4

Crop Evapotranspiration and Water Use Efficiency

Bergson Guedes Bezerra
National Institute of Semi Arid (INSA)
Brazil

1. Introduction

The efficient use of water in any sector of human activity has become an increasingly important need in our daily lives, especially in arid and / or semi-arid regions where water resources have become increasingly scarce. In irrigated agriculture this concern becomes more relevant because globally, water for agriculture is the primary user of diverted water, reaching a proportion that exceeds 70–80% of the total water resources in the arid and semi-arid zones (Fereres & Soriano, 2007).

Currently, world food production from irrigated agricultural represents >40% of total, with this coming form only about 17% of the total land area devoted to food production. However, these percentages tend to increase due to increased human population and climate change, because there is widespread agreement that increasing anthropogenic climate change will exacerbate the present shortages of water, and are likely to increase drought (Intergovernmental Panel on Climate Change [IPCC], 2007). According to Perry et al. (2008) as a consequence of climate change, some areas will receive higher rainfall but most of the currently water-scarce regions will become drier and warmer. These two changes will exacerbate scarcity: reduced rainfall means less flow in rivers; higher temperatures mean increased evaporation and water consumption of natural water demand for agriculture use. On the other hand, the increase in population will result in a greater demand for food. Thus, the competition for water intensifies worldwide, water for food production must be used more efficiently (Steduto et al., 2007). Another concern with water use for irrigated agriculture is the question of sustainability because food production tends to rely increasingly on irrigation. In developing countries, agriculture continues to be an important economic sector as it constitutes a significant contribution to national incomes and economic growth and provides livelihood support for 60–80% of the population (Hussain et al., 2007).

One way to achieve greater water use efficiency in irrigation is switching from the less efficient flood or furrow system to more efficient systems such as microirrigation or to adopt irrigation strategies, such as deficit irrigation, in order to maximize crop yield and/or minimize water losses. According to Perry et al. (2009) switching from flood or furrow to low-pressure sprinkler systems reduces water use by an estimated 30%, while switching to drip irrigation typically cuts water use by half. In addition to having a direct relationship to the total water used, irrigation systems also have a bearing on the crop yield. Cetin & Bilgel (2002) evaluated the effect of the irrigation system on cotton yield and concluded that drip irrigation produced 21% more seed-cotton than with a furrow system and 30% more than with a sprinkler system.

The most fundamental requirement of scheduling irrigation is the determination of crop evapotranspiration, ETc. According to Allen et al. (1998), evapotranspiration is not easy to measure, because specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. The two-step crop coefficient (Kc) versus reference evapotranspiration (ET_0) method is a practical and reliable technique for estimating ETc, and it is being widely used. Besides the accuracy and reliability, the advantage of this method is related to the fact that is inexpensive, requiring only meteorological data to estimate ET_0 which is then multiplied by a crop coefficient to represent the relative rate of ETc under a specific condition (Allen et al., 1998). Additionally, the knowledge of the Kc for each specific crop growth stage is necessary. This inexpensive method makes it popular, accessible and vastly applied by the small farmers which have restricted financial resources. However, several methods which measure evapotranspiration indirectly have been proposed, such as the micrometeorological methods. All these methods present advantages, disadvantages and limitations but generally provide reasonable accuracy.

This chapter presents a review on evapotranspiration and its importance for agricultural water management. This review will focus on the concepts and main methods of estimating crop evapotranspiration. The strategies for improving water use efficiency such as through deficit irrigation and partial root-zone irrigation beyond of irrigation performance indicators will also be discussed.

2. Crop evapotranspiration – Concepts

The crop evapotranspiration is defined like the water transferred to atmosphere by plant transpiration and surface evaporation. The evapotranspiration term was proposed by Thornthwaite (1948) to conceptualize the process of plant transpiration and surface evaporation which occurs simultaneously and no easy way of distinguish them. The evapotranspiration process occurs naturally only if there is inflow of energy in the system, from the sun, atmosphere, or both, and is controlled by the rate of energy in the form of water vapor that spreads from the surface of the Earth (Tucci and Beltrame, 2009). This transfer takes place physically in the forms of molecular and turbulent diffusion.

According to Allen et al. (1998), evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Transpiration, in turn, is the transfer of water from plants through their aerial parts. Water transfer from plant to atmosphere occurs mainly through the stomata through which they pass more than 90% water transpired.

The evapotranspiration can be derived from a range of measurement systems including lysimeters, eddy covariance, Bowen ratio, water balance (gravimetric, neutron meter, other soil water sensing), sap flow, scintillometer and even satellite-based remote sensing and direct modeling (Allen et al., 2011). The micrometeorological method of Bowen Ratio Energy Balance (BREB) has been widely applied due its relative simplicity, practicality, robustness and accuracy. Recently, the Eddy Covariance method has been increasingly applied mainly after the sensors have reduced costs.

However, the most popular method for crop evapotranspiration estimates is the crop coefficient (K_c), which is defined like the ratio between crop and reference evapotranspiration. The K_c method has the advantage of being inexpensive, since it requires only daily weather data to estimate the reference evapotranspiration which is multiplied by a Kc dimensionless value. The Kc value depends of crop growth stage.

2.1 Crop coefficient (K_c)

The K_c concept was introduced by Jensen (1968) and is widely discussed and refined by the Food and Agricultural Organization (FAO) in its Bulletin-56 (Irrigation and Drainage Paper, Allen et al., 1998). In the crop coefficient approach the crop evapotranspiration is calculated by multiplying the reference evapotranspiration, ET_0 (mm d^{-1}), by a crop coefficient, Kc (dimensionless) according to Equation 01.

$$ET = K_c.ET_0 \tag{1}$$

According to Allen et al. (1998) the effects of the various weather conditions are incorporated into the ET_0 estimate. Thus, ET_0 represents an index of climate demand and K_c varies predominately with the specific crop characteristics and only to a limited extends with climate. The FAO-56 report K_c values for the initial, middle and end growth stages, K_{c-ini}, K_{c-mid} and K_{c-end}, respectively, for many crops. However, the K_c values presented in FAO-56 (Table 12) are expected for a sub-humid climate with average daily minimum relative humidity (RH_{min}) values of about 45% and calm to moderate wind speed (u_2) averaging 2 m s^{-1}. For humid, arid and semiarid climates it has been suggested corrections to their values according to equations proposed in FAO-56 (Allen et al., 1998). However, the use of these values can contribute to ETc estimates which are substantially different from actual ETc (Hunsaker et al., 2003), because it has been demonstrated that K_{c-ini}, K_{c-mid} and K_{c-end} values experimentally determined differ from those values listed in the FAO-56. Farahani et al. (2008) compared the cotton evapotranspiration obtained based on FAO-56 Kc and Kc obtained experimentally and found differences ranging from 10 to 33% in three years of observation, in a Mediterrenean environments. Thus, to the accurate application of this methodology, it is necessary to obtain the K_c curve values experimentally, to represent the local weather and water management conditions. Allen et al. (1998) suggest accurate evapotranspiration observed experimentally during years multiples. The Kc values has been experimentally obtained using the evapotranspiration derived from micrometeorologicals methods such as Bowen Ratio Energy Balance (BREB) (Inmam-Bamber & McGlinchey, 2003; Hou et al., 2010; Bezerra et al., 2010)

2.2 Bowen Ratio Energy Balance (BREB)

The crop evapotranspiration is estimated by use of the BREB technique from latent heat flux density which is derived from energy balance equation (Equation 2). Neglicting the advection effects, energy stored in the canopy, and photosysthetic energy flux, the energy balance can be writted as follows:

$$Rn = LE + H + G \tag{2}$$

where: Rn is the net radiation flux density, LE is latent heat flux density, H is sensible heat flux density, and G is soil heat flux density.

