Chapter 13
Crop Water Requirement and Water Use Efficiency

13.1 Crop Water Requirement

Irrigation water is a scarce factor in many regions. Therefore, crop water requirement has to be calculated, and irrigation systems have to be designed carefully. Knowledge of the evapotranspiration inside the greenhouse is important for successful plant growth, calculation of irrigation water consumption, and possible and economical rainwater collection and storage (see Chap. 14).

Evapotranspiration can be calculated by the FAO–Penman–Monteith method that has been developed for open field conditions (Allen et al. 1998). The Penman–Monteith equation for a reference evapotranspiration ET0, derived from an energy balance equation for an evaporating surface of a well-irrigated grass reference crop is:

$$\mathrm{ET0} = \frac{0.408 \times \Delta(q_{\mathrm{RN}} - q_{\mathrm{RG}}) + \gamma \frac{900}{T_{\mathrm{mean}} + 273} \times v \times (e_{\mathrm{S}} - e_{\mathrm{A}})}{\Delta + \gamma(1 + 0.34v)} \tag{13.1}$$

where:

$\Delta = f\,(T_{\mathrm{mean}})$: The slope of vapour pressure curve (kPa/°C), given in a Table (Annex 2, Allen et al. 1998).

$\gamma = f$ (altitude z): Psychometric constant (kPa/°C), given in a Table (Annex 2. Allen et al. 1998).

q_{RN} (MJ/m^2 day): Net radiation at crop surface.

q_{RG} (MJ/m^2 day): Soil heat flux density is very small, and can normally be neglected.

v (m/s): Air velocity.

$e_{\mathrm{S}} = f(T_{\mathrm{mean}})$ (kPa): Saturation vapour pressure, given in a Table (Annex 2, Allen et al. 1998).

$e_{\mathrm{A}} = f(T_{\mathrm{mean}})$ (kPa): Actual vapour pressure.

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13.1.1 This Penman–Monteith Method Can Also Be Applied for Greenhouse Conditions, if the Parameters Are Adapted to Greenhouse Climate Conditions

The climate data for outside conditions can be taken from adequate references, for example Müller 1996 or climate data tools of FAO aquastat (www.fao.org/nr/water/aquastat/gis/index3.stm).

Given data and parameters are:

Mean max temperature, mean min temperature, mean relative humidity, number of sunshine hours, global radiation, mean wind velocity.

The equivalents for the radiation are

1 kWh = 3.61 MJ
1 MJ = 0.277 kWh
1 mm/day = $\mathrm{l/m^2}$ day = 0.408 $\mathrm{MJ/m^2}$ day

If the global radiation is not given, it can be calculated by a method given by Allen et al. (1998).

The inside temperature in unheated greenhouses is normally higher than the outside temperature, and the incoming global radiation is reduced. These factors have to be taken into consideration when estimating the evapotranspiration in greenhouses. The inside temperature in well-ventilated greenhouses during daytime can be assumed about 3–5° above outside temperature (see Chap. 9). The mean inside temperature during the night in unheated greenhouses is about 2°C above outside temperature, due to the storage effect of the soil (Thomas 1994; von Zabeltitz 1986a; Rath 1994).

The mean minimum and mean maximum temperatures for the calculation of the evapotranspiration inside the greenhouse can be assumed to be:

$$T_{\mathrm{gmax}} = T_{\mathrm{max}} + 4$$

$$T_{\mathrm{gmin}} = T_{\mathrm{min}} + 2$$

Mean inside temperature:

$$T_{\mathrm{gmean}} = (T_{\mathrm{gmax}} + T_{\mathrm{gmin}})/2$$

The outside relative humidity decreases during daytime due to the increasing outside temperature. The relative humidity inside the greenhouse remains at a relatively high level due to the continuous evapotranspiration from crop and soil even if the greenhouse is ventilated during daytime. The mean relative humidity in the daytime inside a ventilated greenhouse can be assumed to be:

$\mathrm{RH_{mean}} = 75\text{–}80\%$

Table 13.1 Crop coefficients k_C for various open field grown crops (Allen et al. 1998)

Crop	k_{Cini}	k_{Cmid}	k_{Cend}
Small vegetables (broccoli, cabbage, lettuce, onion)	0.7	1.05	0.95
Eggplant	0.6	1.05	0.9
Tomato	0.6	1.2	0.8
Cucumber	0.6	1.2	0.75
Watermelon	0.4	1.0	0.75

The incoming global radiation is reduced by the cladding material and construction components, and can be expressed by

$$q_{RSI} = \tau \times q_{RS} \tag{13.2}$$

where

τ = 0.6–0.7 for single plastic-film covered greenhouses (see Chap. 6).

q_{RS} = outside global radiation.

