Crop Water Requirements & Irrigation Scheduling with CROPWAT 8.0 Application

By Assoc.Prof.Dr.Varawoot Vudhivanich
Department of Irrigation Engineering
Kasetsart University, Kamphaengsaen

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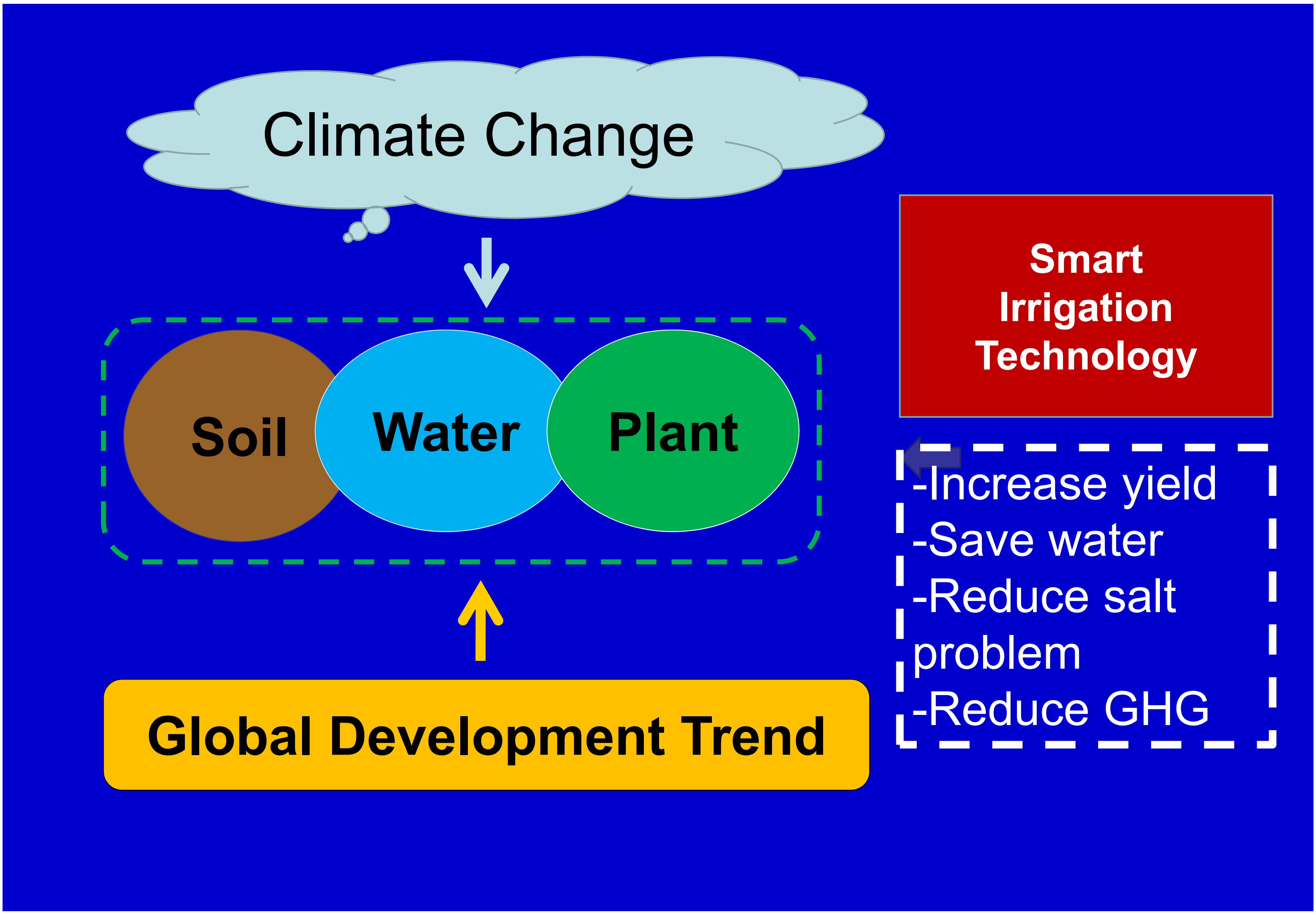


Basic Irrigation Principle

- When to irrigate
- How much water should be applied
- How to apply water efficiently

Soil-Water Relation

- Field Capacity(FC)
- Permanent Wilting Point(PWP)
- Apparent Specific Gravity(As)
- Water Holding Capacity (TAW, RAW)
- Infiltration

Crop & IWR Water Requirements

- ETo
- ETc = Kc.ETo
- ETa = Ks.ETc
- Net IWR, Gross IWR, Efficiency
- Scheme Water Supply

Yield Response

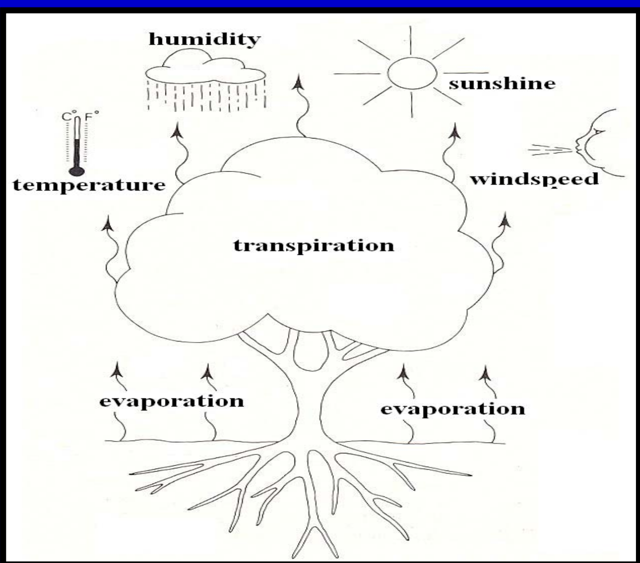
-Depletion Fraction(p)
-Water Stress Coefficients(Ks)
-Yield Response Factor(Ky)
-Yield Response Function: (1-Ya/Ymax) =Ky(1-ETa/ETc)
-Irrigation Scheduling (Optimum irrigation, Deficit Irrigation)

Irrigation Methods

-Surface Irrigation
-Sprinkler Irrigation
-Micro-Irrigation
--Sub-surface Irrigation
-Hydroponics
-Greenhouse

Crop Water Requirements(ETc)

Crop evapotranspiration under standard conditions; disease-free, well-fertilized crops , grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions.

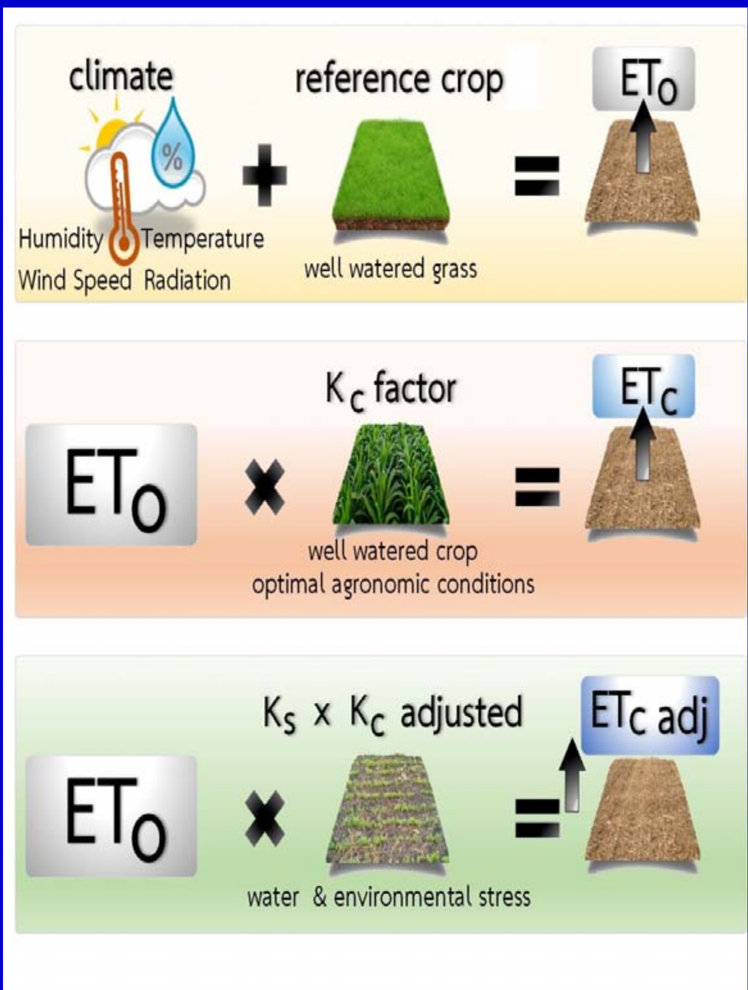


When the standard conditions are not met, the actual crop ET will be lower than ETc.

Crop water requirements for Prachuap Khiri Khan province, Central and Western Thailand
Downloaded from URL: water.rid.go.th/hwm/cropwater/CRWdata/ET

Crop No.	Crop name	Growth period	Crop water requirements	
		days	mm./season	m^3/rai
1	Rice-Rice Department High Yield Variety	100	699	1,119
2	Rice-Khao Dok Mali 105	100	629	1,006
3	Rice-Basmati	100	695	1,112
4	Wheat	100	311	498
5	Maize	100	351	561
6	Sweet corn	75	274	438
7	Sorghum	110	387	619
8	Soy bean	100	373	596
9	Peanut	105	371	594
10	Mung bean	70	215	344
11	Sesame	90	295	471
12	Tobacco	90	398	637
13	Sun flower	110	392	627
14	Water melon	85	418	668
15	Cotton	160	471	753
16	Sugarcane	300	978	1,564
17	Castor bean	200	745	1,191
18	Taro	170	1,177	1,884
19	Asparagus	365	1,526	2,442
20	Tomato	110	494	791
21	Onion	100	395	632
22	Shallots	85	304	487
23	Garlic	110	269	431
24	Potato	95	368	588
25	Bird's eye chilli	150	483	774
26	Bitter gourd	75	326	522
27	Cauliflowers	45	197	316
28	Chinese kale	55	165	265
29	Yard long bean	80	287	459
30	Graden pea	85	302	484
31	Winged bean	135	396	634
32	Chinese cabbage	60	196	313
33	Chinese radish	45	186	297
34	Baby corn	65	287	459
35	Sweet potato	125	465	744

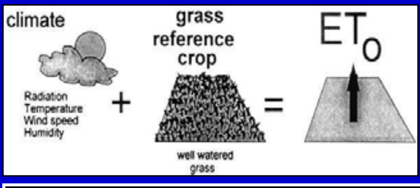
An example seasonal crop water requirement published by RID



ET can be estimated from climatic data, crop data, soil-moisture data.

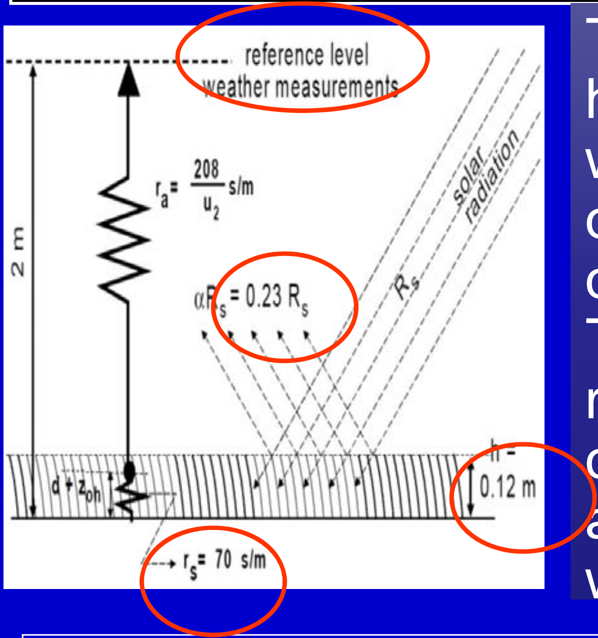
3 ET terms
ETo → ETc → ETa

ETo= Reference crop ET depends on climatic data only.
ETc=Kc.ETo
Kc=Crop coefficient depending types of crop and stage of growth
ETa=Ks.ETc
Ks=Water stress coefficient



ETo = f(climate)

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration (ETo)



The reference surface is a hypothetical grass reference crop with specific characteristics, height of 0.12 m with a surface resistance of 70 s/m and an albedo of 0.23. This crop characteristics is closely resembling the evapotranspiration of green grass of uniform height, actively growing and adequately watered.

Penman-Monteith is recommended method for ETo calculation.

Average ETo for different agroclimatic regions(mm/day)

Regions	Mean daily temperature (°C)		
	Cool ~10°C	Moderate 20°C	Warm > 30°C
Tropics and subtropics			
- humid and sub-humid	2 - 3	3 - 5	5 - 7
- arid and semi-arid	2 - 4	4 - 6	6 - 8
Temperate region			
- humid and sub-humid	1 - 2	2 - 4	4 - 7
- arid and semi-arid	1 - 3	4 - 7	6 - 9

FAO Penman-Monteith Formula

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273.16}\right)U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34U_2)}$$

- ETo = reference evapotranspiration [mm day-1]
- Rn =net radiation at the crop surface [MJ m-2 day-1]
- G = soil heat flux density [MJ m-2 day-1]
- T = air temperature at 2 m height [◦C]
- u2 = wind speed at 2 m height [m s-1]
- es = saturation vapour pressure [kPa]
- ea = actual vapour pressure [kPa]
- es - ea = saturation vapour pressure deficit [kPa]
- Δ = slope of vapour pressure curve [kPa ◦C-1]
- γ = psychrometric constant [kPa ◦C-1].

1 mm/day = 2.45 $MJ/m^2/day$,1bar = 100 kPa

Penman-Monteith Formula

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273.16}\right)U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34U_2)}$$

ET_o	=	Reference crop evapotranspiration	(mm/day)
Δ	=	Slope of saturation vapor pressure curve	(kPa/°C)
γ	=	Psychrometric constant	(kPa/°C)
R_n	=	Net radiation at crop surface	($MJ/m^2/day$)
G	=	Soil heat flux	($MJ/m^2/day$)
T_{max}	=	Maximum air temperature	(°C)
T_{min}	=	Minimum air temperature	(°C)
T	=	Average air temperature	(°C)
U_2	=	Windspeed measured at 2 m height	(m/s)
e_s	=	Saturated vapor pressure	(kPa)
e_a	=	Actual vapor pressure	(kPa)

		1.Calculate Δ, T, e_s	
Δ	=	$\frac{4098 e_s}{(T+237.3)^2}$	[1]
e_s	=	$\frac{e^\circ(T_{max})+e^\circ(T_{min})}{2}$; (Saturation Vapor Pressure)	[2]
$e^\circ(T_{max})$	=	$0.6108 Exp\left(\frac{17.27\,T_{max}}{T_{max}+237.3}\right)$	[3]
$e^\circ(T_{min})$	=	$0.6108 Exp\left(\frac{17.27\,T_{min}}{T_{min}+237.3}\right)$	[4]
T	=	$\frac{T_{max}+T_{min}}{2}$	[5]
		2.Calculate e_a	
e_a	=	$\frac{RH_{mean}}{100} e_s$	[6]
		3.Calculate U_2	
U_2	=	$u_{z'} \frac{4.87}{\ln(67.8z'-5.42)}$; z'=Wind vane elevation (m)	[7]
		4.Calculate γ (Psychrometric constant)	
γ	=	0.665×10^{-3} P	[8]
P	=	$101.3\left(\frac{293-0.0065z}{293}\right)^{5.256}$; (Atmospheric pressure at altitude z m. MSL, kPa)	[9]

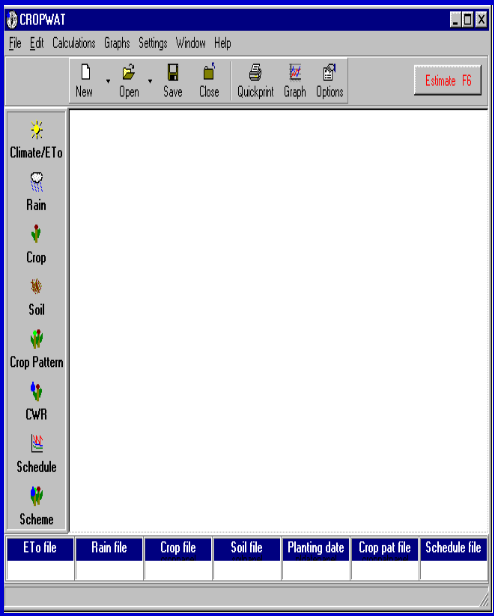
		5.Calculate R_n (Net radiation)	
R_n	=	$R_{ns}-R_{nl}$	[10]
R_{ns}	=	$(1-\alpha)R_s=(1-0.23)R_s$; (Net shortwave radiation)	[11]
R_s	=	$\left(a_s + b_s \frac{n}{N}\right) R_a = \left(0.25 + 0.5\frac{n}{N}\right) R_a$; (Solar radiation)	[12]
n	=	Actual sunshine hours (given data)	
N	=	$\frac{24}{\pi}\omega_s$; (Daylight hours)	[13]
R_a	=	$\frac{24(60)}{\pi} G_{sc} d_r[\omega_s \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)]$	[14]
		(Extraterrestrial radiation, $MJ/m^2/day$)	
G_{sc}	=	0.0820 ; (Solar constant, $MJ/m^2/min$)	[15]
d_r	=	$1 + 0.033\cos\left(\frac{2\pi}{365}J\right)$; (Inverse relative distance between Earth-Sun)	[16]
J	=	Integer(30.4M-15)	[17]
		No. of day in a year (Jan.1 =1, Dec.31=365), M=Month (1, 2, .. ,12)	
J	=	Integer(275M/9-30+D)-2 ; M=month, D=day for leap year	[18]
ω_s	=	$Cos^{-1}[-\tan(\phi)\tan(\delta)]$; (*Sunset hour angle*)	[19a]
or ω_s	=	$\frac{\pi}{2} - tan^{-1}\left[\frac{-\tan(\phi)\tan(\delta)}{X^{0.5}}\right]$	[19b]
X	=	$1-[\tan(\phi)]^2[\tan(\delta)]^2$	[20a]
X	=	0.00001 if $X \leq 0$	[20b]
ϕ	=	Latitude(radians)	
δ	=	$0.409 sin\left(\frac{2\pi}{365}J - 1.39\right)$; (*Solar declination angle*)	[21]
R_{nl}	=	$\sigma\left[\frac{T_{max.k}{}^4 + T_{min.k}{}^4}{2}\right](0.34-0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}}-0.35\right)$	[22]
		(Net long wave radiation, $MJ/m^2/day$)	
σ	=	4.903×10^{-9} ; (Stefan-Boltzman constant, $MJ/m^2/day$)	[23]
Tmax.k	=	Tmax(◦c)+273.16	[24]
Tmin.k	=	Tmin(◦c)+273.16	[25]
$\frac{R_s}{R_{so}}$	=	Relative shortwave radiation ≤ 1.0	
R_{so}	=	$(0.75+2 \times 10^{-5}z)R_a$; (Clear-sky radiation)	[26]
		6.Calculate G	
G	=	0.14 (T_i - T_{i-1}); (Soil heat flux)	[27]

ETo calculation

Given Data		
Month(M)	2	February
Latitude(ϕ)	26.56	°
Tmean(i-1)	18	°c
Tmax	26.3	°c
Tmin	11.9	°c
Tmean	19.1	°c
Altitude(z)	120	m
u_2(m/s)	1.2	m/s
RH_{mean}=	63	%
n	8.4	hrs.

Calculation 1			Description
Tmean=	19.1	°c	
e°(Tmax)=	3.42	kPa	Saturation vapor pressure at Tmax
e°(Tmin)=	1.39	kPa	Saturation vapor pressure at Tmin
e_s=	2.41	kPa	Saturation vapor pressure
Δ=	0.15	kPa/°c	Slope of saturation vapor pressure curve
P=	99.89	kPa	Atmosheric pressure
γ=	0.07	kPa/°c	Psychrometric constant
$(1+0.34u_2)$=	1.41		
$[\Delta+\gamma(1+0.34u_2)]$=	0.24		
$\Delta/[\Delta+\gamma(1+0.34u_2)]$=	0.62		
$\gamma/[\Delta+\gamma(1+0.34u_2)]$=	0.27		
$[900/(Tmean+273.16)]u_2$=	3.71		
$e_a=(RH_{mean}/100)*e_s$=	1.52	kPa	
e_s-e_a=	0.89	kPa	Saturation vapor pressure deficit
Aerodynamic term=	0.9006	mm/day	

Calculation 2			
J=	45	sin	Number of days in year
ϕ=	0.4636	0.4471	Latitude
δ=	-0.2361	-0.2339	Solar declination angle
X=	0.9855		
ws=	1.4502	1.4502	Sunset hour angle
dr=	1.0236		Inverse relative distance between Earth-Sun
Gsc=	0.0820	MJ/m2/min	Solar constant
ws*sin(ϕ)*sin(δ)=	-0.1517		
sin(ws)=	0.9927		
cos(ϕ)*cos(δ)*sin(ws)=	0.8633		
R_a=	27.3794	MJ/m2/day	Extraterrestrial radiation
N=	11.0790	hrs	Daylight hours
Rs=	17.22	MJ/m2/day	
α=	0.23		Albedo
σ=	4.903E-09		Stefan-Boltzman constant
$Tmax.k^4$=	8,041,837,275		Tmax in kelvin
$Tmin.k^4$=	6,603,058,170		Tmin in kelvin
$Tmean.k^4$=	7,322,447,722		Tmean in kelvin
Rso=	20.5351	MJ/m2/day	Clear-sky radiation
Rs/Rso=	0.8388		Relative shortwave radiation
sqrt(e_a)=	1.2315		
R_{nl}=	4.7416	MJ/m2/day	Net longwave radiation
$R_n=R_{ns}-R_nl$=	8.5210	MJ/m2/day	Net solar radiation
G=0.14[Tmean(i)-Tmean(i-1)]=	0.1540	MJ/m2/day	Soil heat flux
Radiation term[1]=	2.10	mm/day	
Aerodynamic term[2]=	0.90	mm/day	
ETo=[1]+[2]	3.00	mm/day	
	84.1	mm/month	



Programme structure = 8 different modules

Data input & basic calculation modules

(1) **Climate/ETo**: Input the measured ETo data or climatic data for ETo calculation

(2) **Rain**: Input the rainfall data and calculation of effective rainfall

(3) **Crop**: Input the crop data and planting date for ETc calculation in (6)

(4) **Soil**: Input the soil data for irrigation scheduling in (7)

(5) **Crop pattern**: Input the cropping pattern for scheme supply calculations in (8)

Note that in fact Climate/ETo and Rain modules are not only for data input but also calculate data, namely Radiation / ET0 and Effective rainfall respectively.