Use of the BREB concept ($\beta = H/LE \rightarrow H = \beta.LE$) (Bowen, 1926) enables solving the energy balance and the latent heat flux density can be written, as:

$$LE = \frac{Rn - G}{1 + \beta} \tag{3}$$

The crop evapotranspiration is estimates dividing the Equation 3 by latente heat of vaporização (L = 2.501 MJ kg^{-1}). The Bowen ratio (β) is calculated assuming equality between the turbulent exchange coefficients for heat and water vapor, according to equation following:

$$\beta = \gamma.\,\Delta T/\Delta e \tag{4}$$

where γ is psichometric constant, ΔT and Δe are the gradients of air temperature and vapor pressure above canopy, respectively.

The application of BREB method requires horizontal advection to be negligible when compared to the magnitude of the vertical fluxes. In this case, the closure of the energy balance equation for an imaginary plane located above the canopy must be satisfied (Figuerola & Berliner, 2006). The disregard of advection effects should be one relevant worry mainly in regions which presenting advection natural events coming to regional circulation. In this case, the ETc has been understimated when compared to lysimeter measurements ranging from 5 to 20% (Blad & Rosenberg, 1974; Gavilán & Berengena, 2007). However, if the advection is originated from local circulation, the effects can be compensated taking some precautions in the instalation procedure. On precautions is to establish an equilibrium boundary layer (EBL). This equilibrium can be achieved providing uniform fetch of sufficient distance from boundary field in the predominant wind direction (Allen et al., 2011). Another caution is to stablish sufficient elevation above the canopy to avoid the roughness sublayer. This elevation is quite varied because the height where the energy closure is calculated may vary because it depends on the distance to the border of the field, humidity conditions of the soil, plant density and height, and also, the energetic and dynamic conditions of the flow field (Allen et al., 2011; Figuerola & Berliner, 2006). According to Steduto & Hsiao (1998) this technique must be used with caution since it does not reproduce the turbulent nature of the evapotranspiration process.

Another relevant limitation was detected on the data colected during nigh-time period and periods during precipitation and irrigation events. According to Perez et al. (1999) the data observed in this periods must be rejected, which corresponds to 40% of the total data.

For application of Bowen ratio technique is necessary accomplish measurements of net radiation and soil heat flux. Additional measures of the air temperatures of the dry and wet bulbs at two levels above canopy. The air temperature wet bulb are used to calculated water vapor pressure.

A accuracy of ETc provided by BREB method depends of accuracy and representativeness to measurements of net radiation (Rn) and soil heat flux (G) (Allen et al., 2011). This dependence is considered a disadvantage of the BREB method mainly related to representativeness of soil heat flux measurements, which is not easy to get due to ground cover provides by crops is not always heterogeneous. Another relevant factor is the difference of scales of Rn and G measurement. While G measurements are representative for a specific location of the field Rn measurements are originate from several hundred meters upwind.

On the other hand Allen et al. (2011) lists some potential advantages of BREB method, which are:

- non-destructive, direct sampling of the turbulent boundary layer;
- no aerodynamic data are required;
- simple measurement of temperature and vapor pressure at two heights;
- can measure ET over both potential and non-potential surfaces;
- gradient-based fluxes are averaged over a medium sized area (200–100,000 m^2);
- automated.

Additionally it's relative simplicity of method made it widely applied (Bezerra et al., 2010, Gavilán & Berengena, 2007, Hou et al., 2010, Silva et al., 2007, Steduto & Hsiao, 1998, Todd et al., 2000).

2.3 Eddy covariance method

The Eddy Covariance method is one of the most direct, defensible ways to measure and calculate turbulent fluxes within the atmospheric boundary layer (Burba & Anderson, 2007). Flux measurements using the eddy-covariance method are a direct measuring method without any applications of empirical constants (Folken, 2008, Lee et al., 2004). However, the method is mathematically complex and requires significant care to set up and process data. The main challenge of the method for a non-expert is the complexity of system design, implementation, and processing of the large volume of data (Arya, 2001; Burba & Anderson, 2007; Stull, 1998). According to Allen et al. (2011), the concept of eddy covariance draws on the statistical covariance (correlation) between vertical fluxes of vapor or sensible heat within upward and downward legs of turbulent eddies.

The eddy covariance method assumes that all atmospheric entities show short-period fluctuations about their longer term mean value (Oke, 1978). Still according to Oke (1978) this is the result of turbulence which causes eddies to move continually around carrying with them their properties derived elsewhere. Therefore the value of an entity variable in time (s) consists of its mean value ($\bar{s}$), and a fluctuating part (s'), according ilustrate the Fig. 1.

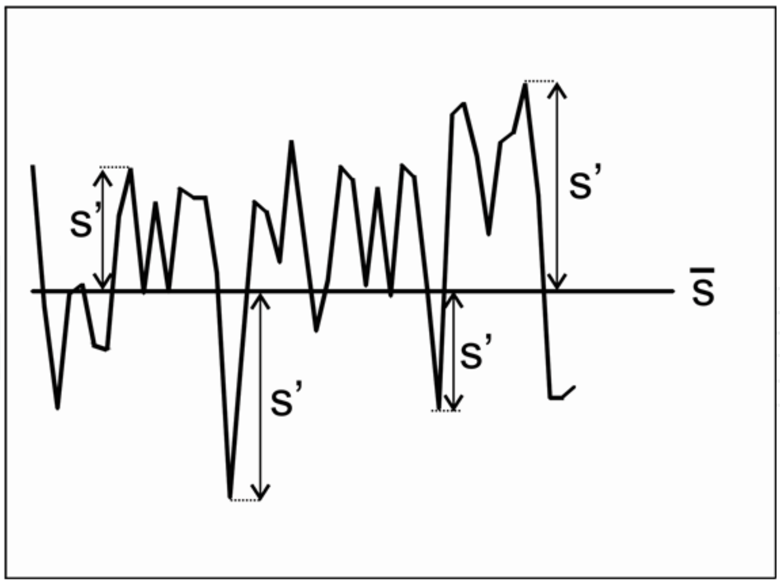


Fig. 1. Instantaneous values of turbulent variable is obtained by its mean ($\bar{s}$) and flutuing values (s')

Thus, its instantaneous value is obtained from following equation, also known as Reynold's decomposition (Arya, 2001; Folken, 2008; Oke, 1978,):

$$s = \bar{s} + s' \quad (5)$$

where the overbar indicates a time-averaged property and the prime signifies instantaneous deviation from the mean.

The air flow over an agricultural ecosystem can be understood as a horizontal flow of numerous rotating eddies, according to Fig. 2. Each eddy has three-dimensional components, including vertical movement of the air (Burba & Anderson, 2007).

