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Effect of Harvest of Air Relative Humidity on Water and Heat Transfer in Soil With Crops Under Arid Climatic Conditions

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ABSTRACT

In this work, the main objective is to analyze the effect of the harvest of air relative humidity on soil temperature, soil water storage and evaporation. An experiment work was conducted in order to evaluate the quantity of soil water adsorbed by harvesting of relative air humidity. This experimental work was conducted on hilly areas with various hypsographic and microclimatic conditions greatly affecting daily fluctuations of air humidity and soil characteristics. The metrological data needed by SISPAT model were obtained by using a Campbell Scientific equipments Station recorder on data loggers every half hour. A numerical model based on SiSPAT (Système d'Interaction Sol Plante Atmosphère) formulation is adopted. The general equations of the proposed model are based on heat and mass transfer in the soil, atmosphere and plant system. This study shows that Soil Water Adsorption (SWA) induce an increasing in the total evaporation and in soil water storage especially on the upper layers. The effect of Soil Water Adsorption on soil temperature appears for the first layers of soil and become absent in the profound zone because the vapour condensation phenomenon is very important at night for the first layers.

Keywords - Harvest, relative air humidity, soil water content, water vapor adsorption, evaporation, .

I. INTRODUCTION

In Mediterranean regions, the development of agriculture is strongly depending on climatic conditions and their economical and social situations are usually unstable. Controlling the consequences of the interaction between human and climatic activities in arid and semi-arid areas is very important and based on the understanding of different processes above all those that are determinant in the hydric balance. The objectives of reducing unbalances in water requirements vs water availability in most arid and semi-arid areas of the Mediterranean region, since by capturing atmospheric moisture a potential enhancement in water available to crops can be achieved without subtracting water to domestic and industrial uses, thus soothing social strains. Finally, the major advantages of exploitation of atmospheric humidity is that it can be captured at zero cost and that a reduction in energy input can be obtained (no water lifting from deep wells, no pressurization are required) as well as the good quality of captured water. In conclusion, the study has such social, economical and environmental advantages. A review in literature indicates that two major's uses in collection of water vapour are dominated.

In this study we have interesting to the atmospheric humidity harvest for agricultural uses. The existing systems for collection were the same in all Mediterranean regions. The importance of this study result on important contribution of harvest relative humidity for stopping desertification especially for our country. In last decade, an important support of works was developed by many institutions research. Generally, the soil is considered as a porous medium with capillaries of various sizes that helping the condensed water to infiltrate by capillarity, [1]. An intensive work was presented to enrich literature in this field. The study developed by [2] indicated that the fluctuations observed in water content profiles is essentially marked in the first upper layer of soil (15-20 cm) that containing major of root of crops. These fluctuations depend on initial moisture of soil and soil porosity. The authors showed that under conditions of moderate water stress, water conservation was generally greater in the stony soils than in soils free of rock fragments.

By referring to [3] and [4], the authors have indicated that soil is considered as a porous medium with capillaries of various diameters. These capillaries condensed water to infiltrate by capillarity but in the same time in the capillaries occurs also condensation of water vapor depending on the air relative humidity. In this work, the authors tried out to qualify water vapor adsorption by soil by using weighing Lysimeters (WL) and Time Domain Reflectometers (TDR) for obtaining data under semi arid climatic conditions. The result shows that the soil moisture content in the upper soil layer fluctuates in correspondence with the diurnal fluctuations of the relative air humidity. Also, they indicate that the process of water vapor adsorption by the sol appears to be more important for areas in which the geomorphological conditions and the proximity to the surface water, such as lakes or sea, favors high diurnal fluctuations in relative air humidity. In the more recent study conducted by [4], the authors show that the contribution of surface water in the neighborhoods is very important; this is why water adsorption by the soil is particularly efficient in coastal areas. The amount of water vapor adsorbed by the soil could replace about 70% of water loosed by evaporation during dry periods under arid or semi arid climatic conditions.

