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Model Based Study of Crop Evapotranspiration under Canopy Shading

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Abstract: California has some of the key agricultural regions in the United States. One of these key regions, San Joaquin Valley, frequently experiences severe droughts leading to shortage of irrigation water. This has a significant impact on the agricultural based economy of the region. It is imperative to develop new strategies to reduce overall water consumption in agriculture without affecting crop yield. A large fraction of irrigation water is lost due to the evapotranspiration (ET) process in the crops and the soil. The classical Penman-Monteith model has been used in the present work to analyze the effect of different environmental variables and water saving strategies on the ET. Some of the scenarios considered show potential for significant water savings without much reduction in the amount of sunlight available to facilitate crop growth. The central idea considered in this study is the use of canopy shading to cover the crop field resulting in reduction in the ET. Among the strategies considered, the most promising strategy is to partially cover the crop field for a certain part of the day by employing a partially covering retractable canopy. Based on numerical calculations, total reduction in ET is calculated to be 37% from June to August for the partially covering retractable canopy.

Keywords: parametric study; water saving; evapotranspiration; canopy shading; FAO Penman–Monteith

1. Introduction

California has the highest agricultural production in the United States with total revenues exceeding $47 billion [1]. The climate and soil are favorable for growing crops but scarcity of annual rainfall is leading to severe droughts, affecting the crop yield, and hampering the local economic development [2,3]. While advanced irrigation technology has somewhat alleviated the situation, frequently occurring drought events may still lead to shortage in irrigation water. Crops typically lose significant amount of irrigation water due to the evapotranspiration (ET) process. This opens up the possibility to save irrigation water by reducing the ET rate in the crop-soil system.

Crop water requirement depends on the growth conditions as well as internal and external factors [4,5]. Biological characteristics, crop species, and growth stage are some of the internal factors influencing the water requirement of a crop. On the other hand, external factors can be classified as climatic and soil conditions. Climatic conditions include solar radiation, temperature, relative humidity, water surface evaporation, wind speed, etc. Soil texture and soil moisture content are some of the key factors related to soil conditions. In case of sufficient soil moisture, climatic conditions can become the limiting external factors affecting crop water demand (as shown in Figure 1). Typically, the amount of water used for the irrigation exceeds the crop water requirement and one of the mechanisms responsible for the loss of water is the ET process.

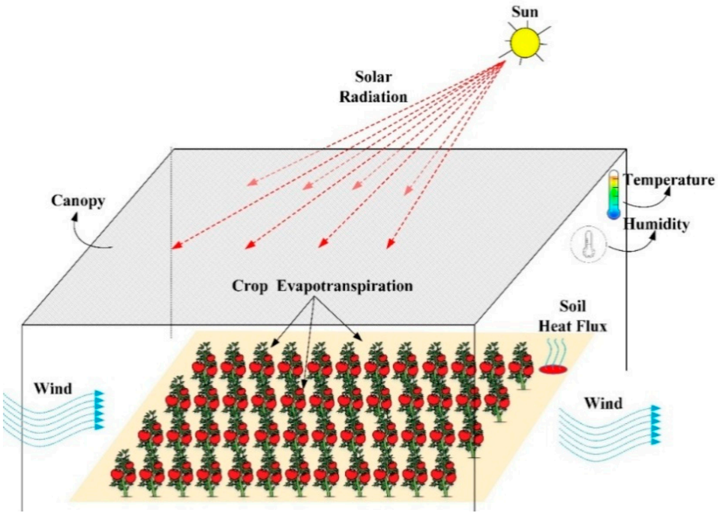

Figure 1. Schematic diagram of climatic conditions and their impact on crop evapotranspiration (ET).

ET is the simultaneous process of transfer of water to the atmosphere by transpiration and evaporation in a soil–plant–atmosphere system [6–8]. The process of measuring crop ET is typically influenced by multiple factors which are difficult to control. Beside the direct measurement through lysimeters [9,10], the Crop ET can be estimated by the indirect method of combining crop reference evapotranspiration (ETo) with crop coefficients (Kc) [11]. This idea of having a reference crop ET is fundamental to study not only irrigation planning and management but also for climatological and hydrological studies [12–15].

There are a number of methods for obtaining ET, which can be roughly divided into two main categories. One is direct/indirect field measurement method, such as in-situ weighing lysimeters [16–18], the eddy covariance method [19–21], Bowen ratio-micrometeorological energy balance method [22–24], the surface renewal method [25,26], and soil water balance method [27]. The other method is based one estimation by some weather data from temperature, relative humidity, wind speed, solar radiation, etc., such as Hargreaves-Samani method [28], Irmark-Allen method [29], Priestley-Taylor method [30], and comprehensive Penman–Monteith method [31]. Besides, there are also some empirical formulas [32]. By applying and comparing these different ET calculation methods, the Penman–Monteith method has been demonstrated to be the most accurate and adaptable to all climatic conditions [12,33,34]. First published in 1998 by the Food and Agriculture Organization of the United Nations [31], it has been considered as a universal standard to calculate ET for more than two decades. Many parameters related to the ET process such as solar radiation, air temperature, vapor pressure deficit, and wind speed have been considered in this method. This method has been found to be in very good agreement when compared with data from lysimeter measurements over grass or alfalfa surfaces.

In the past different methods to calculate and measure ET have been used to study effect of shading screen on the ET and water use efficiency [35–37]. Reduction in ET and increase in water use efficiency due to the use of shading of screen have been reported [35–37]. Using a black shading screen, a reduction of 38% in crop water requirement has been reported [36]. Similarly, an increase of 25% in water use efficiency has also been reported [37].

In this study, using the FAO Penman-Monteith method, several water-saving strategies including the use of shading screen have been analyzed. At first, the FAO Penman–Monteith method is introduced in detail. Then, the effect of several external factors on the ET has been studied by varying one parameter at a time while using the measured values for the rest of the parameters. This model-based parametric study helps identify the key parameters which would lead to significant water savings. A simple energy balance analysis on the crop field leads to Equation (1) as given below [38,39],

$$R_n = \lambda E + H_s + G + Q_r \tag{1}$$

where R_n is net radiation; λE is latent heat flux; H_s is sensible heat flux; G is soil heat flux and Q_r is the residual of the closure of the energy balance which includes advection, CO_2 flux, storage and metabolic activity.