Calculation modules

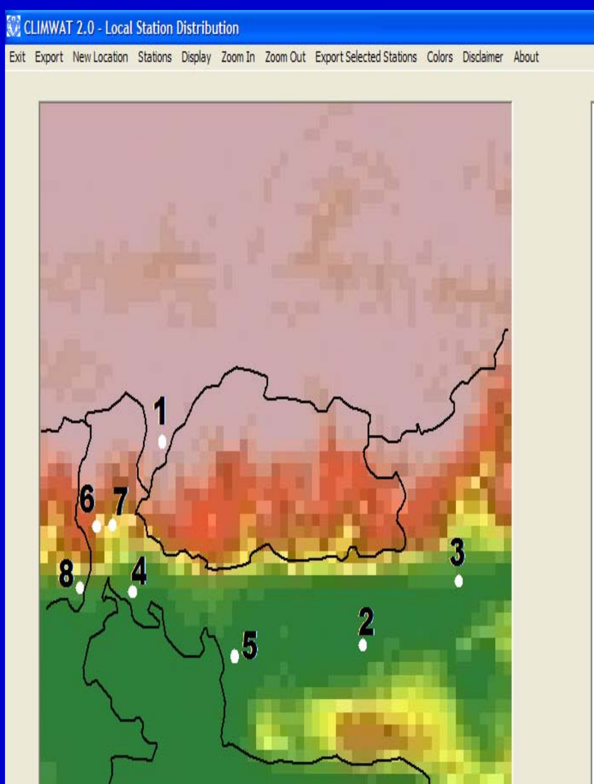
(6) **CWR** - for calculation of Crop Water Requirements

(7) **Schedules** - for the calculation of irrigation schedules

(8) **Scheme** - for the calculation of scheme supply based on a specific cropping pattern

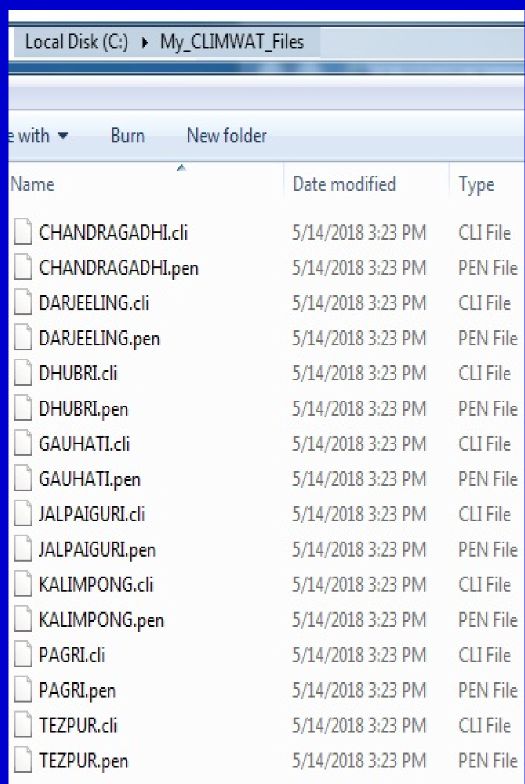
CLIMWAT 2.0

8 climate stations around Bhutan



Nr.	Lon [?]	Lat [?]	Alt [m]	Name	Country
1	89.08	27.73	430	PAGRI	CHINA
2	91.58	26.1	54	GAUHATI	INDIA
3	92.78	26.61	79	TEZPUR	INDIA
4	88.71	26.53	83	JALPAIGURI	INDIA
5	89.98	26.01	35	DHUBRI	INDIA
6	88.26	27.05	2128	DARJEELING	INDIA
7	88.46	27.06	1209	KALIMPONG	INDIA
8	88.05	26.56	120	CHANDRAGADH:	NEPAL

1=PAGRI-CHINA
2=GAUHUTI-INDIA
3=TEZPUR-INDIA
4=JALPAIGURI-INDIA
5=DHUBRI-INDIA
6=DARJEELING-INDIA
7=KALIMPONG-INDIA
8=CHANDRAGADHI-NEPAL



EXAMPLE - ETo Calculation

Monthly ETo Penman-Monteith - D:\Training\00-Bhutan training 21-25 May2018\Bhutan-Data\Climat...

Country: Location 8 — Station: CHANDRAGADHI-Nepal

Altitude: 120 m. — Latitude: 26.56 §N — Longitude: 88.05 §E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/month
January	10.5	23.4	66	86	7.9	14.6	70.11
February	11.9	26.3	63	104	8.4	17.3	84.44
March	15.9	32.0	56	121	8.8	20.4	135.85
April	20.2	34.8	37	147	8.8	22.3	177.60
May	23.1	34.0	67	147	8.1	22.1	166.81
June	25.1	33.0	77	130	5.3	18.1	131.34
July	25.3	32.2	82	121	4.2	16.3	119.69
August	24.9	32.3	84	104	4.6	16.3	116.06
September	24.0	31.7	86	95	5.7	16.6	108.51
October	21.7	31.4	74	86	7.1	16.3	109.05
November	15.4	29.8	69	78	8.1	15.2	87.95
December	10.9	24.7	76	78	7.8	13.7	66.95
Average	**19.1**	**30.5**	**70**	**108**	**7.1**	**17.4**	**1374.36**

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 1 — Station: PAGRI-China

Altitude: 430 m. — Latitude: 27.73 §N — Longitude: 89.08 §E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	-23.0	-7.1	39	199	7.8	14.1	0.92
February	-17.0	-3.4	53	207	7.6	16.0	1.12
March	-12.2	1.2	63	181	7.2	17.9	1.47
April	-6.0	6.0	66	207	6.9	19.4	2.02
May	-3.0	9.4	70	233	7.1	20.6	2.45
June	-3.0	11.0	77	259	5.6	18.5	2.37
July	-3.5	12.0	81	225	4.1	16.1	2.19
August	-3.5	11.7	82	216	5.0	16.8	2.16
September	-5.0	10.1	80	207	4.8	15.1	1.92
October	-8.0	8.0	69	190	6.7	15.5	1.84
November	-13.5	2.1	57	190	7.8	14.5	1.41
December	-17.5	-5.5	40	147	7.6	13.2	0.96
Average	**-9.6**	**4.6**	**65**	**205**	**6.5**	**16.5**	**1.74**

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 2 — Station: GAUHATI-India

Altitude: 54 m. — Latitude: 26.10 §N — Longitude: 91.58 §E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	10.5	23.6	77	52	7.1	13.8	1.97
February	11.9	26.0	65	69	7.5	16.3	2.68
March	15.7	29.9	57	95	6.8	17.7	3.70
April	19.9	30.7	65	147	6.7	19.3	4.50
May	22.4	31.0	74	95	5.9	18.8	4.14
June	24.8	31.9	81	95	3.4	15.2	3.57
July	25.3	31.7	81	69	3.3	14.9	3.46
August	25.4	32.1	82	69	3.8	15.1	3.49
September	24.4	31.4	81	69	4.5	14.9	3.35
October	21.9	30.2	81	69	6.3	15.3	3.18
November	16.8	27.5	83	69	7.5	14.6	2.61
December	11.8	24.4	83	52	7.0	13.0	1.95
Average	**19.2**	**29.2**	**76**	**79**	**5.8**	**15.8**	**3.22**

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 4 — Station: JALPAIGURI-India

Altitude: 83 m. — Latitude: 26.53 §N — Longitude: 88.71 §E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	10.8	23.4	71	26	7.8	14.5	1.89
February	12.7	25.2	63	26	8.2	17.0	2.41
March	16.4	29.6	53	86	8.8	20.4	3.94
April	20.4	31.6	57	130	8.6	22.0	5.03
May	22.9	30.9	73	147	6.8	20.1	4.63
June	24.3	30.6	81	121	5.3	18.1	4.04
July	25.0	30.6	84	112	4.1	16.1	3.66
August	24.9	30.8	83	95	4.6	16.3	3.65
September	24.4	30.7	81	86	4.9	15.4	3.44
October	21.4	30.0	75	78	7.4	16.7	3.42
November	16.2	27.7	73	35	8.3	15.4	2.54
December	12.1	25.0	72	35	8.1	14.1	1.99
Average	**19.3**	**28.8**	**72**	**81**	**6.9**	**17.2**	**3.39**

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 3 — Station: TEZPUR-India

Altitude: 79 m. — Latitude: 26.61 §N — Longitude: 92.78 §E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	11.4	23.7	100	26	8.7	15.4	2.04
February	13.7	25.4	81	61	8.1	16.9	2.59
March	17.1	29.0	65	95	8.7	20.2	3.87
April	20.2	30.3	67	130	8.3	21.6	4.66
May	22.5	30.3	88	95	6.9	20.3	4.12
June	24.7	31.6	93	61	5.6	18.5	3.92
July	25.3	32.1	90	26	5.3	17.9	3.91
August	25.4	32.2	91	26	5.7	17.9	3.90
September	24.7	31.7	96	26	6.1	17.1	3.66
October	21.8	30.2	94	26	7.7	17.0	3.36
November	16.5	27.6	100	35	8.8	16.0	2.66
December	12.4	24.7	100	35	9.1	15.1	2.08
Average	**19.6**	**29.1**	**89**	**53**	**7.4**	**17.8**	**3.40**

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 5 | Station: DHUBRI-India
Altitude: 35 m. | Latitude: 26.01 °N | Longitude: 89.98 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	11.7	23.3	86	61	7.8	14.6	2.02
February	13.3	25.5	78	95	8.2	17.2	2.75
March	17.2	30.0	57	121	8.5	20.1	4.23
April	21.1	30.5	61	156	8.1	21.3	4.96
May	22.8	30.0	90	138	6.0	19.0	3.86
June	24.4	30.0	96	121	6.0	19.1	3.80
July	25.5	30.0	93	112	5.8	18.7	3.85
August	26.1	30.0	92	95	5.6	17.8	3.74
September	25.0	29.4	91	95	6.0	17.0	3.50
October	22.8	29.4	93	95	6.9	16.1	3.15
November	17.8	26.7	95	78	7.9	15.1	2.54
December	12.8	23.3	91	69	8.4	14.6	2.02
Average	20.0	28.2	85	103	7.1	17.5	3.37

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 6 | Station: DARJEELING-India
Altitude: 2128 m. | Latitude: 27.05 °N | Longitude: 88.26 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	3.0	9.3	100	26	5.1	11.4	1.27
February	4.3	11.1	100	61	4.8	12.7	1.49
March	7.7	14.8	92	61	5.5	15.7	2.20
April	10.8	18.0	100	95	5.5	17.4	2.66
May	12.9	18.6	100	61	3.3	14.9	2.58
June	14.7	19.3	100	61	1.1	11.8	2.22
July	15.4	19.8	100	52	0.0	10.0	2.01
August	15.4	19.8	100	61	1.1	11.1	2.14
September	14.6	19.9	100	43	1.4	10.5	2.03
October	11.5	18.6	100	26	4.9	13.4	2.26
November	7.4	15.3	100	26	5.5	12.1	1.73
December	4.4	11.9	99	26	5.6	11.3	1.36
Average	10.2	16.4	99	50	3.6	12.7	2.00

Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

Country: Location 7 | Station: KALIMPONG-India
Altitude: 1209 m. | Latitude: 27.06 °N | Longitude: 88.46 °E

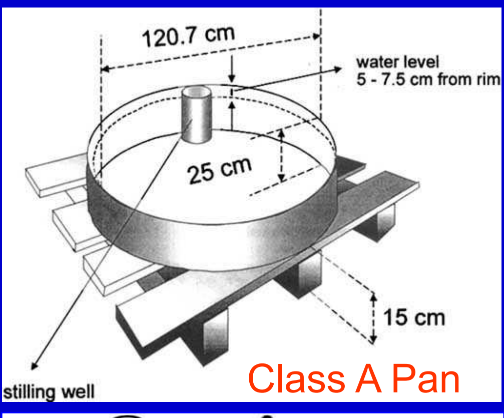
Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	7.8	15.5	78	164	6.2	12.6	1.81
February	9.1	16.7	76	164	6.7	15.1	2.25
March	12.2	20.6	68	164	8.0	19.2	3.34
April	15.0	23.1	72	190	8.0	21.1	3.99
May	17.3	24.1	82	164	6.8	20.1	3.82
June	18.9	24.4	87	130	7.0	20.6	3.87
July	19.2	24.1	90	130	6.0	19.0	3.55
August	19.3	24.3	88	130	4.7	16.4	3.20
September	18.8	24.1	90	130	3.7	13.7	2.67
October	16.1	23.3	82	164	7.1	16.2	2.97
November	11.6	20.0	78	164	7.2	14.0	2.36
December	8.8	17.3	76	164	7.3	13.1	1.96
Average	14.5	21.5	81	155	6.6	16.7	2.98

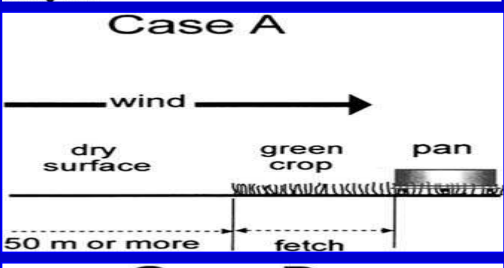
Monthly ETo Penman-Monteith - G:\00-training\Irrigation project planning-7Mar\Bhu...

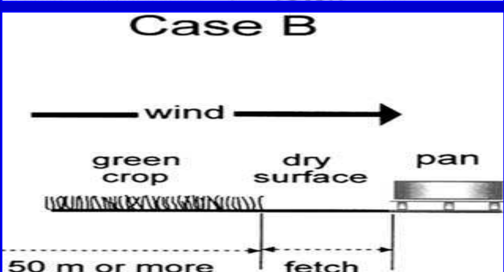
Country: Location 8 | Station: CHANDRAGADHI-Nepal
Altitude: 120 m. | Latitude: 26.56 °N | Longitude: 88.05 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	?C	?C	%	km/day	hours	MJ/m?/day	mm/day
January	10.5	23.4	66	86	7.9	14.6	2.26
February	11.9	26.3	63	104	8.4	17.3	3.02
March	15.9	32.0	56	121	8.8	20.4	4.38
April	20.2	34.8	37	147	8.8	22.3	5.92
May	23.1	34.0	67	147	8.1	22.1	5.38
June	25.1	33.0	77	130	5.3	18.1	4.38
July	25.3	32.2	82	121	4.2	16.3	3.86
August	24.9	32.3	84	104	4.6	16.3	3.74
September	24.0	31.7	86	95	5.7	16.6	3.62
October	21.7	31.4	74	86	7.1	16.3	3.52
November	15.4	29.8	69	78	8.1	15.2	2.93
December	10.9	24.7	76	78	7.8	13.7	2.16
Average	19.1	30.5	70	108	7.1	17.4	3.76

Alternative ETo Calculation (ETo = Kp.Epan)







Kp = pan coefficient

Epan = pan evaporation [mm/day]

TABLE 4 Pan coefficients (K_p) for Class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (FAO Irrigation and Drainage Paper No. 24)

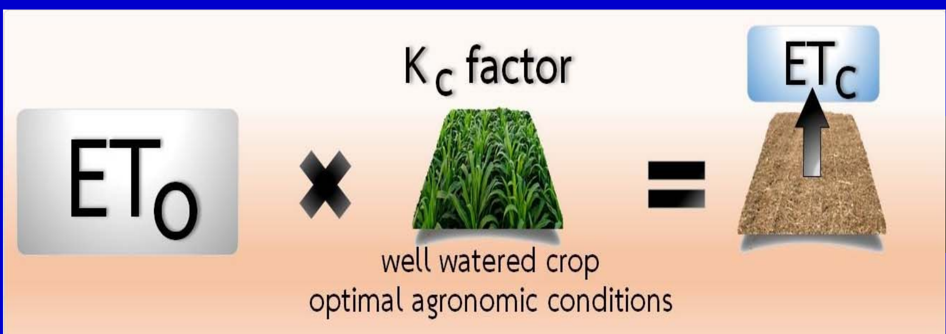
Class A pan	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean (%) →		low < 40	medium 40 - 70	high > 70		low < 40	medium 40 - 70	high > 70
Wind speed (m s-1)	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light	1	0.55	0.65	0.75	1	0.7	0.8	0.85
< 2	10	0.65	0.75	0.85	10	0.6	0.7	0.8
	100	0.7	0.8	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.5	0.6	0.7
Moderate	1	0.5	0.6	0.65	1	0.65	.75.	0.8
2-5	10	0.6	0.7	0.75	10	0.55	0.65	0.7
	100	0.65	0.75	0.8	100	0.5	0.6	0.65
	1000	0.7	0.8	0.8	1000	0.45	0.55	.6.
Strong	1	0.45	0.5	0.6	1	0.6	0.65	0.7
5-8	10	0.55	0.6	0.65	10	0.5	0.55	0.65
	100	0.6	0.65	0.7	100	0.45	0.5	0.6
	1000	0.65	0.7	0.75	1000	0.4	0.45	0.55
Very strong	1	0.4	0.45	0.5	1	0.5	0.6	0.65
> 8	10	0.45	0.55	0.6	10	0.45	0.5	0.55
	100	0.5	0.6	0.65	100	0.4	0.45	0.5
	1000	0.55	0.6	0.65	1000	0.35	0.4	0.45

Estimation of Kp for class A pan

Class A pan with green fetch
$K_p = 0.108 - 0.0286\, u_2 + 0.0422 \ln(FET) + 0.1434 \ln(RH_{mean}) - 0.000631 [\ln(FET)]^2 \ln(RH_{mean})$
Class A pan with dry fetch
$K_p = 0.61 + 0.00341\, RH_{mean} - 0.000162\, u_2\, RH_{mean} - 0.00000959\, u_2\, FET + 0.00327\, u_2 \ln(FET) - 0.00289\, u_2 \ln(86.4\, u_2) - 0.0106 \ln(86.4\, u_2)\ln(FET) + 0.00063 [\ln(FET)]^2 \ln(86.4\, u_2)$
Coefficients and parameters
K_p=pan coefficient **u_2 =average daily wind speed at 2 m height (m s^{-1})** **RH_{mean} = average daily relative humidity [%] = (RH_{max} + RH_{min})/2** **FET= fetch, or distance of short green crop for case A, dry crop or bare soil for case B upwind of the evaporation pan)**
Range for variables
$1\ m \leq FET \leq 1000\ m$, $30\% \leq RH_{mean} \leq 84\%$, $1\ m\ s^{-1} \leq u_2 \leq 8\ m\ s^{-1}$

ETo Under standard conditions

disease-free, well-fertilized, grown in large fields, under optimum soil water conditions.



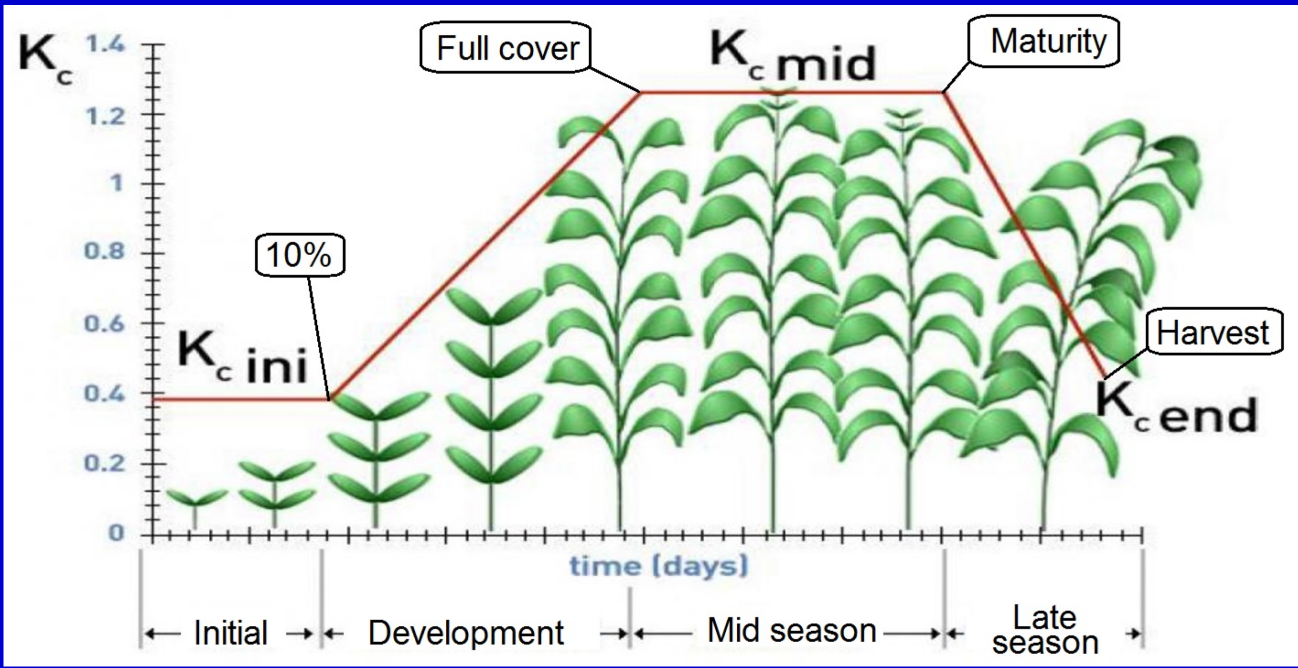
ETc=Kc.ETo

ETc = crop evapotranspiration under standard condition [mm/day]

ETo = reference crop evapotranspiration [mm/day]

