# 氣象資料預測作物灌溉需水量
# (邀請論文)

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## 摘　　要

本研究爲介紹氣象資料預測作物灌漑時間及需水量，其中以水蜜桃和蕃茄作爲試驗材料，藉中子水份測定儀直接到田間測量土壤水份決定灌漑時間，另外利用氣象資料估計作物蒸發散量以決定灌漑時間及需水量，兩者比較，結果非常相近。

利用氣象資料預測作物灌漑時間及需水量非但可靠、方便而且甚快速，只要了解土壤有效水份含量及作物根系深度，氣象方法可以很簡單的用來預測不同作物種植於不同土壤之灌漑需水量。一般來說，預測灌漑所需之氣象資料可以從附近氣象站得知，或者利用儀器直接測得。

## 前　　言

作物之生長和產量與土壤水份有密切關係，作物因氣候、土壤、作物品種、生長階段及根系發展之不同，其用水量也隨之改變。灌漑最主要的目的就是保持最適宜作物生長和產量的土壤水份，土壤水份之補給除了靠天然降雨之外，必須靠人爲之灌漑，要達到灌漑最高效益有二個條件必須了解，第一灌漑時間，第二灌漑需水量。

一般決定灌漑時間和需水量有三種基本方法：第一、測量土壤水份，第二、測量作物水份，第三、測量作物蒸發散量。上述三種方法在實際使用上都受某些程度上之限制。例如利用Resistance block 測量土壤水份。Fulton[4]，1966 曾經用這種儀器預測馬鈴薯灌漑需水量，但這種種儀器受土壤溫度、鹽份之不同，都可能影響其準確性。另外有些人利用Tensiometer測土壤水份作爲灌漑之準則，但因其敏感度之不同，這種儀器僅適用於某種土壤。中子水份測定儀（Neutron meter）也用作灌漑需水量之測定，這種儀器成本高，再加上輻射線會影響人類身體，農民直接利用它來預測灌漑需水量之可能性就大減。直接測量作物本身缺水之狀況應該是預測作物灌漑需水量最好之方法，但因作物缺水狀況隨氣象，作物生長階段，測量時間之不同而有很大之差異，因此利用這種方法來預測作物灌漑需水量，必須同時記錄其他影響作物生長之因子，否則其準確性就大減。上述二種預測作物灌漑需水量之方法必須利用儀器直接到田間去測土壤水份或植物本身之水份。第三種方法可以利用電腦輸入有關氣象資料計算作物蒸發散量作爲

灌溉之準則。在美國已經有400,000 公頃之土地利用這種方法來預測灌溉需水量，本文將特別介紹利用氣象資料預測作物灌溉時間及需水量。

利用氣象資料預測作物灌溉時間和需水量必須具備下列幾種知識(1)作物不同階段蒸發散量。(2)土壤儲水特性。(3)土壤缺水可容許之程度和作物生長和產量之關係。(4)根系有效深度，上述(2)(3)(4)項可以從實驗或文獻中得知，其中第一項計算作物蒸發散量是本文介紹之重點，也是決定氣象資料作爲灌溉準則最重要之因子。

## 作物蒸發散量之估計方法

### 一、滲漏計(Lysimeter)

滲漏計可用來直接測定作物蒸發散量，但用作預測灌溉需水量之準則，受到成本較高之限制，同時作物種植於滲漏計內，因土壤水份，根系發展等可能與外面作物有所差距，這些因素可能造成測定蒸發散量之準確性。但一般在裝設滲漏計時如果符合規格，同時儘量使作物在滲漏計內保持與外面作物相同之環境，則滲漏計可用來準確的測量作物蒸發散量。

### 二、蒸發皿(Evaporation pan)

目前最廣用的蒸發皿是美國氣象局的標準Class A Pan（直徑 1.22 公尺，高 0.25 公尺），使用蒸發皿蒸發量（ Epan ）來推求作物需水量必須用下列公式修正：

$$ET_c = K_c \times K_p \times E_{pan} \quad \cdots\cdots (1)$$

式中，$ET_c$：作物蒸發散量（ Crop evapotranspiration ）

$K_c$：作物係數（參考附錄一）

$K_p$：蒸發皿係數（參考附錄二）

在台灣，各主要作物係數值可根據施教授主編的雜作灌溉手冊[2]。

### 三、Penman equation

Penman[9] 於 1948 年提出計算作物最高蒸發散量（ $ET_0$ ）之公式：

$$ET_0 = \frac{\triangle(R_n - G) + r f(u)(e_z^* - e_z)}{\triangle + r} \quad \cdots\cdots (2)$$

式中 $ET_0$：作物最高蒸發散量（ Potential evapotranspiration ）

$R_n$：淨輻射量（ net radiation ）

G：土壤熱通量（ soil heat flux ）

r：濕度常數（ Psychrometric constant ）

△：飽和蒸汽壓斜率（ slope of saturation vapour pressure ）

$$f(u) = 0.27\left(1+\frac{u}{100}\right) \quad \cdots\cdots(3)$$

u ：高度2公尺全天風速之總值（ total wind run in km／day ）

$e_z^* - e_z$ ：空氣蒸汽壓力差（ Vapour pressure deficit of the air ）

## 四、Penman-Monteith equation

Penman[9]於1948年提出計算作物最高蒸發散量之公式，Montith[8]於1965年將作物葉冠之阻力（ Canopy resistance ）加入Penman 提出之公式用來計算作物蒸發散量（ Crop evapotranspiration ）。

$$ET_c = \frac{ET_o}{1+[r/(\triangle+r)](\Upsilon_c/\Upsilon_a)} \quad \cdots\cdots(4)$$

式中，$\Upsilon_c$ ：作物葉冠阻力（ Canopy resistance ）

$\Upsilon_a$ ：空氣阻力（ aerodynamic resistance ）

Tan and Black[11]於1976年提出下列公式計算葉冠阻力（ $\Upsilon_c$ ）：

$$\frac{1}{\Upsilon_c} = \sum_{j=1}^{n} (LAIj/\Upsilon_{sj}) \quad \cdots\cdots(5)$$