Water loss due to the ET can be reduced by reducing the latent heat flux. For some fixed amount of net radiation (R_n), the latent heat flux (λE) due to ET can be reduced by allowing the sensible heat flux (H_s) or the soil heat flux (G) to increase. However, there is a limit to which these two can be increased in an economical manner. A more feasible strategy would be to reduce R_n of the crop field by using a partially or fully covering canopy shade. This reduction in R_n would directly translate into reduction of λE due to ET leading to water saving. In this paper, the FAO Penman-Monteith equation is taken to calculate the ET and determine the sensitivity of each parameter to ET. Finally, a partially or fully covering canopy as well as a retractable canopy will be primarily considered to quantify their effectiveness for water saving. It should be noted the results provided in this study are from numerical calculations only. While experimentally measured values from the field are used in calculating the ET, measurement of ET has not been conducted for the various cases considered in this study.

2. Materials and Methods

2.1. Field Description

The present study is based on the measurements obtained from a 1.6 ha mature peach orchard located near Parlier, CA, USA. Each year, the peaches are harvested between late May and early June. In order to study the effect of postharvest deficit irrigation on the peach orchard, a three-year study from 2008 to 2010 was carried out during the postharvest months of June to August.

Schematic of peach field layout is shown in Figure 2. The dimensions of the orchard are 122 m in the east–west direction and 133 m in the north–south direction. The trees are spaced 1.8 m apart between the rows and 4.9 m within a row. The whole orchard is equally divided into 72 irrigation plots with each plot consisting of 24 trees in three rows with eight trees per row [2].

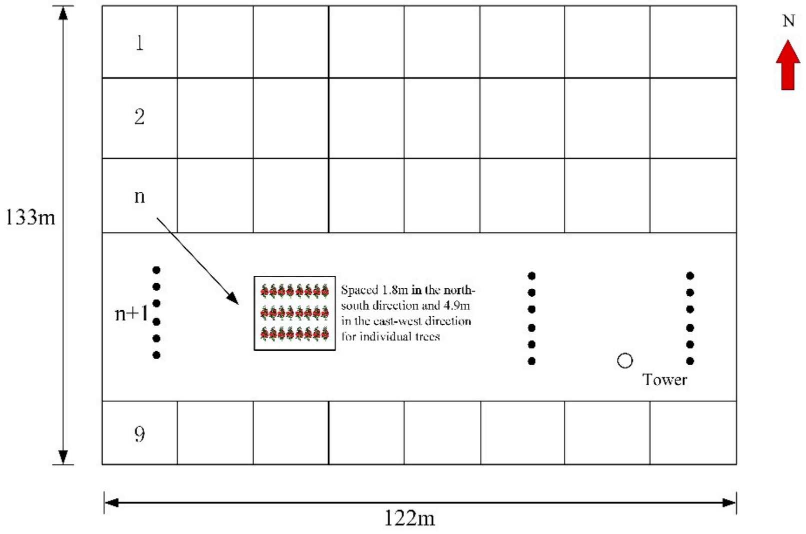

Figure 2. Schematic of peach orchard lay-out (orchard dimension: 122m east-west, 133m north–south).

2.2. Meteorological Measurements

As shown in Figure 2, in order to obtain the meteorological data, a system tower was installed near the southeast corner of the orchard approximately 138 m downwind from the northwest corner of the orchard (Because the predominant wind was from the northwest direction). The tower site consisted of a set of meteorological and soil sensors for energy balance measurements. Sensors mounted on the upper beam included a LI-COR silicon pyranometer for solar radiation (LI200X, Campbell Scientific, Inc., Logan, UT, USA), a net radiometer for net radiation (Q7, Radiation and Energy Balance Systems, Seattle, WA, USA), an air temperature and relative humidity sensor (Vaisala HMP 45C, Campbell Scientific, Inc., Logan, UT, USA), and a wind speed and direction sensor (R.M. Young Wind Monitor Sensor Model 05103, Campbell Scientific, Inc., Logan, UT, USA). Sensors mounted on the lower beam included an air temperature and relative humidity sensor (Vaisala HMP 45C, Campbell Scientific, Inc., Logan, UT, USA) and a wind speed and direction set (Met One model 034B, Campbell Scientific, Inc., Logan, UT, USA).

To account for partial ground shading from the tree canopy, the soil heat flux was measured with three heat flux plates (HFT3, Radiation and Energy Balance Systems, Seattle, WA, USA). All of them were buried at 1 cm depth. The first one was installed in the tree row half way between two adjacent trees, the second one located half way between two adjacent tree rows, the third one was at half distance between the first and second plates. An arithmetic average from the three plates was used to represent the soil heat flux in energy balance calculations. In addition to the heat flux measurement, six type T copper—constantan thermocouples were installed at the tower site for soil temperature measurements. They were located at the same relative distances to the tree and tree rows as the heat flux plates but placed 10 cm away from the heat flux plates. Three of them were installed at 1 cm depth and the other three at 10 cm depth, and an average temperature was used for each soil depth. A thermocouple was also installed in the tree canopy at 1 m above ground to monitor air temperature within canopy.

A datalogger (model CR23X, Campbell Scientific, Inc., Logan, UT, USA) was used to record sensor measurements at 1 Hz. These measurements are averaged over 5-min readings in 2008 and 15-min readings in 2009 and 2010. Sensor readings were monitored daily to weekly for quality control and to repair possible sensor malfunction. At the beginning of each season, all sensors and their installation were rechecked for accuracy in readings and physical installation.

2.3. ET and Crop Coefficient Calculations

ET is the combined process consisting of evaporation and transpiration in the plant-soil system. Apart from the water availability in the crop root system, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases as the crop grows. When the crop is small, water is predominately lost by soil evaporation. However, after the crop grows sufficiently to completely cover the soil, transpiration becomes the main process through which water loss occurs [40]. The FAO Penman-Monteith method is used to calculate the ET. The Penman–Monteith reference evapotranspiration (ET_o) equation is as given below,

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

This ET_o is representative of ET from an extensive surface of growing green grass of uniform height, completely shading the ground and with adequate water [31]. In this equation, the climatological data for solar radiation, air temperature, humidity, and wind speed used are based on the measurements from the field described in Section 2. To ensure the integrity of computations, the meteorological data are measured at 2 m above an extensive surface of green grass.