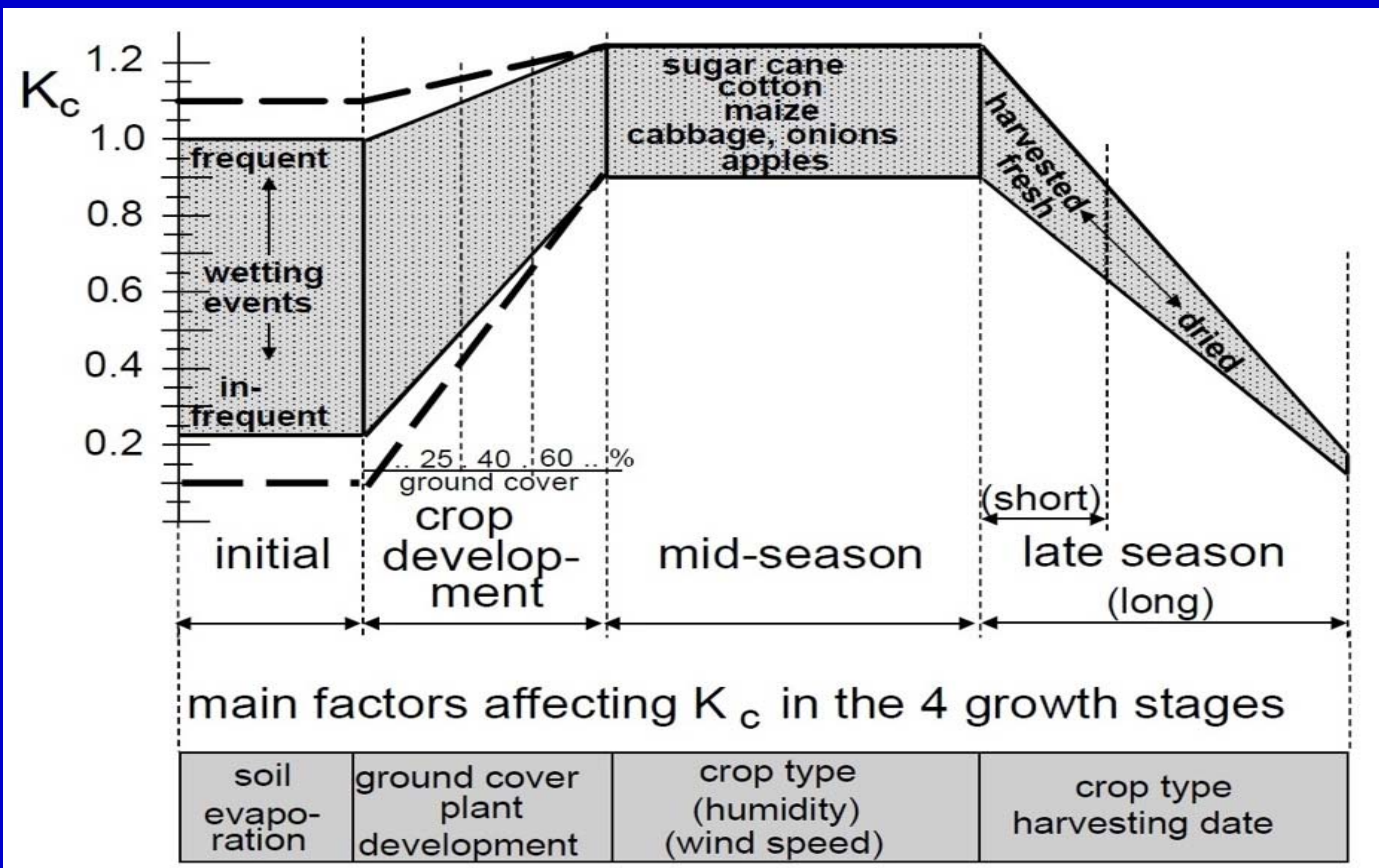
Kc = crop factor or crop coefficient varying with the crop type and growing periods

General Crop coefficient curve Kc_{ini}, Kc_{mid}, Kc_{end}



Initial stage –This stage runs from planting date to approximately 10% ground cover.
Crop development stage-This stage runs from 10% ground cover to effective full cover.
Mid-season stage –This stage runs from effective full cover to the start of maturity.
Late season stage –This stage runs from the start of maturity to harvest.

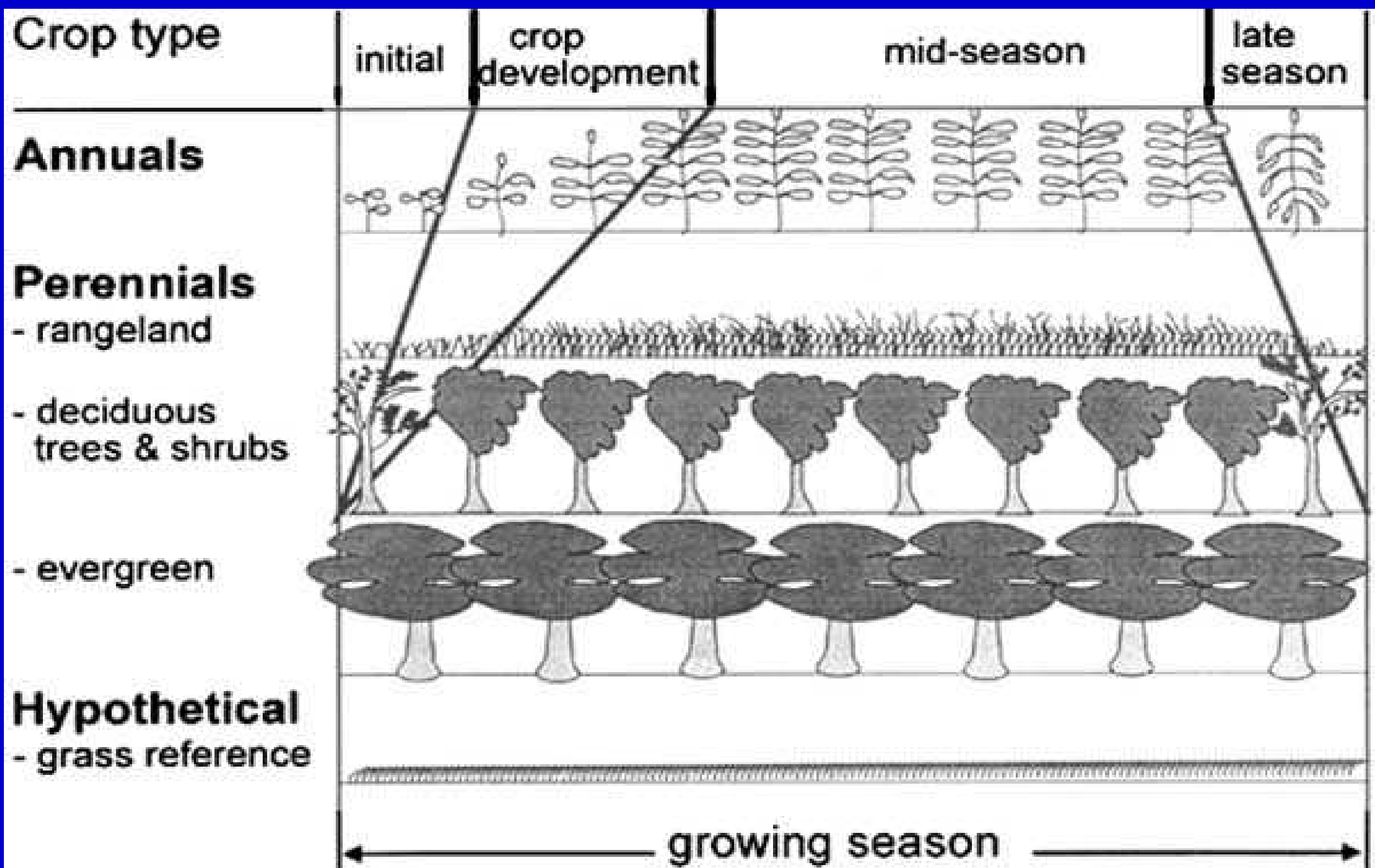
Typical ranges expected in Kc for the four growth stages



ETc calculation procedure

- identifying the crop growth stages, determining their lengths, and selecting the corresponding Kc
- adjusting the selected Kc coefficients for frequency of wetting or climatic conditions during the stage
- constructing the crop coefficient curve
- calculating ETc = Kc.ETo

Crop growth stages for different types of crops



EXAMPLE – Growth stages and Kc (FAO)

TABLE 11
Lengths of crop development stages* for various planting periods and climatic regions (days)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
a. Small Vegetables							
Broccoli	35	45	40	15	135	Sept	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi)Arid
	25	40					
	30	55					
Crucifers[1]	20	30					
	25	35					
	30	35					
Lettuce	20	30					
	30	40					
	25	35					
	35	50					
Onion (dry)	15	25					
	20	35					
Onion (green)	25	30					
	20	45					
	30	55					

TABLE 12
Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o.

Crop	$K_{c\ ini}$[1]	$K_{c\ mid}$	$K_{c\ end}$	Maximum Crop Height (h) (m)
a. Small Vegetables	**0.7**	**1.05**	**0.95**	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions - dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3

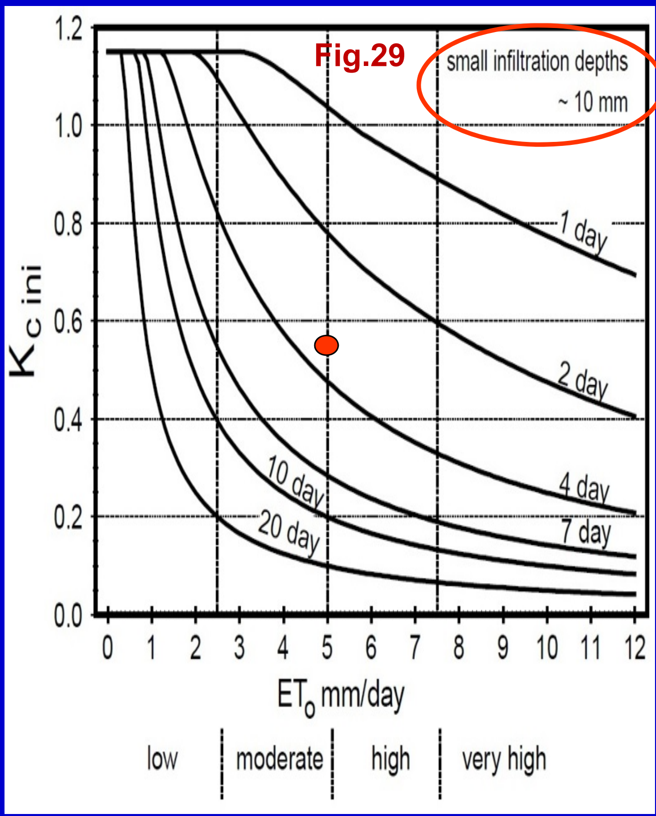
Kc for initial stage

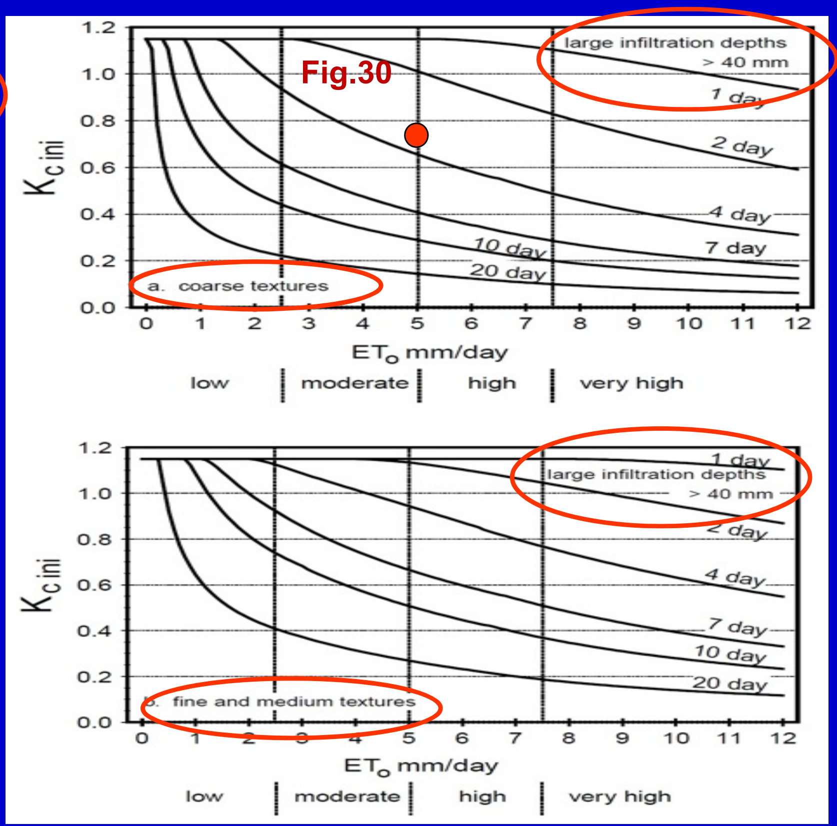
Kc for initial stage varies between 0.1 – 1.15
In general Kc for initial stage can be determined from Table 12(FAO I&D 56) for typical irrigation water management.

For more accurate estimate, Kc from Table 12 should be adjusted according soil moisture and evaporative power.

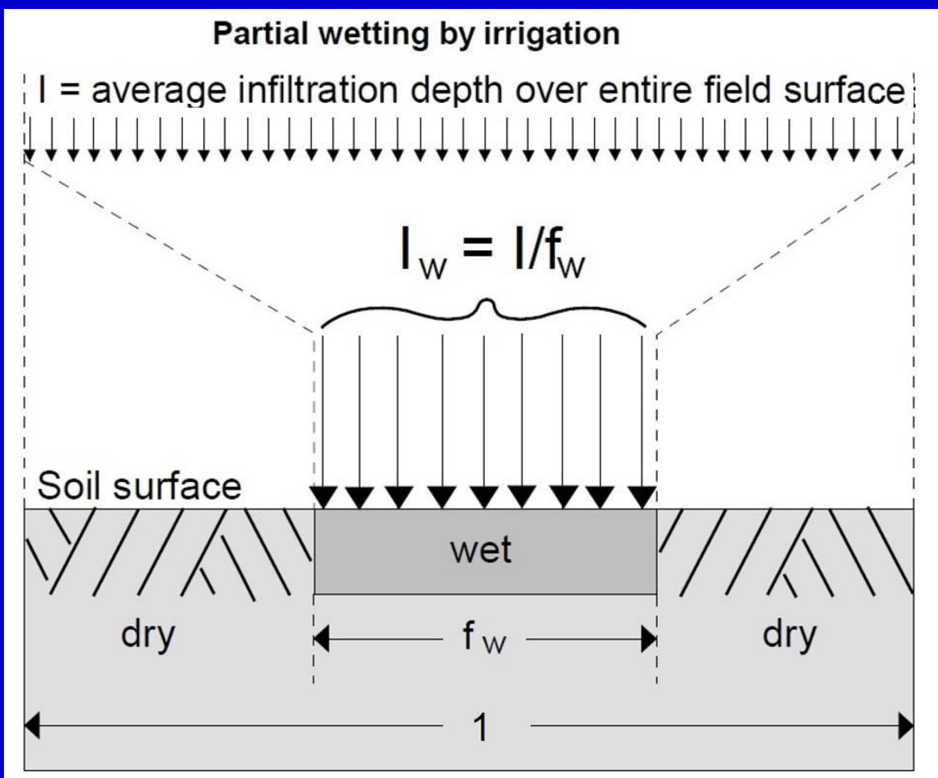
(1) Time interval between wetting events, the more frequently wetting the soil is the larger Kc(ini).
(2) Evaporative power of the atmosphere, the higher ETo is the smaller Kc(ini) due to the lower soil moisture
(3) Magnitude of wetting events, the larger wetting events is the higher Kc(ini).

$$K_{Cini} = K_{Cini(Fig.29)} + \frac{(I-10)}{(40-10)}\left[K_{Cini(Fig.30)} - K_{Cini(Fig.29)}\right]$$





Calculate I for adjusting Kc(ini) for non-uniform water application



$I*1 = Iw*fw$

$I = Iw*fw$

EXAMPLE 25. Interpolation between light and heavy wetting events			
Small vegetables cultivated in a dry area on a coarse textured soil receive 20 mm of water twice a week by means of a sprinkler irrigation system. The average ET_o during the initial stage is 5 mm/day. Determine Kc(ini).			
For: twice a week irrigation	7/2=	3.5	day interval
	ET_o =	5	mm/day
From Fig. 29:	$K_{c\ ini\ (Fig.\ 29)} \approx$	0.55	-
From Fig. 30. a:	$K_{c\ ini\ (Fig.\ 30a)} \approx$	0.7	-
For:	I =	20	mm
From Eq. 59:	$K_{c\ ini}$ = Kc ini(Fig29)+(I-10)*[Kc ini(Fig30)- Kc ini(Fig29)]/(40-10)	0.6	

Kc(ini)=0.55+(20-10)*(0.7-0.55)/(40-10) = 0.6

Kc for mid season stage (Kc mid)

Kc mid can be determined from Table 12, [Kc mid(Tab)].

The effect of climate on Kc mid can be determined by the following equation.

$$K_{Cmid} = K_{Cmid(Table)} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3}$$

where

$K_{c\ mid\ (Tab)}$ value for $K_{c\ mid}$ taken from Table 12,

u_2 mean value for daily wind speed at 2 m height over grass during the mid-season growth stage [m s^{-1}], for 1 m s^{-1} $\leq u_2 \leq$ 6 m s^{-1},

RH_{min} mean value for daily minimum relative humidity during the mid-season growth stage [%], for 20% $\leq RH_{min} \leq$ 80%,

h mean plant height during the mid-season stage [m] for 0.1 m < h < 10 m.

Kc for late season stage (Kc end)

Kc end can be determined from Table 12, [Kc end(Tab)].

The effect of climate on Kc end is similar to Kc mid which can be determined by the following equation.

$$K_{C\,end} = K_{C\,end(Table)} + \left[0.04(u_2 - 2) - 0.004(RH_{min} - 45)\left(\frac{h}{3}\right)^{0.3}\right]$$

where

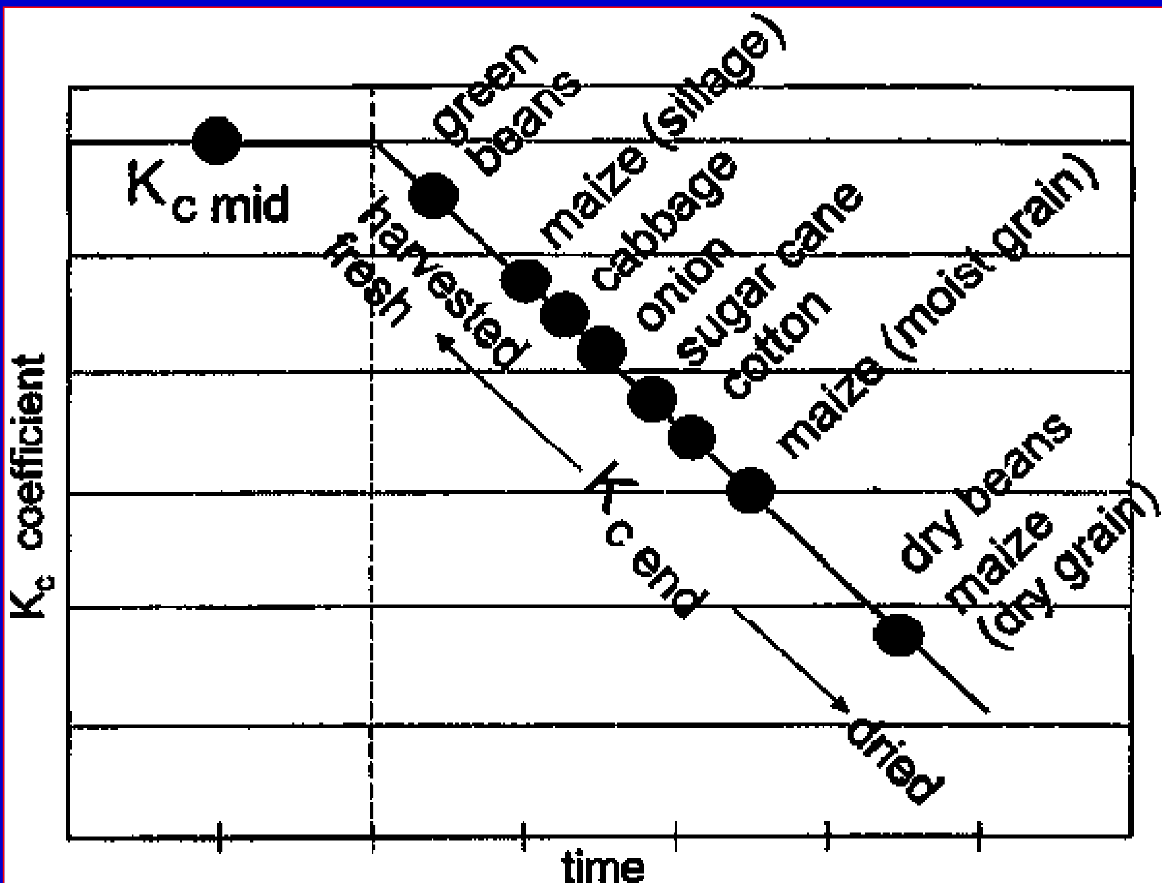
$K_{c\ end\ (Tab)}$ value for $K_{c\ end}$ taken from Table 12,

u_2 mean value for daily wind speed at 2 m height over grass during the late season growth stage [m s^{-1}], for 1 m $s^{-1} \leq u_2 \leq 6$ m s^{-1},

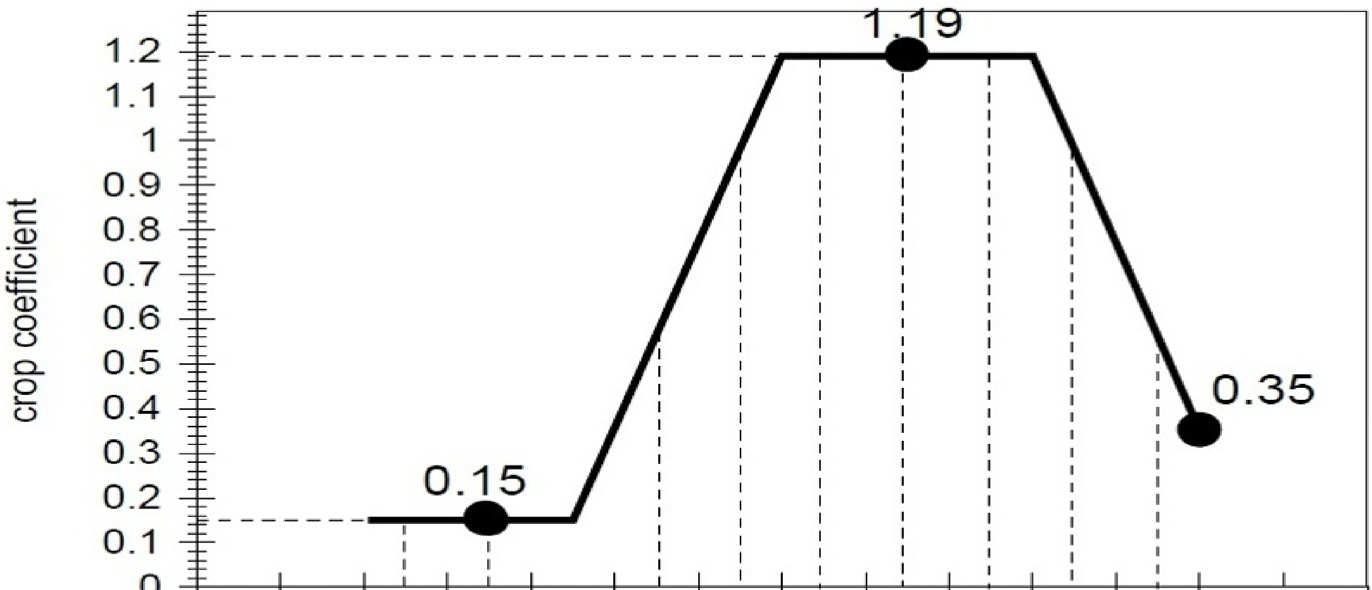
RH_{min} mean value for daily minimum relative humidity during the late season stage [%], for 20% $\leq RH_{min} \leq$ 80%,

h mean plant height during the late season stage [m], for 0.1 m $\leq h \leq$ 10 m.