式中，$\Upsilon_{sj}$ ：j層葉冠氣孔阻力（ stomatal resistance of the jth canopy layer ）

LAIj ：j層葉面積指數（ LAI of jth canopy layer ）

空氣阻力（ $\Upsilon_a$ ）可以用下列公式計算：

$$\Upsilon_a = [l_n(Z-d)/Z_o]^2/[K^2 U_Z] \quad \cdots\cdots(6)$$

式中，$Z_o$：粗糙長度（ Roughness length ）

d ：地面修正量（ Zero Plane displacement ）

K ： Von Karmon constant

$U_Z$ ：高度Z之水平風速

Van Bavel[14]於1966年稍微修正，Penman[9] 1948年提出計算作物最高蒸發散量之公式如下：

$$ET_o = \left(\frac{\triangle}{\triangle+\Upsilon}\right)(R_n - G - M) + \frac{\rho C_p (e_z^* - e_z)}{(\triangle+\Upsilon)\Upsilon_a} \quad \cdots\cdots(7)$$

式中，$\rho$ ：空氣密度（ density of moist air ）

$C_p$ ：定壓比熱（ specific heat of moist air ）

M ：葉冠體積之熱容量（ rate of heat storage in the canopy volume on an area basis ）

## 五、Priestley and Taylor equation

Priestley and Taylor[10]於1972年介紹下面方程式計算作物最高蒸發散量：

$$ET_0 = \alpha \left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) \quad \cdots\cdots (8)$$

式中，$\alpha$：係數$\simeq 1.26$

Jury and Tanner [6] 於 1975 年指出$\alpha$之值可能因作物和地方性氣候而改變，所以他們建議稍微修正 Priestley and Taylor 公式：

$$ET_0 = \left[1 + (\alpha - 1)(e_z^* - e_z) / (\overline{e_z^* - e_z})\right]\left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) \quad \cdots\cdots (9)$$

式中，$\overline{e_z^* - e_z}$：長時間空氣蒸汽壓力差（ long-term vapour pressure deficit during non-advective periods ）

$e_z^* - e_z$ ：空氣蒸汽壓力差（ vapour pressure deficit on a given day ）

在潮濕（ humid ）和半潮濕（ sub-humid ） 地區，空氣蒸汽壓力差可用下列公式計算：

$$e_z^* - e_z \simeq e^*[(T_a max + T_a min)/2] - e^*(T_a min) \quad \cdots\cdots (10)$$

式中，$T_a max$：最高氣溫

$T_a min$ ：最低氣溫

## 六、Modified priestley and Taylor equation

Tan and Fulton [12]，Tan and Layne [13] 於 1981年將 Priestly and Taylor 原來提出之公式簡單化，用來計算作物最高蒸發散量：

$$ET_0 = 1.26(0.48 + 0.01 T_a)(c + d R_s) \quad \cdots\cdots (11)$$

式中，$T_a$ ：日平均氣溫，可用下列公式估計：

$T_a = (T_a max + T_a min) / 2$

c, d ：係數（參考附錄三）

$R_s$ ：日射量（ solar radiation ）

日射量（$R_s$）可以直接用儀器測量或用下列公式間接求得：

$$R_s = \left(a + b\frac{n}{N}\right) R_a \quad \cdots\cdots (12)$$

式中，a，b ：地域性參數（參考附錄四）

n ：實際日照時數

N ：可能日照時數（參考附錄五）

$R_a$ ：完全碧空日射量（參考附錄六）

## 作物灌溉需水量之預測

本文僅將介紹利用氣象資料預測作物灌溉需水量之方法，一般常用公式如下：

$$SM_d = SM_{d-1} - ET_c + P_e + I - D \quad \cdots\cdots (13)$$

式中，$SM_d$ ：當天內土壤固定根系深度水份含量

$SM_{d-1}$：前一天土壤固定根系深度水份含量

$ET_c$ ：作物蒸發散量（ $K_c \times ET_o$ ）

$P_e$ ：降雨有效雨量（ Effective rainfall ）

I ：灌溉量

D ：排水量

在第一次利用公式(13)，式中前一天土壤固定根系深度水份（ $SM_{d-1}$ ）必須事先測出，以後 $SM_{d-1}$ 值就可以利用公式(13)計算出之數值，作物蒸發散量（ $ET_c$ ）可以利用上節所提任何公式〔(1)，(2)，(4)，(7)，(8)，(9)，(11)〕來推算，降雨有效水份（ $P_e$ ）是指植物可利用之降雨總量，Kanemasu et. al.[7] 1978 年利用下列公式計算降雨有效量（ $P_e$ ）：

$$P_e = (P / 25.4)^{0.75} \times 25.4, \quad \text{If } P \geq 25.4 \text{ mm} \quad \cdots\cdots (14)$$

$$P_e = P, \quad \text{If } P < 25.4 \text{ mm} \quad \cdots\cdots (15)$$

土壤最高水份含量（ $SM_{fc}$ ）通常稱為 Field capacity ，在一般灌溉實際作業裡，大部份之作物都應該至少保持在百分五十土壤有效水份（ $SM_{\frac{1}{2}fc}$ ），假如土壤水份（ $SM_d$ ）超出 Field capacity，多餘之水份必須排出，其排水量（ D ）可以由下列公式計算：

$$D = SM_d - SM_{fc} \quad \cdots\cdots (16)$$

假如土壤水份（ $SM_d$ ）低於百分之五十土壤有效水份（ $SM_{\frac{1}{2}fc}$ ），不足之水份，則由灌溉（ I ）來補充，其灌溉量可由下列公式計算：

$$I = SM_{fc} - SM_d \quad \cdots\cdots (17)$$

## 灌溉需水量預測實際資料比較

本文以蕃茄和水蜜桃試驗資料為例，試驗地點：Harrow , Southwestern Ontario ,Canada，灌溉需水量根據中子水份測定儀和氣象資料預測方法，其中氣象資料預測方法，估計作物蒸發散量根據公式(11)，(12)。