In Equation (2), the slope of the saturation vapor pressure with respect to temperature is required to calculate reference ET. The slope of the curve at a given temperature can be calculated by:

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27\times T}{T+237.3}\right)\right]}{(T+237.3)^2} \tag{3}$$

The net radiation (Rn) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}) as given below,

$$R_n = R_{ns} - R_{nl} \tag{4}$$

The psychometric constant (γ) relates the partial pressure of water in air to the air temperature. This lets one interpolate actual vapor pressure from paired dry and wet thermometer bulb temperature readings. This psychometric constant (γ) is given by,

$$\gamma = \frac{C_p \times P}{\varepsilon \times \lambda} = 0.665 \times 10^{-3} \times P \tag{5}$$

where P is atmospheric pressure given as a function of altitude by,

$$P = 101.3\left(\frac{293 - 0.0065 \times z}{293}\right)^{5.26} \tag{6}$$

The saturation vapor pressure is related to air temperature, thus, can be calculated from the air temperature. The relationship is expressed by,

$$e^o(T) = 0.6108exp\left(\frac{17.27 \times T}{T + 237.3}\right) \tag{7}$$

Similarly, the actual vapor pressure (e_a) as derived from dewpoint temperature is given as follows,

$$e_a = e^o(T_{dew}) = 0.6108exp\left(\frac{17.27 \times T_{dew}}{T_{dew} + 237.3}\right) \tag{8}$$

Finally, the mean saturation vapor pressure is given by,

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{9}$$

ET_c is mostly calculated by the indirect method combining crop reference ET_0 with corresponding K_c. In the study, K_c is obtained from the same peach variety from an adjacent orchard using a large underground weighing lysimeter [41], and the seasonal K_c curve is shown in Figure 3 [40]. It is noted that the coefficient increases almost linearly starting from June till the early July and remains constant in the later part of July and August.

Using ET_o and K_c, ET_c can be calculated as given below,

$$ET_c = K_c \times ET_o \tag{10}$$

To understand effect of different parameters on the ET, except for the parameter considered in the particular analysis, measured values of the all the other parameters as obtained from field have been used. For example, if effect of wind speed is to be analyzed, only the wind speed value is changed in a reasonable range keeping the other parameters constant at the measured values on a particular day. In the case of analyzing effect of temperature, two different approaches have been considered in analyzing its effect on the ET. In case 1, after choosing a particular day for the analysis, the temperature value has been varied from the measured value while keeping the other parameters constant in the calculation of ET. On the other hand, in case 2, multiple days have been chosen to cover a range of average temperature values. All the parameters as measured from the field have been used in calculating the ET to analyze the effect of temperature.

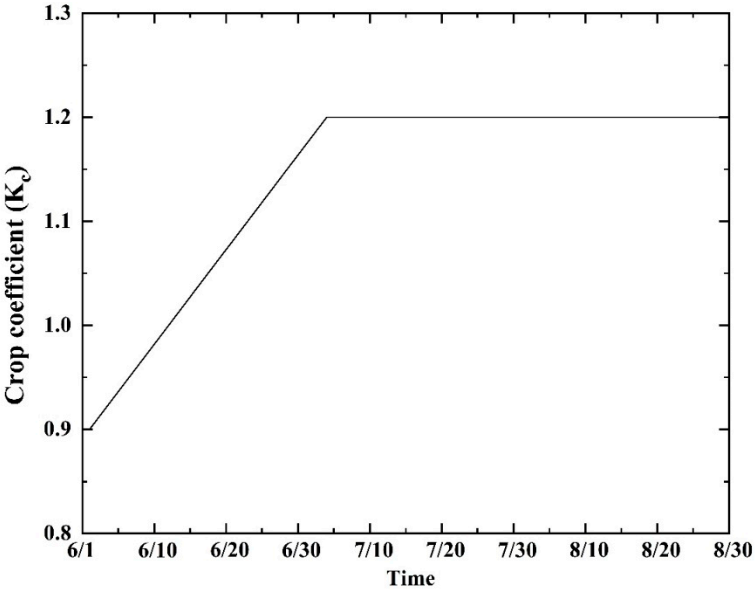

Figure 3. Daily crop coefficients of peach orchard under full irrigation.

3. Results and Discussion

There are multiple factors that influence the ET process in the plant-soil system. Some of these factors are considered in the present study and the effects of these factors on ET have been determined using the FAO Penman-Monteith method described earlier.

3.1. Effect of Temperature

Temperature is one of the key factors influencing the ET rate. This effect is presented in Figure 4 where total daily ET calculated for different ambient temperatures is plotted. Effect of temperature is analyzed first by simply varying the temperature on a typical day chosen for the analysis. The result from this analysis is shown in the figure as case 1. Since the temperature is not independent of other parameters such as solar radiation, length of the day, humidity, etc., analyzing effect of temperature on ET by simply changing the temperature from the actual value may not be realistic. Alternatively, different days with different average temperature are chosen to calculate ET to analyze effect of temperature on ET under realistic conditions in case 2. Total ET is calculated for both the cases and plotted in the same figure. This is to ensure that the variation in ET is primarily due to variation in temperature and not the other parameters. As it can be seen, the ET is a strong function of the temperature irrespective of how the variation in temperature is considered. For case 2, ET rate reduces by almost 23% as the temperature is reduced from 30 °C to 18 °C. This reduction decreases to 20% for case 1. The difference in ET between case 1 and case 2 can be due to small differences in other parameters such as humidity, wind speed, solar radiation, etc. It should also be noted that the solar radiation data used in case 2 is taken at different times during the summer months. As the temperature changes during these summer months, total solar radiation in a day would also vary. This can lead to a lower ET per day in comparison to case 1 where measured data corresponding to only the highest temperature in the study is used for analyzing effect of temperature. While reducing temperature would reduce ET significantly, it may not be economical to reduce the temperature significantly at the scale of a crop field.

