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Review

Implementing Sustainable Irrigation in Water-Scarce Regions under the Impact of Climate Change

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Abstract: The sustainability of irrigated agriculture is threatening due to adverse climate change, given future projections that every one in four people on Earth might be suffering from extreme water scarcity by the year 2025. Pressurized irrigation systems and appropriate irrigation schedules can increase water productivity (i.e., product yield per unit volume of water consumed by the crop) and reduce the evaporative or system loss of water as opposed to traditional surface irrigation methods. However, in water-scarce countries, irrigation management frequently becomes a complex task. Deficit irrigation and the use of non-conventional water resources (e.g., wastewater, brackish groundwater) has been adopted in many cases as part of a climate change mitigation measures to tackle the water poverty issue. Protected cultivation systems such as greenhouses or screenhouses equipped with artificial intelligence systems present another sustainable option for improving water productivity and may help to alleviate water scarcity in these countries. This article presents a comprehensive review of the literature, which deals with sustainable irrigation for open-field and protected cultivation systems under the impact of climatic change in vulnerable areas, including the Mediterranean region.

Keywords: evapotranspiration; water use efficiency; protected cultivation; precision agriculture; screenhouses

1. Introduction

It is projected that by 2080, net crop water requirements will increase globally by 25% despite the increased irrigation efficiency, attributed to changes in precipitations patterns, global warming, and extended crops' growing periods [1]. Nowadays, extreme weather events such as frost, hail, heat waves, percentile of precipitation, and drought periods affected global food security, limiting rain-fed and irrigated agricultural crop production potential [2–5]. Mediterranean countries have been identified globally as climate change "hot spot" areas where the occurrence of hot extremes is expected to increase by 200 to 500% due to elevated greenhouse gas emissions [6,7]. Indeed, crop water demands are relatively high, especially in arid and semi-arid areas, due to high radiation load observed throughout a year, but also in more temperate and sub-tropical zones as periodic drought phenomena and heat waves often occur [5]. Reference evapotranspiration (ETo; the sum of evaporation from the soil and transpiration from a reference crop such as, e.g., grass or alfalfa) is expected to increase in many parts of the world by 2055, increasing the total irrigation water needs [8]. In Spain, under Mediterranean climatic conditions, irrigation water requirements are expected to increase between 40 to 250%, depending on the crop type by 2100 [9]. In Cyprus, a typical water-scarce country with the highest water stress index among

European countries, for the period 2031–2060, the seasonal average temperature is expected to increase by up to 2°C for winter, 3°C for summer, and 2.4°C for the transient seasons; in addition, a mean annual decrease in total precipitation of 5 to 15% is expected [10]. Actually, for a given type of soil and crop, both annual and seasonal rainfall variations are critical for the estimation of a predictable water stress profile which can be addressed [11]. For example, the phenological behavior of rain-fed winter wheat (*Triticum aestivum* L.), which is considered to be an important crop grown in the Mediterranean, is expected to be negatively affected by variations in rainfall patterns, resulting in yields reduction [12]. This is especially true as agricultural water demand is less flexible, while the supply is at or beyond the margin of sustainability, so there is a limitation of crops' abilities to absorb variations in the water supply [13].

Modernization of irrigation increases the water application efficiency. Converting from traditional surface irrigation methods to closed pressurized pipe network systems could lead to as much as 90% of the total water savings, as is the case of trickle irrigation [14]. Therefore, the use of improved irrigation schemes was financially supported through the World of Bank in low-income countries with the aim of reducing poverty. In the European Union, improved irrigation systems are of the priority measures of the European Water Framework Directive for achieving irrigation water sustainability [15]. Nowadays, 40% of the world's food comes from the 18% of the cropland that is irrigated, while in several cases, high water application efficiency irrigation systems estimated to be used in more than 95% of the total irrigated land as is the case of Cyprus [16,17]. Overall, in Mediterranean countries, the irrigated area accounts for less than 40% [18]; however, in Germany, only 2% of the cropland area are irrigated [19].

On the other hand, the traditional assumption that substantial water savings may obtain through the adoption of new/improved technology irrigation systems are under controversy in some instances. This is a consequence of higher irrigation systems' application efficiency, which tends to increase their irrigated area, in addition to less irrigation return flow back to the aquifers. Therefore, the total water consumption calculated on a basin scale increased [13]. Similarly, climatic and economic implications of the modernizing irrigation system are related to the high energy use and carbon emissions for extracting groundwater, pumping it, and distributing it in the appropriate water quantity and pressure [20]. In another occasion, the Chinese government is planning for the expansion of irrigated areas by 4.4% until 2030 [9] under the concept that global irrigation patterns seem to alter climate with some cooling effects observed near irrigated areas during the peak period of irrigation [21,22]. However, in the Mediterranean region, soil salinization and land degradation are often associated with irrigated land [5,20]. Worldwide, it is estimated that by 2050, more than 50% of arable land will have soil quality issues, while at the current time, about 10 million hectares are abandoned every year due to soil salinization [23].

In any case, irrigation scheduling frequently represents a difficult task to accomplish, resulting in significant water losses [24]. Traditionally, irrigation scheduling was based on growers' perspective rather than on climatic characteristics, soil properties, or plant indicators, resulting many times in over-irrigation of crops. Consequently, water and nutrients depleted and potentially lead to groundwater contamination [25]. Indeed, in the Salinas Valley of California, irrigation of vegetables was estimated as 200% above actual crop evapotranspiration [26]. In any case, excessive irrigation is associated with the lack of root aeration and favors plant pathogens [27]. However, it is generally accepted that the use of evapotranspiration models in irrigation practice increases the efficiency of water and nutrient application. In fact, in intensive production systems such as soilless culture systems, irrigation control requires the estimation of crop evapotranspiration over short time intervals, e.g., in the basis of a few minutes [28]. Therefore, more sophisticated/complex irrigation monitoring systems are required with the aim of matching the diurnal evapotranspiration fluctuation with water and nutrient supply. Even in the latter case, there is a need for models' recalibration under prevailing climatic conditions.

Agronomic practices such as "deficit irrigation" (i.e., irrigation application below evapotranspiration) save water and enhance water use efficiency (WUE) of the crops as a result of an improved ratio of carbon fixation to water consumption ratio [29]. In addition, as biomass production and transpiration are tightly linked to each other and both are facilitated by stomata pores, the effective use of water under limited water condition should be the aim of maximum soil moisture capture with minimal water losses by stomata transpiration and soil evaporation [30]. Plastic film mulching has been shown to decrease soil evaporation [21]. In line, protected cultivation systems (greenhouses, screenhouses) have been proved to have higher WUE values comparing with open-field cultivation [31]. Indeed, peppers' water requirements under the screen cover were found to be 38% lower than those of an open-field crop affected by lower evapotranspiration rate [32]. In addition, the water productivity (WP; the ratio of the total value of production to total crop irrigation water supply, € m^{-3}) of protected crops is much higher as opposed to open-field crops' due to the higher economic value of crops that are produced out of season [33]. Katsoulas et al. [34] have demonstrated that increasing the greenhouse cooling system capacity gives higher values in yield in both in the Mediterranean and Central European countries.

Rural areas are expected to experience major impacts of climate change on water availability and supply; infrastructure and agricultural incomes; reduced agricultural production; and food security with socioeconomic consequences, such as increasing poverty and migration. Farmers only recently start to adopt water-saving practices and technological improvements in irrigation. The adoption is relatively low because in many cases, these systems are of high cost and growers do not benefit directly by water saving [35]. Thus, sustainable irrigation adaptation to climate change in water-scarce regions should be implemented in terms of demand and supply enhancement of water management, even though measures are often linked through the hydrological cycle.

Increasing the productivity of water, the use of non-conventional irrigation waters, crop diversification, and crop rotation are some of the adaptation/mitigation measures discussed in the following. Reliable estimates of consumptive use are especially needed for water allocation by policy makers at the basin scale and beyond and for optimizing farm irrigation management under water scarcity. Anyhow, it is important to understand that implementing sustainable irrigation in water-scarce regions will be feasible only by a combination of measurements, rather than by individual actions. In view of the above, this publication makes a contribution by providing information regarding sustainable irrigation in water-scarce regions.

2. Improving Irrigation Efficiency

The majority of irrigated land in the world is of the category surface irrigation. The field water application efficiency of traditional surface irrigation methods such as, e.g., furrow, basin, or border strips (Figure 1) is estimated to be as low as 40% [36] with excessive deep percolation losses and low water distribution uniformity [37]. However, in countries with the largest irrigated area, these methods are prevailing because they are low-cost and easily implemented.

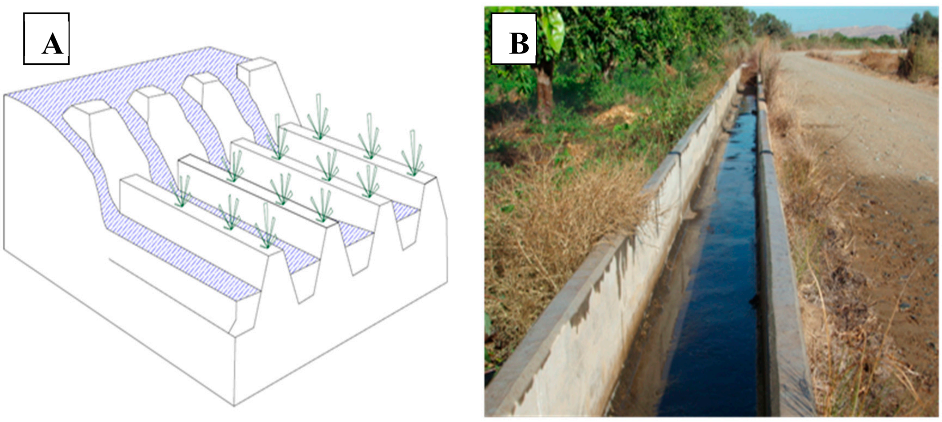

Figure 1. Traditional surface irrigation method (furrow irrigation, (**A**)); open canal water distributing network (**B**).