從圖 1 的結果，比較二種估計灌溉需水量方式，根據中子水份測定儀直接測量土壤水份及利用氣象資料所推估之值非常相近。圖 2 介紹利用氣象資料預測灌溉需水量所需之不同氣象因子。

表 1 介紹蕃茄，表 2 介紹水蜜桃，利用氣象資料預測灌溉時間和需水量實際作業的例子。

## 結　　論

利用氣象資料，證明可用來推估灌溉時間及需水量，這種方法比直接測量土壤水份之方法要簡單而且有效。氣象資料預測作物灌溉需水量最大之優點如下：①比較具有通融性；②可以不需要用儀器直接到田間去測量；③所需之氣象資料可以從附近氣象站獲得；④準確性高；⑤實際作業非常簡單，一般農民可以直接使用；⑥可以利用於各種不同土壤及作物灌溉需水量之估計。

表1　利用氣象方法預測水蜜桃灌溉時間及需水量之例子

**TABLE 1** Sample of peach irrigation schedules in June, 1978 based on climatological method

| | Date | $P_e$ (mm) | $ET_c$ (mm) | $SM_d$ (mm) | D (mm) | I (mm) |
|---|---|---|---|---|---|---|
| | Previous Day | | | 48.1 | | |
| June | 1 | | 5.5 | 42.6 | | |
| 1978 | 2 | 1.4 | 2.2 | 41.8 | | |
| | 3 | | 3.5 | 38.3 | | |
| | 4 | 1.4 | 4.7 | 35.0 | | |
| | 5 | | 4.8 | 47.7 | | 17.5 |
| | 6 | 1.0 | 5.6 | 43.1 | | |
| | 7 | 12.2 | 2.6 | 52.6 | 0.2 | |
| | 8 | | 1.9 | 50.6 | | |
| | 9 | | 4.3 | 46.3 | | |
| | 10 | | 5.4 | 40.9 | | |
| | 11 | | 5.9 | 35.0 | | |
| | 12 | 12.2 | 4.0 | 48.5 | | 5.3 |
| | 13 | | 3.0 | 45.5 | | |
| | 14 | | 3.7 | 41.8 | | |
| | 15 | | 3.1 | 38.7 | | |
| | 16 | 3.1 | 2.7 | 39.1 | | |
| | 17 | | 3.4 | 35.7 | | |
| | 18 | | 3.5 | 49.0 | | 16.8 |
| | 19 | | 4.3 | 44.7 | | |
| | 20 | 15.2 | 5.5 | 52.5 | 1.9 | |
| | 21 | | 4.3 | 48.2 | | |
| | 22 | | 5.4 | 42.8 | | |
| | 23 | | 5.5 | 37.3 | | |
| | 24 | | 4.9 | 32.4 | | |
| | 25 | 20.0 | 4.0 | 48.4 | | |
| | 26 | 4.0 | 1.6 | 50.8 | | |
| | 27 | 1.0 | 5.1 | 46.7 | | |
| | 28 | | 6.0 | 40.7 | | |
| | 29 | 0.6 | 5.9 | 35.4 | | |
| | 30 | | 3.7 | 48.8 | | 17.1 |
| Total | | 72.1 | 126.0 | 2.1 | | 56.7 |

Note: Soil type - Fox sand; crop - peach; effective rooting depth - 30 cm; mm of water at field capacity ($SM_{fc}$) - 52.5 mm; mm of water at 50% ASM ($SM_{\frac{1}{2}fc}$) - 36.0 mm.

表2　利用氣象方法預測蕃茄灌溉時間及需水量之例子

**TABLE 2** Sample of tomato irrigation schedules in July, 1979 based on climatological data

| | Date | $P_e$ (mm) | $ET_c$ (mm) | $SM_d$ (mm) | D (mm) | I (mm) |
|---|---|---|---|---|---|---|
| | Previous Day | | | 78.7 | 1.3 | |
| July | 1 | 2.8 | 1.5 | 78.7 | | |
| 1979 | 2 | | 2.2 | 76.5 | | |
| | 3 | 10.2 | 3.8 | 78.7 | 4.2 | |
| | 4 | | 4.3 | 74.4 | | |
| | 5 | | 5.7 | 68.7 | | |
| | 6 | | 5.7 | 63.0 | | |
| | 7 | | 5.8 | 57.2 | | |
| | 8 | 12.4 | 5.6 | 64.0 | | |
| | 9 | 9.8 | 2.5 | 71.3 | | |
| | 10 | | 4.8 | 66.5 | | |
| | 11 | 0.5 | 5.0 | 62.0 | | |
| | 12 | | 4.7 | 57.3 | | |
| | 13 | 1.0 | 2.1 | 56.2 | | |
| | 14 | | 4.0 | 52.2 | | |
| | 15 | | 5.5 | 46.7 | | 32.0 |
| | 16 | | 5.7 | 73.0 | | |
| | 17 | | 5.0 | 68.0 | | |
| | 18 | | 6.0 | 62.0 | | |
| | 19 | | 5.9 | 56.1 | | |
| | 20 | | 6.0 | 50.1 | | |
| | 21 | | 6.0 | 44.1 | | 34.6 |
| | 22 | | 5.3 | 73.4 | | |
| | 23 | | 4.5 | 68.9 | | |
| | 24 | 0.5 | 4.1 | 65.3 | | |
| | 25 | 5.0 | 2.5 | 67.8 | | |
| | 26 | 0.3 | 2.6 | 65.5 | | |
| | 27 | | 4.7 | 60.8 | | |
| | 28 | | 3.1 | 57.7 | | |
| | 29 | | 5.9 | 51.8 | | |
| | 30 | 1.6 | 5.1 | 48.3 | | 30.4 |
| | 31 | | 2.3 | 76.4 | | |
| Total | | 44.1 | 137.9 | | 5.5 | 97.0 |

Note: Soil type - Fox sandy loam; crop - tomato; effective rooting depth - 30 cm; mm of water at field capacity ($SM_{fc}$) - 78.7 mm; mm of water at 50% ASM ($SM_{\frac{1}{2}fc}$) - 46.4 mm.