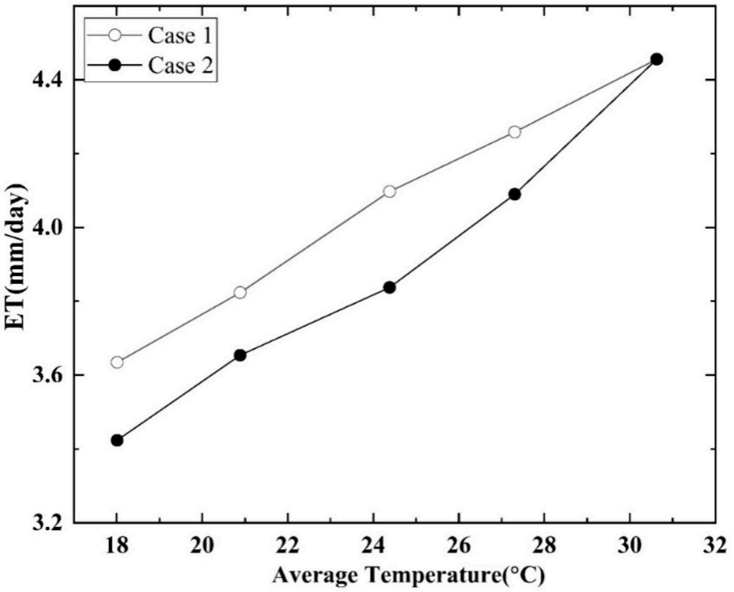

Figure 4. Relationship curves between ET (mm/day) and ambient temperature based on case 1 and 2.

3.2. *Effect of Soil Heat Flux*

The ET rate varies only slightly with variation in soil heat flux as shown in Figures 5 and 6. In Figure 5, hourly ET rate profile is shown for a typical day with two different soil heat flux values. To clearly show the effect of soil heat flux on ET rate, calculations are carried out using the model for a few different values of soil heat flux within a realistic range. The total daily ET calculated for different soil heat flux is plotted in Figure 6. As seen in this figure, if the soil heat flux is increased by 3 times from its typical value in some way, the resulting decrease in total ET is merely 10%. Hence, there is little to gain in terms of water saving by varying the soil heat flux. This also indicates that it is the transpiration in the plant that accounts for majority of water loss due to ET. Therefore, it would be advantageous to employ strategies which would significantly reduce water loss due to transpiration.

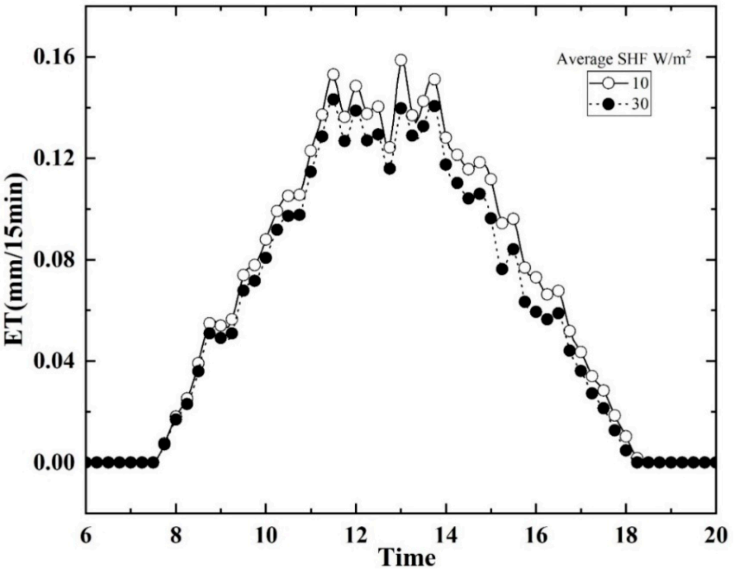

Figure 5. Relationship curves between ET and soil heat flux (SHF: Soil Heat Flux).

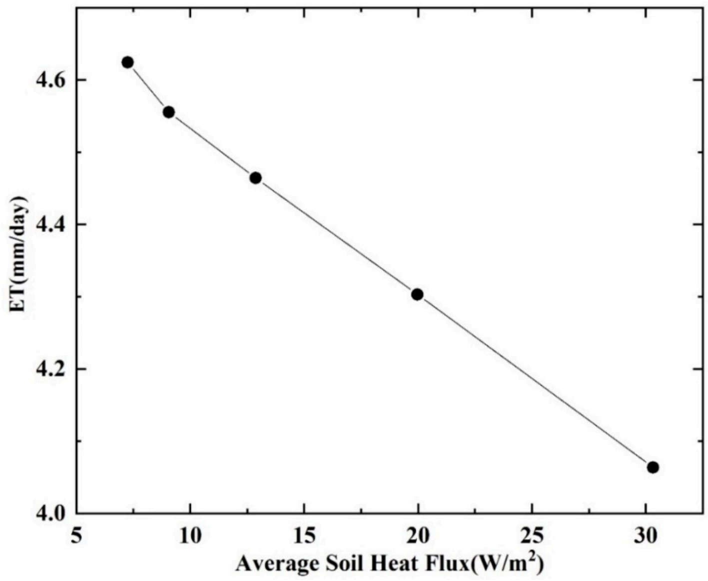

Figure 6. Relationship curve between ET and soil heat flux on a typical day.

3.3. Effect of Relative Humidity

In Figure 7, ET rate is plotted over a day for relative humidity of 30% and 70%. As seen from the figure, the profile of the ET rate obtained for both humidity conditions is very similar. This clearly shows that ET rate may not change significantly over a wide range of relative humidity. To further illustrate the nature of this relationship, in Figure 8, total ET in a day is plotted for different values of relative humidity considered. As the relative humidity is varied from 30% to 70%, total ET decreases only by 9%.

