particular climate conditions. With ten crop types, four soil types and six climate zones in the ULB, a total of 225 LUs were defined. Data were gathered from local government offices and available literature. Also, we collected some data through our field survey that took place in the Litani River Basin in Bekaa Valley from 31 June to 19 July 2017. The surveys provided geo-referenced technical information of crop, soil, water sources (quantity and quality), irrigation, fertilisation, groundwater and yield; these data were partly used in the simulation process and partly in the validation process. The two most cultivated crops, potato and wheat, were selected to be surveyed in more detail. Geo-referenced crop-soil-water information was collected at 50 farms interviewing 25 potato producers and 25 wheat producers.

Climate data for the period 2009–2016 were derived from six weather stations within the ULB provided by the Lebanese Agricultural Research Institute (LARI). After cleaning the data and using Thiessen Polygons, the ULB was divided into six climate zones; the largest distance from a station was about 25 km. Fig. 3a displays six climate zones in the ULB.

Soil data were obtained from the ISRIC database with soil data at a resolution of 250×250 m^2 (Hengl et al., 2017). The TAXOUSDA classification system was used to derive different soil types in the ULB. Fig. 3b represents the spatial distribution of four main soil types of Orthents, Xeralfs, Xerepts and Xerolls in the ULB.

We used the 5×5 m^2 spatial resolution land-use maps by USAID (2014) for three growing seasons as base maps to plot the spatial distribution of different land uses in the ULB (Fig. 3c). The land uses distinguished include major crops, bare lands, urban, water bodies, woodlands and fallow lands. A crop calendar was established based on these maps in combination with field surveys (Table 4).

Some LUs have single cropping; others have multi-cropping (a summer/winter rotation of two different crops). Since the annual crop calendar substantially influences the soil water balance, the different combinations and order of crops and fallow period were simulated separately.

Our field survey and available literature on farming practices in the ULB were employed for management data. All farmers in the surveys growing potato and wheat used sprinkler irrigation. On average, the irrigation depth of 75 mm was recorded for wheat, and 63 mm for potato. The irrigation depths, irrigation efficiency and surface wetted per irrigation technique for the remaining crops were derived from Raes et al. (2017). The interval between irrigation events was documented 60 days for wheat (in the form of supplementary irrigation) and seven days for potato (full irrigation). These intervals were used for all winter and summer crops respectively.

The wet period in the ULB is from November to April and the dry period from May to October. The planting dates for the winter crops (barley, chickpeas, fava beans, and wheat) and early potato were generated from rainfall events. As planting criterion, we applied a successive period of 4 days with at least 10 mm of rainfall. The summer crops were planted on fixed dates since they were highly dependent on irrigation schedules.

Table 4
Overview of cropping practices in different land-use types in the Upper Litani Basin.

Land-use type	Area (ha)	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	700	Fallow								Corn			Fallow
2	4300	Fallow							Tomato				Fallow
3	4400	Fallow			Early-Potato						Fallow		
4	5500	Wheat								Fallow			
5	500	Fava beans							Fallow				
6	2300	Wheat								Corn			Fallow
7	3200	Barley								Late Potato			
8	2800	Chickpeas							Tobacco			Fallow	
9	700	Fava beans							Alfalfa				Fallow
10	800	Fava beans							Fallow	Corn			Fallow
11	6500	Fallow											

3. Results

3.1. WF of crops in the ULB basin

The green, blue and total WF of the ten major crops in the ULB are presented in Fig. 4.

When considering differences in the total WF per unit of crop across different soil types and climate zones (Fig. 5), we find a very small variation of WFs across soil types but a substantial variation over different climate zones.

A descriptive statistical analysis of the annual total WF for 225 LUs in the ULB during 2011–2016 was performed. The minimum and maximum annual WF (mm/y) within the basin were 231 mm (barley in Xerolls soil and climate zone 4 in 2013) and 1254 mm (barley in Xerolls soil and climate zone 4 in 2012), respectively. The range of mean annual WF was 705–737 mm. Jaafar and King-Okumu (2016) studied the cumulative seasonal ET for irrigated crops in the ULB in 2013 (May–Oct) by measuring the reference ET from a local weather station and the actual ET using two approaches of NDVI (approximation) and DisAlexi (energy balance). They reported a cumulative ET of 754 mm and 391 mm, respectively. Using AquaCrop-OS, we estimated a seasonal mean WF of 555 mm during May–Oct 2013 – in the range of 391 and 754 mm. Also, they reported a seasonal ET (May–Oct) of 600 mm for 2016 based on a local weather data and their survey; our seasonal WF for 2016 was 593 mm.