In this study we have interesting to the atmospheric humidity harvest for agricultural uses. The existing systems for collection were the same in all Mediterranean regions. The importance of this study result on the important contribution of harvest relative humidity for stopping desertification especially for our country. In many regions of word, precipitation is normally considered as the only source of groundwater. In fact, it is the only source of fossil water in the past. However, there are areas, primarily in upland regions, where the collection fog droplets by vegetation can not only support the vegetation but also make contributions to aquifers. In the humid tropics these regions are known as cloud forests because the source of the fog is clouds moving over the terrain, [5].

An intensive work was presented to enrich literature in this field. The authors attempt to approach and simulate the above described complicated phenomena of capillary condensation by using either fractal, [6] , different methods, [7] or Monte Carlo, [8]. Many approaches were conducted in order to modulate of transport of condensable vapors in porous structures, [9] and [10]. Theses studies indicate that the condensable vapors in the pore are generally attributed to the sorption of the water molecules. Other studies indicate that the capillary condensation is the studies of sorption of water by building materials [11], absorption of water into a porous media containing non-sorptive inclusions, [12].

In early experimental study conducted by [13], the authors has been demonstrated that the soil moisture content of the upper soil layers fluctuates in the same manner of the diurnal fluctuation of water evaporation from the free surface. The amplitude of the diurnal fluctuation decreased with soil depth and time, and the daily maxima and minima exhibited an increasing phase lag at greater depth, [14]. So, the importance of dew for crop growth has already been observed by [15]. The authors has found that in a one month period, the amount of dew water accumulated on corn and soybeans grow in Indiana reached as much as 13 and 33 mm, respectively.

An important support of works was developed by many institutions research. Generally, the soil is considered as a porous medium with capillaries of various sizes that helping the condensed water to infiltrate by capillarity, [16] and [17].

The work conducted by [18] is interested to the evaluation of a two stage evaporation approximation for contrasting vegetation cover by using a full analytical solution and SISPAT model. The result of the full solution is closer to the evaporation rate time series simulated by SISPAT than the asymptotic approximations. The full solution can be used to improve the supply limited soil evaporation and transpiration rates in the operational tools for irrigation forecasting such as the FAO method.

In recent study, [19] have study the effect of many important parameters on humidity harvesting such: maximal and minimal air relative humidity, the soil potential of water, the average temperature of air and we have present some correlation laws. Also, we have noted that the state of soil has an important effect on humidity harvesting, because when the soil is humid, the soil temperature decreases and the condensation becomes more important than a dry soil. They have presented some new results in order to estimate the real contribution of harvesting humidity in the total water balance. The evapotranspiration is been estimated and it is demonstrated that for such climatic conditions and soil characteristics, water captured from air relative humidity contribute about 30% of the total water balance.

II. PROBLEM FORMULATION

1. Soil storage model

In order to modeling the soil storage water, two approaches were used. The first is based on the root zone water balance during a specified period of time may that expressed by the following expression:

$$\Delta S + \Delta V = P + I + U - (R + Dr + E + Tr) \qquad (1)$$

Where ΔS is the change in root-zone soil-moisture storage, ΔV is the amount of water incorporated in vegetative biomass, P is the amount of precipitation, I is the amount of irrigation water applied, U(Z, t) is the amount of water moved upward into the root zone by capillary flow, R is the amount of rainfall per unit area, Dr is the amount of downward drainage out of the root zone, E the amount of evaporation from the soil surface, and Tr is the amount of water transpired by plants.

2. Measurement of soil water adsorption by harvest of relative air humidity

Several reaches have been qualified the diurnal fluctuations in measurement of soil moisture content to the adsorbed water by soil during night especially when optimal values for air temperature and relative humidity were attempt, [3] because the evaporation and transpiration were stopped. So, when a dry soil adsorbs from the atmosphere, the phenomenon of diffusion and adsorption are simultaneously occurred. The water diffusivity D (mm^2s^{-1}) as a function of soil water content is expressed by the following expression:

$$D = -\frac{1}{2}\frac{d\lambda}{d\theta}\int_{\theta_i}^{\theta}\lambda d\theta \qquad (2)$$