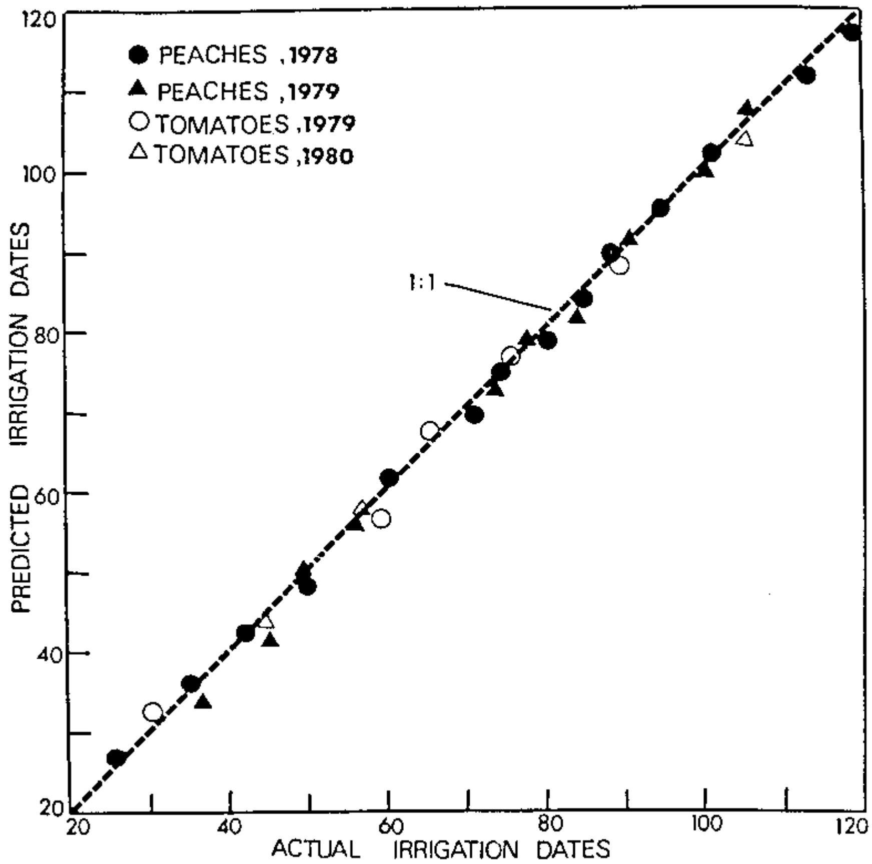


圖 1　利用土壤水份和氣象資料預測灌溉時間之比較

**Figure 1.** Comparison of actual versus predicted irrigation dates, based on soil moisture and climatological data, respectively.