Ranges of expected for Kc end



Kc curve and 10 values for Kc and ETc for dry bean crop



	May 1	May 2	May 3	June 1	June 2	June 3	July 1	July 2	July 3	August 1	August 2	August 3	
K_c			0.15	0.15	0.20	0.57	0.98	1.19	1.19	1.19	0.98	0.56	
ET_o			3.0	3.4	4.0	4.2	4.5	5.1	5.6	6.0	5.5	5.2	mm/day
ET_c			0.5	0.5	0.8	2.4	4.4	6.1	6.7	7.1	5.4	2.9	mm/day

Numerical determination of Kc

$$K_{Ci} = K_{C\,prev} + \left[\frac{i - \sum L_{prev}}{L_{stage}}\right]\left(K_{C\,next} - K_{C\,prev}\right)$$

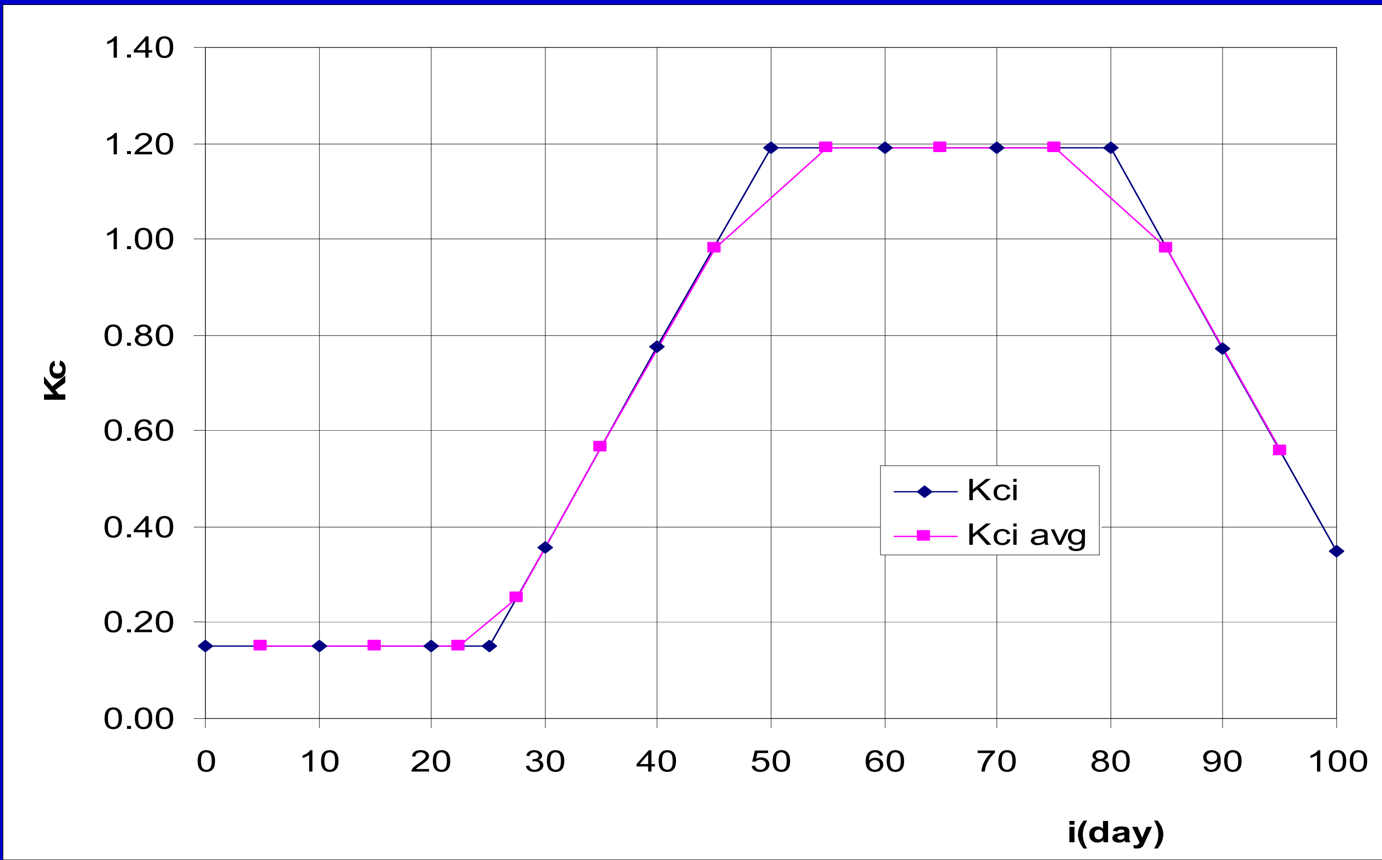
- i = day number within the growing season [1.. length of the growing season]
- Kci = crop coefficient on day i
- Lstage = length of the stage under consideration [days]
- Σ(Lprev) = sum of the lengths of all previous stages [days].

Table 7 Numerical determination of K_c		
Determine K_c at every 10 day for the dry bean crop		
Crop growth stage	**Length (days)**	**K_c**
initial	25	$K_{c\ ini}$ = 0.15
crop development	25	0.15... 1.19
mid-season	30	$K_{c\ mid}$ = 1.19
late season	20	1.19 .. $K_{c\ end}$ = 0.35

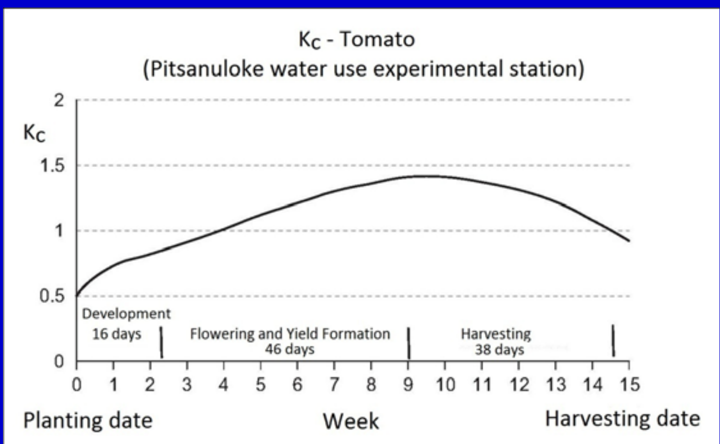
i(day)	Given Kc	Lstage	(Kc next- Kc prev)	slope=(Kc next - Kc prev
0	0.15			
25	0.15	25	0	0
50	1.19	25	1.04	0.0416
80	1.19	30	0	0
100	0.35	20	-0.84	-0.042

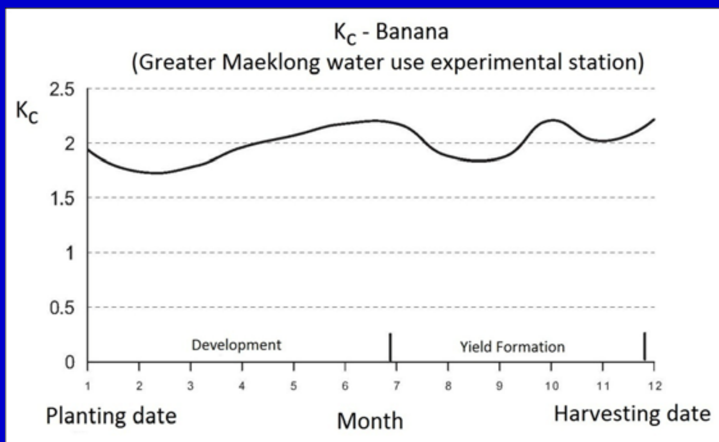
i(day)	S(L prev)	slope	Kc prev	Kci	Kci avg	I avg
0	0	0	0.15	0.15		
10				0.15	0.15	5
20				0.15	0.15	15
25	25	0.042	0.15	0.15	0.15	22.5
30				0.36	0.25	27.5
40				0.77	0.57	35
50	50	0	1.19	1.19	0.98	45
60				1.19	1.19	55
70				1.19	1.19	65
80	80	-0.042	1.19	1.19	1.19	75
90				0.77	0.98	85
100			0.35	0.35	0.56	95

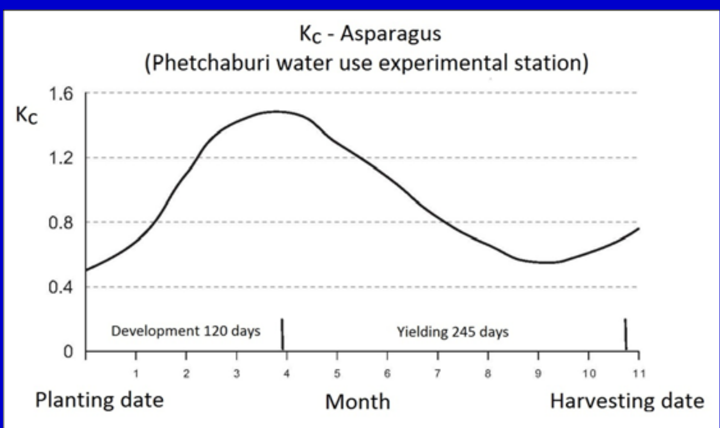
Kc curve as calculated in previous table

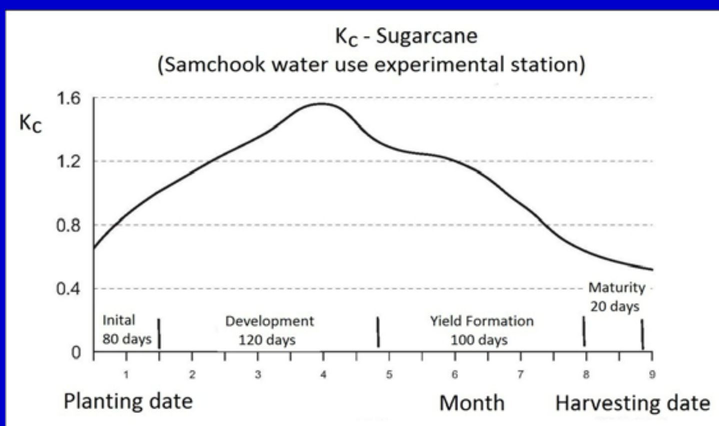


EXAMPLE – Kc (RID)