Where θ_i is the initial water content (cm^3cm^{-3}), λ a parameter which can be estimated by the Boltzman transform equation: $\lambda = xt^{-1/2}$ with t=time (min) and x=distance (cm). D(θ) is the flow parameter controlling sorption. It can evaluate from the distribution of water content with distance at any time. The total water adsorbed (Q_{ad} in cm of water) by the soil is given by:

$$Q_{ad} = U(z,t) = \int_{\theta_i}^{\theta} x d\theta \;=\; t^{1/2}\int_{\theta_i}^{\theta}\lambda d\theta \;=\; Sor \times t^{1/2} \qquad (3)$$

Where: Sor is sorptivity, in $cm.s^{-1/2}$. The sorptivity is considered a water content function in equilibrium with atmospheric relative humidity and soil initial water content (θ_i). This sorptivity is described as a measure of the capacity of the medium to absorb liquid by capillarity. The result (not presented here) shows that the maximum of water adsorption by the soil coincides with the maximum of relative air humidity normally reaching from midnight to five, six or seven o'clock in the morning that lets consider that adsorption was proportional to the drop of the relative air humidity, depending also on soil conditions (Rainfall, irrigation, mulching etc…) and period of year. This result has been demonstrated by [3]. According to the evaporation from the soil surface ceased during this period, the adsorption of water is attributed to the increase of soil moisture content during this time.

3. Simulation of water flow by SiSPAT Model

SiSPAT is a one-dimensional model, assuming that horizontal heat and water transfer in the soil-plant-atmosphere continuum can be neglected and that movements can be considered as vertical, [20]. In the soil, coupled heat and water transfer are considered. They include liquid and vapor phase transfer. A sink term accounting for water extraction by roots is also considered. The model can deal with soils made of several horizons, characterized by different hydrodynamic and thermal properties.

The model of heat and water transfer in the soil-plant-atmosphere system described here was designed to reach at least two goals:

i) to give as physical as possible a representation of the main processes involved: coupled heat and water movement in the non-saturated zone, plant root uptake, turbulent transfer above and within the canopy, interception, infiltration and surface runoff, ii) to achieve a balanced degree of simplification between the various compartments of the model. The model, called SiSPAT, is a unidirectional model theoretically suited for studies at the field scale, although it has tentatively been applied at much larger scales. In the soil, coupled heat and water transfer equations are solved with a sink term corresponding to plant root uptake.

The approach of [21], modified by [22], forms the basis of the model of coupled moisture and heat flows in a partially saturated porous medium used in the SiSPAT model. The dependent variables are the temperature T and the soil matric potential of water h. With the choice of matric potential, the model is able to deal with no homogeneous soils, made up of several horizons, because the matric potential is continuous at the interface of these horizons. The corresponding one dimensional equations for vertical movement (axis Z orientated positively downward) are given by [23] as follow:

$$C_h\frac{\partial h}{\partial t} = \frac{\partial}{\partial Z}\left(D_{mh}\frac{\partial h}{\partial Z} + D_{mT}\frac{\partial T}{\partial Z} - K\right) - \frac{S}{\rho_w} \qquad (4)$$

(3)

$$C_T\frac{\partial T}{\partial t} = \frac{\partial}{\partial Z}\left(D_{Ch}\frac{\partial h}{\partial Z} + D_{CT}\frac{\partial T}{\partial Z} - K\right) \qquad (5)$$

III. MATERIALS AND METHODS

1. Description of site

In order to evaluate the importance of harvest relative air humidity effect on soil water content under different land characteristics, the following site named (S1) is chosen. It's characterized by intensive agricultural activities and the irrigation covered only 20% of the agricultural areas. This site is located in Marrakech Tensift Alhaouz region and about 60 from Marrakech city at an average elevation of 600m above see level. The relief of this region is characterized by a great diversity: the interior flats and plates that contain good arable lands; the old solid masses, the littoral plates and high mountains of the Atlas. The climates are warm and dry a relativity cold period during the winter. Precipitations are weak and irregular (in Marrakech 240 mm/year). The summery temperatures are very high (37.7°C at maximum) and the winter ones are low (4.9°C at minimum). The evaporation is important (2300 mm/year) and the rainfall is variable: 50% of the territory has an averaged-300 mm-rainfall per year and almost 30% has a rainfall ranging from 300 to 400 mm per year (Toufliht station).