In another study, Karam et al. (2003) assessed the ET, yield and water use efficiency of drip irrigated corn under deficit and full irrigation in the Bekaa Valley. They reported a seasonal ET of 925–945 mm for growing periods of 120–128 days from sowing to harvest, respectively. Also, Karam et al. (2005) estimated ET of ryegrass and soybean at Tal Amara Research Station in the ULB using lysimeters. They recorded an average crop ET of 800 mm and 725 mm in 2000 and 2001, respectively. Karam et al. (2007) conducted a 2-year experiment (2003–2004) in Bekaa to investigate sunflower response to deficit irrigation. They measured an ET of 765 mm and 882 mm in 2003 and

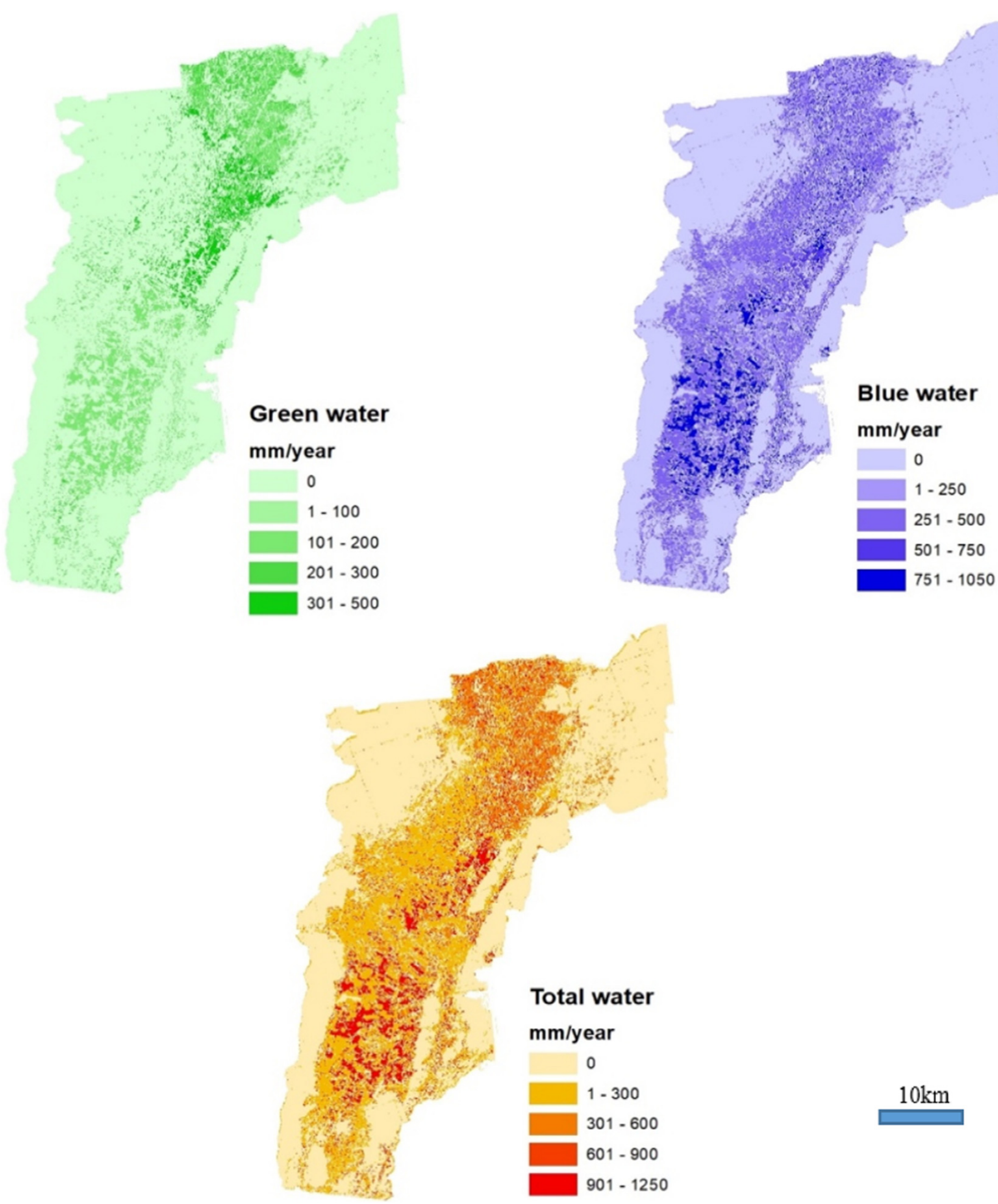

Fig. 4. Average annual green, blue and total WF of major crops in the ULB (2011–2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

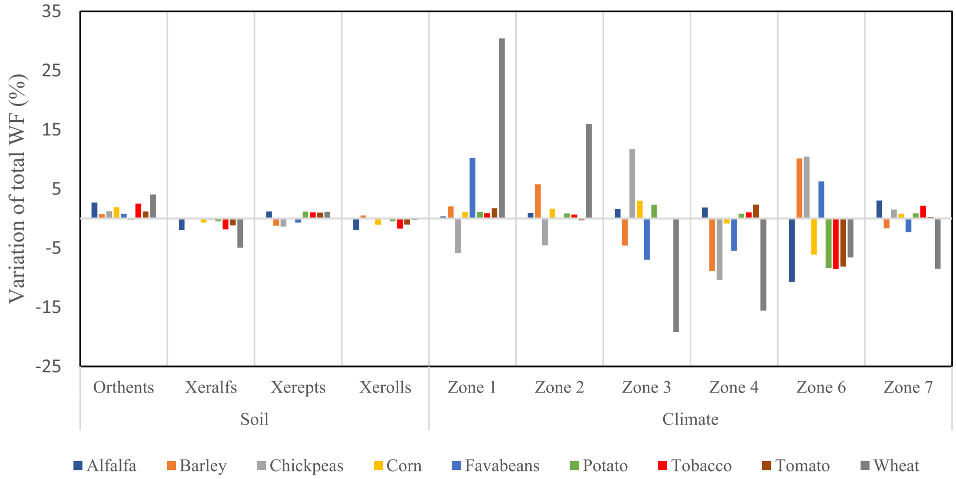

Fig. 5. Deviation of total WF (m^3/t) compared to the crop average during study period 2011–2016 for different soil types (left) and climate zones (right) for major crops in the Upper Litani basin.

2004, respectively. Our total WF results showed the range of 705–737 mm/y for the period 2011–2016.

It should be noted that most studies in the region were focused on single cultivation while we have a significant number of land units representing farms with more than one crop in a year. This means that we expected a higher WF for those LUs, which also appeared to be the case as can be seen in Fig. 6.