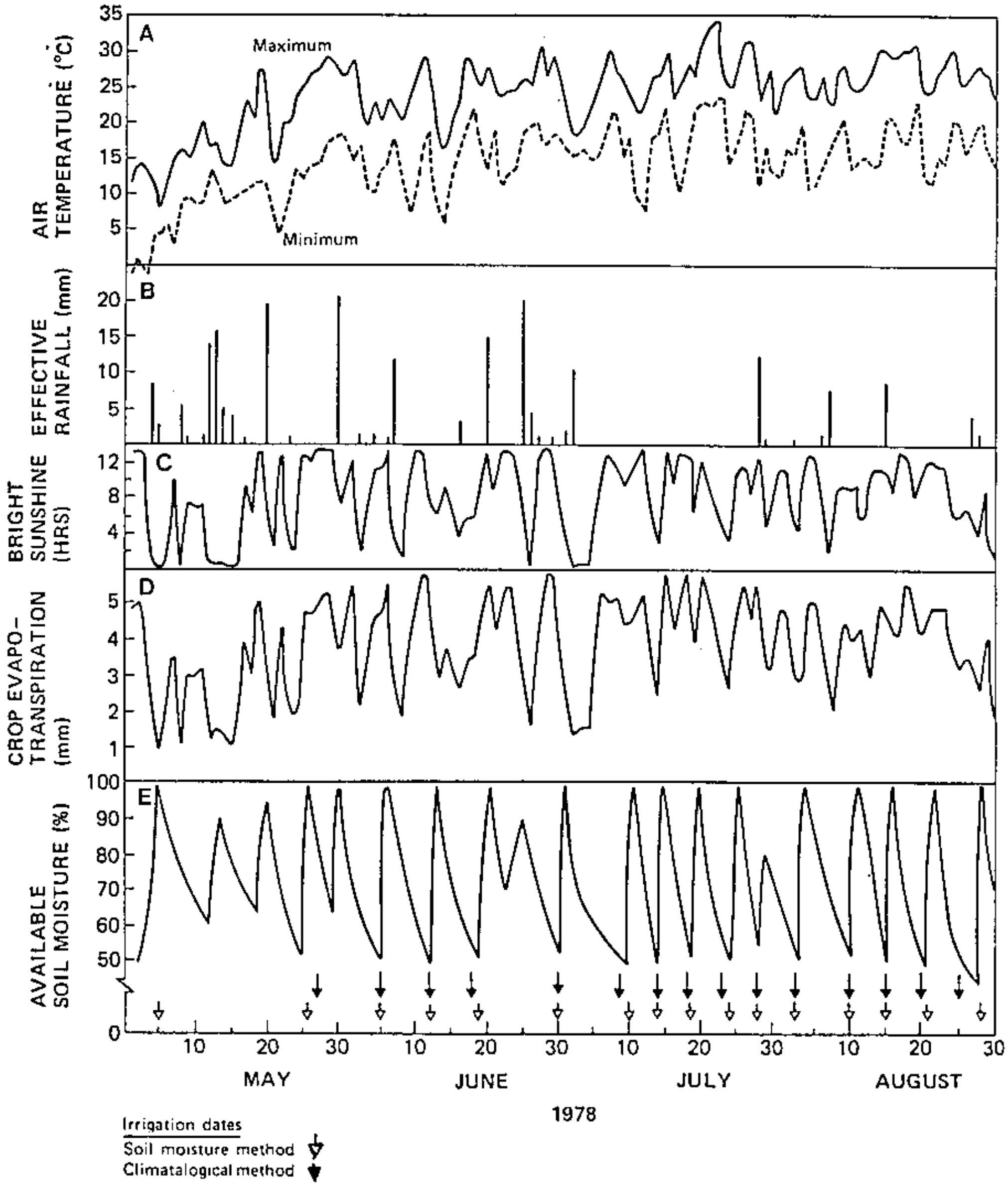


圖2　利用氣象資料預測灌溉時間及需水量所需之不同氣象因子

**Figure 2.** Daily records of climatic data used for scheduling irrigation of peaches from May to August, 1978: **(A)** air temperature, **(B)** effective rainfall and **(C)** bright sunshine. Also shown are **(D)** crop evapotranspiration estimated from the product of potential evapotranspiration and a crop factor and **(E)** available soil moisture obtained from neutron probe. The actual irrigation dates based on soil moisture (⇩) and predicted dates based on climatological method (evapotranspiration data) (⬇) are also included. (From Tan and Layne[13], 1981).

**APPENDIX 1** Generalized crop factors ($K_c$) for use with potential evapotranspiration ($ET_o$) (Hargreaves,[5] 1974, ASAE Transactions 17, No. 4)

| Crop | * Average KC for full crop cover | ** Average seasonal KC |
|---|---|---|
| Field and oil crops including beans, castor beans, corn, cotton, flax, peanuts, potatoes, safflower, soybeans, sorghum, sugar beets, tomatoes and wheat | 1.15 | .90 |
| Fruits, nuts and grapes | | |
| Citrus fruits (oranges, lemons and grapefruits) | .75 | .75 |
| Deciduous fruits (peaches, plums and walnuts) | .90 | .70 |
| Deciduous fruits with cover crop | 1.25 | 1.00 |
| Grapes | .75 | .60 |
| Hay, forage and cover crops | | |
| Alfalfa | 1.35 | 1.00 |
| Short grass | 1.00 | 1.00 |
| Clover pasture | 1.15 | |
| Green manure | 1.10 | .95 |
| Sugar cane | 1.25 | 1.00 |
| Summer vegetables | 1.15 | .85 |

* Recommended for designing system capacity

** To be used in estimating seasonal requirements and for economic analysis. Provides satisfactory results for irrigation scheduling for most soils with good capacity to store redily available moisture.

**APPENDIX 2** Pan coefficient (Kp) for class A pan for different ground cover and levels of mean relative humidity and 24 hours wind. (参考文献(3))

| Class A Pan | CASE A<br>Pan surrounded by short green crop | | | | CASE B[1]<br>Pan surrounded by dry-fallow land | | | |
|---|---|---|---|---|---|---|---|---|
| RH mean % | | low 40 | med 40-70 | high 70 | | low 40 | med 40-70 | high 70 |
| Wind km/day | Upwind distance of green crop m | | | | Upwind distance of dry fallow m | | | |
| Light 175 | 0 | .55 | .65 | .75 | 0 | .7 | .8 | .85 |
| | 10 | .65 | .75 | .85 | 10 | .6 | .7 | .8 |
| | 100 | .7 | .8 | .85 | 100 | .55 | .65 | .75 |
| | 1 000 | .75 | .85 | .85 | 1 000 | .5 | .6 | .7 |
| Moderate 175-425 | 0 | .5 | .6 | .65 | 0 | .65 | .75 | .8 |
| | 10 | .6 | .7 | .75 | 10 | .55 | .65 | .7 |
| | 100 | .65 | .75 | .8 | 100 | .5 | .6 | .65 |
| | 1 000 | .7 | .8 | .8 | 1 000 | .45 | .55 | .6 |
| Strong 425-700 | 0 | .45 | .5 | .60 | 0 | .6 | .65 | .7 |
| | 10 | .55 | .6 | .65 | 10 | .5 | .55 | .65 |
| | 100 | .6 | .65 | .7 | 100 | .45 | .5 | .6 |
| | 1 000 | .65 | .7 | .75 | 1 000 | .4 | .45 | .55 |
| Very strong 700 | 0 | .4 | .45 | .5 | 0 | .5 | .6 | .65 |
| | 10 | .45 | .55 | .6 | 10 | .45 | .5 | .55 |
| | 100 | .5 | .6 | .65 | 100 | .4 | .45 | .5 |
| | 1 000 | .55 | .6 | .65 | 1 000 | .35 | .4 | .45 |

1/ For extensive areas of bare-fallow soils and no agricultural development, reduce Kpan values by 20% under hot windy conditions, by 5-10% for moderate wind, temperature and humidity conditions.

**APPENDIX 3** Coefficients of equations for estimating net radiation from solar radiation ($Rn = c + d\ Rs$; c in mm $day^{-1}$)

| Crop | c | d |
|---|---|---|
| Barley | -2.97 | 0.66 |
| Grass (clear sky) | -2.23 | 0.78 |
| Grass (overcast) | -0.74 | 0.77 |
| Meadow | -2.48 | 0.61 |
| Prairie | -1.98 | 0.58 |
| Oats | -3.22 | 0.72 |
| Pineapple | -4.21 | 0.94 |
| Sugar cane | -3.71 | 0.83 |
| Wheat | -4.21 | 0.81 |
| Rice | -1.49 | 0.65 |
| Douglas-fir | +0.18 | 0.59 |