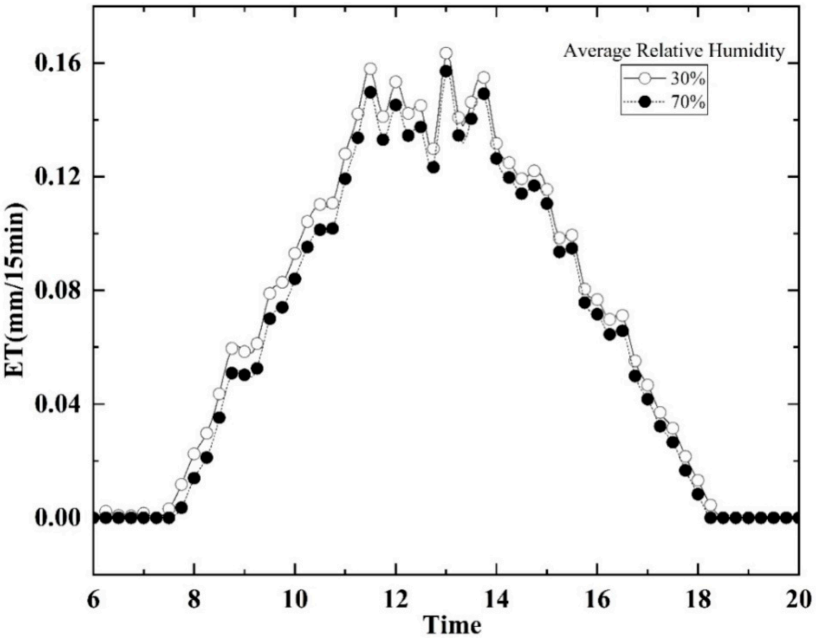

Figure 7. Relationship curves between ET and relative humidity.

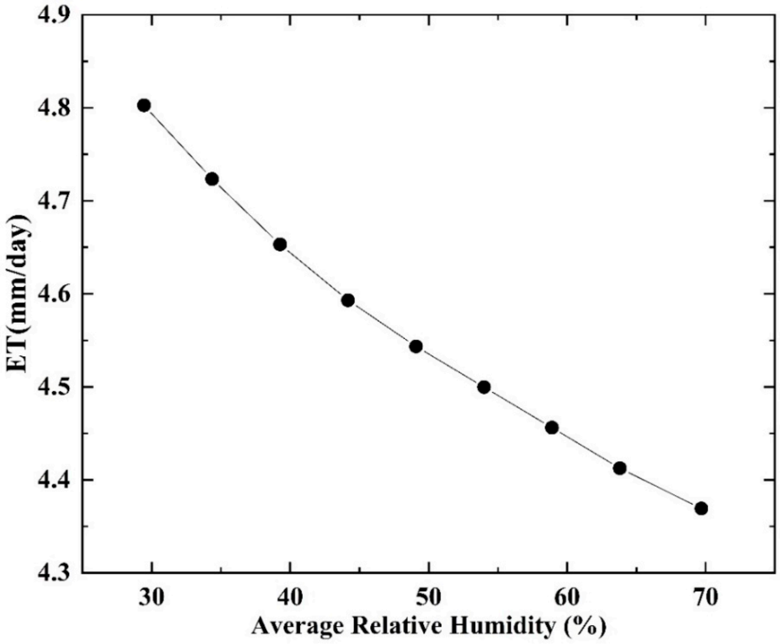

Figure 8. Relationship curves between ET and relative humidity on a typical day.

3.4. *Effect of Wind Speed*

In Figure 9, the effect of wind speed on ET has been presented. Wind speed has been varied from the low average wind speed of 0.3 m/s on a typical day to a high wind speed of 7.6 m/s which may occur on a windy day. Wind speed seems to have a strong effect on the total daily ET. As wind speed is increased four folds from 0.9 m/s to 3.6 m/s, total daily ET increases from 2.7 mm to 10.2 mm. This shows that the ET can be reduced significantly by reducing the wind speed when high wind conditions are present. This can be achieved by erecting a fence around the field which obstructs the passage of the wind, thereby reducing the wind speed. However, this can be an effective strategy only under high wind conditions. Furthermore, effect of reduced wind speed by having a fence around the field would only help reduce ET for orchards on the periphery of the field.

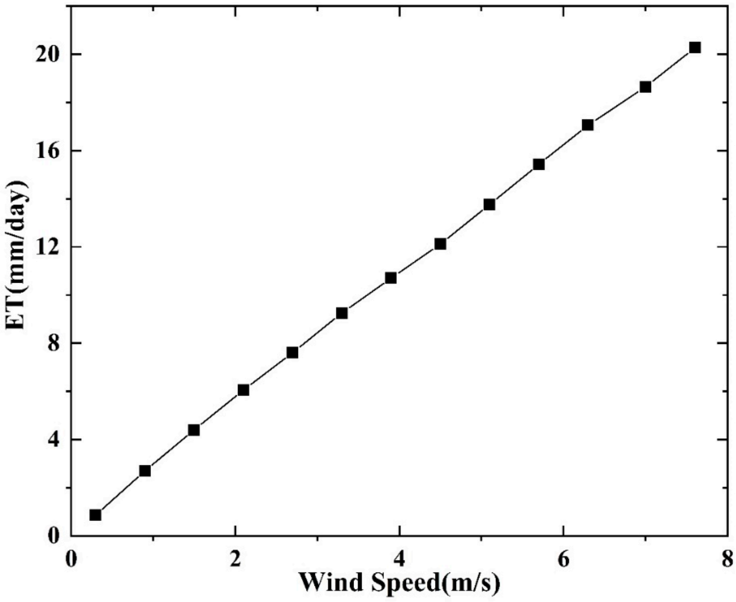

Figure 9. Relationship curves between ET and wind speed on a typical day.

3.5. *Effect of Solar Irradiation*

Solar energy is essential for the photosynthesis process taking place in the plants. Consequently, due to solar irradiation, ET processes also take place in the plant-soil system. This leads to a large fraction of irrigation water being dissipated to the atmosphere. Only a small fraction of the irrigation water is consumed by the plant during the photosynthesis process. Majority of the water is transpired by the plants to the air. Hence, by limiting the ET process, significant water saving can be attained. However, this must be done without hindering growth of the plant which may result in reduced crop yield. Effect of this factor on the crop ET is analyzed in further detail by considering three possible strategies.

3.5.1. Partially Covering Canopy

One of the possible strategies to limit solar irradiation is by partially covering the plants with a canopy. Before implementing such a strategy, it is critical to quantify effectiveness of partial coverage and find the optimal partial coverage which causes significant amount of water saving without adversely affecting the crop yield. In Figure 10, ET rate is shown for different percentage of the partial coverage. As expected, ET reduces significantly even with a nominal coverage of 20%. The fraction of coverage can be varied by using different materials with selective transmission and reflection characteristics for the incident solar radiation. Alternatively, coverage can also be varied by introducing small holes in the canopy allowing passage to certain fraction of the total solar radiation that incidents upon the canopy. The optimal fraction of coverage may vary based on the plant as the amount of sunlight required depends on internal factors of the plant.