2. Man characteristics of the study soils

The constitution of (S1 and S2) soils is dominated clay constitution (47% and 39%) and lemon (34% and 40%). However the constitution of (S3) is principally dominated by sand (52%) and lemon (34.5%). For This study, the relation-ships between soil water content and soil water potential, and between hydraulic conductivity and water content are given respectively by[24] and [25] formulas :

$$\frac{\theta}{\theta_s}=\left[1+\left(\frac{\psi}{\psi_g}\right)^n\right]^{1-(2/n)} \quad \text{and } K=K_s\left(\frac{\theta}{\theta_s}\right)^{\eta} \qquad (6)$$

3. Climate data

The climatic forcing needed was averaged over a 30-min time step. Global radiation, atmospheric humidity, speed of wind, temperature (max and min) and rainfall were measured at the follow sites described above. For the studied site, the results given by meteorological station for ten years in term of average annual relative air humidity, air temperature, evaporation and wind speed, indicate that the average annual relative air humidity varies from 58% to 85%. The average annual air temperature varies from 11°C to 21°C. The wind speeds indicate that all locations are favourable to harvest of relative air humidity because the average values of wind speed were situated between 1.8 m/s to 3.4 m/s. The average total evaporation is very important that varying between 1500 to 2200 mm / year.

IV. RESULT AND DISCUSSIONS

The soil water adsorption (SWA, in mm of water) is calculated by using the differences between maximal and minimal volumetric water moisture content d_θ(cm^3/cm^3) occurred at night for each section of soil and multiplied by the section of soil Z (in mm) as demonstrated by the following expression : SWA= $d_\theta \times$ Z. The result show that d_θ increase when irrigation or rainfall is applied and fluctuated as the same variation of air relative humidity. These variations were important in the first soil depth. For the first day of the measured data, show that the values of d_θ increase with 300% when Z passes from 20cm to 5cm. For a given day, d_θ is equal to zero and the value increase with decreasing Z. The variation of soil water due to water vapour adsorption fluctuates with time.

In order to explain the contribution of soil water adsorption in total soil water, we present the variation of the cumulative of soil water adsorption, CWA, with time for all soil depth. The result presented at Fig. 1 show that the cumulative of soil water adsorption is an increasing function of time for the studied depths. The maximum of cumulative soil water adsorption is observed when Z varies from Z=0 to 10 cm. When Z≥20 cm the cumulative soil water adsorption is a decreasing function of depth. These decreases are due to the reduced of amplitude of undulation of soil moisture content. For 134st day, the cumulative soil water adsorption is 5,2 mm, 8,1 mm and 10,5 mm respectively for Z=20, 5 and 10 cm.