Selecting the appropriate irrigation method will be advantageous to manage limited water supplies and increase crop profitability [38]. Nowadays, it is widely accepted that a pressurized irrigation system (PIS; an installation under pressure network consisting of various pipes, valves, and fittings for supply water from the source to the irrigable area) [39] has significantly higher water application efficiency values as opposed to traditional irrigation methods such as, e.g., furrow and border strips. PIS operate on demand, which allows for higher irrigation frequency, optimization of crop irrigation scheduling, and cropping pattern diversification [13]. The application of fertilizers can also be optimized through fertigation (i.e., irrigation combined with fertilization). A typical arrangement of PIS pipe layout and irrigation components indicated in Figure 2. The control head unit is considered to be the most important part for measuring and appropriately treating the irrigation water [40].

Plastics, as the basic component of PIS, were first produced in British industry in 1935, even though the idea of using plastic pipes for irrigation become feasible during the World War II [41]. Early advances in surface drip (i.e., trickle) irrigation technology, which is considered to be the most efficient irrigation method in terms of water use, took place in Israel from the 1950s into the 1970s [22], although, according to Velasco-Muñoz et al. [42], drip irrigation systems application was first recorded in Australia in the 1940s. Aside from the fact that the installation of PIS remains costly and requires specific skills and knowledge to operate, it is still an important adaptive strategy to reduce agricultural risk during times of drought [43]. However, in humid areas, the application of PIS may not be profitable if droughts are rare [37]. Over the past decades, a significant shift to pressurized irrigation was observed, with a significant component being micro-irrigation, including micro-sprays, mini-sprinklers, surface drip, and subsurface drip irrigation systems (SDI) [44].

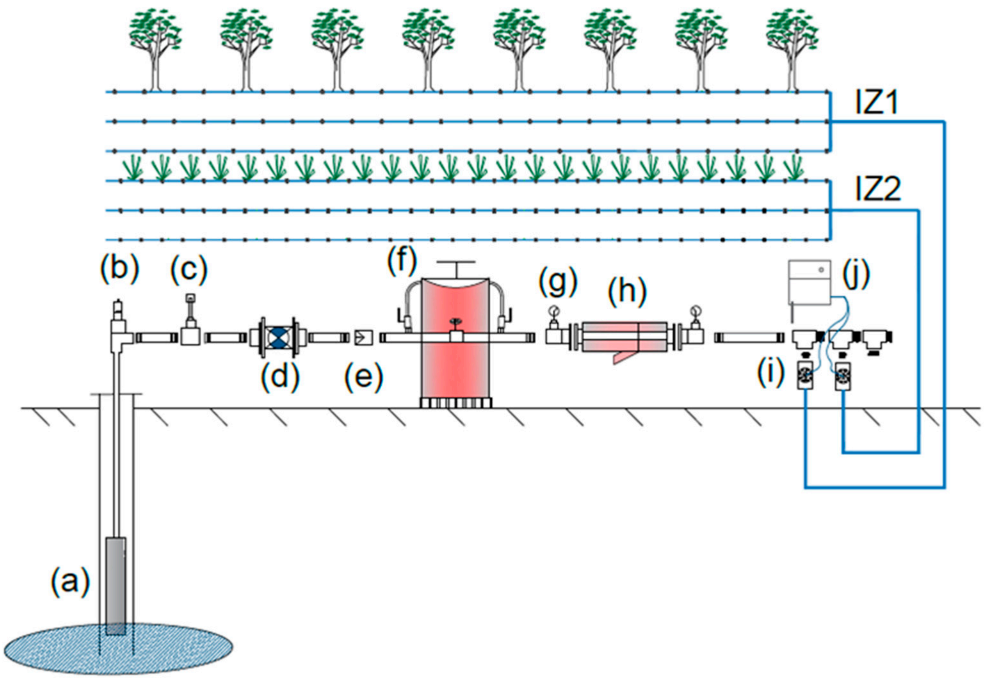

Figure 2. Layout components of a modernized pressurized irrigation system (PIS); supply pump (**a**); central control head unit ((**b**) to (**h**)); pressure regulator and pressure relieve valve (**b**); air release valve (**c**); water meter (**d**); one-way valve or a non-return valve (**e**); injection tank (**f**); pressure gauge (**g**); filtration unit (**h**); manifold and electric valves (**i**); irrigation zone 1 and 2 irrigating crops with different water needs (IZ1,IZ2); irrigation controller (**j**).

Particularly, the field application efficiency is about 50–70% with sprinkler system and 80–90% with surface drippers [45]. That is because as drip irrigation system minimize water losses due to surface runoff and deep percolation of water under difficult soil and terrain conditions [22]. Water is locally applied directly near to the root zone in low application rates and pressure and enables the precise management of soil moisture. Due to the low operating pressure of drippers (e.g., 100 kPa), the energy cost is also decreased compared to the sprinkler system (e.g., micro-sprinkles 200 kPa, spray booms 500–600 kPa) [39,44,46]. Thus, low pressure irrigation systems will result in both water and economics savings [47]. However, in such a case, it is important to assess water quality as lower operating system pressure, increasing the possibility of clogging drippers [46]. The appropriate selection of filtration system based on the water source will ensure the good operating performance of irrigation systems (Figure 3). In any case, drip irrigation can minimize the wetting of leaf surface and thus the risk of leaf sunburn and crop diseases, while sprinkling result in wet leaves and mud splash [48]. In addition, drip irrigation is preferable when recycle water is used, as there is also minimization of the risk of pathogen movement to the crops. Choosing the appropriate irrigation method should also take into consideration several factors such as the soil infiltration rate, the system precipitation rate, and the quality of water. In any case, the main problem of PIS has to do with poor hydraulic design, resulting in low field application water uniformities [49]. Qi et al. [50] concluded that the effects of different irrigation water movement in soil crack closure and soil water storage efficiency were lower in drip irrigation rather than in sprinkler or in surface irrigation. HYDRUS models have been repeatedly used in the literature e.g., [51–53] for simulating irrigation soils' water movement and other related options.

Drip irrigation systems account for up to 90% application efficiency, and they have been used with success in arid and semi-arid regions for vegetable production, forage crops, and maintenance of trees [54–56]. Yield of onions almost doubled using SDI, allowing for more frequent irrigation with smaller depths of water [38]. In tomatoes, the most appropriate irrigation arrangement for optimum growth and production is considered to be SDI with plastic film mulching, according to Wang et al. [57]. In any case, water savings of up to 20% were recorded in olives under the SDI treatment as opposed to surface drip irrigation [58].

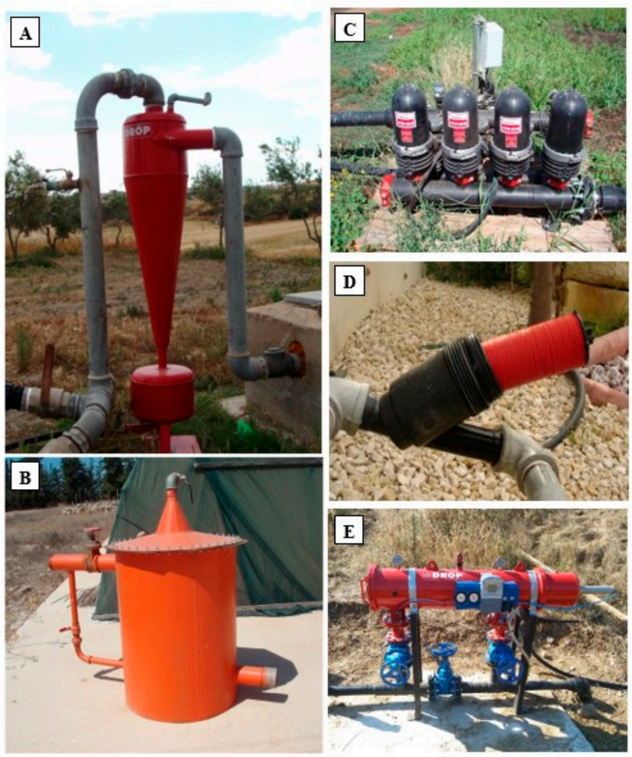

Figure 3. Different types of filters; a hydrocyclone device used for water and sand separation (**A**); a sand–gravel filter used for algae and organic matter removal, usually from an open water reservoir (**B**); a series of an automatic disc filter system (**C**); a manual disc filter (**D**); an automatic self-cleaning filter with a self-cleaning backwash mechanism (**E**).

In another occasion, irrigation sustainability may not always be in accordance with environmental sustainability. Recent work raised a few controversial thoughts that policies of encouraging the adoption of more efficient irrigation technology will potentially lead to the cultivation of more water-intensive crops on previously marginal land, in addition to less irrigation water return flow to the watershed, a phenomenon known as “irrigation paradox” [59,60]. Furthermore, the irrigated area could be increased by 30–40% when shifting from furrow to sprinkler and drip irrigation systems [45].

3. Scheduling Irrigation Methods

The appropriate irrigation scheduling (i.e., determine the amount and the frequency of an irrigation event) has been considered to be the most important factor for crop growth and sustainable irrigation water management. Climatic conditions, soil, and plant-related characteristics may affect crop water uptake [61,62]. Therefore, irrigation scheduling based on those factors must take into account the irrigation system and the water delivery volumes [28,63]. In any case, the applicability of an irrigation schedule computation depends on calibration against direct measurements of yield as a function of irrigation application deducted from carefully designed and conducted field experiments under local conditions [64].

3.1. Evapotranspiration Models

Reference evapotranspiration (ETo; the sum of evaporation from the soil and transpiration from a reference crop such as, e.g., grass or alfalfa) is an essential parameter for crop irrigation estimation optimization [65]. In the past years, a lot of research has been conducted in the field, for calculating ETo, based on measured meteorological variables (e.g., net radiation, temperature, wind, relative humidity), applying similar to the initial Penman–Monteith (P–M) evapotranspiration models (Equation (1)), which were initially developed for open-field cultivations [66].