The calculation of the reference evapotranspiration inside the greenhouse can be done with the help of a calculation sheet, given in Annex 3.

The actual crop evapotranspiration in the greenhouse is

$$\mathrm{AET_C} = k_C \times \mathrm{ET0} \quad (\mathrm{l/m^2\,day = mm/day}) \tag{13.3}$$

The crop coefficients k_C are given in tables for various crops in initial k_{Cini}, middle k_{Cmid}, and end k_{Cend} stage of cropping (Table 13.1, Allen et al. 1998).

The daily crop water requirement $\mathrm{CWR_d}$ can be calculated by

$$\mathrm{CWR_d} = \mathrm{AET_C}(1 + l_i) \times A_{Crop}/A_G \quad (\mathrm{mm/day}). \tag{13.4}$$

l_i = loss factor for irrigation.

l_i = 0.03–0.1 for drip irrigation systems.

A_{Crop}/A_G = crop-covered area to greenhouse floor area.

A_{Crop}/A_G = 0.9 for vegetables and cut flowers on ground beds.

The losses of different irrigation systems are given by De Pascale and Maggio (2005):

Drip irrigation	10–20%
Sprinkler irrigation	30–50%
Furrow irrigation	50–60%

Most of the greenhouses in warm climates will be irrigated by drip irrigation today. Modern irrigation systems can reduce the losses to 5–10%.

The monthly crop water requirement $\mathrm{CWR_m}$ is

$$\mathrm{CWR_m} = \mathrm{CWR_d} \times d_m \quad (\mathrm{mm/month}) \tag{13.5}$$

d_m = number of days in the month.

13.1.2 Example 1: Almeria (Spain)

The reference evaporation for an unheated greenhouse at Almeria (Spain) in May has been calculated by the adapted Penman–Monteith equation (see calculation sheet in Annex 3):

$\mathrm{ET0} = 3.16$ (mm/day) without considering the soil heat flux.

Fernandez et al. (2009) presented an equation for the calculation of the ET0 in unheated greenhouses:

$$\mathrm{ET0} = (0.288 + 0.0019 \times \mathrm{JD}) \times q_{\mathrm{RS}} \times \tau \quad (\mathrm{mm/day}) \tag{13.6}$$

JD = Julian days
q_{RS} (mm/day) = outside global radiation
τ = transmittance of the greenhouse
The calculation for Almeria in the middle of May results in:

$\mathrm{ET0} = 3.61$ (mm/day)

13.1.3 Example 2: Bangkok (Thailand)

Calculation of ET0 and CWR in April and May for Bangkok, Thailand.

ET0 (April) = 3.67 (mm/day)
ET0 (May) = 3.11 (mm/day)

The crop water requirement for a tomato crop is

$\mathrm{CWR} = \mathrm{ET0} \times k_{\mathrm{C}} \times 1.05 \times 0.9$ (mm/day)

The crop coefficient for a high tomato crop in greenhouses can be higher than for tomatoes in open field, here $k_{\mathrm{C}} = 1.25$ in mid-crop stage.

$\mathrm{CWR} = 3.67 \times 1.25 \times 1.05 \times 0.9 = 4.34$ (mm/day)

Harmanto et al. (2005) found 4.1–5.2 (mm/day) for the actual irrigation water of a tomato crop in the Bangkok climate.

13.1.4 Example 3: Antalya (Turkey) and Bangalore (India)

Figure 13.1: shows the calculated values for Antalya, Turkey, and Bangalore, India, Those figures are used for the calculation of rainwater collection (Chap. 14).

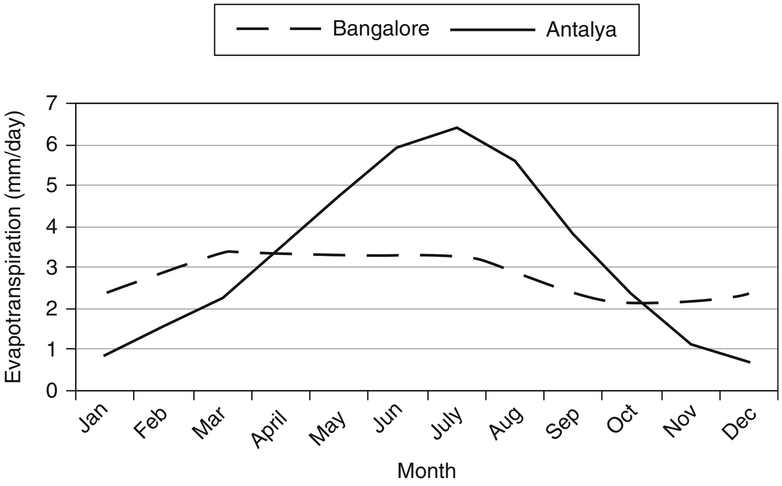

Fig. 13.1 Reference evapotranspiration ET0 for Antalya, Turkey, and Bangalore, India, calculated by the adapted Penman–Monteith equation

13.2 Water Use Efficiency

Water use efficiency is defined as ratio of yield to irrigation water requirement (De Pascale and Maggio 2005)

WUE = yield/irrigation water requirement (kg crop/m^3 irrigation water)

The irrigation water requirement IWR is CWR + eventual soil leaching requirement.