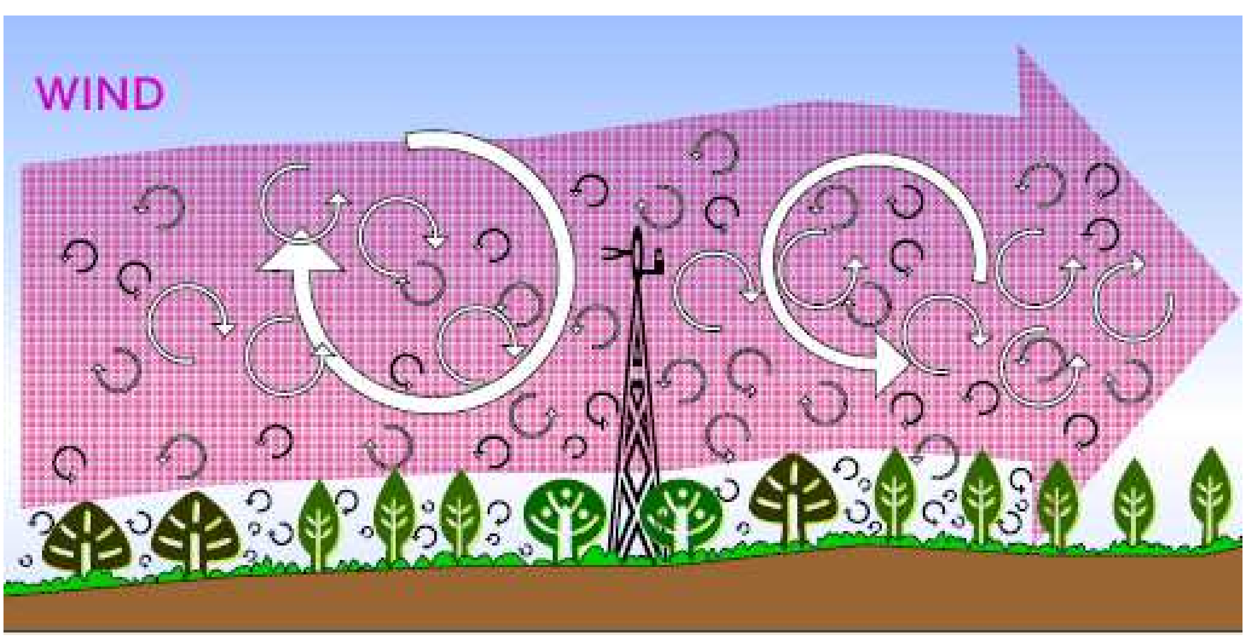


Fig. 2. Air flow over an agricultural ecossystem (Source: Burba & Anderson, 2007)

From these consideration the eddy covariance method is based in the covariance between the properties contained by, and therefore transported by a eddy, which are its mass (which by considering unit volume is given by its density, ρ), its vertical velocity (w) and the volumetric content of any entity it possesses (s). Thus, the turbulent flux of any variable (momentum flux, latent and sensible heat fluxes and CO_2 flux) is equal to product of mean values of variables transported by eddies, according to to following equation:

$$F = \overline{\rho_a . w . s} \tag{6}$$

Applyind the Reynold's decomposition to break into means and deviations:

$$F = \overline{(\overline{\rho_a} + \rho'_a)(\overline{w} + w')(\overline{s} + s')} \tag{7}$$

Opening the parentheses:

$$F = \overline{(\overline{\rho_a}\overline{w}\overline{s} + \overline{\rho_a}\overline{w}s' + \overline{\rho_a}w'\overline{s} + \overline{\rho_a}w's' + \rho'_a\overline{w}\overline{s} + \rho'_a\overline{w}s' + \rho'_a w'\overline{s} + \rho'_a w's')} \tag{8}$$

Although Equation 8 looks quite complex Oke (1978) outlines some considerations which allow simplify it. These considerations are sequentially presented:

1. First, all terms involving a single primed quantity are eliminated because by definition the average of all their fluctuations equals zero (i.e. we lose the second, third and fifth terms);
2. Second, we may neglect terms involving fluctuations of ρ_a since air density is considered to be virtually constant in the lower atmosphere (i.e. we lose the sixth, seventh and eighth terms);
3. Third, if observations are restricted to uniform terrain without areas of preferred vertical motion (i.e. no 'hotspots' or standing waves) we may neglect terms containing the mean vertical velocity (i.e. we lose the first term).

With these assumptions the Equation 7 is reduced to fourth term, but dropping the bar over the ρ_a because it is considered to be a constant.

$$F = \rho_a \overline{w's'} \tag{9}$$

where $\overline{w's'}$ is the covariance between vertical wind speed and between any variable which depends of user interest. In the specific case of evapotranspiration the covariance is between vertical wind speed (w) and specific humidity (q), according to following equation:

$$ET = \rho_a \overline{w'q'} = \frac{0.622}{P} \rho_a \overline{w'e'} \tag{10}$$

where P is atmospheric pressure, $\overline{w'e'}$ is covariance between vertical wind speed and actual vapor pressure.

The covariance indicates the degree of common relationship between the two variables, "a" and "b" (Stull, 1998; Wilks, 2006). In statistics, the covariance between two variables "a' and "b" is defined as:

$$covar(a, b) = \frac{1}{N} \sum_{i=0}^{N-1} (a - \overline{a}).\left(b - \overline{b}\right) \tag{11}$$

Applying the Reynold's decomposition appears;

$$\text{covar}(a,b) = \frac{1}{N}\sum_{i=0}^{N-1}(\bar{a} + a' - \bar{a}).\left(\bar{b} + b' - \bar{b}\right) \quad (12)$$

Thus, we can show, that:

$$\text{covar}(a,b) = \frac{1}{N}\sum_{i=0}^{N-1} a'b' = \overline{a'b'} \quad (13)$$

The data processing is mathematically complex. Several mathematical operations and assumptions, including Reynolds decomposition, are involved in getting from physically complete equations of the turbulent flow to practical equations for computing "eddy flux" (Burba & Anderson, 2007). This mathematical operations use existing methodologies for the control and certification of data quality, such as crosswind correction of sonic anemometer (if not already implemented in the software of sensor), coordinates transformations, spectral corrections, conversions of sonic temperature fluctuations in the actual temperature fluctuations and corrections to the scalar densities of the water vapor flux density based Webb et al. (1980) and described in details by Lee et al. (2004). Several software programs to process eddy covariances and derive quantities such as heat, momentum, and gaseous fluxes. Currently (2011) there are several software programs to process eddy covariances and derive quantities such as heat, momentum, and gaseous fluxes. Examples include EdiRe, ECpack, TK2, Alteddy, EddyPro and EddySof. The eddy covariance method requires high speed measurement of T, w, and and q for evapotranspiration estimates. According to Allen et al. (2011) usually at frequencies of 5–20 Hz (5–20 times per second) using quick response sensors, but 10 Hz is common.

3. Water use efficiency

The increase in human population has caused increased demand for food. On the other hand, the shortage of drinking water in arid and / or semi-arid and is becoming increasing its use efficiently is becoming increasingly necessary. According to Perry et al. (2009) the competition for scarce water resources is already widely evident, from Murray Darling basin in Australia to rivers of the middle East, southern Africa and Americas, and from the aquiffers of northern India, to the Maghreb and the Ogallala in central of United States. The cause of much of the shortage of drinkable water has been the predatory exploitation of natural resources and the almost total absence of effective public policies for water resources management, especially in developing countries. When water use is not regulated or controlled, the imbalance between supply and demand is evident, and occurs as a consequence failling water tables, drying estuaries, inadequate to lower riparian and damaged aquatic ecosystems (Perry et al., 2009). Thus, water use efficiency whether in any human activity, domestic, industrial or agricultural, has become a necessity. The optimization of water use in irrigation has significant relevance in this context because it accounts for approximately 50% of the total world food production. Thus is currently is the main user of water worldwide, reaching a proportion that exceeds 80% of the total available in arid and semiarid. Another worrying fact is that the increase in population coupled with impacts of global climate change pose to global food security under threat (Strzepek & Boehlert, 2010). This threat comes from the increased demand for irrigated agriculture which increases in the same proportion of other sectors demand such as domestic and industrial.