A time series of ET over the growing season for all cropped land units (LUs) in the ULB during 2011–2016 was analysed. We compared the ET of LUs with single-crop (S) and multi-crops (M). As expected, LUs with multi-crops show a higher ET over the growing season (which is longer) than LUs with single-crop.

3.2. WF reduction through mulching and drip irrigation

For each major crop, the green and blue WFs were calculated for the existing management practices (as reported in Table 5) as well as for the two scenarios: mulching of all crop fields (S1), and mulching combined with drip irrigation (S2). Fig. 7 represents the total water consumption of major crops in the ULB during 2011–2016 in the reference case (Ref) and under scenarios S1 and S2. The results show that the WF of all crops decrease by mulching, with for most crops a further decrease when also replacing existing irrigation technology (surface or sprinkler irrigation) by drip irrigation. These results confirm that mulching and drip irrigation have positive impacts on water saving. The WF for all summer crops were higher compared to the literature (Mekonnen and Hoekstra, 2010, 2011); it could be because of including a higher resolution climate data, local crop calendar, and local data on management practices from the survey in our research. We found the green WF estimation in the literature unrealistically high.

The total green and blue WFs in ULB in the reference situation and the two scenarios are shown in Table 6. Overall, scenario S1 saves 6.3 million m^3 of blue water per annum, a relative blue WF reduction of 3.6%. Scenario S2 comes with a total blue water saving of 8.4 million m^3/y; drip irrigation thus saves an additional 2.1 million m^3/y. The relative blue WF reduction in this scenario is 4.7%.