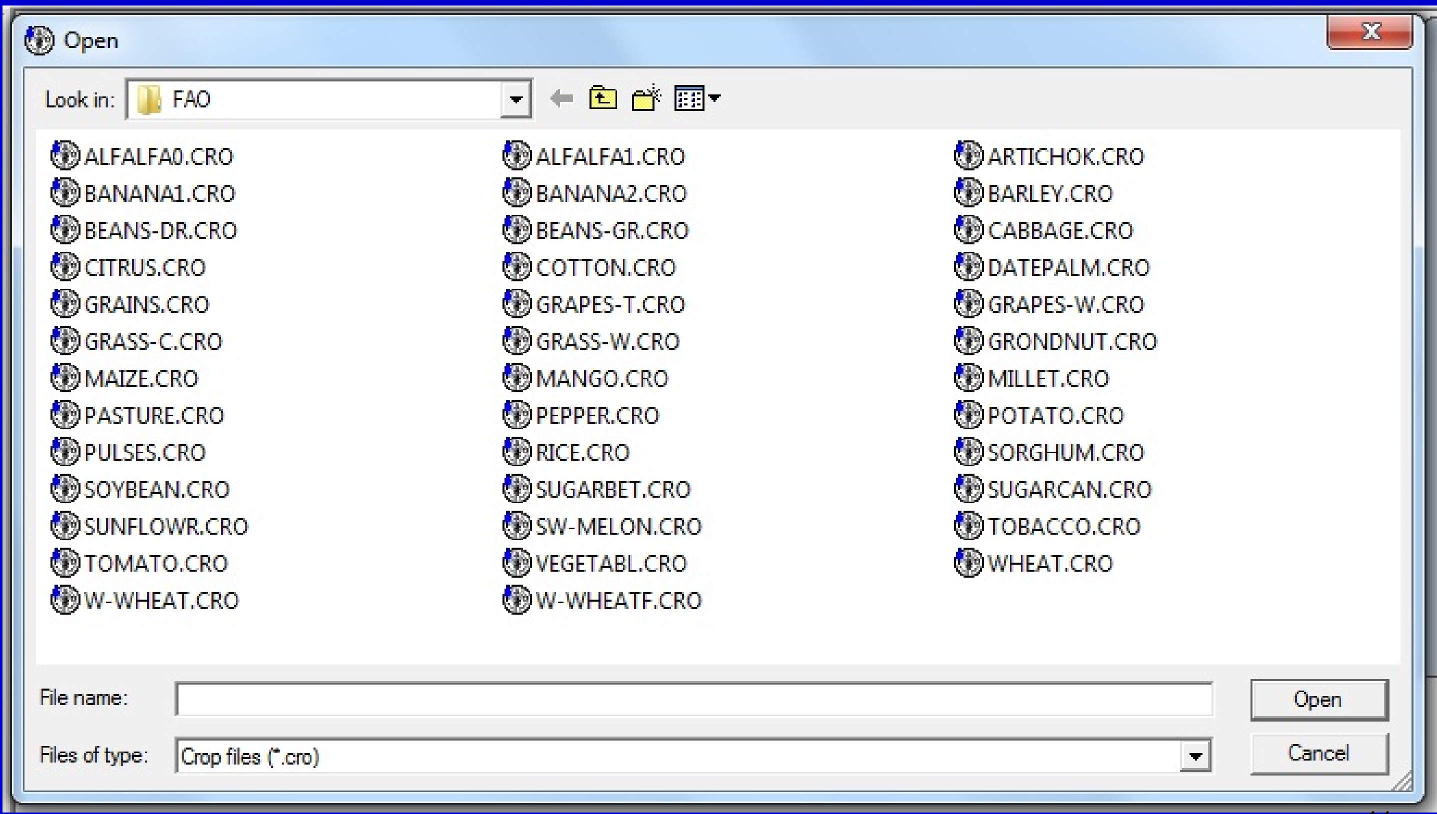




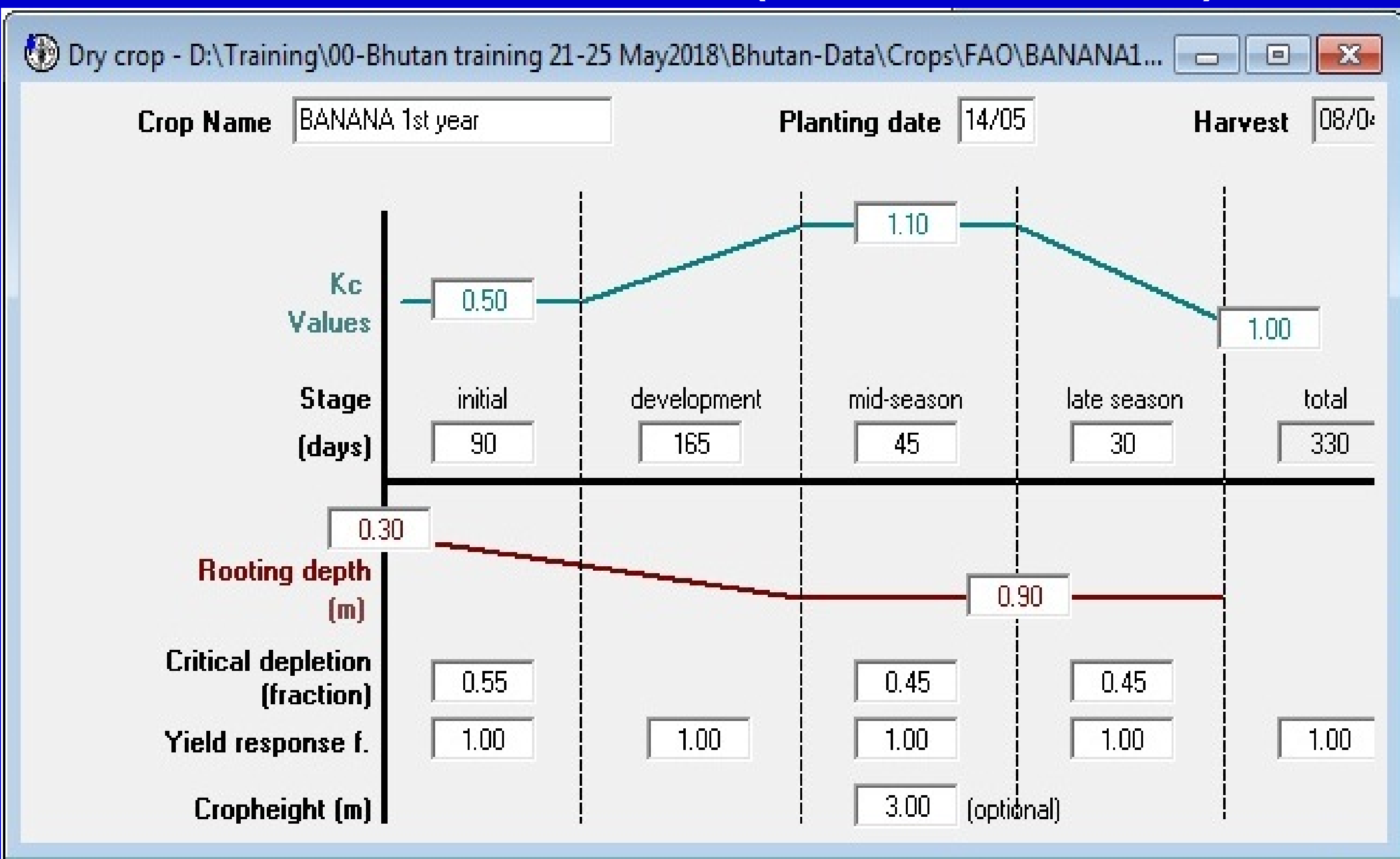




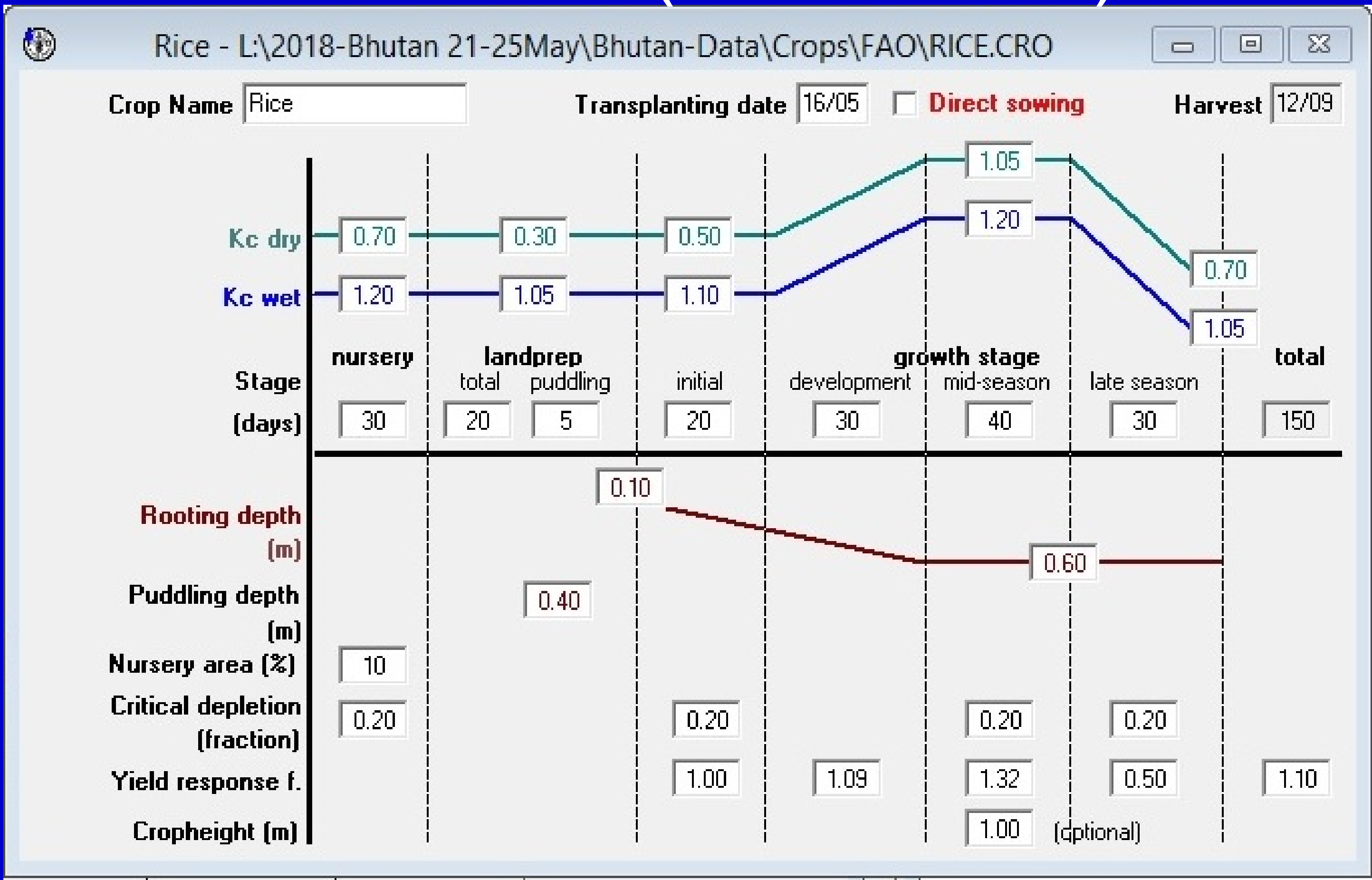
Available CROPS in CROPWAT 8.0



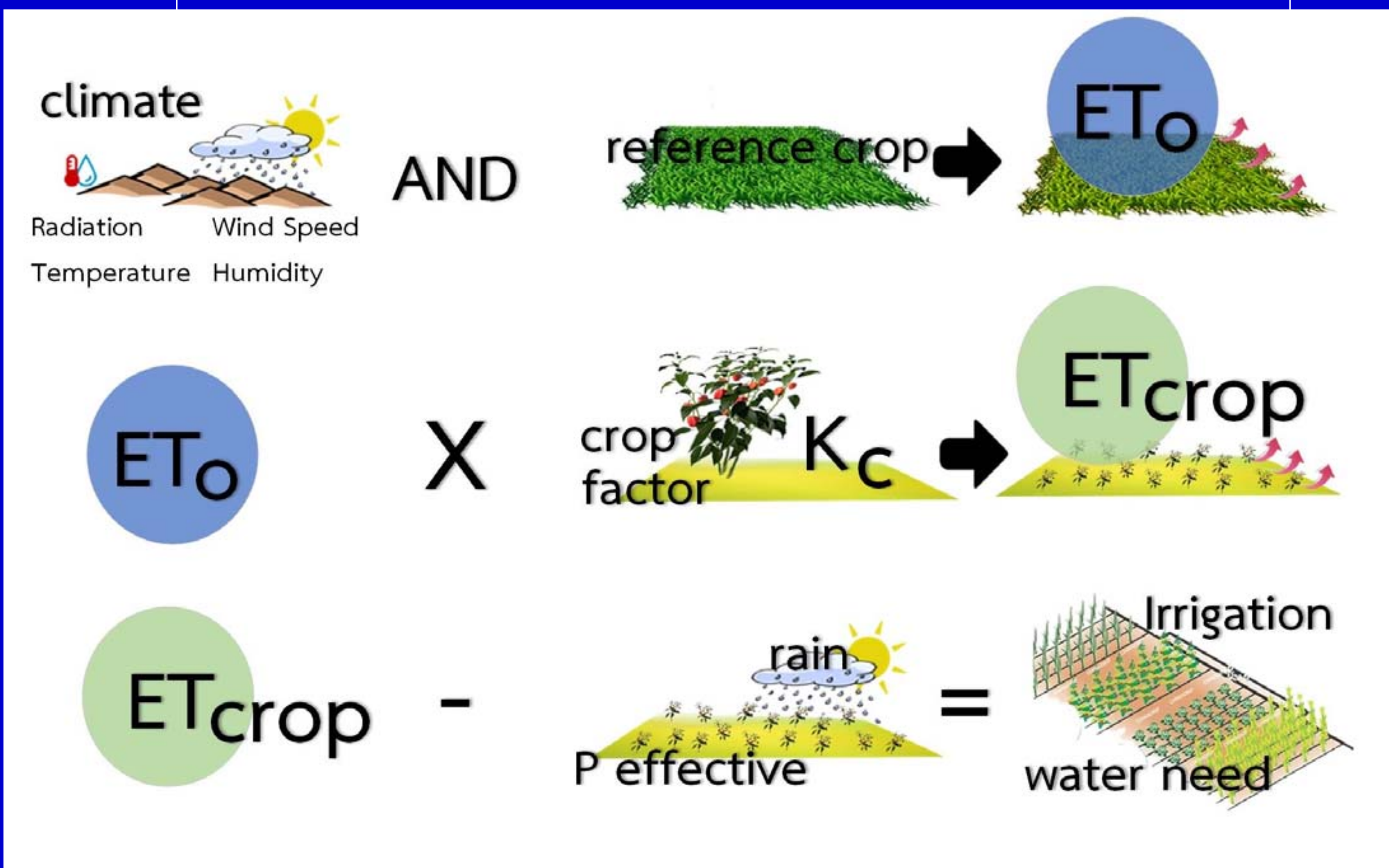
Kc – Banana1 (CROPWAT)



Kc – Rice (CROPWAT)



Net IWR = ETc - Peff



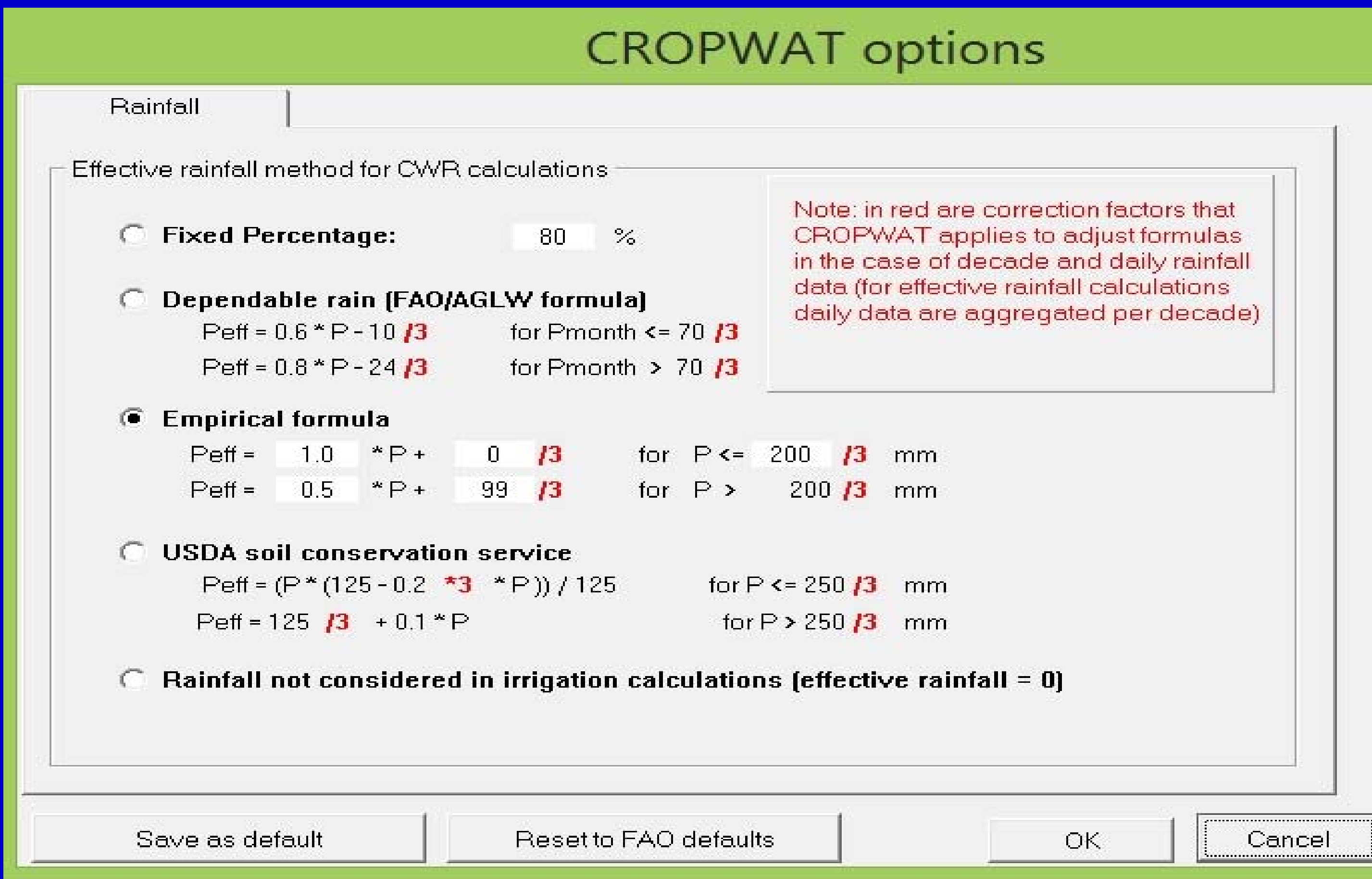
Effective Rainfall (Peff or Re)

Peff = portion of rainfall that can be utilized by crops

Peff = P – RO – DP

Peff = effective rainfall
P = rainfall
RO = runoff loss
DP = deep percolation loss

5 Effective Rainfall Methods



Effective Rainfall Methods

(1) Fixed percentage

Peff = Fixed percentage * P

(2) Dependable rainfall (FAO/AGLW formula)

For different arid and sub-humid climates,

For design purposes where 80% probability of exceedance is required.

Monthly step

Peff = 0.6 * P -10 for Pmonth < 70 mm

Peff = 0.8 * P -24 for Pmonth > 70 mm

Decade step

Peff(dec) = 0.6 * Pdec - (10 / 3) for Pdec < (70 / 3) mm

Peff(dec) = 0.8 * Pdec - (24 / 3) for Pdec > (70 / 3) mm

(3) Empirical formula

Same formula as for Dependable rainfall but the parameters may be determined from an analysis of local climatic records.

Monthly step

Peff = a * Pmonth - b for Pmonth < z mm

Peff = c * Pmonth - d for Pmonth > z mm

Decade step

Peff(dec) = a * Pdec – (b / 3) for Pdec < (z / 3) mm

Peff(dec) = c * Pdec – (d / 3) for Pdec > (z / 3) mm

Values for a, b, c, d and z are the formula coefficients.

(4) USDA Soil Conservation Service

Monthly step

Peff = Pmonth * (125 - 0.2 * Pmonth) / 125 for Pmonth<250 mm

Peff = 125 + 0.1 * Pmonth for Pmonth>250 mm

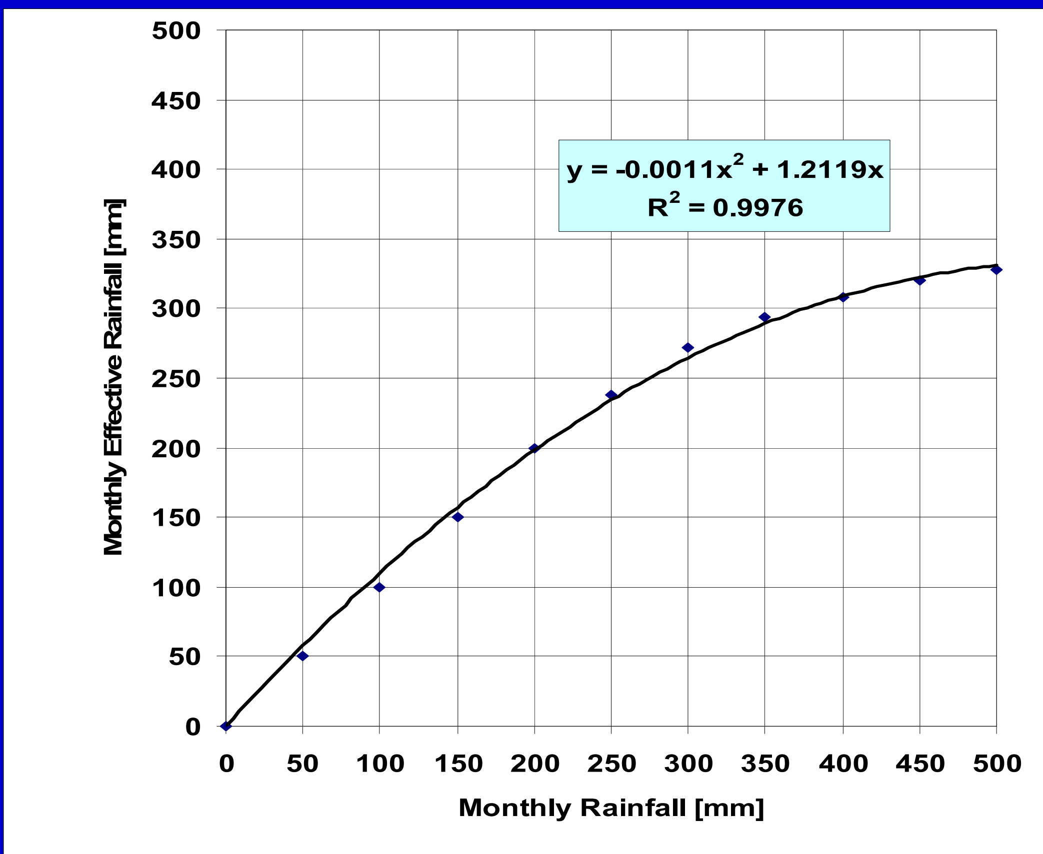
Decade step

Peff(dec) = Pdec * (125 - 0.2*3* Pdec)) / 125 for Pdec<(250/3) mm

Peff(dec) = (125 / 3) + 0.1 * Pdec for Pdec>(250/3) mm

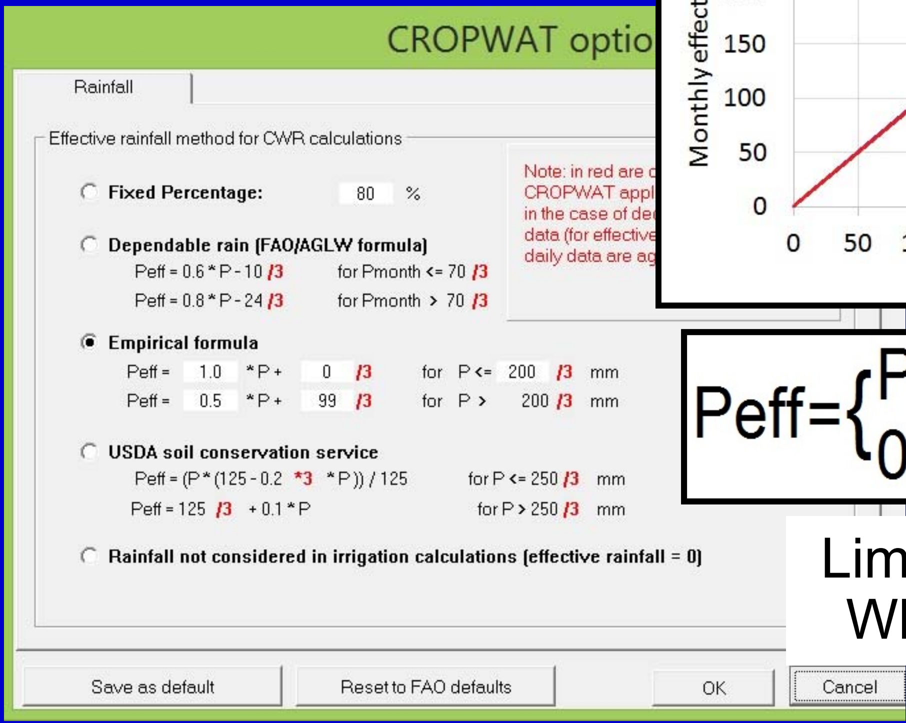
Values for a, b, c, d and z are the formula coefficients.

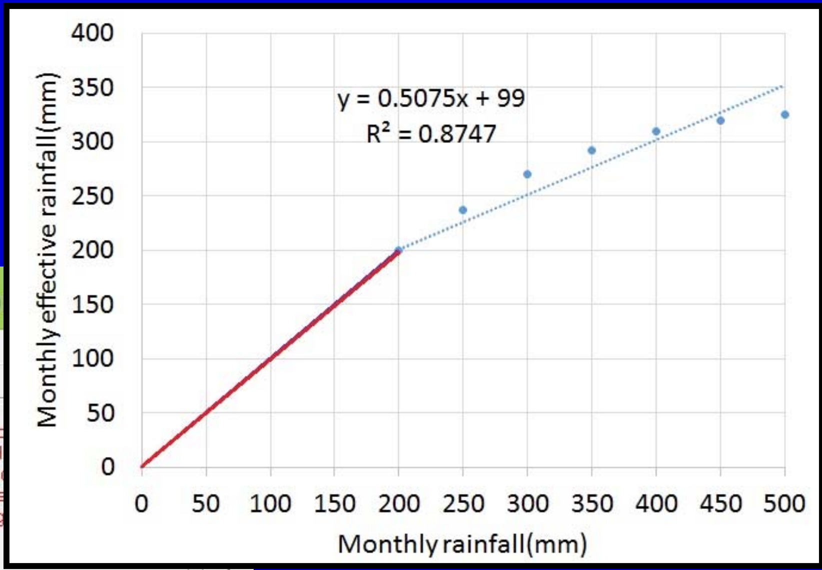
Monthly effective rainfall for rice in Northeast, Thailand



Monthly P(mm)	Monthly Peff(mm)
0	0
50	50
100	100
150	150
200	200
250	237.5
300	270
350	292.5
400	310
450	320
500	325

Modified monthly effective rainfall formula for rice in Northeast, Thailand for CROPWAT 8





$$Peff=\begin{cases} P & \text{if } P \le 200\text{mm} \\ 0.5P+99 & \text{if } P > 200\text{mm} \end{cases}$$

Limitation on Peff=a*P+b
Where b must be <100

Irrigation Water Requirement

Net IWR = ETc – Peff

- Net IWR = net irrgation water requirement of the field [mm/day]
- ETc = crop evapotranspiration [mm/day]
- Peff = effective rainfall [mm/day]

Total IWR = 100* Net IWR / Ei

- Ei=Irrigation efficiency

Irrigation efficiency(%)

	Low	Medium	High
Application Efficiency (E_a)	50	80	65
Surface irrigation	50	80	65
Sub-surface irrigation		<60	
Sprinkler	60	80	70
Paddy field	65	75	70
Field Canal Efficiency (E_b)	70	90	80
Conveyance Efficiency (E_c)	65	90	78
Irrigation Efficiency ($E_i=E_a.E_b.E_c$)	23	65	44

*Doorenbos and Pruitt(1977) and Ilaco/Empire M&T(1979)

Monthly rain - G:\00-training\Irrigation project planning-7Mar\Bhutan\CHA...

Station CHANDRAGADHI-Nepal-8 Eff. rain method USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	6.0	5.9
February	18.0	17.5
March	19.0	18.4
April	62.0	55.8
May	188.0	131.4
June	390.0	164.0
July	730.0	198.0
August	406.0	165.6
September	456.0	170.6
October	111.0	91.3
November	9.0	8.9
December	8.0	7.9
Total	2403.0	1035.4

Monthly step

Peff=P*(125-0.2*P)/125 P<250

Peff=125+0.1*P P>250

ETc and Net IWR of Banana1

Crop Water Requirements

ETo station: CHANDRAGADHI-Nepa

Rain station: CHANDRAGADHI-Nepa

Crop: BANANA 1st year

Planting date: 17/05

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
May	2	Init	0.50	2.69	10.8	18.3	0.0
May	3	Init	0.50	2.52	27.8	48.8	0.0
Jun	1	Init	0.50	2.36	23.6	51.0	0.0
Jun	2	Init	0.50	2.19	21.9	54.6	0.0
Jun	3	Init	0.50	2.10	21.0	58.4	0.0
Jul	1	Init	0.50	2.02	20.2	64.3	0.0
Jul	2	Init	0.50	1.93	19.3	69.1	0.0
Jul	3	Init	0.50	1.91	21.0	64.5	0.0
Aug	1	Init	0.50	1.89	18.9	57.6	0.0
Aug	2	Deve	0.51	1.90	19.0	53.5	0.0
Aug	3	Deve	0.54	2.01	22.1	54.6	0.0
Sep	1	Deve	0.58	2.12	21.2	59.0	0.0
Sep	2	Deve	0.62	2.23	22.3	60.9	0.0
Sep	3	Deve	0.65	2.33	23.3	50.7	0.0
Oct	1	Deve	0.69	2.44	24.4	39.3	0.0
Oct	2	Deve	0.72	2.54	25.4	30.5	0.0
Oct	3	Deve	0.76	2.53	27.8	21.3	6.4
Nov	1	Deve	0.80	2.49	24.9	8.3	16.7
Nov	2	Deve	0.83	2.44	24.4	0.0	24.4
Nov	3	Deve	0.87	2.32	23.2	0.7	22.5
Dec	1	Deve	0.90	2.19	21.9	2.7	19.1
Dec	2	Deve	0.94	2.03	20.3	2.6	17.7
Dec	3	Deve	0.98	2.14	23.6	2.4	21.2
Jan	1	Deve	1.01	2.26	22.6	1.8	20.8
Jan	2	Deve	1.05	2.38	23.8	1.4	22.4
Jan	3	Mid	1.08	2.72	29.9	2.9	27.1
Feb	1	Mid	1.09	3.01	30.1	4.8	25.2
Feb	2	Mid	1.09	3.28	32.8	6.3	26.5
Feb	3	Mid	1.09	3.78	30.2	6.2	24.0
Mar	1	Mid	1.09	4.27	42.7	4.9	37.8
Mar	2	Late	1.08	4.72	47.2	4.4	42.8
Mar	3	Late	1.05	5.13	56.4	9.2	47.2
Apr	1	Late	1.02	5.64	56.4	13.3	43.1
Apr	2	Late	1.00	6.13	6.1	1.7	6.1
					886.5	930.0	451.1

Effective rainfall for rice, Thailand

Monthly rain - I:\2018-...