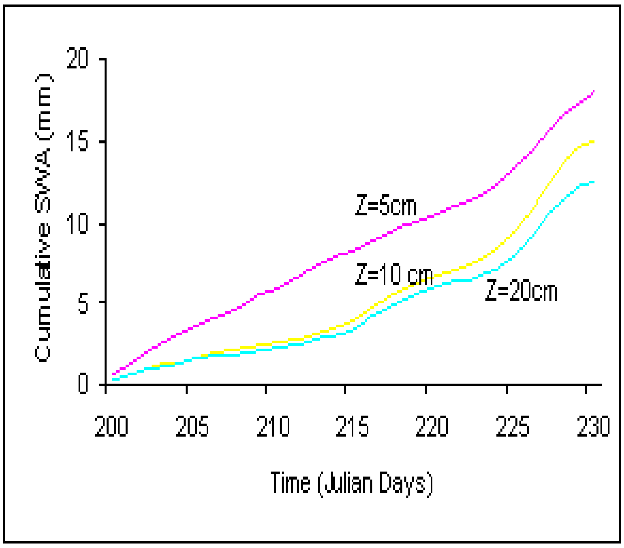
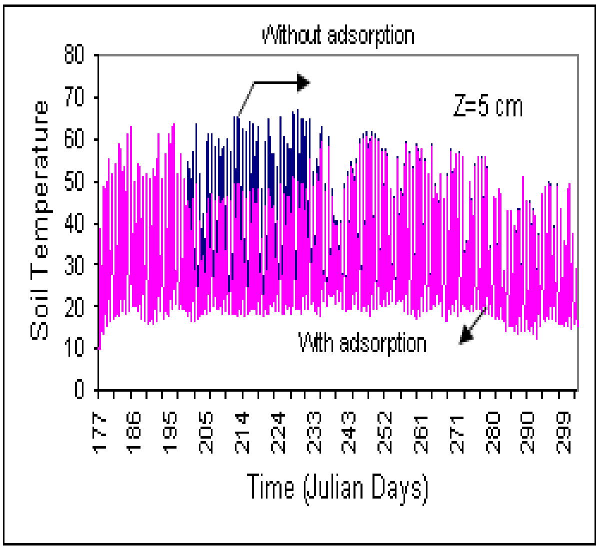


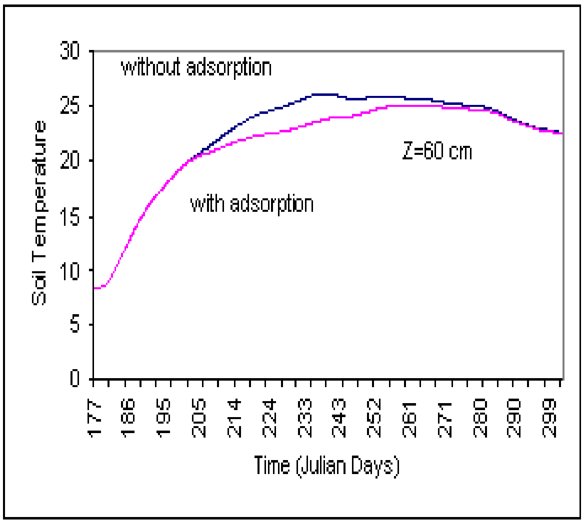
Figure 1: Cumulative soil water adsorption.

1. Effect of soil water adsorption on soil temperature

The result given by SiSPAT model calibrated on the soil characteristic an d meteorological data for the studied site indicate that soil water adsorption has a very important effect of temperature soil especially for the first depth of soil, Fig. (2a) and this effect become insignificant when Z increases (Fig. 2b). So, when adsorption is occurred, the temperature decreases from the 199th to 229th Julian days according to the period of soil water adsorption. This decrease is due to nocturne condensation phenomenon. The maximum difference of soil temperature observed is about 10°C and when water adsorption is not implicated, the results of soil temperature are the same.



(a)



(b)

Figure 2: Effect of harvesting of relative air humidity on soil temperature.

2. Effect of soil water adsorption on evaporation

The result presented in figure 3 show a very important effect of soil water adsorption on the total evaporation rate. They indicate that when soil water adsorption is considered by the SiSPAT model, the evaporation increases quickly in this period and become uniform when the soil water adsorption is not considered. This increases is about 80 mm but they appears only on the first soil layers (Z=5 and 10 cm). The effect of soil water adsorption on the evaporation becomes very weak for the profound sections (Z≥20 cm).