3.3. Water scarcity alleviation in the ULB through mulching and drip irrigation

The monthly blue water footprints of major crops and the blue water footprints of the domestic, industrial and forestry sectors in ULB in the period 2011–2016 were aggregated to be compared with blue water availability and water availability+. The blue WF of major crops was calculated at 127 million m^3/y, the blue WF of the domestic and industrial sectors together at 25 million m^3/y and the blue WF of the forestry sector at 25 million m^3/y as well, so that the total blue water consumption in the ULB was estimated at 177 million m^3/y.

Table 7 shows the rate of the monthly blue water scarcity in the ULB during 2011–2016. Blue water scarcity was calculated here as the ratio of total blue WF in the ULB over the adjusted water availability based on EFR of 60% of natural runoff, irrigation supply from Canal 900 and some allowed fossil abstraction. In all years during the period 2011–2016, overconsumption of water occurs in the summer period from June until September; this is possible by not meeting environmental flow requirements and use of fossil water. September generally

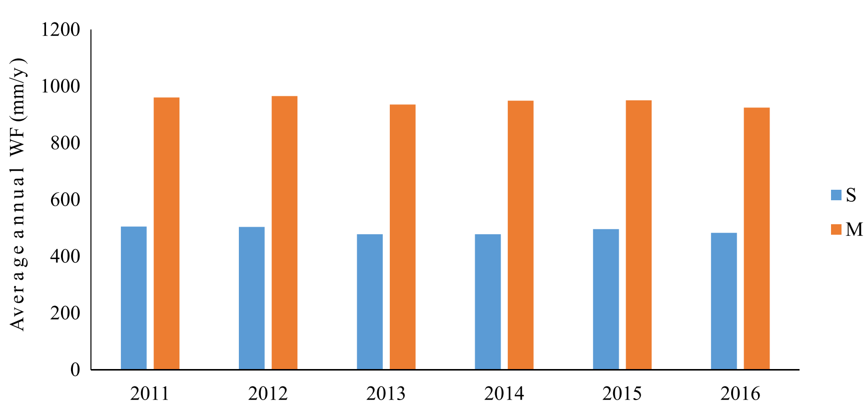

Fig. 6. Comparison of the water footprint (WF) of single-crop (S) and multi-crops (M) land units in the Upper Litani Basin during 2011–2016.

Table 5
Irrigation and mulching practice per crop type in the Upper Litani Basin.

		Drip irrigation			Surface irrigation			Sprinkler irrigation			Mulching
Surface wetted (%)[a]		30			100			100			
Efficiency (%)[a]		90			60			75			
Crop	Area (ha)[b]	%[c]	T (days)[d]	mm[e]	%	T (days)	mm	%	T (days)	mm	
Alfalfa	700	22	7	78	21	7	116	57	7	93	No
Barley	3200	0	60	63	0	60	95	100	60	76	No
Chickpeas	2800	10	60	56	0	60	84	90	60	67	No
Corn	3800	0	4	63	4	4	94	96	4	75	No
Fava beans	2000	8	60	63	39	60	95	53	60	76	No
Early potato	4400	0	7	53	0	7	79	100	7	63	No
Late potato	3200	0	7	59	0	7	89	100	7	71	No
Tobacco	2800	22	7	56	21	7	84	57	7	67	No
Tomato	4300	4	7	41	17	7	61	79	7	49	No
Wheat	7800	0	60	63	0	60	95	100	60	76	No

Sources:
[a] Raes et al. (2017).
[b] USAID (2014).
[c] % irrigation type used (Jaafar and King-Okumu, 2016).
[d] Interval T between irrigation events (field surveys).
[e] Irrigation depth (wheat and potato from our field surveys, other crops from Raes et al. (2017)).