APPENDIX 4 Experimentally determined constants for the radiation equation Rs = (a + b n/N) Ra(参考文獻(3))

| Location or Range of Locations | Constants a | b | a+b | Latitude° | Location or Range of locations | Constants a | b | a+b | Latitude° |
|---|---|---|---|---|---|---|---|---|---|
| Stockholm and Fairbanks | 0.22 | 0.52 | 0.74 | 59 + 65 N | Accra, Chana | 0.30 | 0.37 | 0.67 | 6 N |
| Lerwick, U.K. | 0.23 | 0.56 | 0.79 | 60 N | Batavia (Djakarta) | 0.29 | 0.59 | 0.88 | 6 S |
| Rothamsted, U.K. | 0.18 | 0.55 | 0.73 | 52 N | Kinshasa, Zaire | 0.21 | 0.52 | 0.73 | 4 S |
| Canada | 0.25 | 0.62 | 0.87 | 52 N | Singapore | 0.21 | 0.48 | 0.69 | 1 N |
| Kew, U.K. | 0.19 | 0.57 | 0.76 | 51 N | Kabcie, Kenya | 0.24 | 0.59 | 0.83 | 1 S |
| Cembloux, Belgium | 0.15 | 0.54 | 0.69 | 51 N | Klaangani, Zaire | 0.28 | 0.40 | 0.68 | 1 N |
| Versailles, France | 0.23 | 0.50 | 0.73 | 49 N | Kampala, Uganda | 0.24 | 0.46 | 0.70 | 0 |
| Mean | 0.21 | 0.55 | 0.76 | 54° | Mean | 0.25 | 0.49 | 0.74 | 30° |
| Wisconsin, U.S.A. | 0.18 | 0.55 | 0.73 | 43 N | All in the U.S.A. | 0.35 | 0.41 | 0.96 | - |
| El Aounia | 0.28 | 0.43 | 0.71 | 37 N | Tropics to polar | 0.23 | 0.48 | 0.71 | - |
| Deniliquin, Australia | 0.27 | 0.54 | 0.81 | 36 S | Canada | 0.355 | 0.68 | 1.03 | - |
| Tunisia | 0.16 | 0.59 | 0.75 | 35 N | Australia, 12-43°S | 0.26 | 0.50 | 0.76 | - |
| Canberra, Australia | 0.25 | 0.54 | 0.79 | 35 S | West Africa, 5-15°N | 0.19 | 0.60 | 0.79 | - |
| Dry Creek, S. Africa | 0.30 | 0.50 | 0.80 | 35 S | 40°N - 40°S | 0.23 | 0.52 | 0.75 | - |
| Capetown, S. Africa | 0.20 | 0.59 | 0.79 | 34 S | | | | | |
| Mean | 0.23 | 0.53 | 0.76 | 36° | | | | | |
| Durban, S. Africa | 0.25 | 0.50 | 0.75 | 30 S | Capetown, S. Africa | 0.29 | 0.50 | 0.75 | 34 S |
| New Delhi, India | 0.31 | 0.46 | 0.77 | 29 N | Eastern Mediterranean | 0.32 | 0.47 | 0.79 | 31 N |
| Pretoria, S. Africa | 0.25 | 0.50 | 0.75 | 26 S | Saudi Arabia | 0.36 | 0.47 | 0.83 | - |
| Windhoek, S.W. Africa | 0.26 | 0.52 | 0.78 | 23 S | Virginia, U.S.A. | 0.22 | 0.54 | 0.76 | 37 N |
| Tananarive, Madagascar | 0.30 | 0.48 | 0.78 | 19 S | Salt Lake City, U.S.A. | 0.20 | 0.47 | 0.67 | 41 N |
| Jamaica | 0.31 | 0.49 | 0.80 | 18 N | | | | | |
| Mean | 0.28 | 0.49 | 0.77 | 24° | | | | | |
| Kimberly, S. Africa | 0.33 | 0.43 | 0.76 | 16 S | | | | | |
| Central Africa | 0.32 | 0.47 | 0.79 | 15 S | Israel (daily) | 0.36 | 0.43 | 0.79 | 31 N |
| Dakar, Senegal | 0.10 | 0.70 | 0.80 | 15 N | Israel (weekly) | 0.39 | 0.38 | 0.77 | 31 N |
| Madras, India | 0.31 | 0.49 | 0.80 | 13 N | Israel (monthly) | 0.41 | 0.36 | 0.77 | 31 N |
| Kano, Nigeria | 0.26 | 0.54 | 0.80 | 12 N | Netherlands | 0.18 | 0.54 | 0.72 | 52 N |
| Trinidad | 0.27 | 0.49 | 0.76 | 11 N | Los Ranos, Philipines | 0.24 | 0.54 | 0.79 | 15 N |
| Bonin City, Nigeria | 0.26 | 0.38 | 0.64 | 7 N | Phoenix, Ariz., U.S.A. | - | - | 0.78 | 33 N |
| Mean | 0.26 | 0.50 | 0.76 | 13° | 嘉南，台灣* | 0.20 | 0.43 | 0.63 | 23 N |

*參考文獻(1)

**APPENDIX 5** Mean daily maximum duration of bright sunshine hours(N)for different months and latitudes （参考文献(3)）

| Northern Lats / Southern Lats | Jan. / July | Feb. / Aug. | March / Sept. | April / Oct. | May / Nov. | June / Dec. | July / Jan. | Aug. / Feb. | Sept. / Mar. | Oct. / Apr. | Nov. / May | Dec. / June |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50° | 8.5 | 10.1 | 11.8 | 13.8 | 15.4 | 16.3 | 15.9 | 14.5 | 12.7 | 10.8 | 9.1 | 8.1 |
| 48° | 8.8 | 10.2 | 11.8 | 13.6 | 15.2 | 16.0 | 15.6 | 14.3 | 12.6 | 10.9 | 9.3 | 8.3 |
| 46° | 9.1 | 10.4 | 11.9 | 13.5 | 14.9 | 15.7 | 15.4 | 14.2 | 12.6 | 10.9 | 9.5 | 8.7 |
| 44° | 9.3 | 10.5 | 11.9 | 13.4 | 14.7 | 15.4 | 15.2 | 14.0 | 12.6 | 11.0 | 9.7 | 8.9 |
| 42° | 9.4 | 10.6 | 11.9 | 13.4 | 14.6 | 15.2 | 14.9 | 13.9 | 12.9 | 11.1 | 9.8 | 9.1 |
| 40° | 9.6 | 10.7 | 11.9 | 13.3 | 14.4 | 15.0 | 14.7 | 13.7 | 12.5 | 11.2 | 10.0 | 9.3 |
| 35° | 10.1 | 11.0 | 11.9 | 13.1 | 14.0 | 14.5 | 14.3 | 13.5 | 12.4 | 11.3 | 10.3 | 9.8 |
| 30° | 10.4 | 11.1 | 12.0 | 12.9 | 13.6 | 14.0 | 13.9 | 13.2 | 12.4 | 11.5 | 10.6 | 10.2 |
| 25° | 10.7 | 11.3 | 12.0 | 12.7 | 13.3 | 13.7 | 13.5 | 13.0 | 12.3 | 11.6 | 10.9 | 10.6 |
| 20° | 11.0 | 11.5 | 12.0 | 12.6 | 13.1 | 13.3 | 13.2 | 12.8 | 12.3 | 11.7 | 11.2 | 10.9 |
| 15° | 11.3 | 11.6 | 12.0 | 12.5 | 12.8 | 13.0 | 12.9 | 12.6 | 12.2 | 11.8 | 11.4 | 11.2 |
| 10° | 11.6 | 11.8 | 12.0 | 12.3 | 12.6 | 12.7 | 12.6 | 12.4 | 12.1 | 11.8 | 11.6 | 11.5 |
| 5° | 11.8 | 11.9 | 12.0 | 12.2 | 12.3 | 12.4 | 12.3 | 12.3 | 12.1 | 12.0 | 11.9 | 11.8 |
| 0° | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 |

