Soil Water Balance and Irrigation Scheduling

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INTRODUCTION

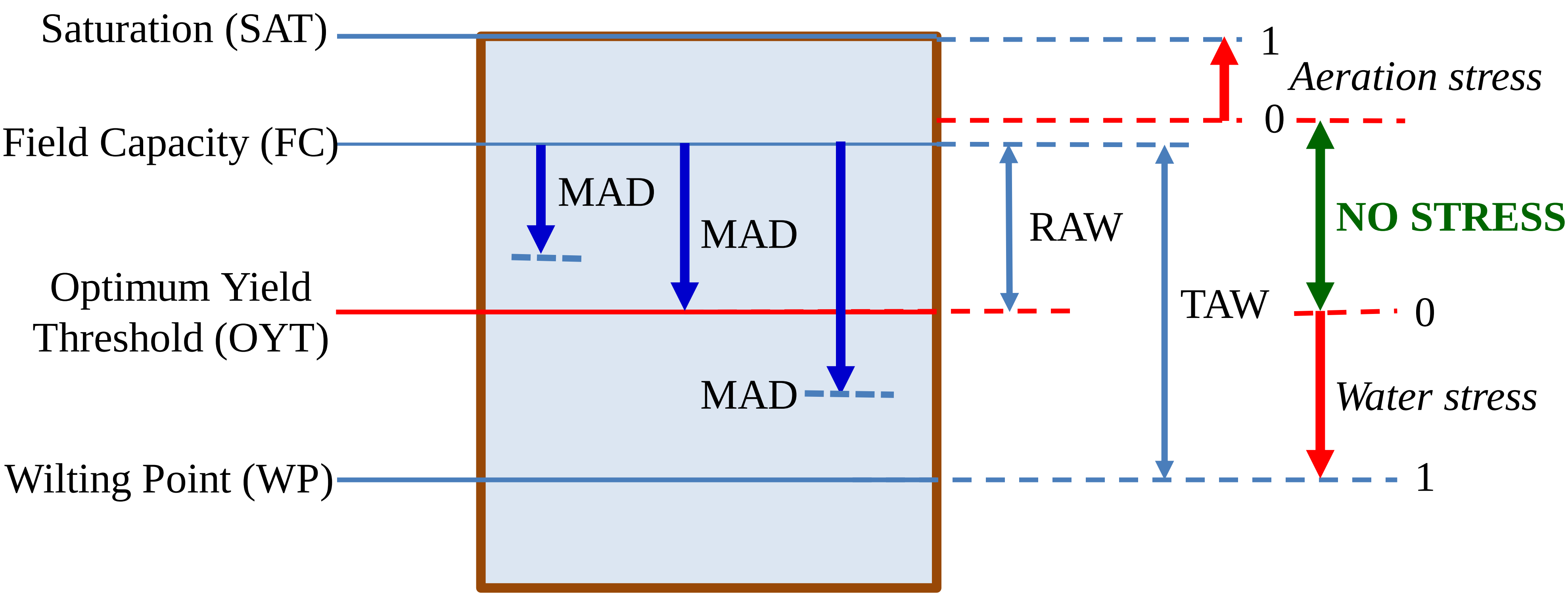
Soil Water Balance – why we need it?

- to asses the root zone soil water depletion/soil water content under different water regimes and soil, climatic and crop conditions;
- to design irrigation scheduling;
- to evaluate irrigation scenarios and strategies for the future (irrigation project design);
- to estimate yield/biomass response to water availability;
- to study the building of salt in the root zone under in the case of application of low quality water.