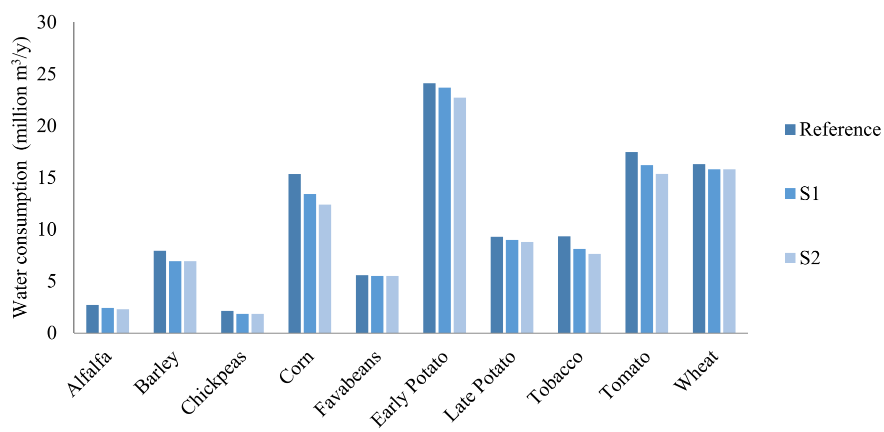

Fig. 7. Mean total water footprint of major crops in the Upper Litani Basin under current practices (Reference), a scenario with mulching (S1), and a scenario with mulching and drip irrigation (S2) for the period 2011–2016.

shows severe water scarcity. Water scarcity in winter is the low, followed by low to moderate water scarcity in spring. Comparing the monthly blue WFs to the stricter measure of water availability (based on EFR of 80% of natural runoff) results in a worse picture, with much higher water scarcity figures in summer and a period with significant to severe water scarcity of five to six months.

The average monthly blue water consumption per user type (major crops, domestic/industrial sector, and forestry sector) is shown in Fig. 8. The overall blue WF remains below water availability+ from October to May, in the current situation as well as in the two scenarios, but exceeds water availability+ from June until September. Although mulching and drip irrigation significantly reduce the blue WF, it does not help to solve overconsumption of water in the ULB.

4. Discussion

Wet winters and dry summers, a common pattern in many semi-arid regions, require supplementary or full irrigation schemes in cultivated lands. Implementing water-saving agricultural practices can reduce the water footprint of crop production and thus alleviate blue water scarcity; the effect of these practices may vary from place to place and therefore needs to be investigated locally.

Roughly spoken, the water-saving potential of soil mulching and drip irrigation is evident. In our case study we found a blue water saving of 5% from the combination of mulching with organic material and drip irrigation. Chukalla et al. (2015) tested the effect of mulching and drip irrigation in a modelling study for four different environments and three different crops (maize, potato and tomato) and found a consistent WF reduction from mulching and drip irrigation, with a bigger impact for mulching than for drip irrigation, as in the current study. In a specific case for Greece, Tsakmakis et al. (2018) assessed the impact of different irrigation technologies on the water footprint of cotton; they found a 5% reduction in the total WF under drip irrigation compared to sprinkler. A long-term field study of coconut planting in India by Jayakumar et al. (2017) showed an improvement in water productivity under a combination of mulching and drip fertigation. Balwinder-Singh et al. (2011) investigated the impact of rice straw mulch on the water productivity of wheat at an experimental site in India and found higher water productivity for fields with mulching compared fields without mulching. In another experimental study, in Pakistan, Jabran et al. (2015) found

Table 6
Green and blue WF and the blue WF saving in the reference and two scenarios.

Variable	Unit	Reference	Scenario 1	Scenario 2
Green WF	million m^3/y	47	46	48
Blue WF	million m^3/y	177	171	169
Blue WF saving	million m^3/y	–	6.3	8.3

Table 7
Monthly blue water scarcity in the Upper Litani Basin over the period November 2011 to October 2016 (based on water availability+). Green-coloured months have low scarcity (≤1.0); yellow-coloured months have moderate water scarcity (1.0–1.5); orange-coloured months have significant water scarcity (1.5–2); red-coloured months have severe water scarcity (>2.0).