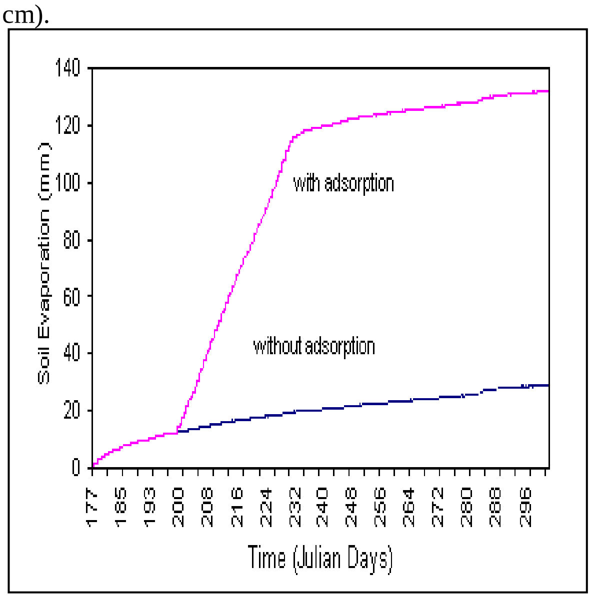


Figure 3: Effect of relative air humidity capitation on soil total evaporation.

3. Effect of soil water adsorption on soil water storage

The effect soil water adsorption by relative air humidity on soil water storage is shown in figure 4. The result indicate that when soil water adsorption is taken into the simulation, the soil water storage increase because the soil water content become an increasing function of time. When soil water adsorbed is stopped, the soil water storage decrease with time since 231th. This quantity of water can supported the evaporation observed at this period and the crops can be crows under these climatic conditions. The contribution of soil water adsorption is considered important that must be introduced in the total soil water storage. Its contribution is about 50% of losses due to evaporation process.

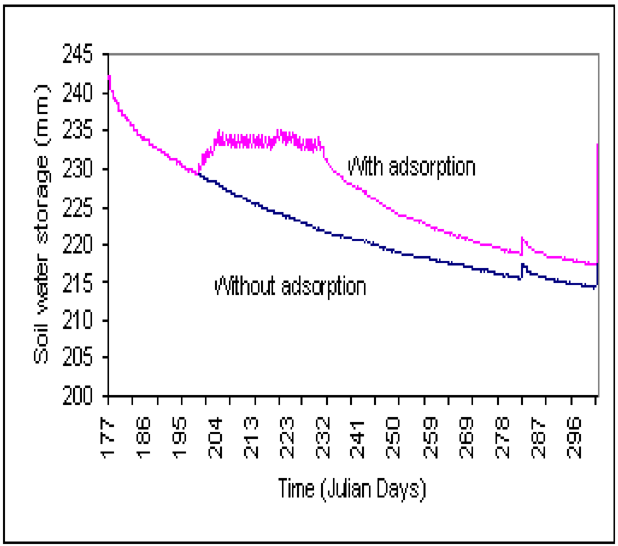


Figure 4: Effect of relative air humidity capitation on soil water storage.

4. Effect of water captured from humidity on total water balance

In order to quantify the contribution of water captured from air relative humidity on total water balance, we present some results corresponding to site (S3) during the period of April through December 2005. The results shown in Table 1 indicate that the average minimum and maximum values of RH fluctuate at 88% and 57% respectively. The atmosphere remained even drier during summer and the daily fluctuation of the amplitude of RH created a significant water vapour adsorption by the soil during the night. The total evapotranspiration ET is calculated by using Penman formulation from experimental data. The contribution of both water vapour adsorption and condensation in total water needed are given in table 1. The results indicate that ET fluctuates in accordance with solar energy radiation and presents a maximum in summer and a minimum in winter. The contribution of sorption (water directly adsorbed by biological process of plants) is not considered in this study, because, this micro physiological term is very difficult to evaluate. The results demonstrate the great importance of CWG (Cumulative Water Adsorbed) under the prevailing climatic conditions in the studied area. A total amount of 570 mm of CWG was adsorbed by the soil during the period from April through December 2005, while during the same period, the total amount of rainfall was only 168 mm and the total water loss by evapotranspiration was 2035 mm, and varying as shown in figure 5. By referring to the results presented in table 1, the contribution of CWG accounts for 28% of the total water demand, while the rainfall contribution is limited to 7.5%. These results change with site and climatic conditions. Finally, we can concluded that the existence in the area of summer growing natural and cultivated vegetables without of rain or irrigation water can be realized by water adsorbed from air relative humidity. This phenomenon contributes to the soil a significant amount of water especially during spring and summer, which may positively affect the existing rainfed vegetation and protect large areas from desertification.