When water supplies are limiting, the farmer's goal should be to maximize net income per unit water used rather than per land unit (Fereres & Soriano, 2007). Thus, producing more with relatively less water has become a challenge for irrigation sector (Kassam et al., 2007, Fereres & Soriano, 2007). The water productivity (WP) reflects this challenge by exposing the relationship between the net benefits of agriculture, forestry, fishing and / or livestock and the amount of water consumed to produce these benefits (Kassam et al., 2007, Molden, 1997, Steduto et al. 2007). In other words, WP represents the fresh crops (in kg ha^{-1}) produced per unit of water applied or consumed (in m^3 ha^{-1}) (Molden, 1997; Teixeira et al., 2009), according to equations followings:

$$WP_{ET} = \frac{Y\left(kg\ ha^{-1}\right)}{ET\left(m^3 ha^{-1}\right)} \tag{14}$$

$$WP_{I} = \frac{Y\ \left(kg\ ha^{-1}\right)}{I\ \left(m^3 ha^{-1}\right)} \tag{15}$$

where WP_{ET} is the WP calculate in terms of crop evapotranspiration, Y is the crop yield, ET is crop evapotranspiration, WP_I is WP calculated in terms of irrigation water applied and I is irrigation water applied.

Some authors (i.e., Droogers & Kite, 1999) recommend analyze the WP in terms of crop evapotranspiration (ET) because this indicator also includes non-irrigation water, such as rainfall, capillary rise, and soil moisture changes. However, according to Oweis et al. (2011), WP_{ET} is more a biological indicator while the WP_I is influenced by the performace irrigation system and the degree of water losses beyond transpiration.

So, the challenge of irrigation sector is producing more with relatively less water implies in increasing water productivity. Several strategies have been widely used at irrigation management for increase WP. The partial root zone irrigation (PRI) and deficit irrigation (DI) are the most used.

PRI is an irrigation practice with which only part of the rootzone is wetted through proper irrigation design and management while the rest of the root system is left in drying soil (Mavi & Tupper, 2004, Tang et al., 2010, Zhang et al., 2001). The dried and wetted side is irrigated by shift periodically according to the rate of soil drying and crop water consumption (Kang & Zhang, 2004, Tang et al., 2010). According to Zhang et al. (2001), this practice is predicted to reduce plant water consumption and maintain the biomass production according to two theoretical backgrounds. Firstly, fully irrigated plants usually have widely opened stomata. A small narrowing of the stomatal opening may reduce water loss substantially with little effect on the photosynthesis. Secondly part of the root system in drying soil can respond to the drying by sending a root sourced signal to the shoots where stomata may be inhibited so that water loss is reduced. In the field, however, this prediction may not be materialized because stomatal control is only part of the transpirational resistance. Because prolonged exposure to drying soil may cause anatomical changes in the roots, such as suberization of the epidermis, collapse of the cortex, and loss of succulent it is necessary to alternatively irrigate the different part of roots system so that the plants could be succulent enough to sense soil drying and produce root-sourced signal to regulate the opening of leaf stomata (Kang and Zhang, 2004; Zhang et al., 2001).

Other strategy which is most used for increase WP is the deficit irrigation (DI). DI is the application of water below ET requirement, i.e., the scheduling irrigation derived as fraction from full irrigation. In other words, DI is the application of only a predetermined percentage of calculated potential plant water use (Morison et al., 2008). DI is also mentioned in literature as regulated deficit irrigation (RDI). Thus, according to Fereres & Soriano (2007) to quantify the level of DI it is first necessary to define the full. It has been experimentally established that the DI translates increase of WP (Zwart & Bastiaanssen, 2004). Thus, has become an important strategy in the maintenance of agricultural production in arid and semi arid zones due of declining water resources in these areas. Besides the improvement of irrigation efficiency, the costs reduction and environmental benefits are potential virtues of DI practice. According to Fereres & Soriano (2007) there are several reasons for the increase in WP under DI. One of these reasons is the relationship between yield and irrigation water for a crop. Small irrigation amounts increase crop ET, more or less linearly up to a point where the relationship becomes curvilinear because part of the water applied is not used in ET and is lost. In this point yield reaches its maximum value and additional amounts of irrigation do not increase it any further. Still according to Fereres & Soriano (2007), the location of that point is not easily defined and thus, when water is not limited or is cheap, irrigation is applied in excess to avoid the risk of a yield penalty. These points are called I_W and I_M and indicate the point beyond which the water productivity of irrigation starts to decrease, and the point beyond which yield does not increase any further with additional water application, respectively (Fereres & Soriano, 2007). For investigate the reasons presented by Fereres & Soriano (2007) was simulated the effect of DI in the water balance components and yield of irrigated cotton crop in Brazilian Semiarid using the SWAP model. The SWAP model was calibrated and validated from data collected in two experimental campaigns carried out at the Rio Grande do Norte state, Northeast of Brazil. The procedure of SWAP model calibration and validation are described minutely in Bezerra (2011). The Table 1 shows the variables observed, measurement frequency, method and finality of each variable. The experimental area are located in west region of Rio Grande do Norte state. The soil texture of experimental area is sandy-clay-loam, according to USDA classification. The SWAP is a physical based, detailed agro-hydrological model that simulates vertical transport of water, solutes and heat in the saturated-unsaturated zone in relation to crop growth.

A first version of the SWAP model was developed by Feddes et al. (1978) with continuous development since. The version used for this study is SWAP 3.2 and is described by Kroes et al. (2008). According to Droogers et al. (2010) the SWAP requires various data as input which can be divided into state variables, boundary conditions (model forcing) and calibration/validation data. The most important state variables are related to soil and crop characteristics. The soil characteristics were often described by van Genuchten-Mualem (VGM) parameters which called hydraulic functions. The growth and yield of cotton crop were simulated using the detailed crop growth module which is based on the World Food Studies (WOFOST) model (Supit et al., 1994). The detailed crop growth is based on the incoming photosynthetically active radiation absorbed by crop canopy and photosynthetic characteristics of leaves, and accounts for water and salt stress of the crop (van Dam et al., 2008).

Data	Method	Frequency	Purpose
Meteorological data	Meteorology station	Daily	Input
Crop evapotranspiration	Bowen Ratio Energy Balance	Daily	Validation
Soil moisture	Probe of soil moisture profile	Two times for week	Calibration
Crop development stage, i.e. emergence, anthesis, maturity and harvest	Field observation	Once	Input
Leaf area	Leaf area meter	5 – 6 times	Input
Plant height	Field observation	5 – 6 times	Input
Dry matter portioning	Field observation and drying in oven	5 – 6 times	Input
Soil texture	Granulometric method and USDA classification	Once	Input
VGM parameters	Gravimetric method	Once	Input
Soil saturated conductivity	Porchet method	Once	Input
Irrigation depth	From crop coefficient	Weekly	Input
Irrigation date	Field observation	After each irrigation	Input
Crop Yield	Field observation	Once (harvest)	Validation

Table 1. Summary of data field observation for calibration and validation of the SWAP model

The SWAP model was calibrated for full irrigation condition. The scheduling of full irrigation was defined weekly using the crop coefficient method. The crop was irrigated using sprinkler irrigation system.

The irrigation depth of each treatment simulated was scheduled as full irrigation fraction, according showed in Table 2. Still in the Table 2 are showed the irrigation depth for each treatment. The irrigation frequency was same for all treatments.

The simulated water balance components for all treatments are presented in Table 3. These values correspond to mean of two study years.

Treatment	Water level (% of full irrigation)	Irrigation amount (mm)		
		2008	2009	Mean
DI_{40}	40	357.2	353.6	355.4
DI_{60}	60	535.8	530.5	533.2
DI_{75}	75	670.5	663.0	666.8
FI	100	894.0	884.0	889.0
FI_{130}	130	1161.0	1149.2	1155.1

Table 2. Irrigations treatments and its irrigation amount

The DI effects are evidenced in several water balance components. For example, the relative water use (RWU) (i.e., ratio between actual and potential transpiration) is lower than one, evidencing the water stress, which cotton crop has been submitted. However, in the full and excessive irrigation treatments (FI and FI_{130}, respectively), the relative water use lower than one is caused for water loss for drainage. These losses are evidenced by drainage at 100 cm (D) which increased as the applied irrigation has also increased. The water loss ranged 13.8 mm (DI_{40}) to 352 mm (FI_{130}). In the treatments under DI regimes the water loss by drainage was lower than 6% of irrigation water applied, while that in full and excessive irrigation treatments (FI and FI_{130}, respectively) the water loss by drainage was 14.9% and 31.1%, respectively.