The WUE in greenhouses normally is much higher than in open field production because of

- Reduced evapotranspiration (less radiation, higher humidity).
- Increased crop yield by production techniques, climate control and pest control.
- Advanced irrigation techniques (drip irrigation, reuse of drainage water).

The mean WUE of some crops in Mediterranean countries is given by Pardossi et al. (2004) in Table 13.2:

Mean values for some crops in Mediterranean countries (Cyprus, Egypt, Greece, Israel and Spain) in comparison to the Netherlands were also given by Pardossi et al. (2004)

	WUE Mediterranean countries (kg/m^3)	WUE Netherlands (kg/m^3)
Tomato	21.8	58.2
Cucumber	14	28
Sweet pepper	30.3	77

Table 13.2 Water use efficiency WUE of tomato crops under different climate conditions and using different growing systems (Pardossi et al. 2004)

Growing conditions	Country	WUE (kg/m^3)
Open field soil culture	Israel	17
	France	14
Unheated plastic-film greenhouse		
Soil culture	Spain	25
Soil culture	France	24
Soil culture	Israel	33
Open substrate culture	Italy	23
Closed substrate culture	Italy	47
Climate-controlled greenhouse		
Open soil-less culture	France	39
Open soil-less culture	Netherlands	45
Closed soil-less culture	Netherlands	60

Table 13.3 Mean cooling efficiency in the pad depending on air flow rate (Sabeh 2007)

Air flow rate (m^3/s)	Pad efficiency (%)
4.5	83.2
9.4	80.6
13.0	77.4
16.7	73.5

Sabeh (2007) quantified and compared the water use efficiency of a fan and pad cooling system and a fog cooling system in a round-arched single-span greenhouse, 9.8 m by 28 m, 3.4 m gutter height, 6.3 m ridge height, with roof and side wall ventilation.

The fan and pad cooling system consisted of an 8.5 m by 1.2 m cellulose pad, 1.3 m above ground level, at the northern gable. Three exhaust fans producing different ventilation rates were installed at the southern gable.

The high-pressure fog cooling system operated at a pressure of 8,960 kPa (89.6 bar) and produced droplets less than 50 μm in diameter. A central overhead fog line was installed 3.1 m above the floor.

Table 13.3 shows the mean cooling efficiency for the pad with different air flows through the pad. Increasing ventilation rate decreases the cooling efficiency, because the higher air velocity reduces the contact time of the air with the water surface in the pad. The saturation of air by water vapour is lower.

The water use efficiency for the fan and pad system and a tomato crop with a total yield of 0.14 kg/m^2 day is given in Table 13.4.

The total WUE decreased with increasing ventilation rate because the fan and pad system uses more water for evaporation at higher ventilation rates. Increasing ventilation rate reduced the air temperature gradient between pad and fan from 8.6°C at 4.5 m^3/s to 4.0°C at 16.7 m^3/s, but the smaller temperature gradients were accompanied by lower relative humidity levels.

Table 13.4 Water use efficiency WUE_{fp} of a fan and pad cooling system, WUE_{oirr}, of an open irrigation system for tomato crop, and resulting WUE_{tot} for both systems together. Tomato yield 0.14 kg/m^2 day

Air flow (m^3/s)	WUE_{fp}	WUE_{oirr}	WUE_{tot}
4.5	44	31	18
9.4	22	31	13
13.0	17	31	11
16.7	14	31	10

Table 13.5 The water use efficiency WUE_{fog} for the high-pressure fog system, the WUE_{oirr} of an open irrigation system for a tomato crop, and the resulting WUE_{tot} for both systems

Air flow (m^3/s)	WUE_{fp}	WUE_{oirr}	WUE_{tot}
3.0	18	31	11
4.5	19	31	12
9.4	15	31	10

Table 13.5 shows the water use efficiencies for the high-pressure fog cooling system in the same greenhouse and under the same climate conditions. The inside temperature could be held at the control set point. The water use efficiency was highest with a ventilation rate of 4.5 m^3/s, and lowest with the highest ventilation rate. The central overhead nozzle line produced uniform greenhouse climate conditions.