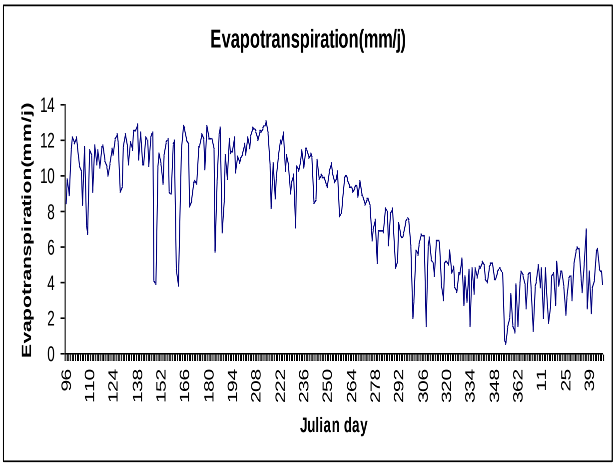


Figure 5: Daily variation of ET during period April 2005 to February 2006.

Table 1: Contribution of humidity harvesting on water demand for non-irrigated crops.

Month	Solar Radiation (KW.m^2)	Maximum Relative Humidity(%)	Minimum Relative Humidity(%)	Temperature (°C)	Win Speed (m/s)	ET (mm)	Rainfall (mm)	CGW (mm)
April	0 ,27	85,7	57,6	16,6	2,0	241,9	0,8	86.1
May	0,28	88,6	63,8	18,4	1,8	289,7	1	66.2
June	0,27	90,3	65,1	20,8	1,4	285,5	0,4	73.1
July	0,29	87,4	63,4	21,5	1,5	300,5	0	52.3
August	0,27	89,9	65,4	22,7	1,2	287,5	0	57.5
September	0,24	88,3	64,1	21,5	1,3	210,1	0,8	68.6
October	0,18	89,3	55,4	20,5	1,3	165,3	24	50.1
November	0,13	86,7	56,5	16,0	1,6	143,0	71	64.7
December	0,11	88,6	61,0	13,9	1,8	117,0	70	52.3
Total						2035.5	168	570.9

V. CONCLUSION

The combined experimental and numerical models for estimating the soil water storage and analyzing the effect of soil water adsorption on soil temperature and soil evaporation has been conducted. The SiSPAT model is calibrated on reel soil characteristics and meteorological data that characterizing the studied site. The Experimental data obtained by Time Domain Reflectometers indicate that soil moisture content in the upper soil layer fluctuates with the same manner to diurnal fluctuation of relative air humidity. These fluctuations due to water vapour adsorption decreased with increasing soil depth and daily amplitude of air relative humidity. The contribution of water vapour adsorption is considered important that must be introduced in the total soil water storage. Its contribution is about 50% of losses due to evaporation process. The incorporation of Soil water Adsorption (SWA) in the general formulation of SiSPAT model give the reel estimation of evaporation and estimate correctly the time to stress for a given combination of soil type and climatic data. This study shows that SWA induce an increasing in the total evaporation and in soil water storage especially on the upper layers. The effect of SWA on soil temperature appears for the first surface of soil and become absent in the profound zone because the vapour condensation phenomenon is very important at night for the first layers.

With the present model, a conceptual mathematical formulation and experimental input data concerning the greatest part of the complicated heat and mass transfer phenomenon taking place by atmospheric humidity harvest processes is developed. This model predict the efficiency in daily water production or direct water supply for the plants would permit to the optimization of the use of these techniques and would enlarge their application in arid areas.

Finally, The main objectives of this work are the following: to give as physical as possible a representation of the main processes involved: coupled heat and water movement in the non-saturated zone, plant root uptake, turbulent transfer above and within the canopy, interception, infiltration and surface runoff ; to achieve a balanced degree of simplification between the various compartments of the model. The model, called SiSPAT, is a unidirectional model theoretically suited for studies at the field scale, although it has tentatively been applied at much larger scales. In the soil, coupled heat and water transfer equations are solved with a sink term corresponding to plant root uptake.

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