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{Rn}-\mathrm{G}) + \gamma\frac{900}{\mathrm{T}+273}\mathrm{u}_2(\mathrm{e_s}-\mathrm{e_a})}{\Delta + \gamma(1+0.34\mathrm{u}_2)} \quad (1)$$

where ETo, reference evapotranspiration (mm d^{-1}); Δ, slope vapour pressure curve (kPa °C^{-1}); G, soil heat flux density (Mj m^{-2} day^{-1}); Rn, net radiation at the crop surface (Mj m^{-2} day^{-1}); γ, psychrometric constant (kPa °C^{-1}); u_2, wind speed at 2 m height (m s^{-1}); T, air temperature at 2 m height (°C); e_s, saturation vapour pressure for a given time period (kPa); e_a, actual vapour pressure (kPa); and $e_s - e_a$, saturation vapour pressure deficit (kPa).

In the meantime, a meteorological database named LocClim and several software programs were developed (e.g., CropSyst, AquaCrop) with a view of predicting crop evapotranspiration and crop growth in any region of the word based on historical climatic data [11,67]. Other methodologies for estimating ETo were also used in cases where fewer climatic data were available [68]. In any case, commercial agro-automatic weather stations can be used inside by farmers, increasing the accuracy of ETo estimation (Figure 4) [69].

Comparatively, Class-A evaporation pans and atmometers are considered to be low-cost devices that can reduce the complexity associated with the ETo-weather based estimation procedure, even though atmometers, in open-field crops, seem to underestimate ETo by as much as 21% in comparison with the P–M model equation estimation [70]. However, as supported by Blanco and Folegatti [71], atmometers had the best performance in estimating irrigation requirements in the greenhouse; therefore, they could be used advantageously in relation to the evaporation pans. The weekly ETo values estimation inside a greenhouse and the high correlation coefficients between the Class-A evaporation pan and the reduced-size pan and an atmometer were demonstrated by Fernandes et al. [72].

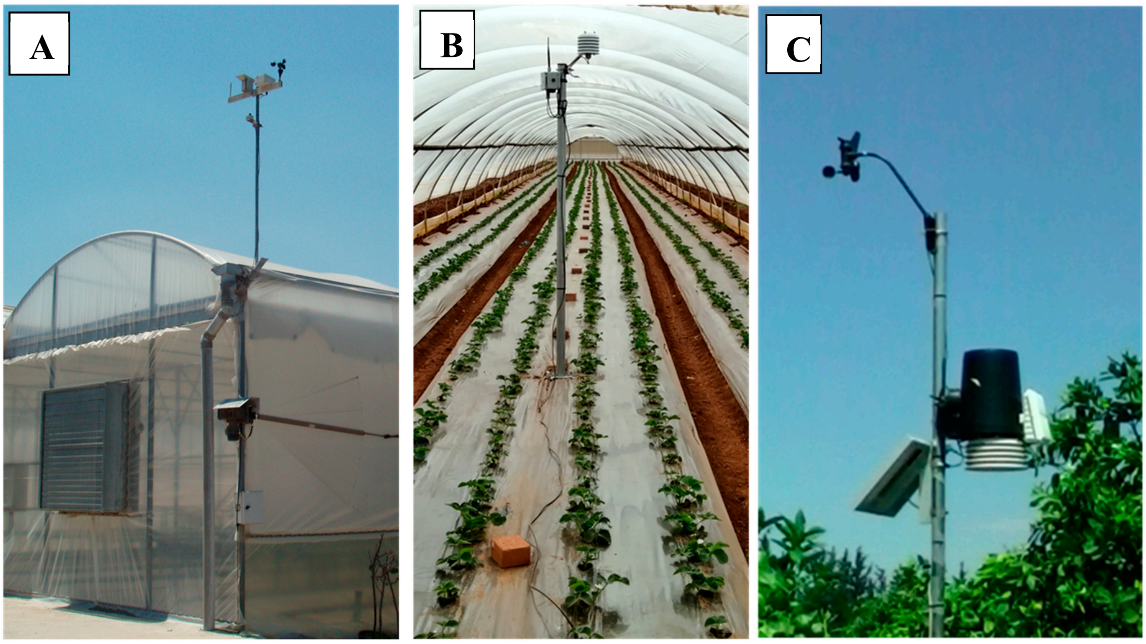

Figure 4. Meteorological station for monitoring weather data and calculating ETo; outside a high tech-greenhouse (**A**); inside a tunnel-type greenhouse (**B**); and in the field (**C**).

Crop evapotranspiration (ETc; the sum of evaporation from the soil and transpiration from a crop) can be calculated by multiplying a specific crop coefficient value (Kc) with the reference evapotranspiration ETo (Equation (2)) following the procedure of Allen et al. [66].

However, Kc reporting values are differentiated even within the same crop, as affected by different climatic conditions and crop management practices [73,74]. It has to be noted that the impact of climate change on Kc values was also investigated by many researchers in the past [75,76].

$$\text{ETc} = \text{Kc x ETo} \quad (2)$$

where ETc, crop evapotranspiration (mm d^{-1}); Kc, specific crop coefficient; and ETo, reference crop evapotranspiration (mm d^{-1}).

Many researchers used the P–M method based on ETo calculation and Kc values for estimating ETc [63,73,74]. In the meantime, the dual crop coefficient method was used for predicting the effects of specific wetting events on the values for the crop coefficient by separating Kc into two coefficients for soil evaporation and crop transpiration [77]. Meanwhile, remote sensing imagery from airplanes, drones, and satellites have been used in the open field as a tool to obtain information for crop evapotranspiration estimation [75]. Chen et al. [76] show that the vegetation fraction obtained with unmanned aerial vehicles can be used "on the spot" by the farmer in order to directly define the Kc values.

The method for estimating crop evapotranspiration based on Class-A evaporation pan using local Kc values was adopted and used by the Cyprus Agriculture Research Institute (Table 1), taking into account local climatic conditions (eastern Mediterranean region). From Table 1, we can observe that in open-field crops, the irrigation period starts between March and April and ends in October, with maximum crop evapotranspiration values estimated in July. During winter months, there is no need for irrigating open-field crops due to sufficient rainfall. However, as drought events often occur, supplementary irrigation of rain fed crops helps them to improve and stabilize yields. The colocasia (2400 mm), the lucerne (1350 mm), and the banana (1252 mm) are considered to be among the most water-demanding crops, while olives (430 mm) and pistachios (355 mm) are less water-demanding tree crops. Hence, the estimation of crop-specific irrigation volumes is a major aspect in sustainable irrigated agriculture and particularly in arid and semi-arid regions where irrigation water is limited.

In high-technology greenhouse production systems, climatic data acquisition could be analyzed on a real-time basis on short time intervals, i.e., in the basis of a few minutes, allowing re-adjustments of irrigation. The following simplified form of the Penman–Monteith equation (Equation (3)) was proposed for estimating soilless crop transpiration rate within greenhouses [78].

$$\lambda \mathrm{Tc} = \mathrm{A}(1 - \exp(-\mathrm{KLAI}))\mathrm{RSi} + \mathrm{BLAIVPD} \quad (3)$$

where Tc, crop transpiration rate (kg m^{-2} s^{-1}); Rsi, solar radiation inside greenhouse (W m^{-2}); VPD, the greenhouse air vapor pressure deficit (kPa); LAI, the calculated leaf area index (m^2 leaf m^{-2} ground); K, light extinction coefficient; λ, vaporization heat of water (J kg^{-1}); and A and B, values of equation parameters (A, dimensionless; B, W m^{-2} kPa^{-1}).

A practical way to determine the irrigation frequency in soilless culture systems is the procedure proposed by Katsoulas et al. [79], based on "the accumulated radiation method". A main drawback of the method is that it does not take into account the effect of greenhouse air vapor deficit on the transpiration rate. However, due to the simplicity of the method several authors proposed on accumulated radiation values for starting irrigation [80,81]. For tomatoes grown in a solar greenhouse, the Priestley–Taylor model revealed superiority compared to the pan evaporation or radiation models [82]. In another study, no statistical differences were observed in estimating ETc for different crops within plastic greenhouses based on the radiation model, either by using historical climatic data or values obtained in real time [83]. A comprehensive review of the accuracy of different evapotranspiration models used under prevailing greenhouse conditions can be found in the literature [84,85].

Similarly, for open-field crops, a form of a simple linear regression between potential evapotranspiration and solar radiation has been proposed a long time ago [86].

$$\mathrm{Ep} = \mathrm{c}\left(\frac{W}{Rs}\right) \quad (4)$$

where Ep, potential evapotranspiration (mm d^{-1}); *Rs*, solar radiation expressed in equivalent (mm d^{-1}); *W*, weighting factor depends on altitude and temperature; and c, adjustment factor which depends on mean humidity and daytime wind conditions.

Table 1. Monthly and yearly estimated evapotranspiration requirements (mm) for several crops in Meditteranean climatic conditions, as is the case of Cyprus. Data adapted from [76,87].