Treatment	ΔW (mm)	Water balance component (mm)					
		I	D	T_P	T_A	E_S	RWU
DI_{40}	-9.5	355	13.8↓	256.1	136.2	208.8	0.53
DI_{60}	-25.4	533	31.2↓	373.1	264.4	226.1	0.71
DI_{75}	-25.6	674	34.2↓	466.3	389.4	235.6	0.84
FI	16.8	899	133.8↓	538.0	510.2	224.3	0.95
FI_{130}	18.9	1154	358.8↓	549.0	537.2	223.3	0.98

Table 3. Mean water balance component simulated by SWAP. ΔW = change water stored, I = irrigation, D = drainage at 100 cm or bottom flux, T_P = potential transpiration, T_A = actual transpiration, E_S = soil evaporation, RWU = relative water use = ratio between actual and potential transpiration and ↓ = downward flux.

The water stored was reduced at all deficit irrigation treatments, according to change water stored (ΔW), exhibiting of shortages of water. In the full and excessive irrigation treatments, the water stored increased and in this case can also be considered a loss. The soil evaporation, such as drainage and change water storage, also shows the evidences of deficit irrigation effect. In the DI_{40} treatment the soil evaporation corresponds to an amount in excess of 60% of ET. This ratio decreases with the irrigation increase in such way that decreases to 29% in the FI_{130} treatment. This decrease occurs due to increase crop growth as irrigation increases.

The greatest crop growth in line with the irrigation increase is evidenced by leaf area index (LAI) showed in Fig. 3. Usually the leaf area and consequently the LAI of cotton crop, increase with increasing soil moisture. The lower crop growth provides lower ground cover which favors water loss by soil evaporation mainly if sprinkler irrigation system was frequently used. The frequent use of sprinkler irrigation system causes surface wetting intense. Thus, when the crop does not provide full surface coverage, soil evaporation losses are inevitable (López-Urrea et al., 2009, Cavero et al., 2009).

The means values of irrigation (I), yield (Y), and evapotranspiration (ET) of cotton crop for all treatments simulated by SWAP are showed in Table 4. The increments in the irrigation depth implied in the increments in ET values, while increments of irrigation depth did not implied in increments in the yield values, corroborating with described by Fereres & Soriano (2007). Note that crop yield increased as the irrigation increased from treatments under DI regimes to full irrigation condition. In the excessive irrigation depth treatment the yield decreased and presented values lower than presents to DI_{75}. The yield loss verified in the treatment under excessive irrigation is attributed to excessive vegetative growth that causes reduction in the total number of bolls by plants which occurs due to increased competitiveness for assimilated available. This yield loss can also be attributed to the appearance of diseases and nematodes in the roots of the plant due to excessive soil moisture in the root zone.

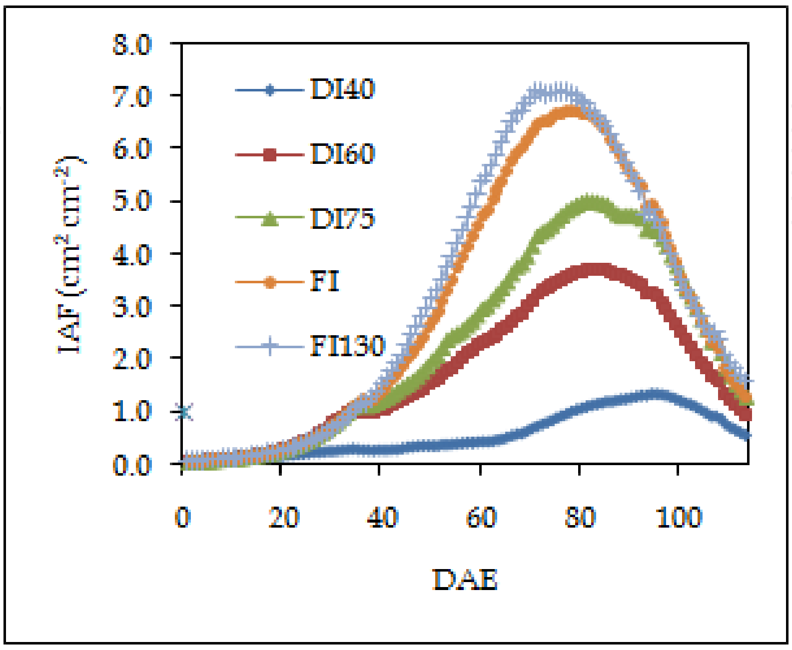


Fig. 3. IAF curves of all treatments simulated by SWAP

	I (mm)	Y (kg ha^{-1})	ET (mm)
DI_{40}	356	1367	345
DI_{60}	533	2167	491
DI_{75}	666	3336	625
FI	899	3517	734
FI_{130}	1154	3317	761

Table 4. Irrigation depth, yield and evapotranspiration of cotton for each treatment simulated by SWAP model

The relationships between evapotranspiration and irrigation and between yield and irrigation are showed in Fig. 4 (top). The Fig. 4 (bottom) shows the relationship between WP_{ET} and irrigation and between WP_I and irrigation.

The curves of these relations expose the reasons pointed by Fereres & Soriano (2007) which guide the DI practices. As showed in Fig. 4 the points I_M and I_W do not was located in same treatment. The crop yield was increasing from DI_{40} and reached its maximum value at the FI treatment. In the FI_{130} treatment the yield decreased in relation to FI treatment and present yield similar to DI_{75}. The ET, in turn increased in all treatment, corroborating with Fereres & Soriano (2007), i.e., additional irrigation amounts causes increase of crop ET. From FI to FI_{130} crop ET increased, unlike yield. So in the FI treatment was identified the I_M point. The I_W point was located in the DI_{75}. In this treatment the performance indicators of