IRRIGATION : BASIC MANAGEMENT TERMS & CONCEPTS

Water content levels in a unit of soil

Irrigation management terms and stresses



1 mm of water = 1 l/m^2 = 10 m^3/ha

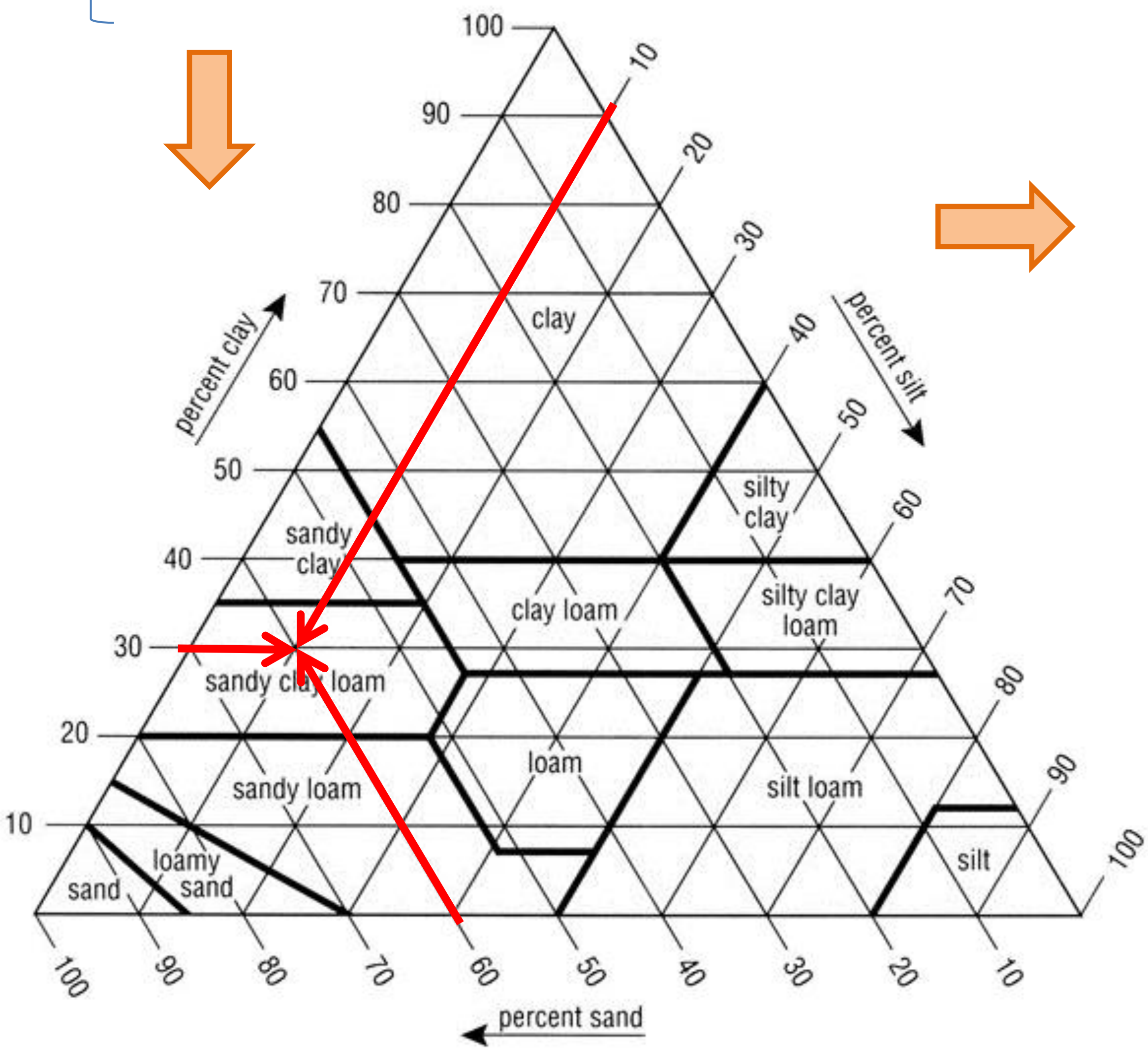
RAW : Readily Available Water
TAW : Total Available Water
MAD : Management Available Depletion
RAW = p * TAW,
p – varies from 0.3 to 0.7, average 0.5

IRRIGATION : BASIC MANAGEMENT STEPS

Soil granulometric analysis:

- clay 30%,
- sand 60%,
- silt 10%

Soil triangle



Soil texture	SAT	FC	WP
Sand	36	13	6
Loamy sand	38	16	8
Sandy loam	41	22	10
Loam	46	31	15
Silt loam	46	33	13
Silt	43	33	9
Sandy clay loam	47	32	20
Clay loam	50	39	23
Silty clay loam	52	44	23
Sandy clay	50	39	27
Silty clay	54	50	32
Clay	55	54	39

Soil water content vol%

SWHC=FC-WP [vol%]

SWHC=32-20=12%

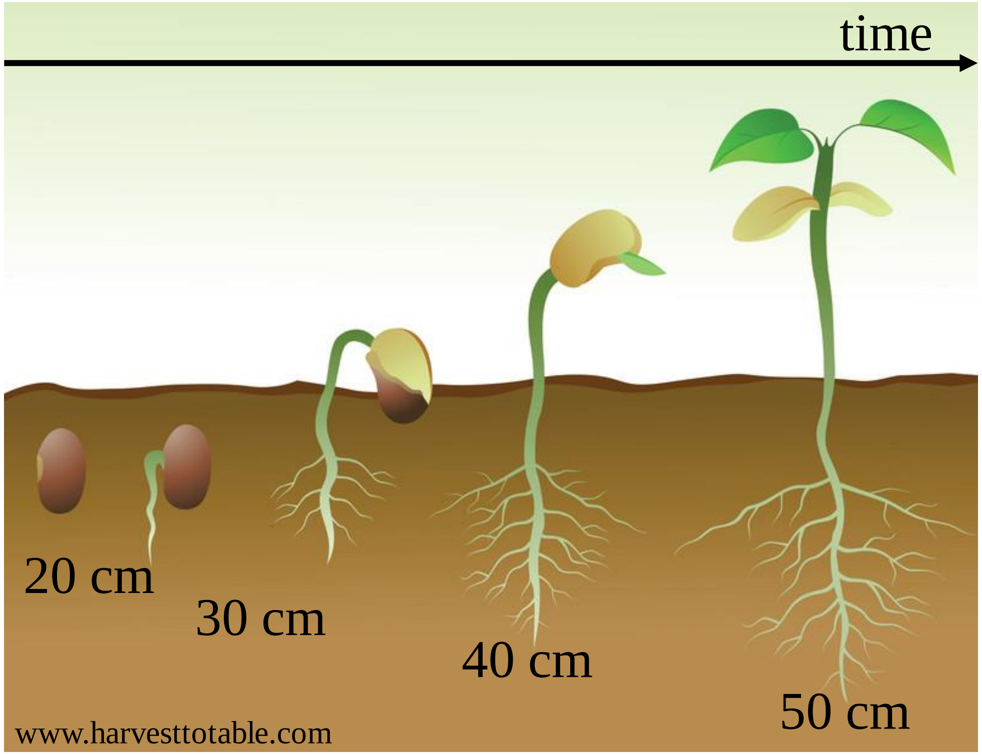
SWHC=120 mm/m

120 mm of water per 1 m of soil

SWHC – Soil Water Holding Capacity