CROP	J	F	M	A	M	J	J	A	S	O	N	D	Total
Citrus, Avocado	-	-	20	68	107	133	145	138	124	55	10	-	800
Table Olives	-	-	-	34	53	78	87	81	65	32	-	-	430
Banana	-	-	25	73	125	175	230	241	203	129	51	-	1252
Deciduous (mountain)	-	-	-	-	62	175	182	182	82	-	-	-	683
Deciduous (plain)	-	-	-	-	70	214	244	210	82	-	-	-	820
Almond	-	-	-	-	-	100	100	100	55	-	-	-	355
Pistachio	-	-	-	-	-	91	112	100	52	-	-	-	355
Pecan	-	-	-	73	113	149	186	187	160	127	-	-	995
Table grapes	-	-	-	44	112	150	-	-	-	-	-	-	306
Tomato													
greenhouse	42	60	85	120	180	168	-	-	-	12	40	36	743
low tunnel	12	24	60	90	120	156	-	-	-	-	-	-	462
open field	-	-	-	15	75	150	168	168	78	-	-	-	654
Cucumber													
greenhouse	42	48	72	120	208	-	-	-	-	-	40	36	566
low tunnel	12	24	40	60	104	50	-	-	-	-	-	-	290
open field	-	-	-	15	75	170	216	-	-	-	-	-	476

Table 1. *Cont.*

CROP	J	F	M	A	M	J	J	A	S	O	N	D	Total
French bean													
greenhouse	42	48	84	140	70	-	-	-	-	-	24	28	436
open field	-	-	10	50	180	210	160	-	-	-	-	-	610
Aubergines													
low tunnel	12	24	40	60	76	100	68	-	-	-	-	-	380
open field	-	-	-	15	43	100	168	168	78	22	-	-	594
Pepper													
low tunnel	12	24	40	60	76	100	112	-	-	-	-	-	424
open field	-	-	-	15	43	100	168	168	62	-	-	-	556
Water melon													
low tunnel	10	20	32	48	84	28	-	-	-	-	-	-	222
open field	-	-	-	-	15	70	165	200	60	-	-	-	510
Courgettes													
low tunnel	12	24	50	78	136	88	-	-	-	-	-	-	388
open field	-	-	-	15	70	165	200	60	-	-	-	-	510
Potato													
spring	-	-	60	100	140	-	-	-	-	-	-	-	300
Autumn	-	-	-	-	-	-	48	98	146	140	70	-	502
Cauliflower													
early	-	-	-	-	-	36	124	210	150	28	-	-	548
normal	-	-	-	-	-	-	-	40	100	112	28	-	280
Peas grean													
early	-	-	-	-	-	-	-	42	150	150	48	-	390
normal	-	-	18	122	54	-	-	-	-	-	-	-	194
Onions													
fresh	-	-	-	-	-	-	-	-	144	156	66	-	366
Dry	-	-	30	80	130	120	-	-	-	-	-	-	360
Broadbeans fresh	-	-	-	-	-	-	-	-	130	90	-	-	220
Colocasia	-	-	36	164	200	380	470	470	380	160	140	-	2400
Lettuce	-	-	-	-	-	-	-	-	132	144	60	-	336
Celery	-	-	66	-	-	-	-	-	144	156	66	-	432
Radishes	-	-	50	-	-	-	-	-	144	156	66	-	416
Artichoke	-	-	60	100	-	-	-	146	62	54	26	-	448
Okra	-	-	12	35	68	145	245	175	-	-	-	-	680
Lucerne	-	-	-	100	170	240	300	260	180	100	-	-	1350
Common beans	-	-	-	-	-	-	70	100	140	140	-	-	450
Grounnuts	-	-	-	50	50	70	165	165	30	-	-	-	530
Maize	-	-	-	15	40	190	240	75	-	-	-	-	560
Tobacco	-	-	-	-	75	150	150	75	-	-	-	-	450

3.2. Lysimeters and the Water Balance Method

Knowledge of crop water requirements is the first step in optimizing irrigation regimes. Crop evapotranspiration estimation is based on the "water balance method", calculating the water volume differences from a system between irrigation/precipitation and the water outflow (i.e., drainage, runoff, and evapotranspiration; Equation (5)) [63,88].

$$ETc = \Delta SWC + R + I \tag{5}$$

where ETc, evapotranspiration (mm); ΔSWC, the variation of the volumetric soil water between seeding and harvest dates; R, rainfall (mm); and I, irrigation (mm); runoff and capillary water are considered negligible.

Even though the water balance method is not very accurate for open-field crops, it has generally been found to be sufficiently robust under a wide range of conditions [88]. The water balance method in open-field conditions can usually only give evapotranspiration estimations over longer time periods such as in a week or a ten-day basis [66]. The soil/substrate volumetric water content may be estimated using dielectric sensors such as, e.g., time-domain reflectometry or with devices and sensors that are measuring the water potential such as, for example, the tensiometers and electrical resistance sensor (Figure 5). A comprehensive review of field irrigation based on soil water potential measurement can be found in the literature in addition with available software for scheduling irrigation based on the water balance method such as, e.g., Saltmed, Simis, Marlvand, and Ims [16,89].

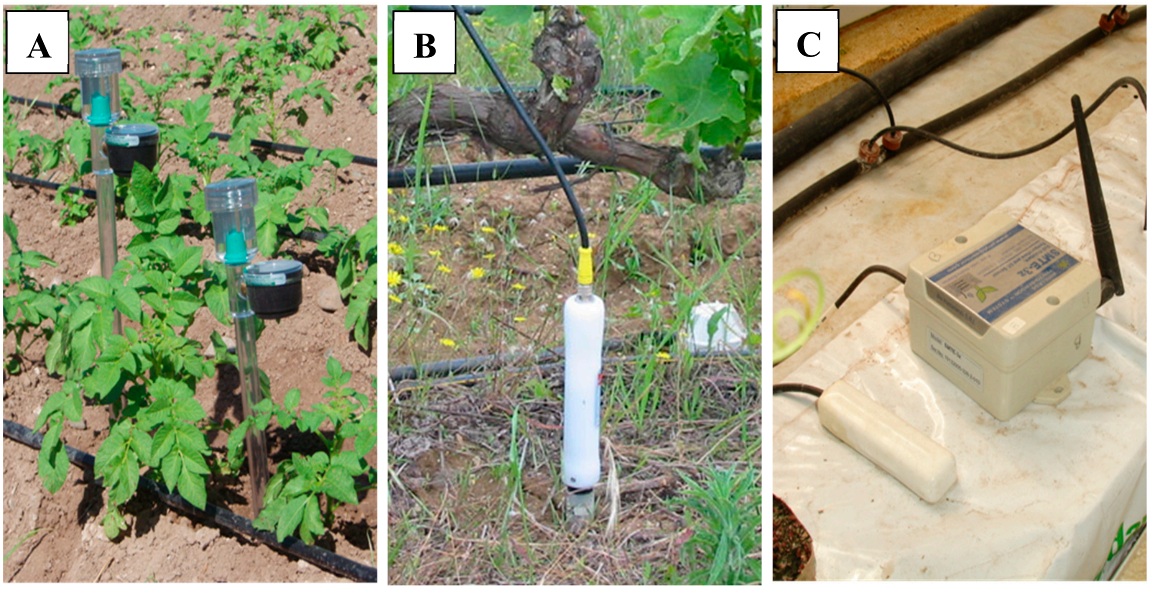

Figure 5. Devices for monitoring the soil water content; a pair of manual reading tensiometers installed in a potato crop (**A**), analog tensiometer installed in a vine open-field crop ((**B**); source: ScientAct S.A., Thessaloniki) and a wireless time domain reflectometry sensor installed in soilless media (**C**).

The "moisture allowable deficit" can be calculated as a percentage of the available water, which is usually 10% in soilless cropping systems and between 30–50% in soil open-field crops. Multiplying this deficit with a coefficient account for irrigation application uniformity and water salinity (typical values range from 1.15 to 2), the irrigation dose may be estimated. The irrigation interval rate should be compatible with specific soil limitations of infiltration and water holding capacity; therefore, it can be estimated when the accumulated daily ETc for the study period between two irrigations approaches the upper level of the allowable moisture deficit [45]. Otherwise, Yildirim and Erken [90] used the equation initially proposed by Doorenbos and Pruitt [86] for irrigation amount estimation of field melon as below:

$$\mathrm{I} = \mathrm{Ep} \times \mathrm{A} \times \mathrm{Kcp} \times \mathrm{P} \quad (6)$$

where I, the amount of irrigation water (mm); Ep, evaporation between irrigation intervals from Class–A pan (mm); A, the plot area (m^2), Kcp, is crop–pan coefficient (0.8 until fruit development and 1.3 until the ripening period); and P is the crop coverage as percent (%).

Other than the direct measurement of plant evapotranspiration, weighing and drainage lysimetric systems may be used as the only way of calibrating evapotranspiration models [91–93]. Even though lysimeters are used preferably for containerized crops rather than for soil-based crop systems, as in the latter case, they required expensive constructions. For example, sixteen lysimeters (a large soil tank that situated on a scale) were constructed in a semi-commercial scale at the Western Negev Desert Agro-Research Center in Israel for the calculation of optimal irrigation schemes by directly recording changes in the soil tank weight [94]. The accuracy of the lysimetric method proved to be very high for soilless-based culture systems where the water uptake could be monitored several times on a day-to-day basis in a representative group of plants. A simplified model based on a weighing-drainage lysimetric system in a soilless-based cultivation system could be as below [78,95]:

$$\mathrm{Tr} = \frac{(\mathrm{IV} - \mathrm{RV} \pm \mathrm{DSM})}{\mathrm{n}} \quad (7)$$

where Tr, crop transpiration rate (Kg $\mathrm{pl}^{-1}\ \mathrm{d}^{-1}$); IV, water volume supplied to the crop; RV, water volume collected by the drainage system; DSM, difference in substrate moisture between measurement; and n, measurement period (d^{-1}).

3.3. Sensing Plant Water Status

In the past, growers inspected plants for identifying early water stress symptoms. Plant indicators may include changes in leaf color (e.g., beans), plant movement or elongation (e.g., corn and sorghum leaves), and fruit growth (e.g., citrus) [96]. Nowadays, technological improvements incorporate advanced instrumentation and application techniques; therefore, it is possible to implement new integrated information for supporting the decision-making process in industrial horticulture [97]. Plant-sensing could be applied with success for irrigation scheduling, as the crop water status is directly related to the soil/substrate available water content (Figure 6) [72,98]. However, a significant limitation of plant-based sensing is that they could rather predict the irrigation frequency rather than the irrigation dose.

Figure 6. Plan-sensing devices; stem micro-variation (**A**); sap flow ((**B**); source: ScientAct S.A., Thessaloniki); leaf temperature (**C**).

Abiotic and biotic stress factors could also affect water uptake [99]. Therefore, plant sensing irrigation is preferably to be used in combination with other irrigation approaches such as the available water in the root zone. Comparatively, sensing technologies have been mainly applied in open-field crops rather than in protected cultivation systems. Boini et al. [100] indicated the high correlation of apple daily fruit growth with plant water status and highlighted the potential to use automatic fruit gauges in irrigation scheduling. Similarly, for apple trees, the signal intensity based on maximum stem shrinkage proved to be an accurate indicator of the plant water status under deficit irrigation supply [101]. For avocado trees, the maximum trunk diameter variation correlated with water stress history rather than on the actual plant water status, even though, in a relative basis, it may form an efficient aid for irrigation controlling [102]. Sap flow measurements are also used for determined plant water consumption and transpiration in fruit trees as well as in soilless-based crops [103,104] Aside from that, the determination of leaf and stem water potential is still difficult to commercialized.