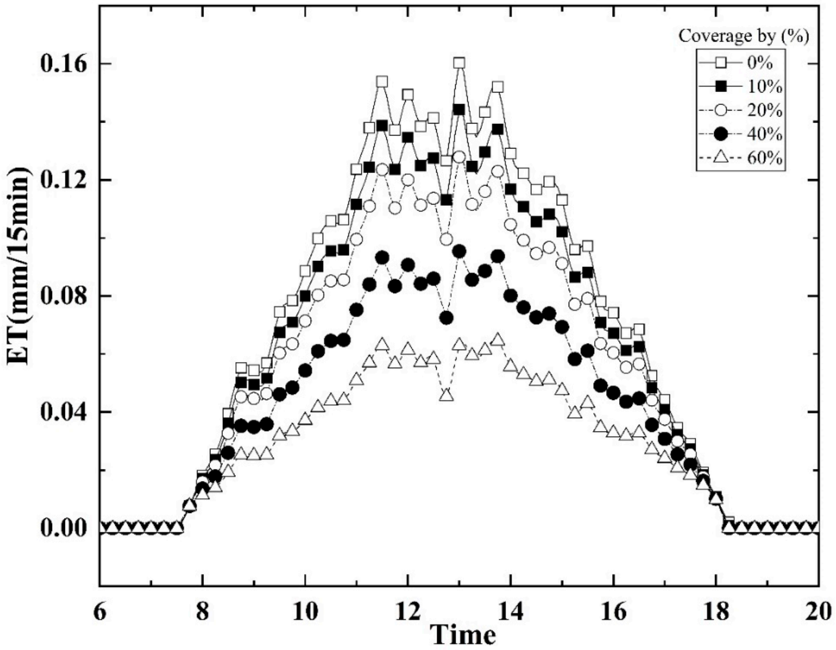

Figure 10. Relationship curves between ET and solar radiation on a typical day.

3.5.2. Retractable Canopy

An alternative to changing the coverage area of the canopy can be having a retractable canopy instead of a fixed canopy. With a retractable canopy, it would be possible to limit the time duration of solar irradiance to the plants. For example, it might be beneficial to cover the plants for a few hours during the afternoon when the solar radiation is the highest. Thus, the plants will have access to solar energy for the most part of the day except for a few hours when water losses due to ET will be the highest. The number of hours for the coverage would depend on the internal factors of the plant.

This strategy would allow spatially uniform solar energy distribution to the plants on the field for the most part of the day. This would be at the expense of lack of solar energy during the few hours when the field will be covered with the retractable canopy. The ET rate as a function of time with different time and time duration of coverage by retractable canopy is shown in Figure 11. It has been found that the reduction in ET is significant when covering the field for different time duration centered about 1PM.

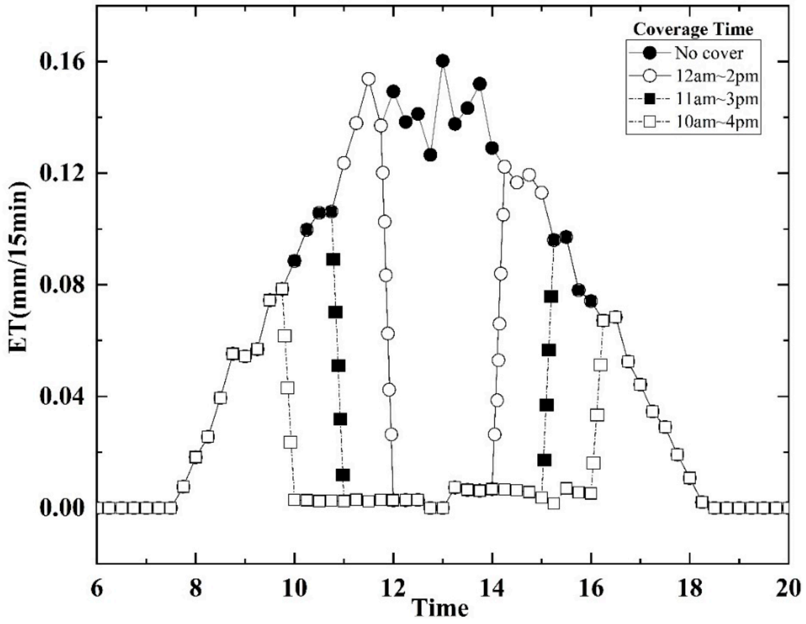

Figure 11. Relationship curves between ET and coverage time on a typical day.

3.5.3. Hybrid Canopy System

Combining the effect of partially covering canopy and retractable canopy, a hybrid canopy system can also be considered. Such a system would combine the benefits of both the approaches to reduce the impact of the shortcomings of either. For this method, a partially covering retractable canopy is considered which facilitate spatial coverage of the field for a specific time window. In Figure 12, total daily ET is shown for different fraction of coverage as the time window of coverage is changed from entire day to a couple of hours during the afternoon. Similarly, in Figure 13, fraction of the total available solar energy is plotted as a function of fraction of coverage for different time window considered. Here, the total available solar energy is the amount of solar energy available to the plants in an uncovered open field. It's obvious that canopy with full coverage for the entire day would result in most water saving. However, this would provide no to very little solar energy to the plants for photosynthesis adversely affecting the crop yield. On the other hand, a partial coverage during a certain time period may allow significant water saving at the expense of only a fraction of total available solar energy. For example, a partial coverage of 60% with time window 11 AM–4 PM leads to 37% reduction in ET with 70% total available solar energy still provided to plants for photosynthesis. Such a hybrid strategy can help design optimal system with reduction in water loss without adversely affecting crop production. The optimal configuration of such system would highly depend on the type of crop as the photosynthetic photo flux density requirement can vary with the type of crop. In this study, we have attempted to choose a balanced configuration which not only leads to significant water saving but also ensures availability of ample amount of sunlight for the photosynthesis process. It is important to quantify effectiveness of such a configuration by quantifying water saving potential over an extended period of time. For this purpose, coverage configuration with 60% coverage in the time window 11 AM–3 PM is considered to calculate seasonal water saving over the three summer months. In Figure 14, daily ET has been plotted for the duration of three months from 06/01 to 09/01 for both uncovered and selected coverage configuration. For the covered case, over the duration of these three months, total ET reduces from 361 mm for the uncovered case to 226 mm for covered case. This is a reduction of 37% in ET leading to significant water saving.