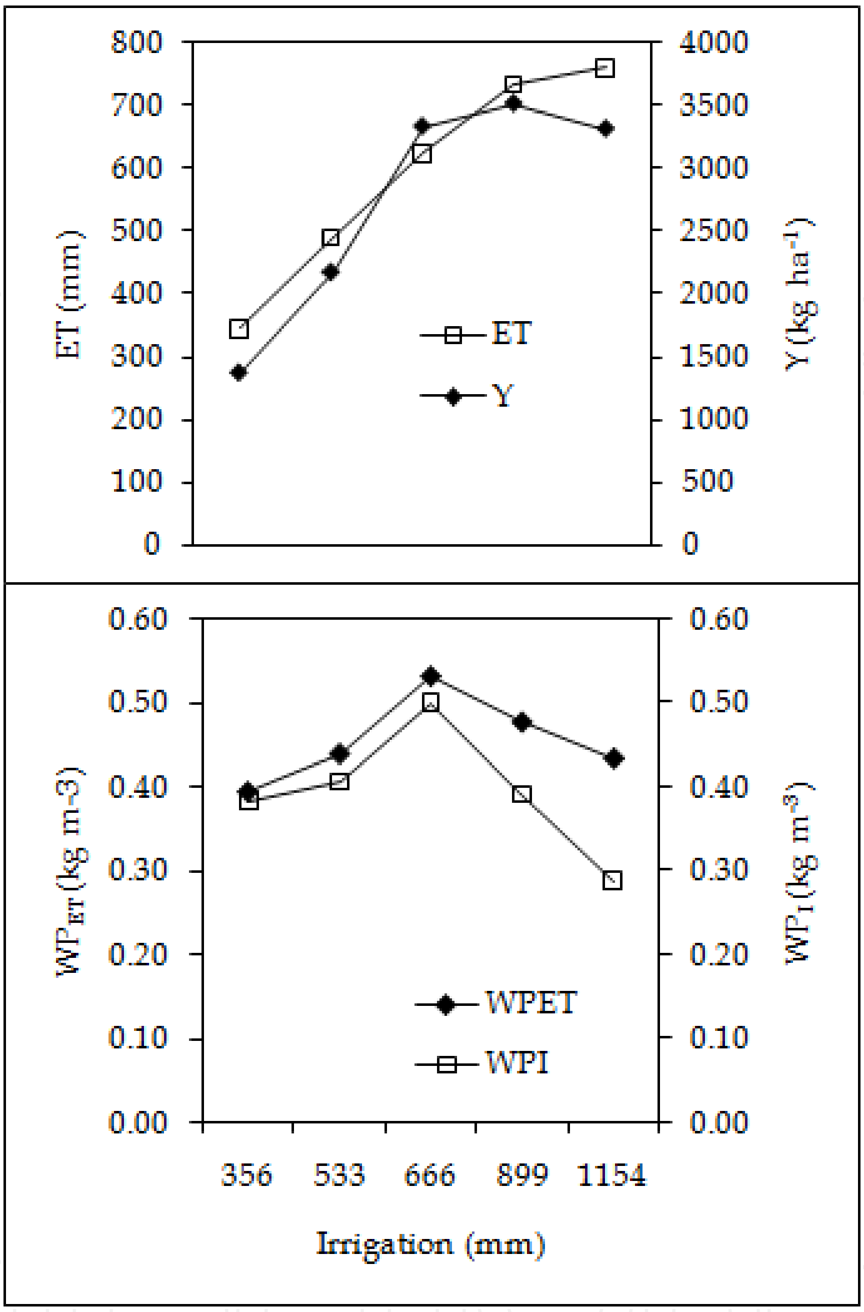


Fig. 4. Relationships between ET and irrigation and between yield and irrigation (upper) and WP_{ET} and WP_I curves of cotton crop in Brazilian semi arid

irrigations WP_{ET} and WP_I achieve its maximum values. The average WP_{ET} varied from 0.395 to 0.535 kg m^{-3} in both years (Table 5). WP_{ET} for the DI_{75} treatment was the largest, while for DI_{40} it was the smallest in both years. The WP_{ET} values increased with increasing water stress. However, from FI_{75} WP_{ET} decreased in such way that in FI_{130} excessive water treatment WP_{ET} value was equal to DI_{60}. Note that WP_I, unlike other studies (Dağdelen et al., 2009, Du et al., 2008, Ibragimov et al., 2007, Singh et al., 2010), was always less than WP_{ET}. This behavior could be attributed to groundwater depth of Brazilian semi arid which becomes impossible capillary rise. So, the water consumed by plants is restricting to irrigation water supplied.

	WP_{ET} (kg m^{-3})			WP_I (kg m^{-3})		
	2008	2009	Mean	2008	2009	Mean
DI_{40}	0.39	0.40	0.395	0.37	0.40	0.385
DI_{60}	0.43	0.45	0.440	0.37	0.44	0.405
DI_{75}	0.53	0.54	0.535	0.46	0.54	0.500
FI	0.48	0.48	0.480	0.38	0.41	0.395
FI_{130}	0.44	0.44	0.440	0.28	0.29	0.285

Table 5. Water Productivity values for cotton crop simulated by SWAP

These WP_{ET} values of cotton in semi arid lands of Brazil according to SWAP simulations were lower than most those of other studies in different regions (Table 6). This should be attributed to used irrigation system because in general the studies which used irrigation system less efficient, for example flood and furrow (Jalota et al., 2006, Saranga et al., 1998, and Singh et al., 2010) presented the worst performance.

Source	Irrigation system	WP_{ET} (kg m^{-3})	WP_I (kg m^{-3})
In this study	Sprinkler	0,39 – 0,54	0,38 – 0,50
Dağdelen et al. (2006)	Furrow	0,61 – 0,72	0,77 – 1,40
Dağdelen et al. (2009)	Drip	0,77 – 0,96	0,82 – 1,44
Du et al. (2008)	Drip	0,52 – 0,79	1,07 – 1,51
Ibragimov et al. (2007)	Drip	0,63 – 0,88	0,82 – 1,12
Ibragimov et al. (2007)	Furrow	0,46 – 0,50	0,55 – 0,62
Jalota et al. (2006)	Flood	0,26 – 0,31	0,25 – 0,87
Karam et al. (2006)	Drip	0,80 – 1,30	-
Saranga et al. (1998)	Furrow	0,22 – 0,35	-
Singh et al. (2010)	Drip	0,39 – 0,42	0,54 – 0,65
Tang et al. (2010)	Furrow	0,54 – 0,76	-
Ünlü et al. (2007)	Furrow	0,19 – 0,53	0,11 – 0,81
Yazar et al. (2002)	Drip	0,50 – 0,74	0,60 - 0,81
Yazar et al. (2002)	LEPA	0,55 – 0,68	0,58 – 0,78

Table 6. Comparison of WP_{ET} and WP_I values with other studies

4. Conclusions

The current global scenario on disputes over scarce water resources associated with climate change highlights the urgent need for the efficient water use in any human activity. In irrigated agriculture this need is even more relevant because more than 40% of total world food production comes from agricultural lands under irrigation. The water use efficiency in irrigated agriculture can be improved through the adoption of strategies, such as deficit irrigation (DI). It has been established that this can result in increased water productivity (WP). The use of DI as tool for agriculture water management was evaluated through simulations of the SWAP model. The results indicate that with DI it was able to increase WP of cotton crop in conditions of semi arid lands in Brazil, conforming to what has been reported in the literature. However, DI do not result in an increase of cotton yield per area used, but increased the relation between yield and consumed water. According to Fereres &

Soriano (2007) when water for irrigation is limited the goal should be to maximize net income per unit water used rather than per land unit. Thus, the DI strategy meets this criteria establishing water economy and achieving efficiency.

For the case of cotton crop in semi arid lands of Brazil, the treatment which presented superior performance was the DI_{75} treatment. In this treatment only 5% of irrigation water supplied was percolated, while in the full irrigation and excessive water (FI and FI_{130}) the percolated volume was more than 10%, resulting in substantial water losses and thus efficiency. Finally, based on the results DI practices it is recommended as an important tool for optimization in agriculture water management.

5. References

Allen, G.R., Pereira, S.L., Raes, D., Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requerements. *Food and Agrocultural Organization of the United Nations,* FAO-56. Rome. 300p.

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E. (2011). Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water Management*, Vol.98, No.6, (April 2011), pp. 899-920, ISSN 0378-3774,

Arya, S.P. (2001). *Introduction to Micrometeorology*, Academic Press, ISBN 0-12-059354-8, San Diego, United States.

Bezerra, B.G. (2011). *Avaliação da eficiência de uso da água no algodoeiro irrigado na Chapada do Apodi segundo simulações do modelo SWAP* (Evaluation of the water use efficiency for irrigated cotton crop at the Apodi Plateau second simulation of SWAP model). PhD thesis, Federal University of Campina Grande, Academy Unit of Atmospheric Science, Campina Grande, Brazil.

Bezerra, J.R.C., Azevedo, P.V., Silva, B.B., Dias, J.M. (2010). Evapotranspiração e coeficiente de cultivo do algodoeiro BRS-200 Marrom, Irrigado. *Revista Brasileira de Engenharia Agrícola e Ambiental*, Vol.14, No.6, (June 2010), pp. 625-632, ISSN 1807-1929.