Ribera-Fonseca et al. [105] concluded that near-infrared and visible reflectance spectral indices could be used as a non-destructive predictor of plant water stress in blueberry orchards. Similarly, a prototype framework for high-resolution thermal infrared vineyard site in the Central Valley of California, U.S. was developed by Lei et al. [106]. Recently, crop water status indicators were estimated based on satellite remote sensing. Sentinel-2 revealed superiority compared to older generations of public domain satellite data, allowing irrigation decisions based on fine spatial resolution of 10 m [107,108]. In another study, carbon nanotube sensors were embedded in plant leaves for reporting hydrogen peroxide signal waves, a stress report signal for crops' infections, injury, and light damage [109]. Printed carbon nanotubes were also applied on plant stomata as an early warning of water shortage. It was found that after 7 min of light, stomata opened, and that after 53 min, stomata closed when darkens falls. However, under water shortage, they take an average of 25 min to open and 45 min to close [110]. In any case, the use of plant-based irrigation scheduling requires the definition of reference or threshold plant stress values, beyond which irrigation is necessary [88]. In soilless culture systems, the main limitation of linking crop water status with plant sensing techniques has to do mainly with the water content status in restricted root zone which is constantly changing due to the high irrigation frequency intervals rate, the crop fast growth, continual product harvesting, and crop defoliation. However, Morales et al. [111] suggested that infrared thermography can be used as a tool for identifying water stress symptoms in soilless-based systems.

In any case, the most important plant sensors used are those which could run continuously and automatically, and thus can be implemented in a data transmission system [72]. Commercialized phyto-monitoring systems based on leaf temperature sensing are considered by many researchers among the most promising sensors used for irrigation monitoring due to the early warning signals resulting from stomata closure. According to the authors, previous work on the timing of irrigation, even in soilless cucumber crops, was found to be highly correlated with leaf temperature. Based on the P–M equation reformulation, a proposed irrigation model was calibrated and validated under Mediterranean greenhouse conditions using leaf temperature as an indicator for estimating crop tranpsiration rate (Equation (8)) [112].

$$\lambda T = \mathrm{A}(1 - \exp(-\mathrm{K.LAI}))(70.694\mathrm{T} - 1376.69) + \mathrm{BLAI}(0.192\mathrm{T} - 3.156) \quad (8)$$

where T, mean crop transpiration rate (kg m^{-2} s^{-1}); K, light extinction coefficient; LAI, leaf area index (m^2 leaf m^{-2} ground); A and B, values of equation parameters (A, dimensionless; B, W m^{-2} kPa^{-1}); and T, the leaf temperature (°C).

An overview of direct and remote-based sensors that are used in the open field and protected cultivation systems can be found in [88,99].

4. Water Application Below Evapotranspiration

Deficit irrigation (DI or regulated deficit irrigation RDI; i.e., the application of water at a lower rate and/or volume than the plants evapotranspiration) has been considered as a sustainable irrigation strategy as opposed to conventional irrigation under limited water supply conditions [113,114]. The principal attitude of DI is to increase water productivity by irrigating crops only at critical crop growth stages without causing severe yield reductions or to save water for expanding farmlands [115,116]. It is a common practice for farmers to roughly double the nominal irrigated area with a given amount of water by applying DI strategy [117]. Following literature, DI strategies may be grouped as below:

- Sustained deficit irrigation (StDI), where a fixed fraction of the crop water needs is supplied throughout the irrigation period [118],
- Stage-based deficit irrigation (SBDI), where water applied to meet full plant water requirements only at the critical growth stages and less water applied at the non-critical growth stages [119],

- Partial root zone drying (PRD), where partial half of the root system irrigated, while the remaining half is exposed to drying soil switching to the other half every 2–3 weeks [119].
- Supplemental irrigation (SI), optimally scheduled for the amount and timing of irrigation to ensure that a minimum water amount is available to the crops during the critical stages that it would permit a significant increase in the yield. Usually, SI is combined with earlier planted dates in order to prevent exposure of crops to drought stress and heat in hot areas and frost in cold areas [120].

Aside from DI, cultural practices must also be adopted by farmers for increasing crops' adaptation to the reduced water application volumes, such as, for example, the use of moderate plant densities, the minimum amount of fertilizer application, the flexible planning dates, and the limited use of fallowing, especially when it is desired for precipitation storage [117]. In any case, the water deficit level characterization corresponded to a percentage of soil field capacity reduction as below (Table 2) [119].

Table 2. Water deficit level in relation to a percentage reduction in soil field capacity.

Water Deficit Level	Soil Field Capacity
Severe water deficit	<50%
Moderate water deficit	50–60%
Mild water deficit	60–70%
No deficit/full irrigation	>70%
Over-irrigation	Excess amount of water

Actually, several field crops like cotton, sugar beet, sunflower, wheat, and maize are well-suited for applying DI. For example, minimal yield reductions are expected when SBDI is imposed during flowering and grain filling stages of wheat, flowering and boll formation stages of cotton, vegetative growth of soybean, and vegetative and yielding stages of sunflower and sugar beet [121]. However, DI in potatoes is not regimented as the small financial benefits would not offset the high risks of reduced yields and profits from the reduced water applications [122]. PRD irrigation in sugar beet leads to water savings up to 35% in a semi area, compared to a full irrigation treatment [123]. For watermelon, the best compromise between water productivity, yield, and quality was obtained by applying full irrigation needs up to the ripening stage and then by applying half of the irrigation needs for restoration [124]. In tomatoes, wetting and drying off the root zone alternative under drip irrigation increased WUE and reduced nitrogen loss to the environment [125]. In another work, slight DI corresponded to 80% of ETc and was the most appropriate DI strategy for greenhouse tomato crop growth rate [126]. In grapes, PRD showed superior performance compared to other DI strategies; therefore, it should be recommended under water shortages periods [62]. In cotton SI, increased yield by 14% [127]. The water deficits effects at critical growth stages for several crops can be pronounced, as summarized by Doorenbos and Pruitt [86] in the following table (Table 3).

Table 3. Critical stages for several crops. Data adapted from [117].

Crop	Critical Stage
Apricots	During the flower period and bud development
Peaches, Cherries	During the rapid fruit growth period and prior to maturity
Table Olives	Just before the flowering period and during the enlargement of fruits
Citrus	The flowering period and during the fruit settings stages
Broccoli, Cabbage	In the head formation and enlargement period
Cauliflower	From planning to harvesting it requires frequent irrigation
Lettuce	Requires wet soil conditions especially before harvesting
Tomatoes	When the flowers are formed and during the phase that fruits are rapidly enlarging
Watermelon	From blossom to harvesting period
Turnips	During the period of the rapidly increased of the size of edible root till harvesting
Radish	During the period of enlargement of the root

Table 3. *Cont.*

Crop	Critical Stage
Castor bean	Requires high wet soil conditions during the full growing period
Soybeans	In the flowering and fruiting stage and during the period of maximum vegetative growth
Strawberries	From the fruit development to ripening
Potatoes	Requires high soil water levels after tubers formation and from blossom to harvest
Oats	From the beginning of ear emergence possibly up to heading
Cotton	From flowering and boll formation, then at the early stages of grown and the stage after boll formation
Alfalfa	After each cutting for hay and at the start of flowering for seed production
Maize	Requires high soil water conditions during the pollination period, from tasseling to blister kernel stages; prior to tasseling and during the grain filling periods. The pollination period is very critical if no prior water stress conditions
Small grains	From boot to heading stage
Sugar beet	3 to 4 weeks after emergence
Sugarcane	The period of maximum vegetative growth
Tobacco	Knee high to blossoming
Wheat	During booting and heating and two weeks before pollination

The Cyprus Agricultural Research Institute working on DI strategies during a long-term experimental period time concluded the following:

- For olives trees, it is recommended to fully cover the annual irrigation needs which are relatively low compared to other perennial crops (Table 1), even though when water is the limiting resource, a minimum yield reduction is expected. Indeed, the annual yield production was unaffected when irrigation up to 70% of evapotranspiration needs of *Olea europeae* L. *cv Koroneiki* was applied uniformly throughout the irrigation period, or by complete cessation of irrigation during the two summer months. However, reduction of irrigation in *Olea europeae* L. *cv Manzanillo* causes the wilting of the fruit; it reduces its size and adversely affects production in the long term [128].
- In citrus, the yield is expected to decline by 10.7% if the water application amount is reduced by 37% of evapotranspiration, while by reducing it by 26%, the yield is expected to decline by 5.8%. In a citrus tree cultivar *(Citrus reticulata x Citrus sinensis, cv.'Mandora')*, DI negatively affects the number and the size of fruit per tree during spring, while in autumn, it affects the quality of the juice (ratio of sugars to acids). However, the effects of DI on yield of *Citrus sinensis, cv. 'Valencia'* and *Citrus reticulata* × *Citrus sinensis, cv.'Mandora'* are smaller than on others' citrus varieties, because harvesting, in Mediterranean zone countries, took place usually towards the end of the rainy season and trees may recover. In lemon trees, DI negatively affects the prematurity of production and, to a lesser extent, its volume. In grapefruits, the lack of water delays the ripening of the fruit, negatively affecting the fruit size and yield [129–132].
- The total irrigation needs for *Vitis vinifera* L. *cv "Sultanina"* was estimated at 250–300 mm from flowering to the beginning of ripening. DI reduces production while over-irrigating delays ripening. In *Vitis vinifera* L. *cv "Cardinal"*, irrigation with 200 mm from flowering (mid-April–early May) until harvesting (late June-early July) positively affects product quality. This amount of water corresponded to 50% of evaporation. Irrigation below evapotranspiration negatively affects the vigor of vines and reduces yields. In *Vitis vinifera* L. *cv "Superior"*, irrigation with 300–350 mm is recommended from late April to early July. However, irrigation with 210 mm under limited water conditions did not affect the yield in the first year. Over-irrigation reduced the sugar content of the juice [133].
- Optimum yield for oregano was obtained with 400 mm irrigation of water. Irrigation below ETc negatively affected the fresh and dried marketable product and oil yield. In sage, the annual irrigation needs during the first year estimated at 300–320 mm. These needs are expected to increase gradually as plants grow. The reaction of sage to DI is similar to that of oregano [134].