Station: CHANDRAGADHI-Nepal-

Eff. rain method: Empirical formula

$$Peff=\begin{cases} P & \text{if } P\leq 200mm \\ 0.5P+99 & \text{if } P>200mm \end{cases}$$

	Rain	Eff rain
	mm	mm
January	6.0	6.0
February	18.0	18.0
March	19.0	19.0
April	62.0	62.0
May	188.0	188.0
June	390.0	294.0
July	730.0	464.0
August	406.0	302.0
September	456.0	327.0
October	111.0	111.0
November	9.0	9.0
December	8.0	8.0
Total	2403.0	1808.0

Crop Water Requirements

ETo station CHANDRAGADHI-Nepa

Rain station CHANDRAGADHI-Nepa

Crop Rice

Planting date 16/05

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	2	Nurs	1.20	0.73	3.7	8.4	0.0
Apr	3	Nurs/LPr	1.13	3.48	34.8	32.1	28.2
May	1	Nurs/LPr	1.06	5.92	59.2	49.3	10.0
May	2	Init	1.08	5.83	58.3	63.6	128.5
May	3	Init	1.10	5.55	61.1	75.0	0.0
Jun	1	Deve	1.10	5.19	51.9	84.2	0.0
Jun	2	Deve	1.11	4.85	48.5	95.0	0.0
Jun	3	Deve	1.11	4.68	46.8	114.9	0.0
Jul	1	Mid	1.12	4.51	45.1	146.3	0.0
Jul	2	Mid	1.12	4.32	43.2	170.4	0.0
Jul	3	Mid	1.12	4.28	47.1	147.2	0.0
Aug	1	Mid	1.12	4.23	42.3	112.8	0.0
Aug	2	Late	1.11	4.14	41.4	91.8	0.0
Aug	3	Late	1.05	3.90	42.9	97.5	0.0
Sep	1	Late	1.00	3.67	36.7	113.9	0.0
Sep	2	Late	0.97	3.52	7.0	24.1	7.0
					670.0	**1426.4**	**173.7**

ETc, Peff and Net IWR

Other Irrigation Water Requirements

Land preparation requirements(LP)

LP for paddy

LP = saturation water requirements[Dss] + standing water requirements[Dst]

Dss =(n-Pv)*D/100 (Soil saturation requirements)

Dst =5 -10 cm (Standing water requirement)

LP for paddy in Thailand 200-350 mm/2 weeks

LP for upland crops = 50 mm.

Leaching Requirements (LR)

LR = Dd/Di

LR=ECw/ECd = ECw/[5ECe-ECw]

Dd = depth of drainage water [mm]

Dw = depth of irrigation water [mm]

ECw = electrical conductivity of irrigation water [dS/cm]

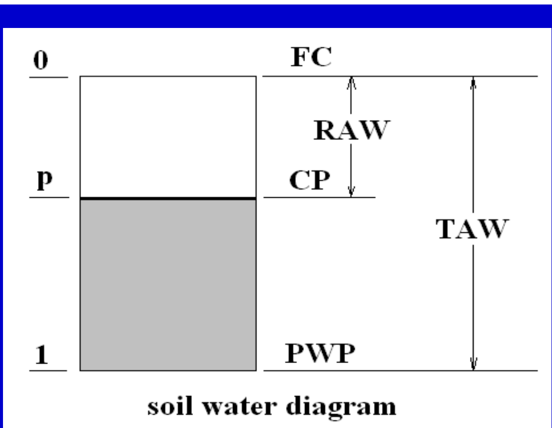
ECe = electrical conductivity of saturation extract at which no yield loss occurred. [dS/cm] , [1 siemen/cm = 1 mho/cm]

Water applied = Crop water requirements/[1-LR]

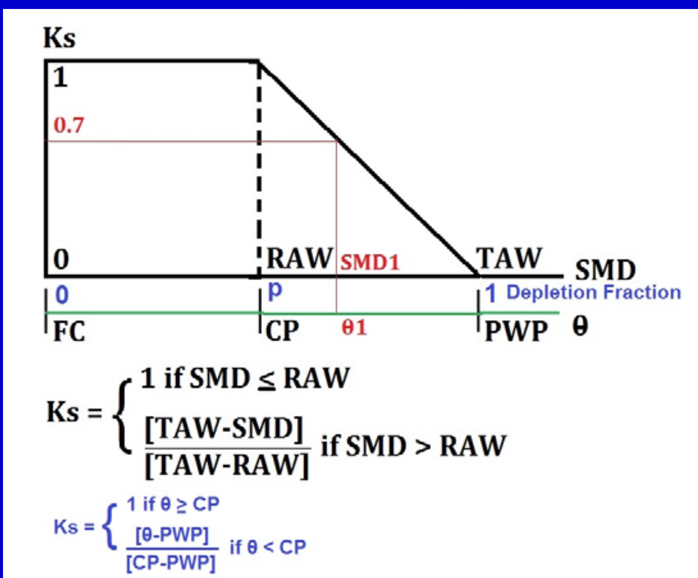
ETc under soil water stress conditions

ETa = Ks.ETc

ETa = Actual crop evapotranspiration under soil water stress [mm/day]
Kc = crop coefficient
ETo = reference crop evapotranspiration [mm/day]
Ks = water stress coefficient



Water Stress Coefficient(Ks)



TAW=total available sol water in root zone [mm] = (FC-PWP).As.D
As=apparent specific gravity
D=root zone depth [mm]
RAW =readily available water [mm]
SMD=soil moisture depletion [mm]
p=fraction of TAW that can be depleted from the root zone before water stress occurs [0-1]

Table 8 Ranges of maximum effective rooting depth (Z_r), and soil water depletion fraction for no stress (p), for common crops			
Crop		Maximum Root Depth [1] (m)	Depletion Fraction [2] (for ET ≈ 5 mm/day) p
a. Small Vegetables			
Broccoli		0.4-0.6	0.45
Brussel Sprouts		0.4-0.6	0.45
Cabbage		0.5-0.8	0.45
Carrots		0.5-1.0	0.35
Cauliflower		0.4-0.7	0.45
Celery		0.3-0.5	0.2
Garlic		0.3-0.5	0.3
Lettuce		0.3-0.5	0.3
Onions			
	- dry	0.3-0.6	0.30
	- green	0.3-0.6	0.30
	- seed	0.3-0.6	0.35
Spinach		0.3-0.5	0.20
Radishes		0.3-0.5	0.30

Soil Properties

Soil Properties on Water Holding Capacity								
Soil types	FC (% dry mass)		PWP (% dry mass)		Porosity(n, %)		Apparent Specific Gravity(As)	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Sand	6-12	9	2-6	4	32-42	38	1.55 – 1.80	16.5
Sandy loam	10-18	14	4-8	6	40-47	43	1.40-1.60	1.50
Loam	18-26	22	8-12	10	43-49	46	1.35-1.50	1.40
Clay loam	23-31	27	11-15	13	47-51	49	1.30-1.40	1.35
Silty clay	27-35	31	13-17	15	49-53	51	1.25-1.35	1.30
Clay	31-39	36	15-19	17	51-55	53	1.20-1.30	1.25

Table A2. Horton's Initial Infiltration by Soil Type

Soil Type	(in/hr)	(mm/hr)
Dry sandy soils with little or no vegetation	5.0	127
Dry loam soils with little or no vegetation	3.0	76.2
Dry clay soils with little or no vegetation	1.0	25.4
Dry sandy soils with dense vegetation	10.0	254
Dry loam soils with dense vegetation	6.0	152
Dry clay soils with dense vegetation	2.0	51
Moist sandy soils with little or no vegetation	1.7	43
Moist loam soils with little or no vegetation	1.0	25
Moist clay soils with little or no vegetation	0.3	7.6
Moist sandy soils with dense vegetation	3.3	84
Moist loam soils with dense vegetation	2.0	5.1
Moist clay soils with dense vegetation	0.7	18

Horton's Final Infiltration Rate also varies with the types of soil. Table A3 contains final infiltration rates suggested by Akan (1993), and others:

Table A3. Horton's Final Infiltration Rate by Soil Type

Soil Type	Final Infiltration Rate (in/hr)	Final Infiltration Rate (mm/hr)
Clay loam, silty clay loam, sandy clay, silty clay, clay	0.01 - 0.08	0.25 - 2.0
Sandy clay loam	0.06 - 0.12	1.57 - 3.1
Silt loam, loam	0.15 - 0.30	3.8 – 7.6
Sandy loam	0.43 - 0.86	11 - 22
Loamy sand	1.2 - 2.4	30 - 60
Sand, ,	4.7 - 9.3	119 - 236

The final infiltration rate is the saturated hydraulic conductivity rate of the soil.

Infiltration Rate

Akan, A. O.(1933), Urban Stormwater Hydrology: A Guide to Engineering Calculations. Lancaster. PA: Technomic Publishing Co., Inc.

Soil Data for non-rice

Soil - D:\Training\00-Bhutan training 21-25 May2018\Bhutan-Data\Soils\FAO\MEDIUM.SOI

Soil name: Medium (loam)

General soil data

Total available soil moisture (FC - WP)	290.0	mm/meter
Maximum rain infiltration rate	40	mm/day
Maximum rooting depth	900	centimeters
Initial soil moisture depletion (as % TAM)	0	%
Initial available soil moisture	290.0	mm/meter

Soil data for Rice

Soil - L:\2018-Bhutan 21-25May\Bhutan-Data\Soils\FAO\HEAVY.SOI

Soil name: Heavy (clay)

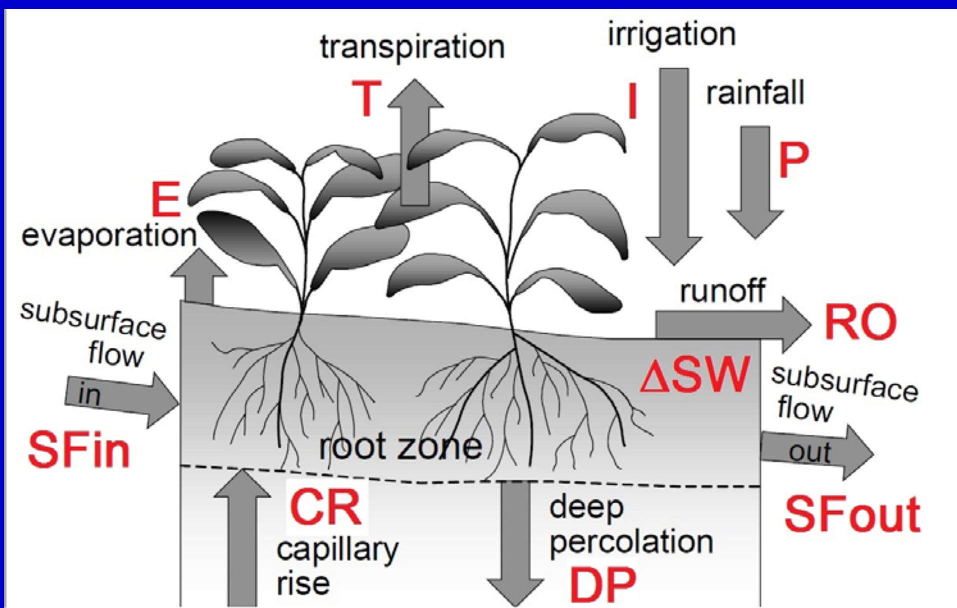
General soil data

Total available soil moisture (FC - WP)	200.0	mm/meter
Maximum rain infiltration rate	40	mm/day
Maximum rooting depth	900	centimeters
Initial soil moisture depletion (as % TAM)	0	%
Initial available soil moisture	200.0	mm/meter

Additional soil data for rice calculations

Drainable porosity (SAT - FC)	6	%
Critical depletion for puddle cracking	0.60	fraction
Maximum Percolation rate after puddling	3.4	mm/day
Water availability at planting	200	mm WD
Maximum waterdepth	50	mm

Irrigation Scheduling Simulation



Irrigation scheduling can be determined from the soil moisture balance calculation based on the daily accounting of all ingoing and outgoing water in the root zone under the given irrigation scheduling criteria.

Soil moisture balance equation

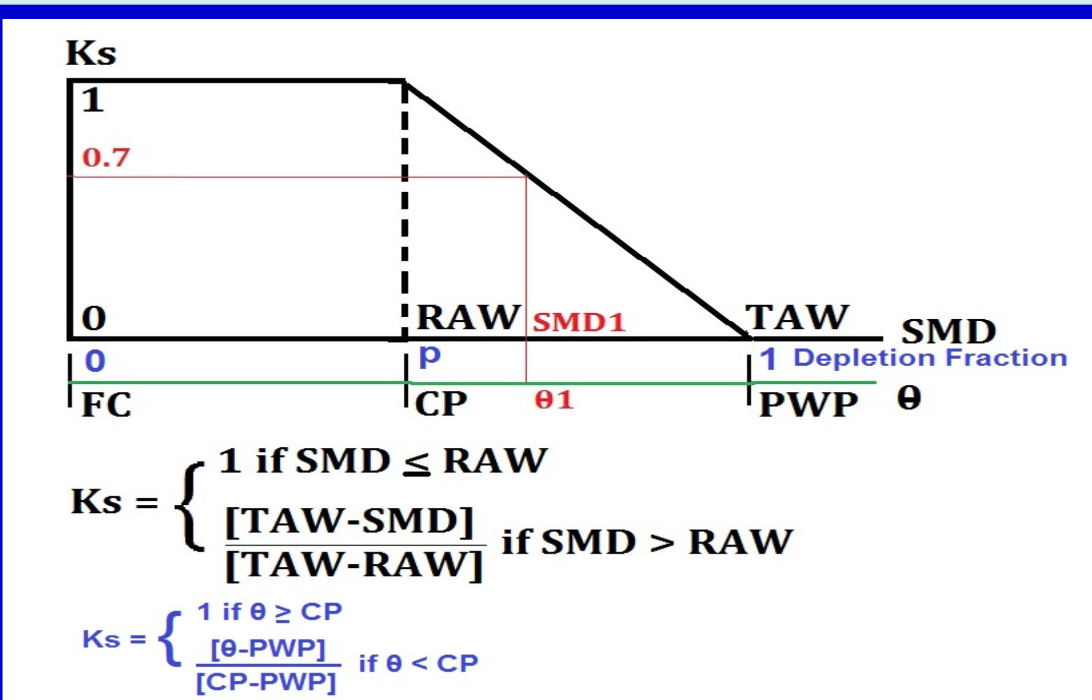
$$\theta(t)=\theta(t-1)-ETa(t)+P(t)+I(t)-L(t)$$

θ= soil moisture in the root zone[mm]
ETa = actual ET[mm]
P = rainfall[mm]
I = irrigation water applied[mm]
L = water losses due to runoff and deep percolation during irrigation water application[mm]
t, t-1= day t and t-1

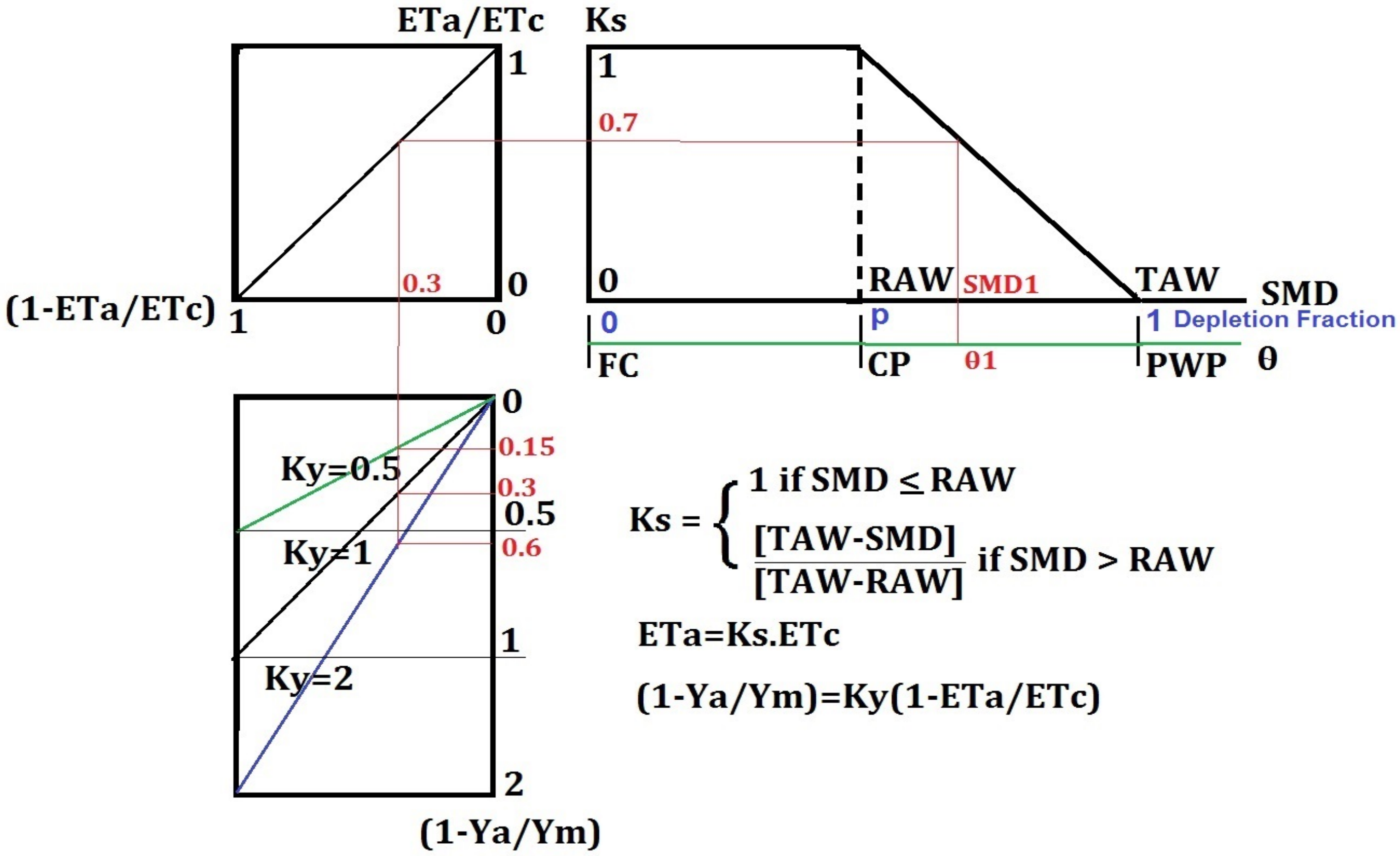
Note that the terms, sub-surface flow and capillary rise, are omitted in the above equation, due to small values in most cases.

Alternatively the above equation can be rewritten in term of soil moisture depletion (SMD) for Ks calculation.

$$SMD(t)=SMD(t-1)+ETa(t)-P(t)-I(t)+L(t)$$



Water Stress→ETa →Yield Response to Water



$$Ks = \begin{cases} 1 \text{ if } SMD \leq RAW \\ \dfrac{[TAW-SMD]}{[TAW-RAW]} \text{ if } SMD > RAW \end{cases}$$

$$ETa = Ks.ETc$$

$$(1-Ya/Ym) = Ky(1-ETa/ETc)$$

Scheduling criteria for non-rice crop

A.Irrigation timing

(1) Irrigate at user defined timing intervals [x days]

(2) Irrigate at critical depletion [100% of RAW]

(3) Irrigate at below or above critical depletion [x% of RAW]

(4) Irrigate at fixed intervals per stage [10 days in each stage]

(5) Irrigate at fixed depletion [40 mm]

(6) Irrigate at given ETc reduction per stage [10% in each stage]

(7) Irrigate at a given yield reduction [10%]

(8) No irrigation (rainfed)

B.Irrigation application

(1) User defined application depth [y mm]

(2) Refill soil to FC [100% FC]

(3) Refill soil below or above FC [y% FC]

(4) Fixed application depth [40 mm]

Scheduling options for rice

(1)General settings for Land Preparation (LP)

Normal percolation rates are 1 to 3 mm/day

Maximum percolation rate(puddled soil) = Maximum percolation rate(non-puddled soils) ^ 0.33 (FAO default)

(Maximum percolation rate(non-puddled soils) = Maximum infiltration rate)

[CROPWAT sets the maximum percoration rate =3.4 mm/day]

Daily decrease in max. percolation rate during puddling

Nonlinear = [1/days puddling]*LN(max.percolation rate after puddling/max.percolation rate of non-puddling] ….FAO default

Linear: (Max. percolation rate after puddling – Max.percolation rate of non-puddling)/days puddling

(2) SCHEDULING PRE PUDDLING OPTIONS - RICE

Soaking requirement on day 1 + [10] cm (default =10)

Irrigation timing options

- **Irrigation at fixed percentage desaturation [100 %]**
  [0% = Saturated conditions, 100%= Field capacity]
- **Irrigation at fixed percentage depletion of Field Capacity [20%]**
  (NOT % of RAW, since this is the pre-puddling stage, no crop yet)

Irrigation application options

- **Fixed application depth [50 mm]**
- **Refill to fixed percentage of saturation [100 %]**

(3) SCHEDULING PUDDLING OPTIONS - RICE

Irrigation timing options

- Irrigate at fixed mm water depth [0 mm]
- Irrigation at fixed percentage desaturation [20%]

Irrigation application options

- Refill to fixed water depth [50 mm]
- Refill to fixed percentage of saturation [100 %]
- Fixed application depth [50 mm]