Blad, B.L., Rosenberg, N.J. (1974). Lysimetric calibration of the Bowen Ratio-Energy Balance method for evapotranspiration estimation in the Central Great Plains. *Journal of Applied Meteorology*, Vol.13, No.2, (March 1974), pp. 227-236, ISSN 0894-8763

Bowen, I.S. (1926). The ratio of heat losses byu conduction and by evaporation from any water surface. *Physics Review*, Vol.27, No.6, (March 1926), pp. 779-787, ISSN 1063-651X.

Burba, G., Anderson, D. (2007). *A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and workflows examples for scientific and industries applications,* Li-Cor Biosciences, Retrieved from <https://www.licor.com/env/applications/eddy_covariance/book.jsp>.

Cavero, J., Medina, E.T., Puig, M., Martínez-Cob, A. (2009). Sprinkler irrigation changes maize canopy microclimate and crop water status, transpiration, and temperature. *Agronomy Journal*, Vol.101, No.4, (July 2009), pp. 854-864, ISSN 1435-0645.

Cetin, O., Bilgel, L. (2002). Effects of different irrigation methods on shedding and yield of cotton. *Agricultural Water Management*, Vol.54, No.1, 4, (March 2002), pp. 1-15, ISSN 0378-3774.

Dağdelen, N., Başal, H., Yilmaz, E., Gürbüz, T., Akçay, S. (2009). Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western

Turkey. *Agricultural Water Management*, Vol.96, No.1, (January 2009), pp. 111-120, ISSN 0168-1923.

Dağdelen, N., Yilmaz, E., Sezgin, F., Gürbüz, T. (2006). Water-yield relation and water use efficiency of cotton (Gossypium hirsutum L.) and second crop corn (Zea mays L.) in western Turkey. *Agricultural Water Management*, Vol.82, No.1-2, (april 2006), pp.63-85, ISSN 0168-1923.

Droogers, P., Immerzeel, W.W., Lorite, I.J. (2010). Estimating actual irrigation application by remotely sensed evapotranspiration observations. *Agricultural Water Management*, Vol.97, No.9, (September 2010), pp. 1351-1359, ISSN 0168-1923.

Droogers, P., Kite, G. (1999). Water productivity form integrated basin modeling. *Irrigation and Drainage System*, Vol.13, No.3, (September 1999), pp. 275–290, ISSN 1573-0654.

Du, T., Kang, S., Zhang, J., Li, F. (2008). Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China. *Irrigation Science*, Vol.26, No.2, (January 2008), pp. 147-159, ISSN 0342-7188.

Farahani, H.J., Oweis, T.Y., Izzi, G. (2008). Crop coefficient for drip-irrigated cotton in a Mediterranean environment. *Irrigation Science*, Vol.26, (July 2008), pp. 375-383, ISSN 0342-7188.

Feddes, R.A., Kowalik, P.J., Zaradny, H. (1978). *Simulation of Field Water Use and Crop Yield*. Simulation Monographs. Pudoc, Wageningen, The Netherlands.

Fereres, F., Soriano, M.A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany,* Vol.58, No.2, (January 2007), pp. 147-159, ISSN 0022-0957.

Figureola, P.I., Berliner, P.R. (2006). Characteristics of the surface layer above a row in the presence of local advection. *Atmósfera*, Vol.19, No.2, (April 2006), pp. 75-108, ISSN 0187-6236.

Folken, T. (2008). *Micrometeorology*, Spring-Verlag, ISBN 978-3-540-74665-2, Berlin, Germany.

Gavilán, P., Berengena, J. (2007). Accuracy of the Bowen ratio-energy balance method for measuring latent heat flux in a semiarid advective environment. *Irrigation Science*, Vol.25, No.2, (June 2006), pp. 127-140, ISSN 0342-7188.

Hou, L.G., Xiao, H.L., Si, J.H., Zhou, M.X., Yang, Y.G. (2010). Evapotranspiration and crop coefficient of Populus euphratica Olivi forest during the growin season in the extreme arid region northwest China. *Agricultural Water Management*, Vol.97, No.2, (February 2010), pp. 351-356, ISSN 0168-1923.

Hussain, I., Turral, H., Molden, D., Ahmad, M. (2007). Measuring and enhancing the value of agriculture water in irrigated river basins. *Irrigation Science*, Vol.25, No.3, (February 2007), pp. 263-282, ISSN 0342-7188.

Ibragimov, N., Evett, S.R., Esanbekov, Y., Kamilov, B.S., Mirzaev, L., Lamers, J.P.A. (2007). Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. *Agricultural Water Management*, Vol.90, No.1-2, (may 2007), pp. 112-120, ISSN 0168-1923.

Inman-Bamber, N.G., McGlinchey, M.G. (2003). Crop coefficients and water-use estimates for sugarcane based on long-term Bowen ratio energy balance measurements. *Field Crops Research*, Vol.83, (August 2003), pp. 125-138, ISSN 0378-4290.

IPCC, 2007 Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds S. D. Solomon, M. Qin, M. Manning, Z. Chen, M. Marquis, K. B.

Averyt, M. Tignor & H. L. Miller). Cambridge, UK and New York, USA: Cambridge University Press.

Jalota, S.K., Sood, A., Chahal, G.B.S., Choudhury, B.U. (2006). Crop water productivity of cotton (Gossypium hirsutum L.) – wheat (Triticum aestivum L.) system as influenced by deficit irrigation. soil texture and precipitation. *Agricultural Water Management*, Vol.84, No.1-2, (July 20067), pp. 137-146, ISSN 0168-1923.

Kang, S.Z., Zhang, J.H. (2004). Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. *Journal of Experimental Botany*, Vol.55, No.407, (November 2004), pp.2437–2446, ISSN 0022-0957.

Karam, F., Lahoud, R., Masaad, R., Daccache, A., Mounzer, O., Rouphael, Y. (2006). Water use and lint yield response of drip irrigated cotton to the length of irrigation season. *Agricultural Water Management*, Vol.85, No.3, (October 2006), pp. 287-295.

Kassam, A.H., Molden, D., Fereres, E., Doorenbos, J. (2007). Water productivity: science and practice – introduction. *Irrigation Science*, Vol.25, No.3, (February, 2007), pp. 185-188, ISSN 0342-7188.

Kroes, J.G., van Dam, J.C., Groenendijk, P., Hendricks, R.F.A., Jacobs, C.M.J., 2008. SWAP Version 3.2. theory Description and User Manual. Alterra-Report 1649, Alterra, Research Institute, Wageningen, The Netherlands, 262 pp.

Lee, X., Massman, W. and Law, B.E. (2004). *Handbook of micrometeorology. A guide for surface flux measurement and analysis*. Kluwer Academic Press, ISBN 1-4020-2265-4, Dordrecht, The Netherlands.

López-Urrea, R., Montoro, A., González-Piqueras, J., López-Fuster, P., Fereres, E., 2009. Water use of spring wheat to rise water productivity. *Agricultural Water Management*, Vol.96, No.9, (September 2009), pp. 1305-1310, ISSN 0168-1923.

Mavi, H.S., Tupper, G. J. (2004). *Agrometeorology: principles and application of climate studies in agriculture*, Food Products Press, ISBN 1-56022-972-1, New York, United States.

Molden, D. (1997). *Accounting for water use and productivity. SWIM Paper 1,* International Irrigation Management Institute (IIMI), ISBM 91-9090-349 X, Colombo, Sri Lanka.

Morison, J.I.L., Baker, N.R., Mullineaux, P.M., Davies, W.J. (2008). Improving water use in crop production. *Philosophical Transactions of the Royal Society B*, Vol.363, (February 2008), pp. 639-658, ISSN 1471-2970.

North, G.B., Nobel, P.S., 1991. Changes in hydraulic conductivity and anatomy caused by drying and rewetting roots of Agave deserti (Agavaceae). *American Journal of Botany*, Vol.78, p.906–915, ISSN

Oke, T.R. (1978). *Boundary Layer Climates,* Routledge, ISBN 0-203-71545-4, Abindon, United Kingdon.