Year	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
2011	0.31	0.58	0.42	0.32	0.58	0.86	1.09	1.20	1.71	1.80	2.28	0.99
2012	0.67	0.59	0.38	0.37	0.52	1.01	1.13	1.30	1.68	1.82	2.25	0.55
2013	0.64	0.56	0.39	0.35	0.60	0.77	0.93	1.21	1.50	1.75	2.10	0.85
2014	0.60	0.56	0.44	0.38	0.63	0.86	0.90	1.28	1.70	1.88	2.12	0.77
2015	1.07	0.68	0.43	0.37	0.63	0.81	0.97	1.20	1.65	1.81	2.12	0.49
2016	0.31	0.62	0.44	0.44	0.64	0.97	0.98	1.30	1.61	1.92	1.90	0.52
Mean	0.60	0.60	0.42	0.37	0.60	0.88	1.00	1.25	1.64	1.83	2.13	0.70

that mulching improved the water productivity of rice. In a field study in Chile, Gil et al. (2018) evaluated the water saving effect of mulching in a vineyard and found substantial reductions in water use.

A problem when trying to generalize the water-saving effect of mulching and drip irrigation or when comparing results across case studies is that results are very case-specific. The various studies differ in a number of factors at the same time, like the crop considered, the location (soil, climate) and practices employed (fertilizer and pesticide application, tillage, crop rotation etc.). As a consequence, it will be hard to say what in general sense the water saving impact of adopting mulching or drip irrigation will be compared to conditions of no mulching and surface or sprinkler irrigation. Nevertheless, the results of the current study together with results from earlier studies as mentioned above tend to justify the general conclusion that both soil