(4) Schedule options - Rice

IRRIGATION TIMING OPTIONS

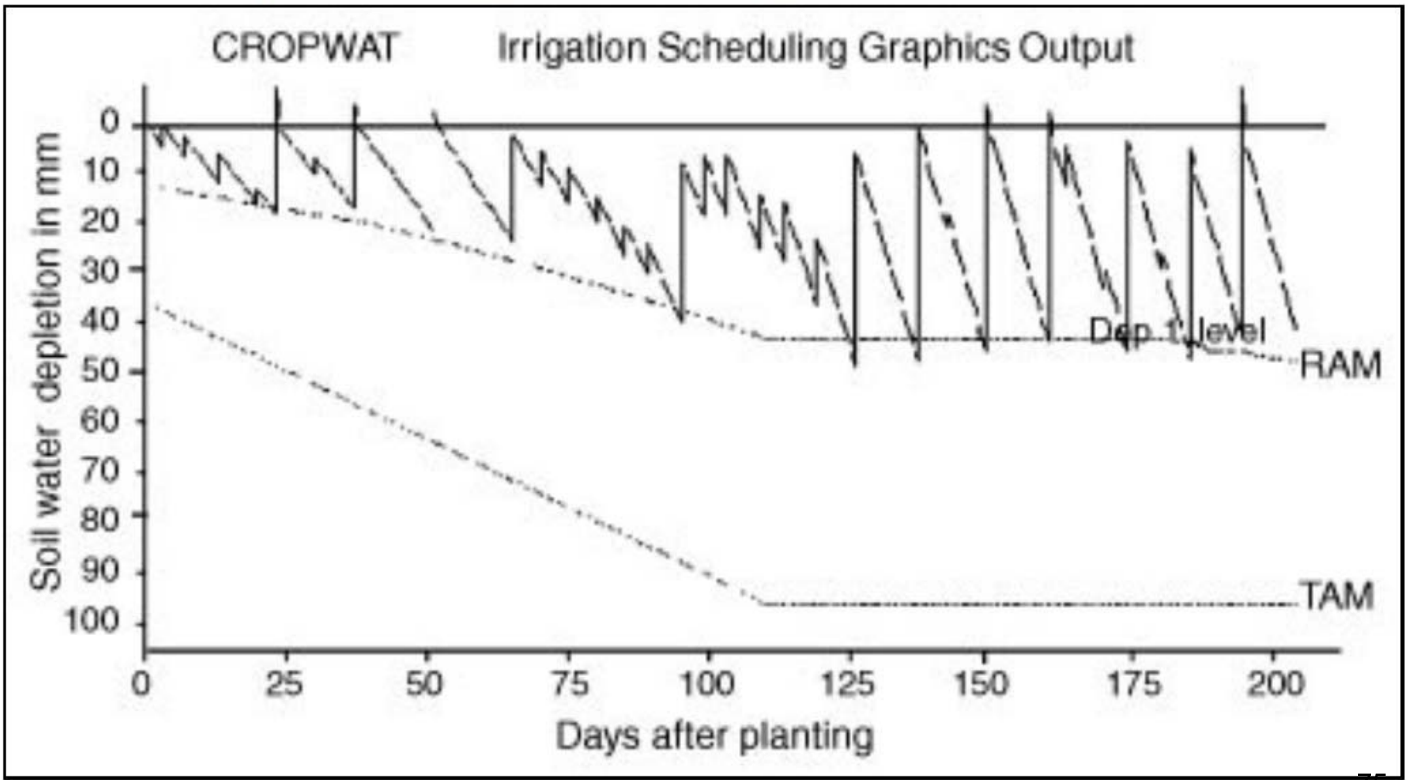
- Irrigate at user defined intervals **[Option Table]**
- Irrigate at fixed water depth **[5 mm]**
- Irrigate at fixed % desaturation **[100%=FC]**
- Irrigate at fixed % of critical depletion **[100 %]**
  [x% of RAW, No stress if x<100%, Stress if x>100%]
- Irrigate at fixed WD/desaturation/critical depletion per stage (initial, development, mid-season, late season) **[0 mm]**
- Irrigate at fixed interval per stage (Suitable in case of rotational water distribution) **[10 days]**
- Irrigate at given ETc reduction per stage **[10 %]**
- Irrigate at given yield reduction **[10 %]**
  (Deficit irrigation)
- Irrigate continuously **[9 mm/day]**
- No irrigation (rainfed)

IRRIGATION APPLICATION OPTIONS

- User defined application depth **[Option Table]**
- Refill to fixed water depth **[10 mm]**
- Refill to or below saturation **[100%=Saturation]**
- Refill soil to or below field capacity **[100%=Field capacity]**
- Refill to fixed WD/saturation/FC per stage **[100 mm]**
- Fixed application depth **[40 mm]**

IRRIGATION EFFICIENCY OPTION [70 %]

Soil water balance for optimal irrigation of sugar beet in Morocco



Soil water balance with stress during flowering stage of cotton in Turkey

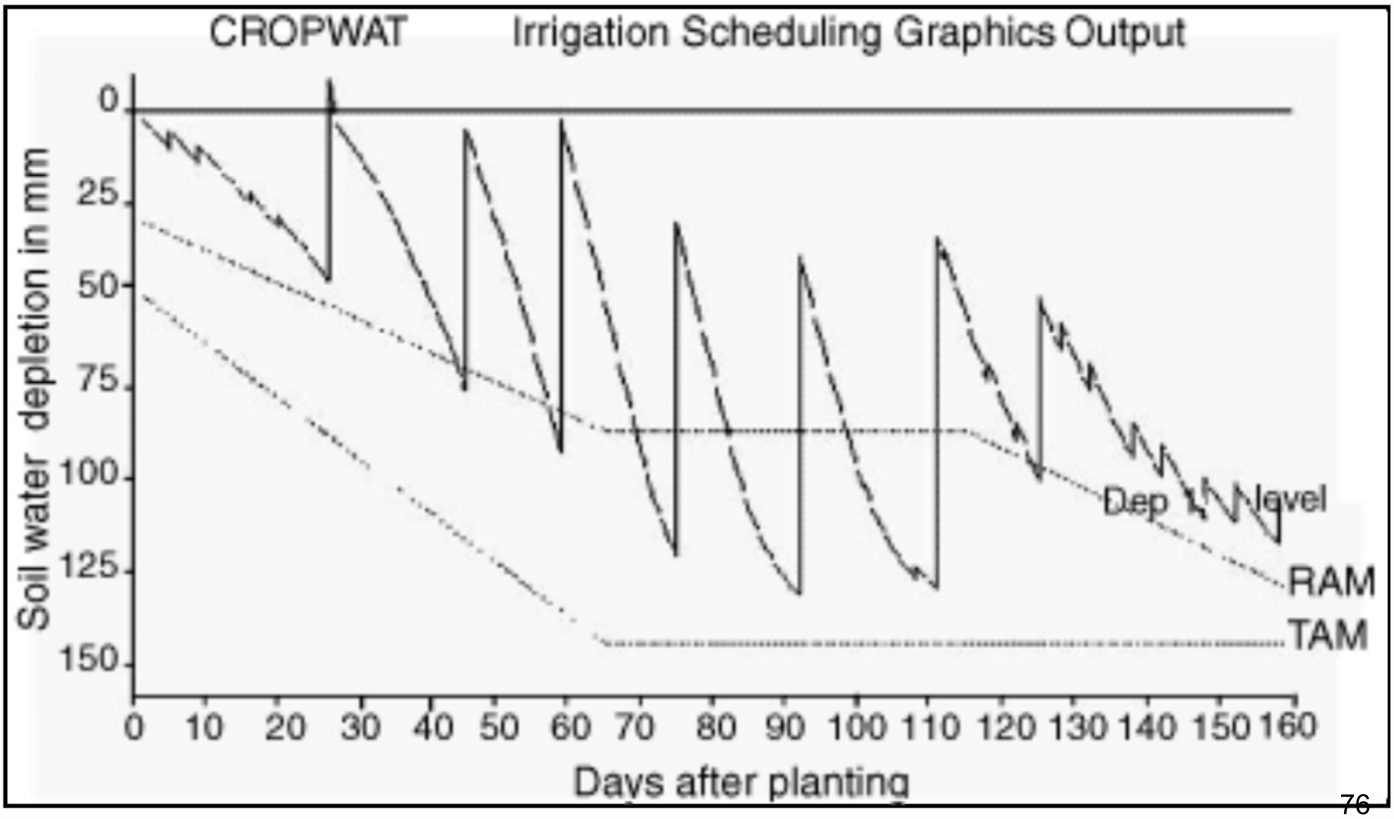
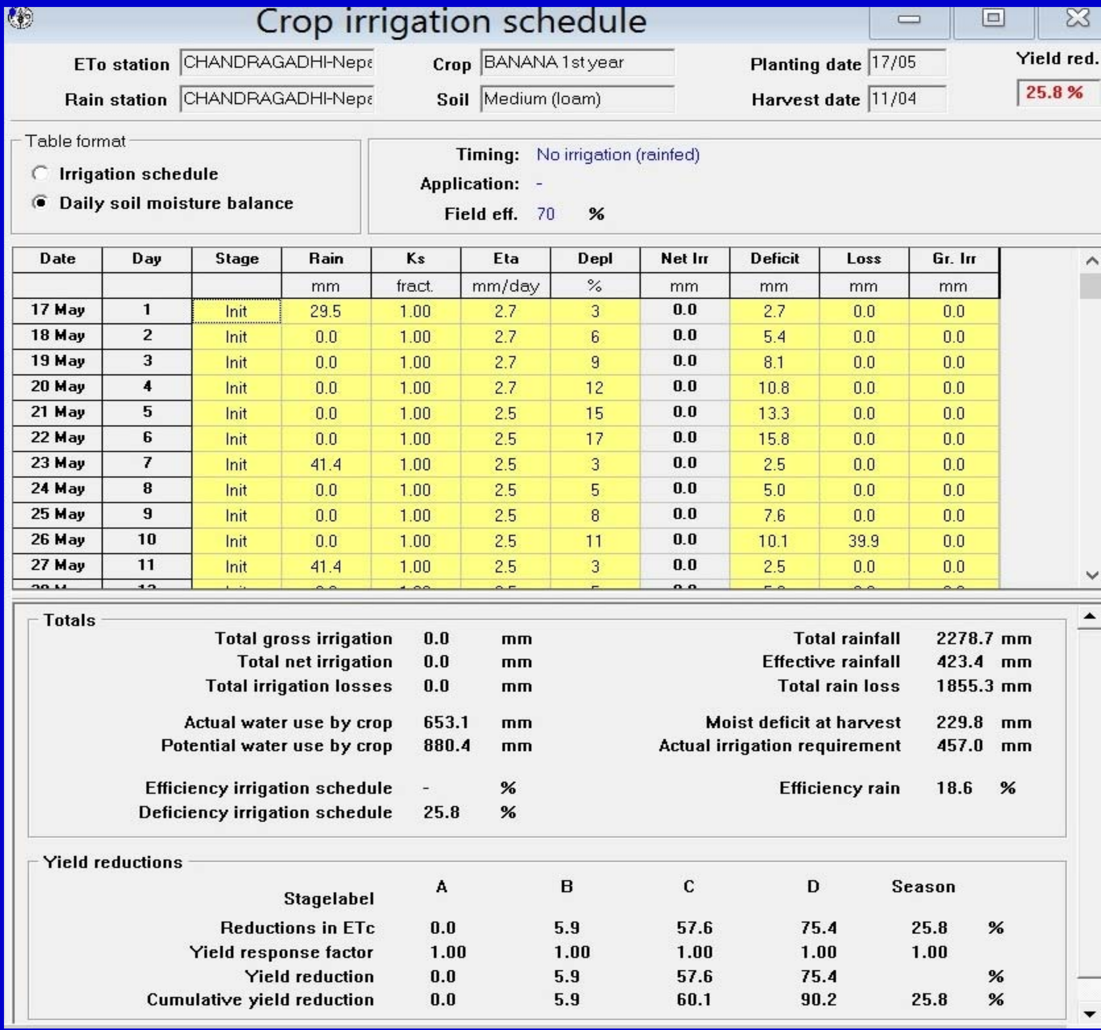


TABLE 24
Seasonal yield response functions from FAO Irrigation and Drainage Paper No. 33.

Crop	K_y	Crop	K_y
Alfalfa	1.1	Potato	1.1
Banana	1.2-1.35	Safflower	0.8
Beans	1.15	Sorghum	0.9
Cabbage	0.95	Soybean	0.85
Citrus	1.1-1.3	Spring Wheat	1.15
Cotton	0.85	Sugarbeet	1.0
Grape	0.85	Sugarcane	1.2
Groundnet	0.70	Sunflower	0.95
Maize	1.25	Tomato	1.05
Onion	1.1	Watermelon	1.1
Peas	1,15	Winter wheat	1.05
Pepper	1.1		

Yied Response Factor(Ky)

Crop	Vegetative period (1)			Flowering period (2)	Yield formation (3)	Ripening (4)	Total growing period
	early (1a)	late (1b)	total				
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5	0.5	0.2	1.25
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1



Crop irrigation schedule

ETo station: CHANDRAGADHI-Nepa | Crop: BANANA 1st year | Planting date: 17/05 | Yield red.: 25.8 %

Rain station: CHANDRAGADHI-Nepa | Soil: Medium (loam) | Harvest date: 11/04

Table format
- Irrigation schedule
- Daily soil moisture balance (selected)

Timing: No irrigation (rainfed)
Application: -
Field eff. 70 %

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr
			mm	fract.	mm/day	%	mm	mm	mm	mm
17 May	1	Init	29.5	1.00	2.7	3	0.0	2.7	0.0	0.0
18 May	2	Init	0.0	1.00	2.7	6	0.0	5.4	0.0	0.0
19 May	3	Init	0.0	1.00	2.7	9	0.0	8.1	0.0	0.0
20 May	4	Init	0.0	1.00	2.7	12	0.0	10.8	0.0	0.0
21 May	5	Init	0.0	1.00	2.5	15	0.0	13.3	0.0	0.0
22 May	6	Init	0.0	1.00	2.5	17	0.0	15.8	0.0	0.0
23 May	7	Init	41.4	1.00	2.5	3	0.0	2.5	0.0	0.0
24 May	8	Init	0.0	1.00	2.5	5	0.0	5.0	0.0	0.0
25 May	9	Init	0.0	1.00	2.5	8	0.0	7.6	0.0	0.0
26 May	10	Init	0.0	1.00	2.5	11	0.0	10.1	39.9	0.0
27 May	11	Init	41.4	1.00	2.5	3	0.0	2.5	0.0	0.0

Totals

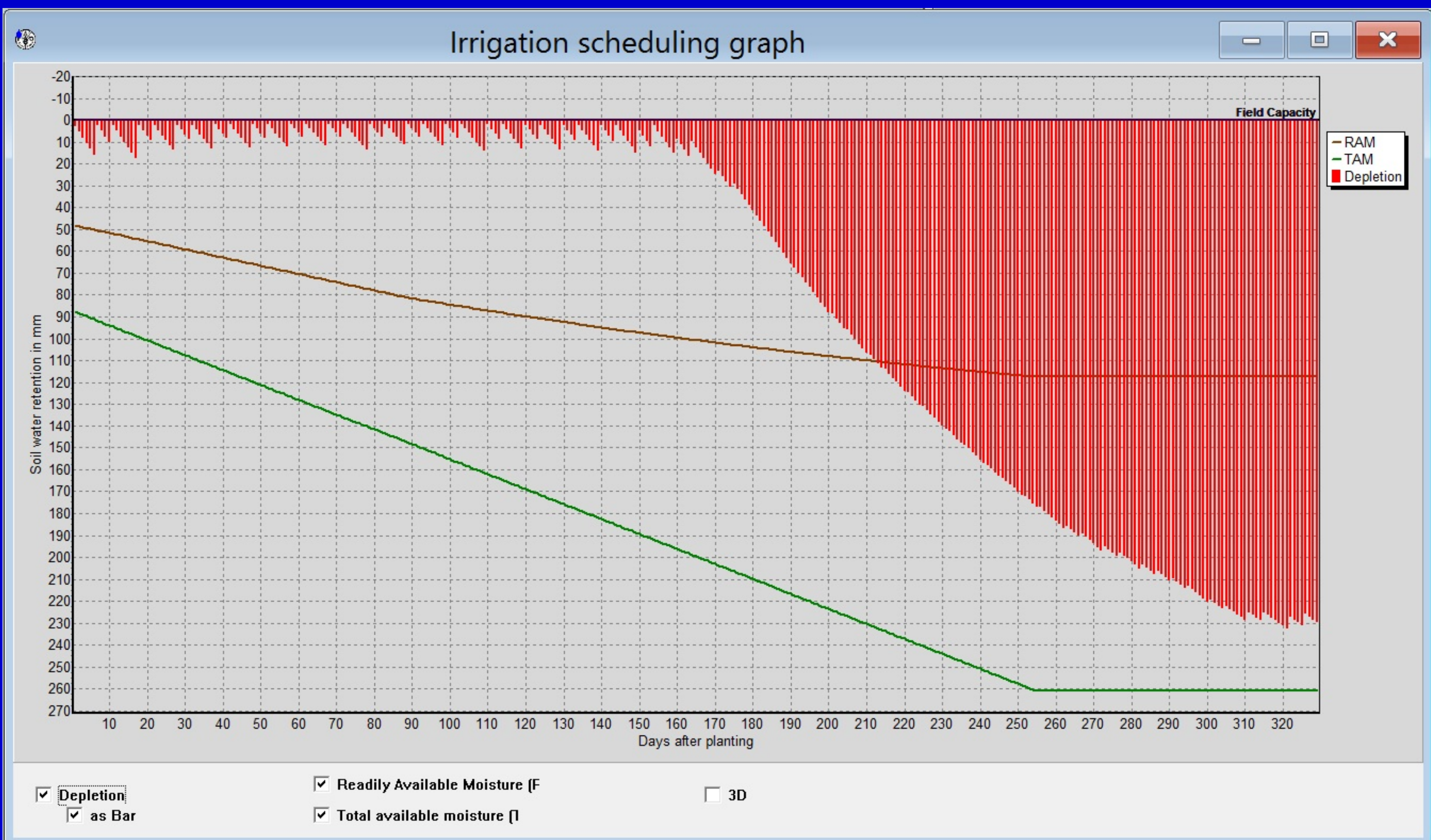
Total gross irrigation	0.0	mm	Total rainfall	2278.7	mm
Total net irrigation	0.0	mm	Effective rainfall	423.4	mm
Total irrigation losses	0.0	mm	Total rain loss	1855.3	mm
Actual water use by crop	653.1	mm	Moist deficit at harvest	229.8	mm
Potential water use by crop	880.4	mm	Actual irrigation requirement	457.0	mm
Efficiency irrigation schedule	-	%	Efficiency rain	18.6	%
Deficiency irrigation schedule	25.8	%			

Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	0.0	5.9	57.6	75.4	25.8	%
Yield response factor	1.00	1.00	1.00	1.00	1.00	
Yield reduction	0.0	5.9	57.6	75.4		%
Cumulative yield reduction	0.0	5.9	60.1	90.2	25.8	%

Banana1 scheduling – Rainfed, Medium soil, SCS Peff

Banana1 scheduling – Rainfed, Medium soil, SCS Peff



Rice scheduling – Rainfed, Clay, Empirical Peff

Rice irrigation schedule

ETo station	CHANDRAGADHI-Nepa	Crop	Rice	Planting date	17/05	Yield red.
Rain station	CHANDRAGADHI-Nepa	Soil	Heavy (clay)	Harvest date	13/09	0.0 %

Scheduling criteria

	Pre puddling	Puddling	Growth stages
Timing	Irrigate at fixed % depletion of FC	Irrigate at fixed mm waterdepth	No irrigation (rainfed)
Application	Refill to fixed % saturation	Refill to fixed water depth	-

Table format: (•) Irrigation schedule ( ) Daily soil moisture balance

Field efficiency 70 % Soaking depth 0.5 m

Date	Day	Stage	Rain	Ks	Eta	Puddl	Percol.	Depl.SM	Net Gift	Loss	Depl.SAT
			mm	fract.	%	state	mm	mm	mm	mm	mm
27 Apr	-19	PrePu	16.0	1.00	100	Prep	10.7	0	20.4	0.0	20.4
12 May	-4	Puddl	0.0	1.00	100	Prep	0.0	7	74.0	0.0	24.0
14 May	-2	Puddl	0.0	1.00	100	OK	15.0	0	50.9	0.0	0.9
13 Sep	End	End	33.8	1.00	100	OK	2.4	0			

Totals

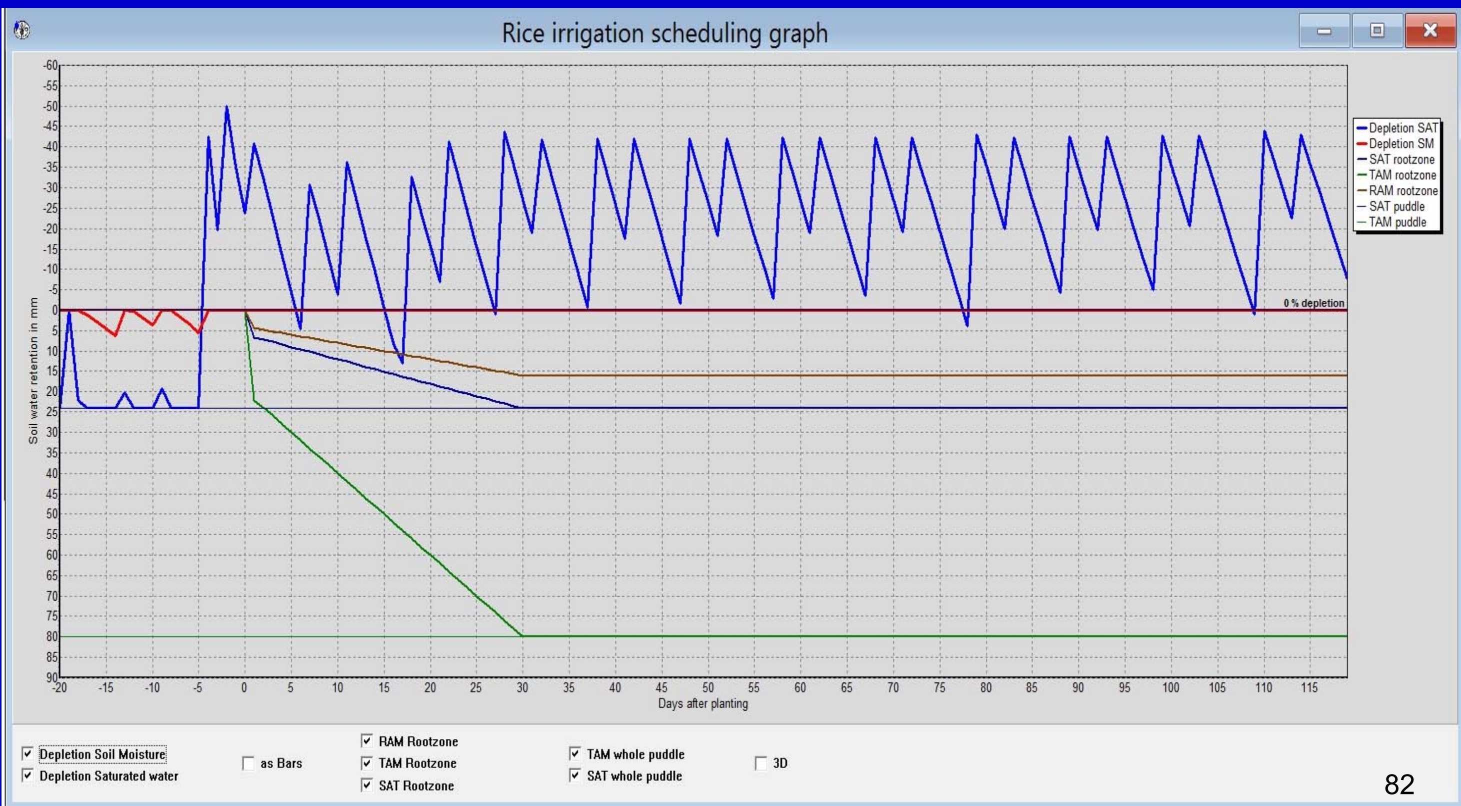
Total gross irrigation	207.6	mm	Total rainfall	1974.5	mm
Total net irrigation	145.4	mm	Effective rainfall	1027.3	mm
Total irrigation losses	0.0	mm	Total rain loss	947.3	mm
Total percolation losses	517.9	mm			
Actual water use by crop	525.4	mm	Moist deficit at harvest	229.8	mm
Potential water use by crop	525.4	mm	Actual irrigation requirement	-501.8	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	52.0	%
Deficiency irrigation schedule	0.0	%			