- The water requirements of alfalfa range from 75% of the evaporation rate of the Class-A evaporation pan from October to April to 110% in July. However, water savings up to 40% of the total crop requirements could be obtained by stopping irrigation during July and August with an expected annual yield reduction by 18–20%. The plants fully recover in September after irrigation [135].
- The irrigation requirements of maize for seed production were estimated at 560 mm. The reduction of irrigation amount from 20–40% caused a reduction of 8–21% in yield, respectively [136].

5. Protected Cropping and WUE

Protected cropping such as, e.g., greenhouses, screen-houses, horizontal screen covers, and shade netting screens (photoselective nets, proof screens, anti-hail), aim to minimize crops' environmental stress through aerial environment modification. In subtropical regions, those systems have been extensively used as they protect crops from extreme weather conditions, which often occur as hailstorm, droughts, wind damage, and sunburn incidence [137]. Protected crops proved to have lower evapotranspiration rates mainly because of the reduction in the wind speed and turbulent exchange rates, the decreased irradiance, and the increased humidity within leaf canopy [138,139]. Sweet pepper grown in a screen-house, during the period August-September indicated 60% reduction in crop water use as opposed to an open-field crop; however, shading factor recommended being no more than 20% [140,141]. For avocado trees, 20% white shade netting minimized the irrigation water requirements by 29% [142]. The use of aluminized plastic nets in lemon trees increased the water use efficiency in comparison with a non-shaded treatment [143]. Similarly, in a hot and arid area of Israel, the estimated WUE values of banana crop in a screen-house estimated being by 30% higher comparing with an open-field crop as cited by Pirkner et al. [144].

In any case, in protected cropping, the ratio between the marketable crop production and the total crop irrigation supply, or the ratio of CO2 assimilation to transpiration (i.e., irrigation water use efficiency, WUE; Kg m-3; transpiration efficiency, TE) is higher comparing with open-field crops (Tables 4 and 5). High WUE values were also observed in soilless cultivation substrate systems (Table 4). The importance of increasing water productivity (WP) by improving the WUE, in arid and semi-arid regions, is considered as a strategic activity highlighted by several authors [145–147].

Table 4. Tomatoes water use efficiency values (WUE; Kg m^{-3}) in different growing conditions and substrate. Data adapted from [33,34,148].

Country	Cropping Conditions	WUE
France	Field-grown	14
	Greenhouse unheated	24
Italy	Greenhouse substrate-open system	23
	Greenhouse substrate-closed system	47
Spain	Greenhouse substrate-system	35
Israel	Field-grown	17
	Greenhouse unheated	33
Netherlands	Greenhouse substrate-open system	45
	Greenhouse substrate-closed system	66
Egypt	Field-grown	3
	Greenhouse unheated	17
	Greenhouse substrate-grown system	45
Cyprus	Field-grown	7
	Tunnel-grown	11
	Greenhouse	23
	Greenhouse substrate-grown system	30
Greece	Greenhouse substrate-open system, low tech greenhouse	20
	Greenhouse substrate- semi-closed system, low tech greenhouse	28
	Greenhouse substrate-closed system, low tech greenhouse	36
	Greenhouse substrate-closed system, high tech greenhouse	50
	Greenhouse substrate-closed system, semi-closed greenhouse (cooling capacity of 100 W m^{-2}), high tech greenhouse	80

Optimal microclimate control in greenhouses usually entails the use of sophisticated equipment such as, for example, cooling and heating systems, artificial illumination and dehumidification and shading techniques. Plastic greenhouses in hot and dry regions during a significant part of a year used active cooling systems to reduce greenhouse heat accumulation [149]. However, the water needed to be evaporated for alleviated the heat load is not always taken into consideration into the total greenhouse water use estimations; in addition, it affects diurnal leaf water potential fluctuation. Overall, lower evapotranspiration rates observed for anisohydric plants (i.e., stomata do not respond to changes in humidity), rather than to isohydric plants which leaf conductances tend to increases leading to higher evapotranspiration rate [139]. However, even though leaf conductances were about 25% higher in a greenhouse cooled by a wetted-evaporative pad; higher transpiration rates by 60% observed for a cucumber crop in a greenhouse with a ventilation system [150]. For cucumber growth during a spring-summer period under Mediterranean conditions the mean daily water evaporated through a wetted pad was measured at 72 L per m^{-2} of wetted pad, increased to 104 L m^{-2} as the outside conditions became warmer and dryer [151]. In any case, the cultivation period of tomato in a screen-house extended with the use of a fogging system irrespectively of the availability of water needed to be evaporated [152].

The concept of generating fresh water by condensation, for reuse, it in a greenhouse is not new [149]. That is the reason there is an increasing interest for using dehumidifiers within greenhouses, even though there are still issues related to energy consumption. That is especially useful in cases of risen humidity levels, in coastal areas, and during winter at cold night were the greenhouse openings are kept closed resulted in the air saturated with moisture.

Table 5. Water Productivity (WP; € m^{-3}) and Water Use Efficiency (WUE; Kg m^{-3}) values of several crops estimated based on market prices and crop water needs [153].

Crop	WUE	WP	Crop	WUE	WP
Avocado	1.30	2.29	Melons		
Cuucmber			open field	6.74	2.39
greenhouse	22.2	30.5	low tunnel	13.7	7.01
low tunnel	14.0	11.2	Peppers		
open field	6.30	4.70	open field	6.31	4.94
Artichoke			low tunnel	12.0	11.7
first year	6.66	3.92	Pistachio	1.13	5.54
second year	7.95	4.67	Orange	5.90	1.57
Almond	2.26	2.39	Radish bunch	23.6	5.11
Pears	3.81	5.35	Peaches	3.52	4.97
Greipfruit	8.86	2.48	Celery bunch	18.2	8.03
Plums	3.52	7.30	Spinach bunch	35.0	7.56
Table Olives	4.18	4.24	Table grapes	6.49	2.77
Water melon			Figs	2.05	3.62
low tunnel	20.6	8.08	Apples	3.52	4.21
open field	12.0	2.83	Tomato		
Carrots	10.6	4.78	greenhouse	23.9	21.0
Pecan	0.41	2.71	low tunnel	11.0	7.55
Colocasia	2.35	7.30	open field	7.04	2.90
Cherries	2.08	1.85	Alfalfa	2.51	0.56
Zucchini			Bean		
low tunnel	7.87	6.63	open field	5.76	7.88
Open field	3.92	2.70	greenhouse	11.0	32.4
Broad beans fresh	8.97	8.35	dry	0.60	1.61
Cauliflowers	6.51	3.96	Peanuts	0.76	1.46
Cabage	7.44	2.49	Strawberries		
Onios bunch	33.2	6.50	greenhouse	5.46	17.0
Onios dry	12.4	4.63	open field	3.75	10.3
Lemon	5.90	1.45	Apricot	3.81	6.98
Tangerines	4.13	1.77	Bananas	2.79	2.69
Lettuce	26.3	6.46	Peas	3.90	4.59
Aubergines	10.1	5.35	Potatoes		
Aubergines low tunnel	20.9	14.3	spring	16.5	4.86
Loquat			mid-season	25.0	8.85
screenhouse	2.94	9.78	autumn	6.15	2.06
open field	1.02	1.81	Okra	3.13	4.60

6. Precision Agriculture

Increasing agricultural systems' resource efficiency and building resilience to climate change is the key actions for producing adequate food quantities while coping with water scarcity and land degradation issues. To this end, climate-smart agriculture is an integrated approach used to support customized agricultural practices (smart farming techniques) aimed at higher efficiency and lower impact to the environment (circular economy).

In this framework, information technology, remote sensing techniques and proximal data gathering and analyzing (i.e., precision agricultural systems; PA) is a key factor for efficient agricultural water management [154]. Recent technological advantages such as, e.g., Cooperative Information Systems (CIS), enable analyzing autonomously information systems executing locally or cooperate for implementing specific tasks such as computer-generated interactions in real time, between soil-plant-atmosphere under real conditions [155,156]. Indeed, the efficient use of water, fertilizers and energy through the Internet of Things (IoT) adaptation applications reduce the production cost, improves yield while protecting the environment [157].

For instance, a variety of Agricultural Cyber-Physical System (ACPS) has been developed for the management of different services in precision agriculture. A "smart irrigation system" considered to be a perfect cyber-physical test bed, a collection of hardware for delivering water in a spatially precise, timely manner assisted by algorithms that use multiple layers of digital information from sensors, drones, weather stations and soil maps [158]. A new approach to the cyberisation of solar photovoltaic water systems for remote irrigation management was also tested by Selmani et al. [159]. Based on the back propagation (BP) neural network, a water demand prediction model was planned for open fields, as it has shown great potential in solving pipe network optimization and precision irrigation [160]. Meanwhile, Netafim developed the "NeatBeat", an intelligent, self-learning cloud-based platform for precision irrigation and fertigation crop management based on agronomic, atmosphere, plant and soil input parameters [161]. In addition a fuzzy control system was used for monitoring the speed and therefore the depth of water application (i.e., variable rate irrigation, VRI) in a field irrigated with a pivot system taking into account differences of soil type and crops [162]. In line, VRI in wheat crop based on differences of soil available water holding capacity reduces by 7% the irrigation water used as opposed to a uniform rate irrigation management application [163].In another experiment with cotton; even though the WUE between the manual irrigation method and the plant-feedback control incorporated with a VRI treatment were not differ; in the latter case VRI was less time consuming [164].