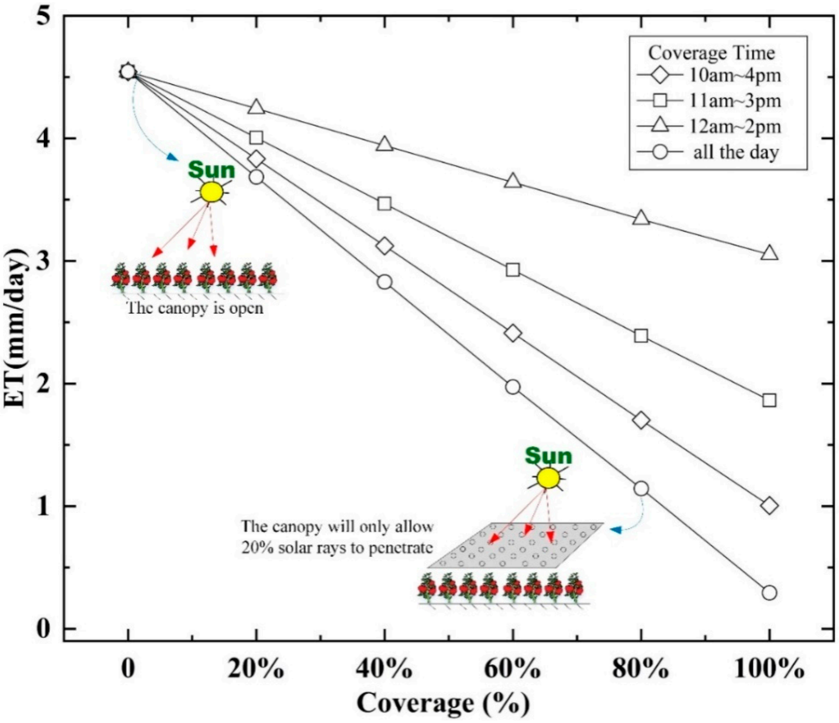

Figure 12. Relationship curves between ET and different coverage percentage on a typical day.

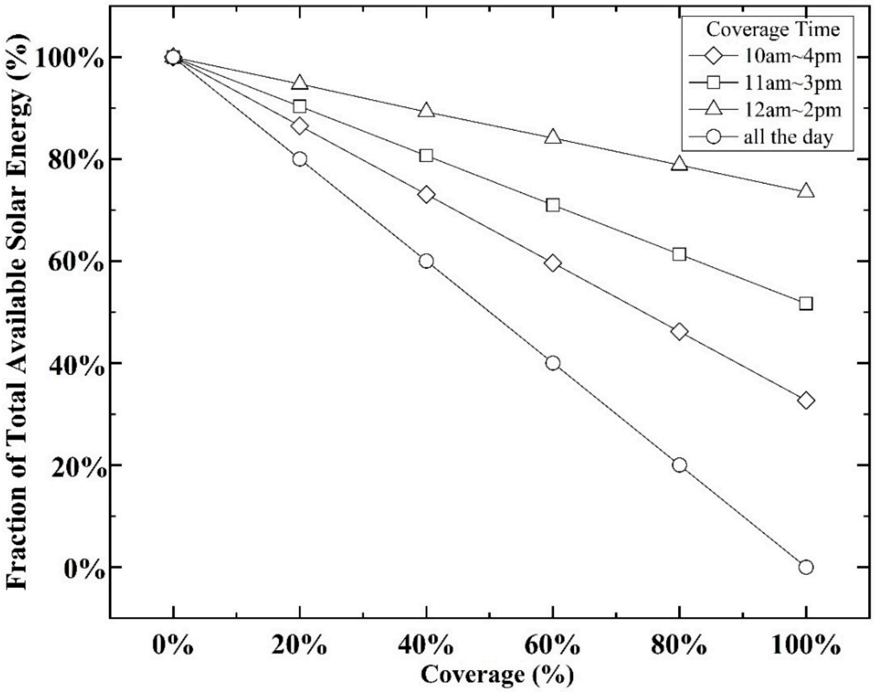

Figure 13. Relationship curves between Fraction of Total Available Solar Energy (%) and different coverage percentage on a typical day.