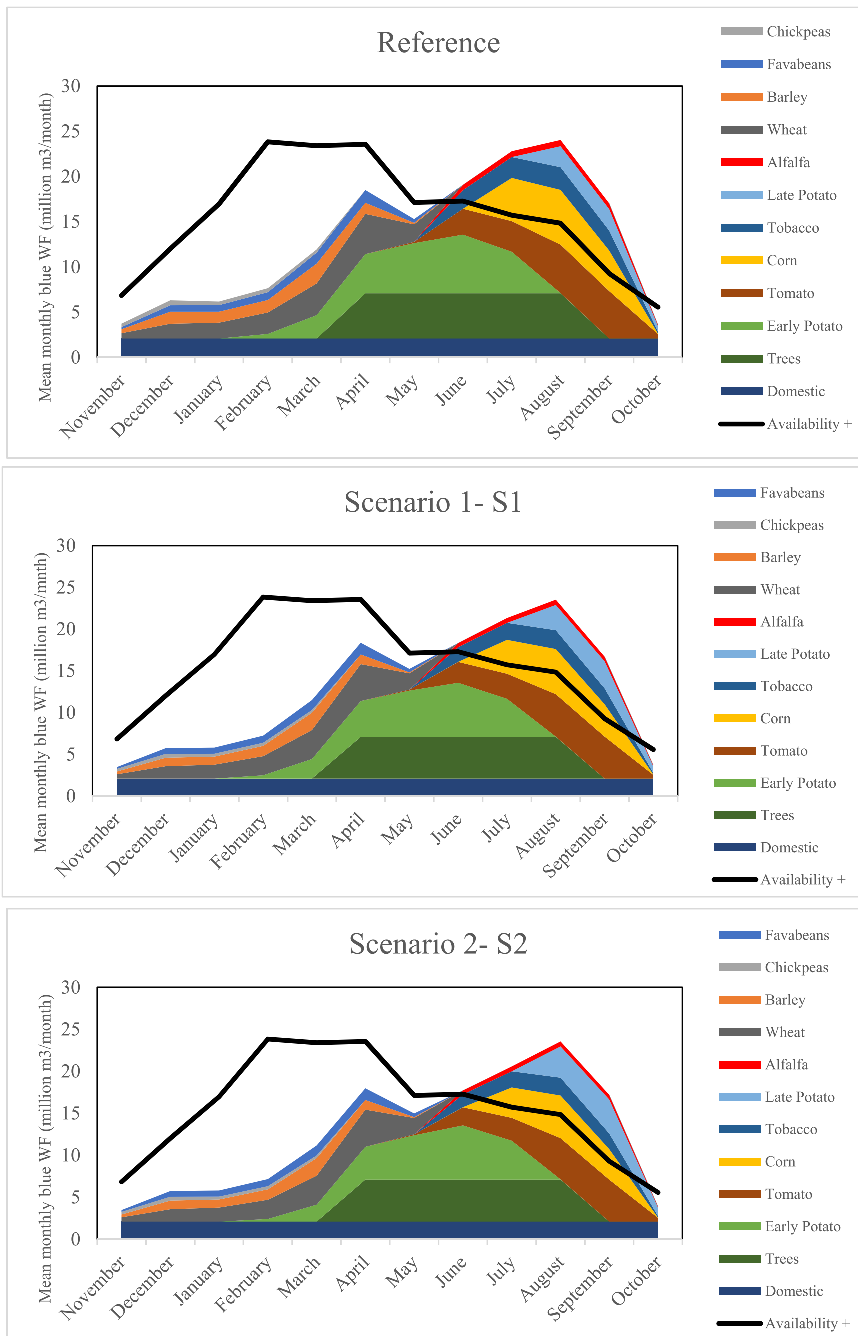

Fig. 8. Mean monthly blue WF, shown by type of use, in the Upper Litani Basin, compared to water availability (availability$^+$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mulching and drip irrigation reduce water use, with the largest effect when combined.

A confusing factor when comparing results across studies is that different indicators are used when measuring 'water saving'. While some studies focus on reduced irrigation water *applied* (e.g. Lovarelli et al., 2018; Jayakumar et al., 2017), others focus on reduced *evapotranspiration* of irrigation water (e.g. the current study; Chukalla et al., 2015; Zhuo and Hoekstra, 2017). Considering the impact on evapotranspiration is particularly relevant when the interest is on the impact of measures on water saving and water scarcity reduction at catchment scale, because it is the evaporated irrigation water that causes water scarcity.Another confusion is that the metrics of green, blue or total consumptive water footprint, water productivity, and irrigation efficiency all differ, so it really matters what is being measured (Zhuo and Hoekstra, 2017).

We find a relatively small variation of WFs across soil types but a substantial variation over different climate zones. This finding is in line with Zhuo et al. (2014), who, in a study for China, also found WFs of crops to be sensitive to climatic factors rather than soil types. This is a relevant finding once we start formulating WF benchmarks based on best-available technology as proposed by Hoekstra (2014), because it implies that WF benchmarks will need to be differentiated for different climate zones in particular.

The current study considered the benefits of mulching and drip irrigation (in terms of water saving and water scarcity alleviation) but not the costs. A marginal cost assessment like carried out by Chukalla et al. (2017) is needed to evaluate the costs of measures to reduce the WF. Particularly drip irrigation is expensive, so that the beneficial effect should outweigh the costs, which will vary from crop to crop and place to place.

The value of the current study lies in the scaling up of results to catchment level. Most studies on technical and managerial measures to improve yields while reducing water consumption focus on the field level and show that substantial improvements are possible. Our study shows, however, that when adding up to catchment level, the improvements are not sufficient to lower the overall blue WF within the catchment of the ULB to a sustainable level. Particularly in the dry period, precisely when water availability is extremely low, irrigation demands are highest. Artificial reservoirs – as illustrated for the Yellow River basin in China by Zhuo et al. (2019) and as we show here for the Qaraoun reservoir in Litani basin – can store water in the wet period for release in the dry period and thus increase water availability in the dry period, but dams are generally associated with various environmental and social impacts and need to be evaluated carefully.

5. Conclusion

To assess the possibility of blue water saving in the Upper Litani Basin through alternative agricultural practices, we formulated two scenarios: mulching for all crops (S1), and mulching plus drip irrigation for all summer crops (S2). The results, when compared to the current status, show that both scenarios have a positive but minor impact on blue water saving in the catchment as a whole. Introducing mulching and drip irrigation for all major crops in the catchment will reduce WFs and alleviate blue water scarcity to some extent, but by far insufficient to solve the problem of current overconsumption of water. Other measures need to be explored in addition to the two measures studied here, including deficit irrigation, conservation tillage, use of better crop varieties, changing crop patterns and possibly, if all measures do not add up to achieve what is needed, reducing the irrigated area.

This research mainly focused on the technical aspects of alternative agricultural practices; further research is needed to study the feasibility and practicality of these strategies. For instance, implementing pressurized irrigation is costly, so further research on the cost and benefits of these alternatives are needed. In addition, the impact of climate change on water availability was not included in this research and will need to be included in further study to evaluate the future robustness of measures proposed today.

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