Soilless–based systems may be part of the solution to the problems created by the lack of water and fertile soils increasing the yield per square meter of cultivated land. Those systems considered been one of the most intensive production methods recognized globally for its ability to support efficient and intensive plant production and at the same time applying environmentally friendly technology [165,166]. They are adapted as technological components where the ability of a computer-based system to learn a specific task resulting from experimental observation for automatic monitoring and control, could be implemented (i.e., Computational Intelligence Systems) [167,168]. For example, the "Crop Assist system" which used on real-time data from a pairs of load cells for monitoring of up to 11 physiological and irrigation parameters measured simultaneously in a greenhouse vine crop [169]. In line, the frequency of irrigation cycles in tomato crops could be implemented through an algorithm namely "Hidro-Control", which estimated plant transpiration rates and monitoring the electrical conductivity of leachate under pre-set limits [170].

However as semi-arid regions are more vulnerable to climate change it is necessary to implemented sustained water management practices considering energy conservation as well. Indeed, the energy consumption for irrigation and greenhouse cooling processes was recorded to be the highest among all energy needed for greenhouse operation under Eastern Mediterranean conditions. That because a significant amount of water is needed to be evaporated within greenhouse to alleviate the high head load observed year-round. Therefore, modifying the aerial environment using transpiration as one of the main cooling processes is of critical factor in protected cropping systems and should be accounted for the prober design and climate control decisions [171,172]. Consequently, PA aims of monitoring of plants actual responses to their environment with the implementation of phyto sensing technology. According to authors' previous work; the timing of an irrigation event and the amount of water was significantly correlated with leaf temperature and stem microvariation even in high frequency soilless culture systems [112,173]. Differences in the greenhouse enironment (i.e., VPD values) shows to affect significantly the stem variations and the water uptake leading to less amounts of greenhouse emmisions outflows into the environment [151,152]. In order to reach a suitable greenhouse microclimate a fuzzy logic control system presented by [174].

7. Alternative Water Sources as Part of Water Balance

With the implementation of the Urban Wastewater Treatment Directive (91/271/EEC) in all EU Member states, municipalities with over 2000 population equivalents are obliged to collect sewage and treated them properly. Nowadays, treated wastewater (i.e., TWW) is considered as a valuable alternate water source aim of reducing the risk of water shortages. Being a low-cost water source; TWW reuse for irrigation is considered being an environmentally friendly disposal practice [175]. A large amount of nutrients such as nitrogen, phosphorous and organic matter which appears in TWW contributed to crop nutrient needs, minimizing the need of commercial fertilizer application [176]. Following the strictest existing legislation, tertiary treated wastewater and disinfection which is the highest degree of treatment could be reused for irrigation in agriculture, mainly for fodder crops, olive trees, citrus trees and vegetables; except for leafy vegetables, bulbs and condyles that are eaten raw. It is extensively used for the irrigation of green areas, public parks and play fields following specific restrictions on the type of the irrigation system to be used. Cyprus proceeds with the municipal wastewater treatment since 1998. The estimated quantity of recycle water produced in 2015 was about 65 million m^3 and by the 2025 is expected to increase to 85 million m^3. About 75% of the TWW produced is reused for irrigation of agricultural crops and green areas (e.g., turf grass and landscaped areas) and 12% applied for groundwater recharge. The rest amount is discharged into the sea, mainly in winter months. That is because during winter irrigation water needs are relatively low. The existing rate of tertiary treated TWW is about the one third of that from governmental water works. Locally the total irrigation needs it is estimated about 162 million m^3. Nowadays about 10–15% of the total irrigation needs are met by TWW; however, in the long term, the objective is the replacement of fresh water used in agriculture by TWW up to 40%.

TWW should be appropriately managed in order to protect public health; in addition, minimizing negative impact to the environment such as, e.g., soil salinization, the accumulation of heavy metals [177,178]. Several authors reported on the effects of recycle water on crops growth. Bourazanis et al. [175] concluded that in *Olea europeae* L. *cv Koroneiki* the superior quality of oil production was enhanced under TWW. In addition, Christou et al. [179] reported that tertiary treated wastewater could be safely used even for vegetables irrigation, in terms of public health safety and environmental sustainability.

Several well-developed countries that have long ago incorporated TWW reuse for irrigation in their integrated water management schemes (i.e., Israel, Cyprus, Spain, United States, Italy) have set and implement comprehensive guidelines and criteria aiming to safeguard the public health and environmental sustainability from potential adverse impacts of such a practice, while most other countries are following the WHO guideline (WHO, 2006). Recently, the European Union (EU) have adopted the EU 2020/74 regulation on the minimum requirements for water reuse, highlighting the importance of reducing the impacts of TWW reuse, thus ensuring water savings, and human and animal health and environmental protection, simultaneously promoting circular economy and supporting adaptation to climate change. The EU 2020/74 regulation incorporates extensive risk management scheme which comprise the identification and management of risks in a proactive way, aiming at the production of TWW of a specific quality required for a particular need. Thus, four TWW quality classes have been established (A,B,C,D), with the best quality (class A) being suitable for the irrigation of all crops consumed raw where the edible part is in direct contact with TWW and root crops consumed raw. Importantly, the regulation may include additional quality requirements concerning heavy metals, pesticides and contaminants of emerging concern (CECs) (i.e., disinfection by-products, pharmaceuticals, other micropollutants including micro- and nano-plastics, and antimicrobial resistance determinants). Such a need is driven by the fact that despite the major advances that have been made with respect to producing safe TWW for reuse, TWW may contain undesirable CECs that pose negative environmental and public health impacts [180]. Thus, several important questions concerning the presence of CECs in TW and their subsequent release to the environment through TW irrigation are still unanswered and barriers exist regarding the safe and sustainable reuse practices. Applied technologies fail to completely remove CECs while no consolidated information exists concerning the efficacy of the conventional activated sludge (CAS) process (which is the most widely applied process) to remove antibiotic resistant bacteria and antibiotic resistance genes (ARB&ARGs) from TWW in the framework of reuse applications (i.e., irrigation, groundwater replenishment, storage in surface waters for subsequent reuse) [181,182].

CECs are now commonly detected in relevant concentrations in TWW effluents and in both the aquatic (surface and groundwater systems, even drinking water) and the terrestrial environments (TW-irrigated soils and runoff from such sites) as a consequence of their continual introduction in the environment through the disposal of TWW [181]. The uptake and bioaccumulation of CECs in the edible parts of food crops and fodders and their subsequent entry into the human food chain have gained prominence over the last decade [182]. Also, the continuous disposal of TWW (and biosolids and manure as well) renders soil as the largest environmental reservoir of antibiotic resistance (AR), while ARGs may persist in the environment and be transferred to other microbial populations (e.g., human pathogens of clinical relevance), posing major health and economic implications [183–185]. It is now widely accepted that the phytoavailability of CECs in the soil is closely related to the properties of the compound, as well as the soil properties [186]. Recently studies dealing with the long-term effects of TWW irrigation under commercial agricultural farming on the fate of a number of CECs in soil and their uptake by crop, revealed that the uptake and biomagnification of CECs in the edible parts of crop plants varied depending on the qualitative characteristics of the TWW applied, the crop itself, and the duration of irrigation [184,187–189]. Risk assessment in most studies revealed that the consumption of fruits harvested from crop plants irrigated for long period with the TWW represent a de minimis risk to human health [190]. However, more studies are needed to reach a definite conclusion for the classification of TWW reuse as a safe practice regarding human health. Such studies should take into the potential additivity of the mixture of few dozen CECs that may present in TWW, their metabolites of pharmaceuticals present in agricultural commodities, the potential sensitivity of subgroups of the population (i.e., pregnant, infants, elderly people, chronic sufferers) and the dietary habits of the distinct population [187]. Least but not last, the potential adverse effects of CECs released to the agricultural environment through TWW reuse on the growth and development of crop plants [191] and on aquatic organisms [192] should also be taken into consideration for further studies.

Brackish or seawater desalination increases the water availability of conventional water resources [193,194]. However, water desalination represents an energy intensive water treatment technology in addition several issues related to adverse effect on the climate change caused by the brine discharge [194,195]. A different option, is to use seawater as a complementary irrigation source at salts concentrations not harmful for the cultivated crops [196]. An economic optimization model has been proposed and developed to optimize water mixture and usage when different sources of non- uniform quality irrigation water are available for the irrigation of greenhouse crops in semiarid regions, a blend of desalinated and brackish water for irrigation of greenhouse crops [193]. Indeed, each crop tolerance to an upper threshold value of salinity; beyond that yield is decreasing (Table 6).

Leaching (i.e., irrigate with good quality water for moving salt below the root zone) should be calculated in the basis of maintaining the soil saturated electrical conductivity values bellow to the upper threshold values for each cultivar. Yet, apparent salinity and yields vary significantly even between different varieties of the same crop and as affected with different nutritional needs (i.e., different fertilizer applications), soil amendments, the timing and the amount of irrigation, drainage etc [198]. Indeed, salt tolerance of several crops and varieties which were tested under Dutch field conditions were proved to be at least a factor two higher, and in some cases, even a factor three in comparison with FAO report on crop salt tolerance [199].

Table 6. Crop salt tolerance classification to irrigation water salinity (dS m^{-1}) and % yield decreased per unit of salinity increase in salinity beyond threshold. Data adapted from [197].