IRRIGATION : BASIC MANAGEMENT CONCEPTS

Plant root growth



Root depth (Rd) = 50 cm

SWHC=120 mm/m

TAW = (FC-WP)*Rd = SWHC*Rd

TAW = 120 mm/m * 0.5 m = 60 mm

RAW = p * TAW, where p is fraction of TAW

p = 0.5

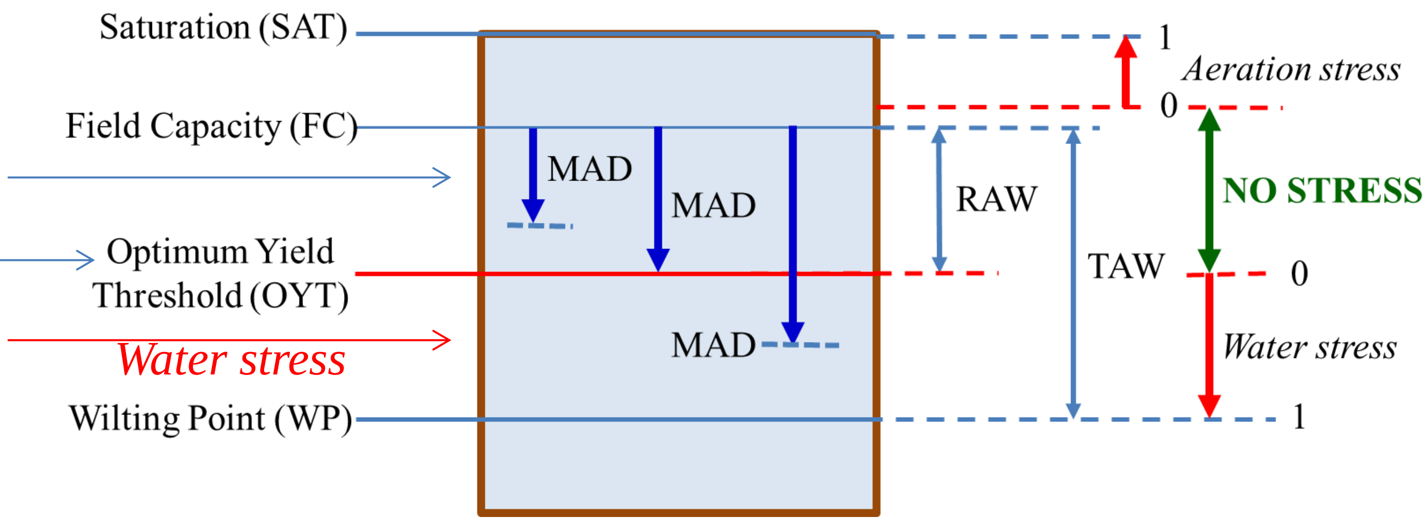
RAW = 0.5 * TAW = 30 mm

Management options:

MAD < RAW

MAD = RAW

MAD > RAW



IRRIGATION : BASIC MANAGEMENT CONCEPTS

Weather station

T, RH, Rs, WS

measured at 2 m height

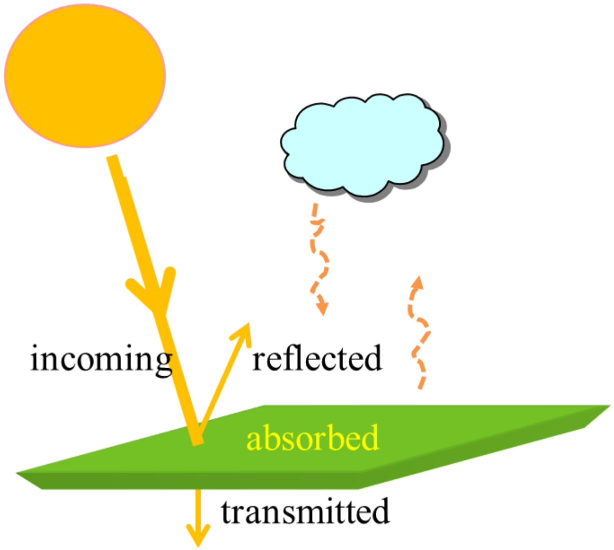
Reference (grass – like) evapotranspiration ET_o