**APPENDIX 6** Extra-terrestrial radiation(Ra)expressed in equivalent evaporation in mm/day （参考文献(3)）

| Northern Hemisphere | | | | | | | | | | | | | Southern Hemisphere | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Lat | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
| 3.8 | 6.1 | 9.4 | 12.7 | 15.8 | 17.1 | 16.4 | 14.1 | 10.9 | 7.4 | 4.5 | 3.2 | 50° | 17.5 | 14.7 | 10.9 | 7.0 | 4.2 | 3.1 | 3.5 | 5.5 | 8.9 | 12.9 | 16.5 | 18.2 |
| 4.3 | 6.6 | 9.8 | 13.0 | 15.9 | 17.2 | 16.5 | 14.3 | 11.2 | 7.8 | 5.0 | 3.7 | 48 | 17.6 | 14.9 | 11.2 | 7.5 | 4.7 | 3.5 | 4.0 | 6.0 | 9.3 | 13.2 | 16.6 | 18.2 |
| 4.9 | 7.1 | 10.2 | 13.3 | 16.0 | 17.2 | 16.6 | 14.5 | 11.5 | 8.3 | 5.5 | 4.3 | 46 | 17.7 | 15.1 | 11.5 | 7.9 | 5.2 | 4.0 | 4.4 | 6.5 | 9.7 | 13.4 | 16.7 | 18.3 |
| 5.3 | 7.6 | 10.6 | 13.7 | 16.1 | 17.2 | 16.6 | 14.7 | 11.9 | 8.7 | 6.0 | 4.7 | 44 | 17.8 | 15.3 | 11.9 | 8.4 | 5.7 | 4.4 | 4.9 | 6.9 | 10.2 | 13.7 | 16.7 | 18.3 |
| 5.9 | 8.1 | 11.0 | 14.0 | 16.2 | 17.3 | 16.7 | 15.0 | 12.2 | 9.1 | 6.5 | 5.2 | 42 | 17.8 | 15.5 | 12.2 | 8.8 | 6.1 | 4.9 | 5.4 | 7.4 | 10.6 | 14.0 | 16.8 | 18.3 |
| 6.4 | 8.6 | 11.4 | 14.3 | 16.4 | 17.3 | 16.7 | 15.2 | 12.5 | 9.6 | 7.0 | 5.7 | 40 | 17.9 | 15.7 | 12.5 | 9.2 | 6.6 | 5.3 | 5.9 | 7.9 | 11.0 | 14.2 | 16.9 | 18.3 |
| 6.9 | 9.0 | 11.8 | 14.5 | 16.4 | 17.2 | 16.7 | 15.3 | 12.8 | 10.0 | 7.5 | 6.1 | 38 | 17.9 | 15.8 | 12.8 | 9.6 | 7.1 | 5.8 | 6.3 | 8.3 | 11.4 | 14.4 | 17.0 | 18.3 |
| 7.4 | 9.4 | 12.1 | 14.7 | 16.4 | 17.2 | 16.7 | 15.4 | 13.1 | 10.6 | 8.0 | 6.6 | 36 | 17.9 | 16.0 | 13.2 | 10.1 | 6.3 | 6.3 | 6.8 | 8.8 | 11.7 | 14.6 | 17.0 | 18.2 |
| 7.9 | 9.8 | 12.4 | 14.8 | 16.5 | 17.1 | 16.8 | 15.5 | 13.4 | 10.8 | 8.5 | 7.2 | 34 | 17.8 | 16.1 | 13.5 | 10.5 | 8.0 | 6.8 | 7.2 | 9.2 | 12.0 | 14.9 | 17.1 | 18.2 |
| 8.3 | 10.2 | 12.8 | 15.0 | 16.5 | 17.0 | 16.8 | 15.6 | 13.6 | 11.2 | 9.0 | 7.8 | 32 | 17.8 | 16.2 | 13.8 | 10.9 | 8.5 | 7.3 | 7.7 | 9.6 | 12.4 | 15.1 | 17.2 | 18.1 |
| 8.8 | 10.7 | 13.1 | 15.2 | 16.5 | 17.0 | 16.8 | 15.7 | 13.8 | 11.6 | 9.5 | 8.3 | 30 | 17.8 | 16.4 | 14.0 | 11.3 | 8.9 | 7.8 | 8.1 | 10.1 | 12.7 | 15.3 | 17.3 | 18.1 |
| 9.3 | 11.1 | 13.4 | 15.3 | 16.5 | 16.8 | 16.7 | 15.7 | 14.1 | 12.0 | 9.9 | 8.8 | 28 | 17.7 | 16.4 | 14.3 | 11.6 | 9.3 | 8.2 | 8.6 | 10.4 | 13.0 | 15.4 | 17.2 | 17.9 |
| 9.8 | 11.5 | 13.7 | 15.3 | 16.4 | 16.7 | 16.6 | 15.7 | 14.3 | 12.3 | 10.3 | 9.3 | 26 | 17.6 | 16.4 | 14.4 | 12.0 | 9.7 | 8.7 | 9.1 | 10.9 | 13.2 | 15.5 | 17.2 | 17.8 |
| 10.2 | 11.9 | 13.9 | 15.4 | 16.4 | 16.6 | 16.5 | 15.8 | 14.5 | 12.6 | 10.7 | 9.7 | 24 | 17.5 | 16.5 | 14.6 | 12.3 | 10.2 | 9.1 | 9.5 | 11.2 | 13.4 | 15.6 | 17.1 | 17.7 |
| 10.7 | 12.3 | 14.2 | 15.5 | 16.3 | 16.4 | 16.4 | 15.8 | 14.6 | 13.0 | 11.1 | 10.2 | 22 | 17.4 | 16.5 | 14.8 | 12.6 | 10.6 | 9.6 | 10.0 | 11.6 | 13.7 | 15.7 | 17.0 | 17.5 |
| 11.2 | 12.7 | 14.4 | 15.6 | 16.3 | 16.4 | 16.3 | 15.9 | 14.8 | 13.3 | 11.6 | 10.7 | 20 | 17.3 | 16.5 | 15.0 | 13.0 | 11.0 | 10.0 | 10.4 | 12.0 | 13.9 | 15.8 | 17.0 | 17.4 |