Crops Salt Tolerance Classification	Salinity at Initial Yield Decline	% Yield Decreased
Sensitive		
Strawberry	1.0	33
Carrot	1.0	14
Bean	1.0	19
Almond	1.5	19
Apricot	1.6	24
Orange	1.8	16
Moderately Sensitive		
Cowpea	1.3	14
Sweet potato	1.5	11
Corn	1.7	12
Cabbage	1.8	9.7
Alfalfa	2	7.3
Spinach	2.0	7.6
Cucumber	2.5	13
Tomato	2.5	9.9
Moderately Tolerant		
Broccoli	2.8	9.2
Soybean	5.0	20
Tolerant		
Date palm	4.3	3.6
Cotton	7.7	5.2

8. Measures for Sustainable Irrigation and Water Management Recommendations in Water-Scarce Regions

- Adoption of improved high water application efficiency pressurized irrigation system. Frequent system inspection and irrigation systems' maintenance. Irrigation combined with fertilization should also be promoted,
- Appropriate irrigation scheduling based on local conditions,
- Application of low-cost commercial sensors and irrigation controllers (on-farm irrigation management and control technologies); adopted by smallholding aged farmers with low level of technical education [200],
- Big data analysis and artificial intelligence system for implementing precision irrigation for new age farmers with are familiar with technological improvements [155],
- Volumetric water metering and water pricing in each plot. Temporary drought surcharges rates for over-irrigating crops should be promoted [16],
- Groundwater aquifer extraction should be protected appropriately. Drilling wells to access groundwater must require a permission taking into account water quantity and quality issues,
- Adopting water prices that induce farmers to irrigate by night [201] in selected crops,
- Increasing the frequency of irrigation can be helpful for salinity management. Frequent irrigation requires high labor inputs, therefore economic considerations usually favor automated or mechanized irrigation systems [202],
- Leaves wetted by sprinkling water absorbs salts directly; therefore, sprinkler irrigation at night is preferable,
- Reducing water evaporation from open reservoirs (Figure 7) using chemicals films and flooding objects and reduce soil water evaporation with crop residues, plastic mulches etc,

- Enable growers to adopt cropping systems with recycling of the excess irrigation water. Re-use of drainage water especially in large irrigation schemes [203],
- Training growers in operation and management of water savings programs, such as deficit irrigation strategies,
- Selected drought resistant varieties, taking into consideration seasonal rainfall availability. The adaptation of planting dates i.e., after a rainy season ensures more effective conditions for crop establishment [201],
- Established on farm water storage capacities like reservoirs and tanks, for water harvesting, and reused it for irrigation. Practices like terracing construction and small dams can be used to increase aquifer recharge [201],
- Enhance the productive use of rainwater (Figure 7) by supporting sustainable land management and farming methods that increase soil organic matter and improve the water infiltration and water retention capacity of soil [202],
- Develop an Agricultural Insurance Law that includes drought hazards, considering droughts as a natural disaster, therefore developed a legislation to implement competencies and action of public institutions to face a natural disaster [203],
- Protected cropping systems increasing the WUE values. Proper design and operation of climate control within these structures under local conditions, ensures minimum operational cost, enable of controlling crop evapotranspiration and drainage emissions without compromising yields,
- In rain-fed agriculture, enhanced production, and imports of food product through international trade. The concept of 'virtual water' indicated that gains in water productivity can be achieved by growing crops in places where climate enables high water productivity at lower cost and trading them to places with lower water productivity. Although rarely expressed in water terms, virtual water trade is already a reality for many water-scarce countries, and is expected to increase in the future [203],
- Increasing consumption of meat and, to a lesser extent, also dairy products translates into increased water consumption, as their production requires large volumes of water. The extent to which societies are willing to modify their diets as part of a larger effort to reduce their environmental footprint reaches far beyond water scarcity concerns. Yet, it has implications in terms of national food security and associated water-scarcity coping strategies [202],
- Reduction of water losses in the postharvest value chain (i.e., blue water footprints). Indeed, more than one-third of food is lost or wasted in postharvest operations, therefore it could be a sustainable solution to reduce the pressure on natural resources [203],
- Using newly accessible technologies and strategies to achieve high water use efficiency and to promote non-conventional water resources (e.g., wastewater, salt-contaminated) in combination with soil fertility,

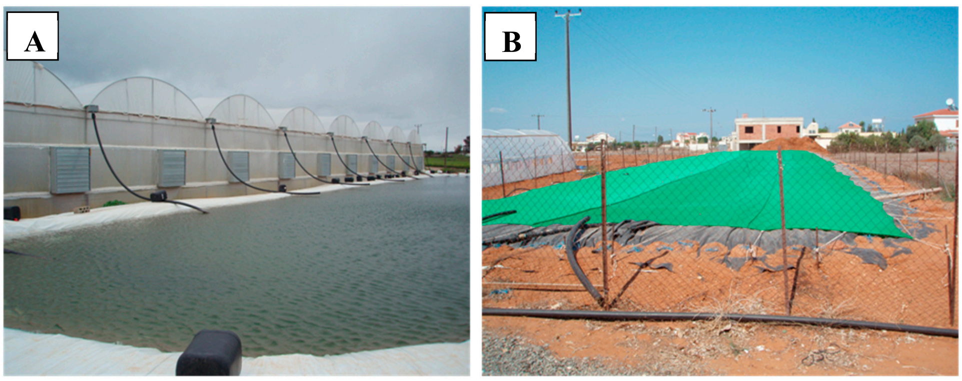

Figure 7. *Cont.*

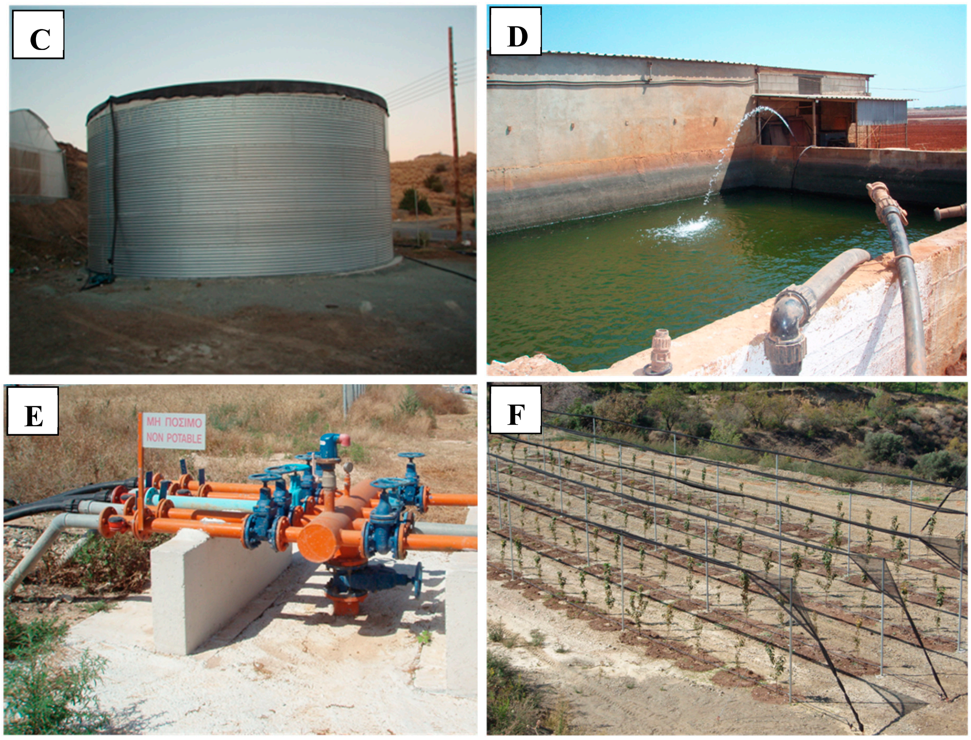

Figure 7. Rain water harvesting and storage in open reservoir (**A**); water storage in a covered reservoir minimizing water evaporation losses and algae growth (**B**); a commercial closed water reservoir (**C**); blended water from different sources (**D**); a water supply main manifold of recycle water (**E**); localized irrigation and net protection in a tree cropping system (**F**).

9. Conclusions

The present report summarizes sustainable irrigation management guidelines in water-scarce regions. In particular, as climate change are increase the intensity and frequency of extreme events; more resilience from people and society is required [203]. Over the longer term, intensive drought events, water scarcity, overexploitation of groundwater resources and water quality issues remains much-less the same between regions in arid and semi-arid climate. Several countries have already developed extensive legislation, institutional capabilities actions and practices that are required for the effective climate change adaptation. Good irrigation and water management practices are highlighted with the aim of transferring knowledge in regions which are in the stage of developing national schemes regarding water productivity optimization. It has to be noted that no individual measure or action could effectively tackle water scarcity issue.

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Abbreviations

List of Symbols and Abbreviations

Abbreviations

ACPS	agricultural cyber-physical system
CIS	cooperative information systems
DI	deficit irrigation
Ep	potential evapotranspiration (mm d^{-1})
ETc	crop evapotranspiration (mm d^{-1})
ETo	reference evapotranspiration (mm d^{-1})
I	irrigation (mm)
IoT	internet of things
IV	irrigation water volume supplied (m^{-3})
IZ	irrigation zone
Kc	crop coefficient
Kcp	crop-pan coefficient
LAI	leaf area index (m^2 leaf m^{-2} ground)
PA	precision agriculture
PIS	pressurized irrigation system
PRD	partial root zone drying
R	rainfall (mm)
RDI	Regulated deficit irrigation
RV	drainage water volume collected (m^{-3})
SBDI	stage-based deficit irrigation
SDI	subsurface drip irrigation systems
SI	supplemental irrigation
StDI	sustained deficit irrigation
SWC	soil water content
Tc	crop transpiration (kg m^{-2} s^{-1})
TWW	treated wastewater
VPD	vapor pressure deficit (kPa)
VRI	Variable rate irrigation
WP	water productivity (€ m^{-3})
WU	water uptake
WUE	water use efficiency (Kg m^{-3})

Symbols

A	equation value model coefficient (dimensionless)
B	values of equation parameters (W m^{-2} kPa^{-1})
c	Adjustment factor which depends on mean humidity and daytime wind conditions
e_a	actual vapour pressure (kPa)
e_s	saturation vapour pressure for a given time period (kPa)
e_s- e_a	saturation vapour pressure deficit
G	soil heat flux density (Mj m^{-2})
K	light extinction coefficient
n	Measurement period (d^{-1})
Rn	net radiation at the crop surface (Mj m^{-2} d^{-1})
Rs	solar radiation (mm d^{-1})
Rsi	solar radiation inside greenhouse (W m^{-2} d^{-1})
T	air temperature at 2 m height (ºC)
u_2	wind speed at 2 m height (m s^{-1})
W	weighting factor depends on altitude and temperature
Greek letters	
Γ	psychrometric constant (kPa $ºC^{-1}$)
Δ	slope of the saturation vapour pressure-temperature curve (kPa $°C^{-1}$)
Λ	vaporization heat of water (J kg^{-1})

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