Yield reductions

Stagelabel	A	B	C	D	Season	
Reductions in ETc	0.0	0.0	0.0	0.0	0.0	%
Yield response factor	1.00	1.09	1.32	0.50	1.10	
Yield reduction	0.0	0.0	0.0	0.0	0.0	%
Cumulative yield reduction	0.0	0.0	0.0	0.0		%

Rice scheduling – Rainfed, Clay, Empirical Peff

Rice scheduling – Rainfed, Clay, Empirical Peff

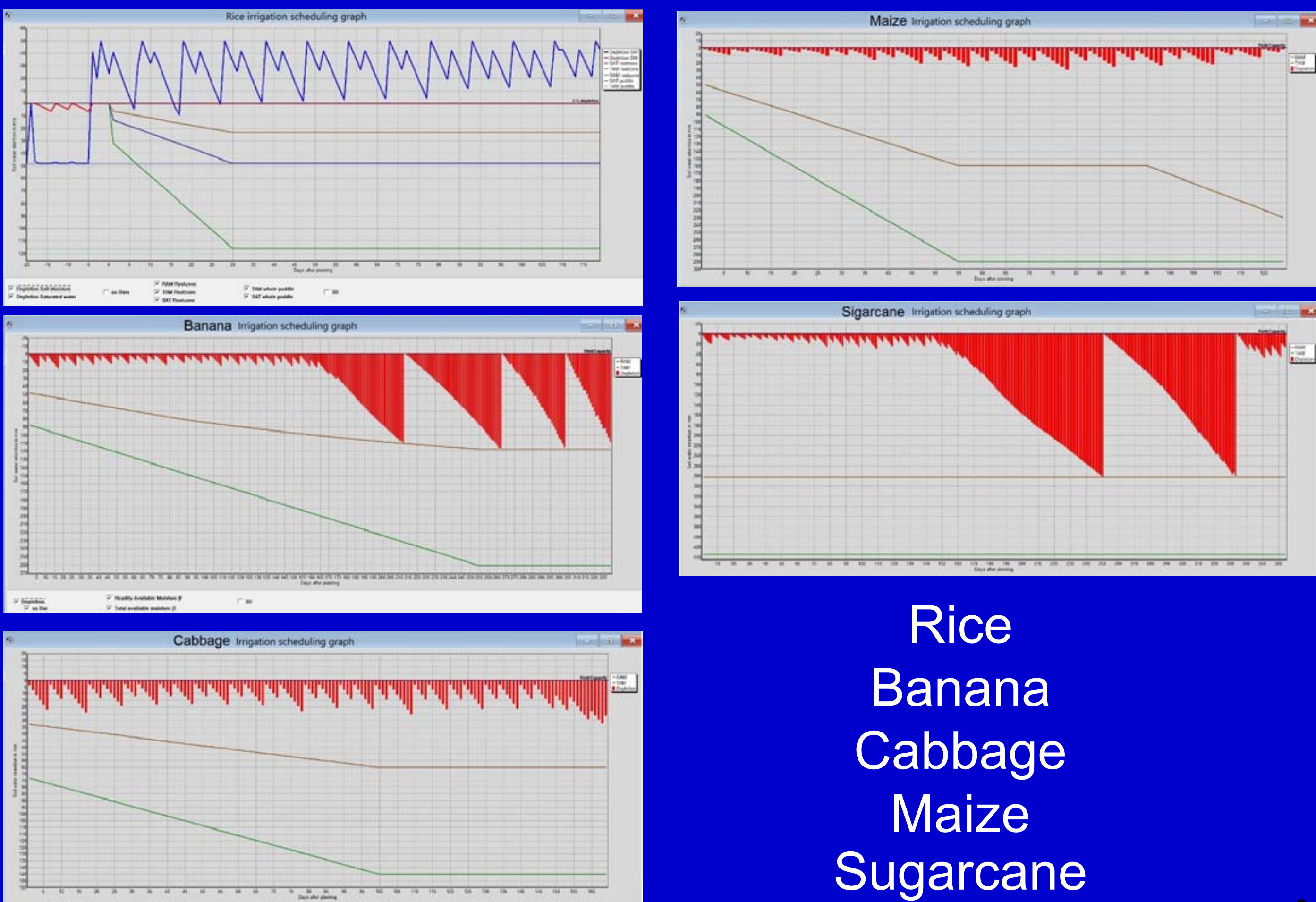


Cropping pattern

Cropping pattern - I:\2018-Bhutan 21-25May\Bhutan-Da

Cropping pattern name: Training cropwat

No.	Crop file	Crop name	Planting date	Harvest date	Area %
1.	...21-25May\Bhutan-Data\Crops\FAO\RICE.CRO	Rice	17/05	13/09	20
2.	...ay\Bhutan-Data\Crops\FAO\BANANA1.CRO	BANANA 1st year	17/05	11/04	20
3.	...ay\Bhutan-Data\Crops\FAO\CABBAGE.CRO	CABBAGE Crucifers	17/05	28/10	10
4.	...-25May\Bhutan-Data\Crops\FAO\MAIZE.CRO	MAIZE (Grain)	17/05	18/09	20
5.	...\Bhutan-Data\Crops\FAO\SUGARCAN.CRO	Sugarcane (Ratoon)	17/05	16/05	20



Rice
Banana
Cabbage
Maize
Sugarcane

Scheme water supply

SCHEME SUPPLY

ETo station: CHANDRAGADHI-Nepal   Cropping pattern: Training cropwat
Rain station: CHANDRAGADHI-Nepal-8

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Rice	0.0	0.0	0.0	49.8	196.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0
2. BANANA 1st year	70.2	75.7	127.8	49.3	0.0	0.0	0.0	0.0	0.0	6.4	63.6	57.9
3. CABBAGE Crucifers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0	0.0
4. MAIZE (Grain)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5. Sugarcane (Ratoon)	80.2	81.6	121.8	99.0	8.5	0.0	0.0	0.0	0.0	36.3	94.8	75.3
Net scheme irr.req.												
in mm/day	1.0	1.1	1.6	1.3	1.3	0.0	0.0	0.0	0.0	0.3	1.1	0.9
in mm/month	30.1	31.5	49.9	39.6	40.9	0.2	0.0	0.0	0.0	9.2	31.7	26.6
in l/s/h	0.11	0.13	0.19	0.15	0.15	0.00	0.00	0.00	0.00	0.03	0.12	0.10
Irrigated area (% of total area)	40.0	40.0	40.0	60.0	40.0	20.0	0.0	0.0	0.0	50.0	40.0	40.0
Irr.req. for actual area (l/s/h)	0.28	0.33	0.47	0.25	0.38	0.00	0.00	0.00	0.00	0.07	0.31	0.25

Scheme Supply

ETo station: CHANDRAGADHI-Nepa
Rain station: CHANDRAGADHI-Nepa
Cropping pattern: Training cropwat

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Rice	0	0	0	49.8	196	0.9	0	0	0	0	0	0
2. BANANA 1st year	70.2	75.7	127.8	49.3	0	0	0	0	0	6.4	63.6	57.9
3. CABBAGE Crucifers	0	0	0	0	0	0	0	0	0	7	0	0
4. MAIZE (Grain)	0	0	0	0	0	0	0	0	0	0	0	0
5. Sugarcane (Ratoon)	80.2	81.6	121.8	99	8.5	0	0	0	0	36.3	94.8	75.3
Net scheme irr.req.												
in mm/day	1	1.1	1.6	1.3	1.3	0	0	0	0	0.3	1.1	0.9
in mm/month	30.1	31.5	49.9	39.6	40.9	0.2	0	0	0	9.2	31.7	26.6
in l/s/h	0.11	0.13	0.19	0.15	0.15	0	0	0	0	0.03	0.12	0.1
Irrigated area	40	40	40	60	40	20	0	0	0	50	40	40
(% of total area)												
Irr.req. for actual area	0.28	0.33	0.47	0.25	0.38	0	0	0	0	0.07	0.31	0.25
(l/s/h)												

Summary
Main Functions of CROPWAT 8

1. Calculation of ETo from climatic data.
2. Estimation of effective rainfall
3. Derivation of crop factor (Kc)
4. Calculation of ETc and Net IWR for each crop
5. Input soil properties
6. Irrigation Scheduling Simulation
7. Estimation of scheme water supply from defined cropping pattern

The end of
Crop Water Requirements &
Irrigation Scheduling
with CROPWAT 8.0

Thank you

Appendix A

Table A1 – Length of Crop Development Stages of Selected Field crops
Table A2 – Crop Coefficient (Kc)
Table A3 – Rooting Depth(D)-Depletion Fraction(p)-RAW
Table A4 – Yield Response Factor (Ky)

Table A1 Length of Crop Development Stages of Selected Field Crops

Crop	Init.	Devel	Mid	Late	Total	Plant Date	Region
Artichoke	40 20	40 40	250 220	30 30	360 310	Apr (1 yr) May (2 yr)	California (cut in May)
Beans (green)	20 15	30 25	30 25	10 10	90 75	Feb/Mar Aug/Sep	Calif., Mediterranean Calif., Egypt, Lebanon
Beans (dry)	20 15	30 25	40 35/50	20 20	110 95	May/June June	Continental Climates Pakistan, Calif.
Beets	15 25	25 30	20 25	10 10	70 90	Apr/May Feb/Mar	Mediterranean Mediterranean & Arid
Carrots	20 30	30 40	50/30 60	20 20	100 150	Oct/Jan Feb/Mar	Arid climate Mediterranean
Castor beans	25	40	65	50	180	March	(Semi)Arid Climates
Celery	25 25	40 40	95 45	20 15	180 125	Oct April	(Semi)Arid Mediterranean
Cotton	30 30 30	50 50 50	60 60 55	55 55 45	195 195 180	Mar;Apr/May Sept April	Egypt; Pakistan Yemen Texas
Crucifers	20 25 30	30 35 35	20 25 90	10 10 40	80 95 195	April February Oct/Nov	Mediterranean Mediterranean Mediterranean
Cucumber	20 25	30 35	40 50	15 20	105 130	June/August Nov; Feb	Arid Region Arid Region
Egg plant	30 30	40 45	40 40	20 25	130 140	October May/June	Arid Region Mediterranean
Flax	25 30	35 40	50 100	40 50	150 220	April October	Europe Arizona
Grains (small)	20 25	30 35	60 65	40 40	150 165	April Oct/Nov	Mediterranean Pakistan; Arid Reg.
Groundnut	25 35	35 45	45 35	25 25	130 140	Dry season May/June	West Africa Mediterranean
Lentil	20 25	30 35	60 70	40 40	150 170	April Oct/Nov	Europe Arid Region
Lettuce	20 30 25	30 40 35	15 25 30	10 10 10	75 105 100	April Nov/Jan Oct/Nov	Mediterranean Mediterranean Arid Region
Maize (sweet)	20 20 20	20 25 30	30 25 50/30	10 10 10	80 80 90	March May/June Oct/Dec	Philippines Mediterranean Arid Climate
Maize (grain)	30 25 20 20 30	50 40 35 35 40	60 45 40 40 50	40 30 30 30 30	180 140 125 125 150	April Dec/Jan June October April	East Africa (alt.) Arid Climate Nigeria (humid) India (dry, cool) Spain (spring, sum.)
Melons	25 30	35 45	40 65	20 20	120 160	May Dec/Jan	Mediterranean Arid Region
Millet	15 20	25 30	40 55	25 35	105 140	June April	Pakistan Central USA

Table A1(Cont') Length of Crop Development Stages of Selected Field Crops

Crop	Init.	Devel	Mid	Late	Total	Plant Date	Region
Onion (dry)	15 20	25 35	70 110	40 45	150 210	April October	Mediterranean Arid Region
Onion (green)	25 20	30 45	10 20	5 10	70 95	April/May October	Mediterranean Arid Region
Peas	15 20	25 30	35 35	15 15	90 100	May March/April	Europe Mediterranean
Peppers	25/30 30	35 40	40 110	20 30	125 210	April/June October	Europe and Medit. Arid Region
Potato	25 25 30+15	30 30 35	30/45 45 50	30 30 30	115/130 130 145	Jan/Nov May April	(Semi)Arid Climate Continental Climate Europe
Radish	10 10	10 10	15 15	5 5	40 40	March/April Winter	Medit.; Europe Arid Region
Safflower	20 35	35 55	45 60	25 40	125 190	April Oct/Nov	California, USA Arid Region
Sorghum	20 20	35 35	40 45	30 30	130 140	May/June March/April	USA, Pakis., Med. Arid Region
Soybeans	20 20	30/35 25	60 75	25 30	140 150	May June	Central USA Japan
Spinach	20 20	20 30	25 40	5 10	70 100	Apr; Sep/Oct November	Mediterranean Arid Region
Squash (pumpkin)	20 25	30 35	30 35	20 25	100 120	March, Aug June	Mediterranean Europe
Squash (zucchini)	25 20	35 30	25 25	15 15	100 90	April May/June	Medit.; Arid Reg. Medit.; Europe
Sugarbeet	45 25 35	75 35 60	80 50 70	30 50 40	230 160 205	November May November	Mediterranean Mediterranean Arid Regions
Sunflower	25	35	45	25	130	April/May	Medit.; California
Tomato	30 35 30	40 45 40	40 70 45	25 30 30	135 180 145	January Oct/Nov April/May	Arid Region Arid Region Mediterranean
Wheat/ Barley	15 20 15	25 25 30	50 60 65	30 30 40	120 135 150	November March/April July	Central India 35-45 °L East Africa
Winter Wheat	30	140	40	30	240	November	Mediterranean

From FAO Irrigation and Drainage Paper 24, Table 22.

Table A2 Crop Coefficients (Kc)

CROP	Crop development stages					Total growing period
	Initial	Crop develop-ment	Mid-season	Late season	At harvest	
Banana						
tropical	0.4-0.5	0.7-0.85	1.0-1.1	0.9-1.0	0.75-0.85	0.7-0.8
subtropical	0.5-0.65	0.8-0.9	1.0-1.2	1.0-1.15	1.0-1.15	0.85-0.95
Bean						
green	0.3-0.4	0.65-0.75	0.95-1.05	0.9-0.95	0.85-0.95	0.85-0.9
dry	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7-0.8
Cabbage	0.4-0.5	0.7-0.8	0.95-1.1	0.9-1.0	0.8-0.95	0.7-0.8
Cotton	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.9	0.65-0.7	0.8-0.9
Grape	0.35-0.55	0.6-0.8	0.7-0.9	0.6-0.8	0.55-0.7	0.55-0.75
Groundnut	0.4-0.5	0.7-0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3-0.5	0.7-0.9	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
grain	0.3-0.5*	0.7-0.85*	1.05-1.2*	0.8-0.95	0.55-0.6*	0.75-0.9*
Onion						
dry	0.4-0.6	0.7-0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8-0.9
green	0.4-0.6	0.6-0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4-0.5	0.7-0.85	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Pepper, fresh	0.3-0.4	0.6-0.75	0.95-1.1	0.85-1.0	0.8-0.9	0.7-0.8
Potato	0.4-0.5	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75	0.75-0.9
Rice	1.1-1.15	1.1-1.5	1.1-1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.7	0.2-0.25	0.65-0.7
Sorghum	0.3-0.4	0.7-0.75	1.0-1.15	0.75-0.8	0.5-0.55	0.75-0.85
Soybean	0.3-0.4	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sugarbeet	0.4-0.5	0.75-0.85	1.05-1.2	0.9-1.0	0.6-0.7	0.8-0.9
Sugarcane	0.4-0.5	0.7-1.0	1.0-1.3	0.75-0.8	0.5-0.6	0.85-1.05
Sunflower	0.3-0.4	0.7-0.8	1.05-1.2	0.7-0.8	0.35-0.45	0.75-0.85
Tobacco	0.3-0.4	0.7-0.8	1.0-1.2	0.9-1.0	0.75-0.85	0.85-0.95
Tomato	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.95	0.6-0.65	0.75-0.9
Watermelon	0.4-0.5	0.7-0.8	0.95-1.05	0.8-0.9	0.65-0.75	0.75-0.85
Wheat	0.3-0.4	0.7-0.8	.05-1.2	0.65-0.75	0.2-0.25	0.8-0.9
Alfalfa	0.3-0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4-0.6

First figure : Under high humidity (RHmin > 70%) and low wind (U < 5 m/sec).
Second figure : Under low humidity (RHmin < 20%) and strong wind (> 5 m/sec).

From FAO Irrigation and Drainage Paper 33, Table 18

Table A3 Depletion Fraction(p) and Readily Available Water(RAW)

GENERALIZED DATA ON ROOTING DEPTH OF FULL GROWN CROPS, FRACTION OF AVAILABLE SOIL WATER (p) AND READILY AVAILABLE SOIL WATER (p.Sa) FOR DIFFERENT SOIL TYPES (in mm/m soil depth) WHEN ETcrop is 5-6 mm/day

Crop	Rooting depth (d) m	Fraction (p) of available soil water[1]	Readily available soil water (p.Sa) mm/m[1]		
			fine	medium	coarse
Alfalfa	1.0-2.0	0.55	110	75	35
Banana	0.5-0.9	0.35	70	50	20
Barley[2]	1.0-1.5	0.55	110	75	35
Beans[2]	0.5-0.7	0.45	90	65	30
Beets	0.6-1.0	0.5	100	70	35
Cabbage	0.4-0.5	0.45	90	65	30
Carrots	0.5-1.0	0.35	70	50	20
Celery	0.3-0.5	0.2	40	25	10
Citrus	1.2-1.5	0.5	100	70	30
Clover	0.6-0.9	0.35	70	50	20
Cacao		0.2	40	30	15
Cotton	1.0-1.7	0.65	130	90	40
Cucumber	0.7-1.2	0.5	100	70	30
Dates	1.5-2.5	0.5	100	70	30
Dec. orchards	1.0-2.0	0.5	100	70	30
Flax[2]	1.0-1.5	0.5	100	70	30
Grains small[2]	0.9-1.5	0.6	120	80	40
winter[2]	1.5-2.0	0.6	120	80	40
Grapes	1.0-2.0	0.35	70	50	20
Grass	0.5-1.5	0.5	100	70	30
Groundnuts	0.5-1.0	0.4	80	55	25
Lettuce	0.3-0.5	0.3	60	40	20
Maize[2]	1.0-1.7	0.6	120	80	40
silage		0.5	100	70	30
Melons	1.0-1.5	0.35	70	50	25
Olives	1.2-1.7	0.65	130	95	45
Onions	0.3-0.5	0.25	50	35	15
Palm trees	0.7-1.1	0.65	130	90	40
Peas	0.6-1.0	0.35	70	50	25
Peppers	0.5-1.0	0.25	50	35	15
Pineapple	0.3-0.6	0.5	100	65	30
Potatoes	0.4-0.6	0.25	50	30	15
Safflower[2]	1.0-2.0	0.6	120	80	40
Sisal	0.5-1.0	0.8	155	110	50
Sorghum[2]	1.0-2.0	0.55	110	75	35
Soybeans	0.6-1.3	0.5	100	75	35
Spinach	0.3-0.5	0.2	40	30	15
Strawberries	0.2-0.3	0.15	30	20	10
Sugarbeet	0.7-1.2	0.5	100	70	30
Sugarcane[2]	1.2-2.0	0.65	130	90	40
Sunflower[2]	0.8-1.5	0.45	90	60	30
Sweet potatoes	1.0-1.5	0.65	130	90	40
Tobacco early	0.5-1.0	0.35	70	50	25
late		0.65	130	90	40
Tomatoes	0.7-1.5	0.4	180	60	25
Vegetables	0.3-0.6	0.2	40	30	15
Wheat	1.0-1.5	0.55	105	70	35
ripening		0.9	180	130	55
Total available soil water (Sa)			200	140	60

1 When ET_{crop} is 3 mm/day or smaller increase values by some 30%; when ET_{crop} is 8 mm/day or more reduce values by some 30%, assuming non-saline conditions (EC_e < 2 dS/m).

2 Higher values than those shown apply during ripening.

Sources: Taylor (1965), Stuart and Hagan (1972), Salter and Goode (1967), Rijtema (1965) and others.

From FAO Irrigation and Drainage Paper 24, Table 39.

Table A4 Yield Response Factor(Ky)

Crop	Vegetative period (1) early (1a)	Vegetative period (1) late (1b)	Vegetative period (1) total	Flowering period (2)	Yield formation (3)	Ripening (4)	Total growing period
Alfalfa			0.7-1.1				0.7-1.1
Banana							1.2-1.35
Bean			0.2	1.1	0.75	0.2	1.15
Cabbage	0.2				0.45	0.6	0.95
Citrus							0.8-1.1
Cotton			0.2	0.5		0.25	0.85
Grape							0.85
Groundnut			0.2	0.8	0.6	0.2	0.7
Maize			0.4	1.5	0.5	0.2	1.25
Onion			0.45		0.8	0.3	1.1
Pea	0.2			0.9	0.7	0.2	1.15
Pepper							1.1
Potato	0.45	0.8			0.7	0.2	1.1
Safflower		0.3		0.55	0.6		0.8
Sorghum			0.2	0.55	0.45	0.2	0.9
Soybean			0.2	0.8	1.0		0.85
Sugarbeet							
beet							0.6-1.0
sugar							0.7-1.1
Sugarcane			0.75		0.5	0.1	1.2
Sunflower	0.25	0.5		1.0	0.8		0.95
Tobacco	0.2	1.0			0.5		0.9
Tomato			0.4	1.1	0.8	0.4	1.05
Watermelon	0.45	0.7		0.8	0.8	0.3	1.1
Wheat							
winter			0.2	0.6	0.5		1.0
spring			0.2	0.65	0.55		1.15

From FAO Irrigation and Drainage Paper 33, Table 24.