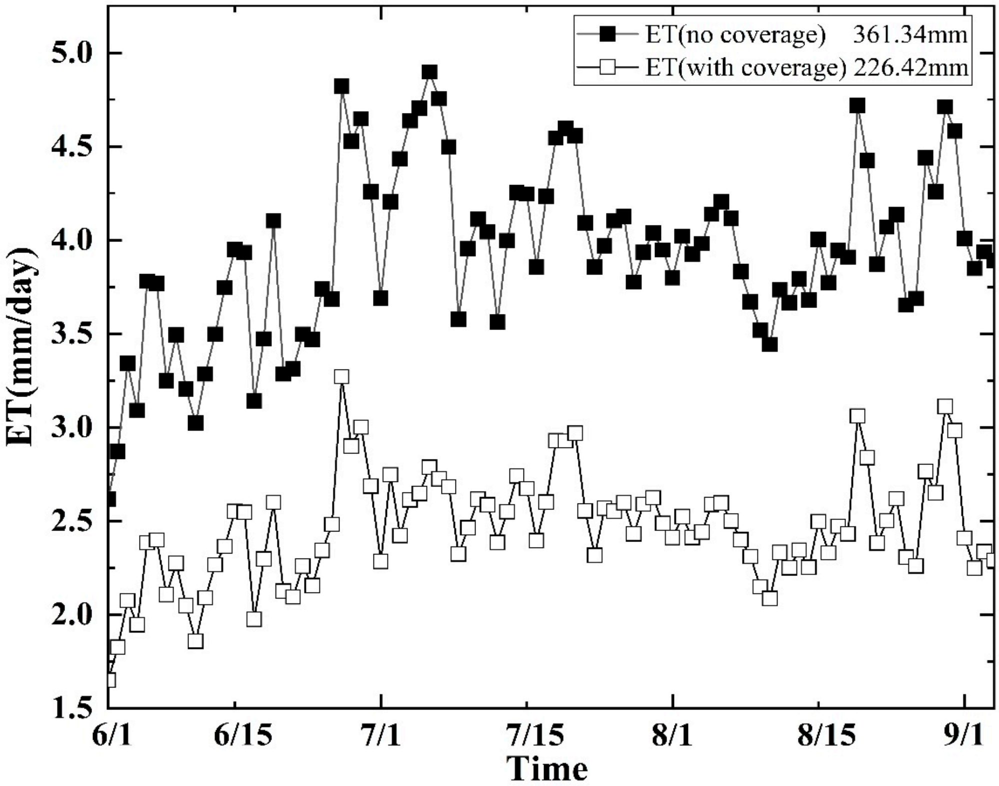

Figure 14. Comparison of real time ET with no coverage and with 60% coverage from 11AM to 3PM.

3.5.4. Effect on Crop Yield

While canopy shading can effectively reduce crop ET leading to water saving, it must not be at the expense of reduced crop yield. There have been several studies in the past where the effect of shading on the crop yield has been studied [42–46]. Based on these studies, under typical moderate shading conditions (shading level < 50%), crop yields have been shown to improve or being unaffected by shading. The cases considered in those studies can be used for determining water saving potential for practical scenarios without comprising on crop yield. Since accurate calculation of water saving potential requires number of parameters related to the local climate as well as the crop, selection of an appropriate study with all the required parameters provided is critical. It is also important to consider a case with climatological conditions similar to that of the field considered in present study. One such study conducted on the growth of sweet pepper under shading in high temperature and high radiation climate has been identified and chosen for the water saving analysis [42]. Using the meteorological data provided and empirical formula to approximate net radiation from global radiation [47], ET calculated using Equation (10) has been shown in Table 1. Canopy shading of 25%, as implemented in the experimental study, has been considered in the numerical analysis. For this shading, the crop yield has been shown to improve in the experimental study. From the numerical analysis, an average monthly water saving of 23.5% has been calculated over the period of three months. This indicates significant water saving without any adverse effect on the crop yield. By using a retractable canopy, water saving and crop yield can be further improved by performing analysis similar to the one presented in Figure 12.

Similar findings have been presented in the past where shading has been shown to improve the crop yield for wide variety of crops at different geographical locations [43–45,48]. In one study on bell pepper plant under shading, the net photosynthesis was relatively unaffected for 30% to 47% shade level and the leaf mineral nutrients increased with increased shading levels within this range [44]. Similarly, a study on tomato has shown an increase of 50% in the yield for marketable fruits due to shading [45]. Similar findings have been reported in some other studies [49–52]. It has been shown that high temperature and light intensity have a negative effect on crop yield [46,47]. Adverse effect on crop yield due to high solar radiation and low air humidity, similar to the climatic condition in the San Joaquin Valley, has been reported [52].

Table 1. Monthly water saving calculated from Rylski's experimental measurement [42].

Month	T_{max} (°C)	T_{min} (°C)	R_G (MJ/m^2.day)	R_n (MJ/m^2.day)	Rn (S-25%) (MJ/m^2.day)	Bright Sunshine (h/day)	ET (no Shading) (mm/month)	ET (25% Shading) (mm/month)	Water Saving (%)
May	29.7	15.0	26.4	6.1	4.3	11.3	135.7	104.0	23.4%
June	30.0	17.2	29.0	7.4	5.2	12.2	142.5	108.0	24.2%
July	31.8	20.5	27.8	6.9	4.9	12.0	150.6	116.2	22.8%

4. Conclusions

California ranks among the highest producing areas in terms of crop yield for vegetables and fruits in the United States. However, due to little annual rainfall, the severe drought events are frequent, leading to adverse effects on local economic development. Since a large fraction of irrigation water is lost due to ET processes in the plant-soil system, it is important to come up with strategies to reduce this water loss. In the present work, the classical Penman-Monteith model is used to analyze the effect of different strategies to reduce water loss due to ET processes. The results from this study show that parameters such as soil heat flux and relative humidity have negligible effect on the ET processes when considered independently. On the other hand, air temperature, wind speed, and solar radiation can significantly affect the ET rate. Among these three, solar radiation is the easiest to control and can be most effective leading to significant water saving. A hybrid strategy based on a partially covering retractable canopy has been found to be the most promising. For a configuration with partial coverage of 60% during 11 AM–3 PM, ET can be reduced by 37% with 70% of the total available solar energy provided to the plants. Implementation and plant specific optimization of such strategy can lead to significant water saving without adversely affecting the crop yield. Water saving potential has been calculated for a case based on an experimental study with a modest covering of 25% where shading led to increase in crop yield.

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Nomenclatures

C_p	specific heat at constant pressure, 1.013×10^{-3} [MJ/ kg °C]
e_s	Saturation vapor pressure [kPa]
e_a	Actual vapor pressure [kPa]
$e_s - e_a$	Saturation vapor pressure deficit [kPa]
ET_o	Reference evapotranspiration [mm/day]
G	Soil heat flux density [MJ/m2.day]
H_s	Sensible heat flux (W/m2)
P	atmospheric pressure [kPa]
Q	the residual of the closure of the energy balance (W/m2)
R_n	Net radiation at the crop surface [MJ/m^2.day]
R_G	Total radiation at the crop surface [MJ/m^2.day]
R_{ns}	Net shortwave radiation [MJ/m^2.day]
R_{nl}	Net long wave radiation [MJ/m^2.day]
T	Mean daily air temperature at 2 m height [°C]

T_{dew}	Dew point temperature [°C]
$T_{\max}$	Maximum air temperature at 2 m height [°C]
T_{min}	Maximum air temperature at 2 m height [°C]
u_2	Wind speed at 2 m height [m/s]
z	elevation above sea level [m]
λE	Latent heat flux (W/m2)
Δ	Slope vapor pressure curve [kPa/ °C]
γ	Psychrometric constant [kPa/ °C]
λ	Latent heat of vaporization, 2.45 [MJ/ kg]
ε	Ratio molecular weight of water vapor/dry air = 0.622

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