| 11.6 | 13.0 | 14.6 | 15.6 | 16.1 | 16.1 | 16.1 | 15.8 | 14.9 | 13.6 | 12.0 | 11.1 | 18 | 17.1 | 16.5 | 15.1 | 13.2 | 11.4 | 10.4 | 10.8 | 12.3 | 14.1 | 15.8 | 16.8 | 17.1 |
| 12.0 | 13.3 | 14.7 | 15.6 | 16.0 | 15.9 | 15.9 | 15.7 | 15.0 | 13.9 | 12.4 | 11.6 | 16 | 16.9 | 16.4 | 15.2 | 13.5 | 11.7 | 10.8 | 11.2 | 12.6 | 14.3 | 15.8 | 16.7 | 16.8 |
| 12.4 | 13.6 | 14.9 | 15.7 | 15.8 | 15.7 | 15.7 | 15.7 | 15.1 | 14.1 | 12.8 | 12.0 | 14 | 16.7 | 16.4 | 15.3 | 13.7 | 12.1 | 11.2 | 11.6 | 12.9 | 14.5 | 15.8 | 16.5 | 16.6 |
| 12.3 | 13.9 | 15.1 | 15.7 | 15.7 | 15.5 | 15.5 | 15.6 | 15.2 | 14.4 | 13.3 | 12.5 | 12 | 16.6 | 16.3 | 15.4 | 14.0 | 12.5 | 11.6 | 12.0 | 13.2 | 14.7 | 15.5 | 16.4 | 16.5 |
| 13.2 | 14.2 | 15.3 | 15.7 | 15.5 | 15.3 | 15.3 | 15.5 | 15.3 | 14.7 | 13.6 | 12.9 | 10 | 16.4 | 16.3 | 15.5 | 14.2 | 12.8 | 12.0 | 12.4 | 13.5 | 14.8 | 15.9 | 16.2 | 16.2 |
| 13.6 | 14.5 | 15.3 | 15.6 | 15.3 | 15.0 | 15.1 | 15.4 | 15.3 | 14.8 | 13.9 | 13.3 | 8 | 16.1 | 16.1 | 15.5 | 14.4 | 13.1 | 12.4 | 12.7 | 13.7 | 14.9 | 15.8 | 10.0 | 16.0 |
| 13.9 | 14.8 | 15.4 | 15.4 | 15.1 | 14.9 | 15.2 | 15.3 | 15.0 | 15.0 | 14.2 | 13.7 | 6 | 15.8 | 16.0 | 15.6 | 14.7 | 13.4 | 12.8 | 13.1 | 14.0 | 15.0 | 15.7 | 15.8 | 15.7 |
| 14.3 | 15.0 | 15.5 | 15.5 | 14.9 | 14.4 | 14.6 | 15.1 | 15.3 | 15.1 | 14.5 | 14.1 | 4 | 15.5 | 15.8 | 15.6 | 14.9 | 13.8 | 13.2 | 13.4 | 14.3 | 15.1 | 15.6 | 15.5 | 15.4 |
| 14.7 | 15.3 | 15.6 | 15.3 | 14.6 | 14.2 | 14.3 | 14.9 | 15.3 | 15.3 | 15.3 | 14.8 | 2 | 15.3 | 15.7 | 15.7 | 15.1 | 14.1 | 13.5 | 13.7 | 14.5 | 15.2 | 15.5 | 15.3 | 15.1 |
| 15.0 | 15.5 | 15.7 | 15.3 | 14.4 | 13.9 | 14.1 | 14.8 | 15.3 | 15.4 | 15.1 | 14.8 | 0 | 15.0 | 15.5 | 15.7 | 15.3 | 14.4 | 13.9 | 14.1 | 14.8 | 15.3 | 15.4 | 15.1 | 14.8 |

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# CLIMATOLOGICAL DATA FOR PREDICTING CROP IRRIGATION WATER REQUIREMENTS

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## ABSTRACT

Two methods of scheduling irrigation of peach and processing tomatoes were investigated in 1978, 1979 and 1980. In each year, irrigation schedules necessary to prevent the available soil moisture (ASM) from falling below 50% level were similar, wheather determined from direct measurement of soil moisture using a neutron meter or predicted from evapotranspiration models using climatological data.

The climatological method for predicting crop irrigation water requirements was as accurate as the soil moisture method but more convenient and less expensive. By use of the proper values of available moisture-holding capacity of soils and rooting depth of crops, the climatological method can be applied to different crops in different areas. The data required to utilize the climatological method are readily available from local weather stations or can be measured directly if necessary.