Oweis, t.Y., Farahani, H.J., Hachum, A.Y. (2011). Evapotranspiration and water use of full and deficit irrigation cotton in the Mediterranean environment in southern Syria. *Agricultural Water Management,* Vol.98, No.8, (May 2011), pp.1239-1248, ISSN 0168-1923.

Perez, P.J., Castelvi, F., Ibañez, M., Rosell, J.I. (1999). Assessment of reliability of Bowen ratio method for partitioning fluxes. *Agricultural and Forest Meteorology*, Vol.97, No.3, (November 1999), pp. 141-150, ISSN 0168-1923.

Perry, C., Steduto, P., Allen, R.G., Burt, C.M. (2009). Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management*, Vol.96, No.11, (November 2009), pp. 1517-1524, ISSN 0378-3774.

Saranga, Y., Flash, I., Yakir, D. (1998). Variation in water-use efficiency and its relation to carbon isotope ratio in cotton. *Crop Science*, Vol.38, No.3, (March 1998), pp. 782–787, ISSN 0011-183X.

Silva, V.P.R., Azevedo, P.V., Silva, B.B. (2007). Surface energy fluxes and evapotranspiratio of a mango orchard grown in a semiarid environment. *Agronmy Journal*, Vol.99, (November 2007), pp. 1391-1396, ISSN 1435-0645.

Singh, Y., Rao, S.S., Regar, P.L. (2010). Deficit irrigation and nitrogen effects on seed cotton yield. water productivity and yield response factor in shallow soils of semi-arid environment. *Agricultural Water Management*, Vol.97, No.7, (July 2010), pp. 965-970, ISSN 0168-1923.

Steduto, P., Hsiao, T.C. (1998). Maize canopies under two soil water regimes: IV. Validity of Bowen ratio–energy balance technique for measuring water vapor and carbon dioxide fluxes at 5-min intervals, *Agricultural and Forest Meteorology*, Vol.89, No.3-4, (February 1998), pp.215-228, ISSN 0168-1923.

Steduto, P., Hsiao, T.C., Fereres, E. (2007). On the conservative behavior of biomass water productivity. *Irrigation Science*, Vol.25, No.3, (February, 2007), pp. 189-207, ISSN 0342-7188.

Strzepek, K., Boehlert, B. (2010). Competition for water for the food system. *Philosophical Transactions of the Royal Society B*, Vol.365, (September 2010), pp. 2927-2940, ISSN 1471-2970.

Stull, R.B. (1998). *An Introduction to Boundary Layer Meteorology*, Kluwer Academy Publishers, ISBN 90-277-2769-4, Dordrecht, The Netherlands.

Supit, I., Hooyer, A.A., van Diepen, C.A. (1994). System description of the WOFOST 6.0, crop simulation model implemented in CGMS, vol. 1: Theory and algorithms. EUR publication 15956, Agricultural series, Luxembourg.

Tang, L-S., Li, Y., Zhang, J. (2010). Partial rootzone irrigation increases water use efficiency, maintains yield and enhances economic porfit of cotton in arid area. *Agricultural Water Management*, Vol.95, No.10, (October 2010), pp. 1527-1533, ISSN 0168-1923.

Teixeira, A.H.C., Bastiaanssen, W.G.M., Ahmad, M.D., Bos, M.G. (2009). Reviewing SEBAL input parameters for assessing evapotranspiration and water productivity for the Low-Middle São Francisco River basin, Brazil Part B: Application to the regional scale. *Agricultural and Forest Meteorology*, Vol.149, No.3-4, (March 2009), pp. 477-490, ISSN 0168-1923.

Thornthwaite, C.W. (1948). An approach toward a rational classification of climate. *Geographical Review*, Vol.38, No.1, (January 1948), pp. 55-94, ISSN 0016-7428.

Todd, R.W., Evett, S.R., Howell, T.A. (2000). The bowen ratio-energy balance method for estimated latent heat flux of irrigated alfalfa evaluated ina asemi-arid advective environment. *Agricultural and Forest Meteorology*, Vol.103, No.4, (July 2000), pp. 335-348, ISSN 0168-1923.

Tucci, C.E.M. & Beltrame, L.F.S. (2009). Evaporação e evapotranspiração, In: *Hidrologia: Ciência e Aplicação*, C.E.M. Tucci, (Ed.), 253-287, UFRGS Editora, ISBN 978-85-7025-924-0, Porto Alegre, Brasil.

Ünlü, M., Kanber, R., Onderm, S., Metin, S., Diker, K., Ozekici, B., Oylu, M. (2007). Cotton yields under different furrow irrigation management techniques in the Southeastern Anatolia Project (GAP) area. Turkey. *Irrigation Science*, Vol.26, No.1, (October 2007), pp. 35-48, ISSN 0342-7188.

van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G. (2008). Advances of modeling water flow in variably saturated soils with SWAP. *Vadose Zone Journal*, Vol.7, No.2, (May 2008), pp.640–653, ISSN 1539-1663.

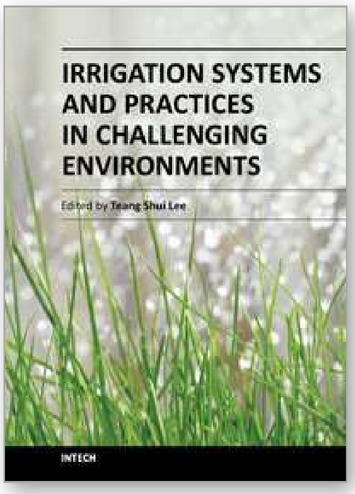
Webb, E.K., Pearman, G.I., Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorology Society*, Vol.106, No.447, (January 1980), pp. 85-100, ISSN 0035-9009.

Wilks, D.S. (2006). *Statistical methods in the atmospheric science*, Academic Press, ISBN 978-0-12-751966-1, San Diego, United States.

Yazar, A., Sezen, S. M., Sesveren, S. (2002). LEPA and trickle irrigation of cotton in the Southeast Anatolia Project (GAP) area in Turkey. *Agricultural Water Management*, Vol.54, No.3, (Aril 2002), pp.189-203, ISSN 0168-1923.

Zhang, J.H., Jia, W.S., Kang, S.Z. (2001). Partial rootzone irrigation: its physiological consequences and impact on water use efficiency. *Acta Botanica Boreali-occidentali Sinica*, Vol.21, No.2, (March 2001), pp. 191-197, ISSN 1000-4025.

Zwart, S.J., Bastiaanssen, W.G.M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, Vol.69, No.2, (September 2004), pp. 115-133, ISSN 0168-1923.



Irrigation Systems and Practices in Challenging Environments
Edited by Dr. Teang Shui Lee

ISBN 978-953-51-0420-9
Hard cover, 370 pages
Publisher InTech
Published online 28, March, 2012
Published in print edition March, 2012

The book Irrigation Systems and Practices in Challenging Environments is divided into two interesting sections, with the first section titled Agricultural Water Productivity in Stressed Environments, which consists of nine chapters technically crafted by experts in their own right in their fields of expertise. Topics range from effects of irrigation on the physiology of plants, deficit irrigation practices and the genetic manipulation, to creating drought tolerant variety and a host of interesting topics to cater for the those interested in the plant water soil atmosphere relationships and agronomic practices relevant in many challenging environments, more so with the onslaught of global warming, climate change and the accompanying agro-meteorological impacts. The second section, with eight chapters, deals with systems of irrigation practices around the world, covering different climate zones apart from showing casing practices for sustainable irrigation practices and more efficient ways of conveying irrigation waters - the life blood of agriculture, undoubtedly the most important sector in the world.

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821