T – air temperature

RH – air relative humidity

Rs – solar radiation

WS – wind speed

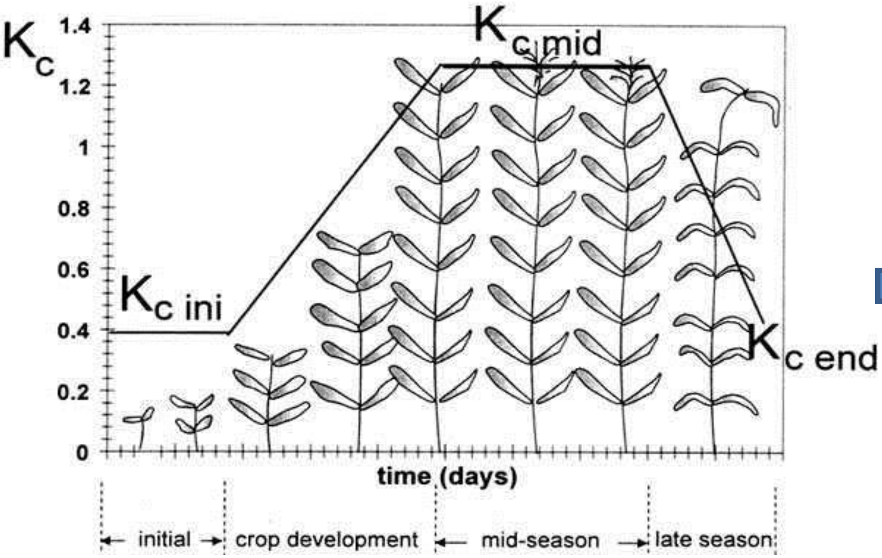


Penman-Monteith equation

$$\lambda ET_o = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma (1 + r_s / r_a)}$$

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)}$$

Crop coefficient K_c



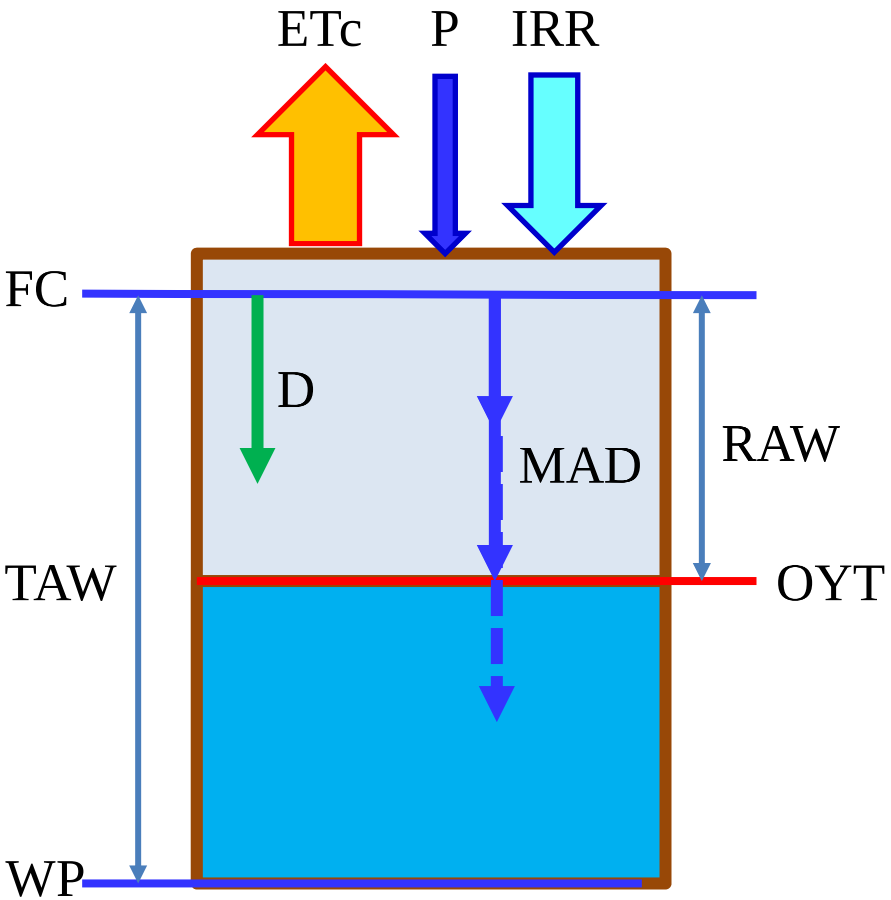
ET_o

K_c

$$ET_c = K_c * ET_o$$

Crop Evapotranspiration

IRRIGATION : BASIC MANAGEMENT CONCEPTS



ETc – Crop Evapotranspiration

P – Precipitation

IRR – Irrigation

D – Soil Water Depletion in the root zone

D = ETc – P – IRR

If P = 0 and IRR = 0, then D = ET_c

D = ET_c/day * T (days)

Irrigation should start when D reaches MAD
MAD can be equal to RAW but also
lower/greater than RAW – it is *manager decision*

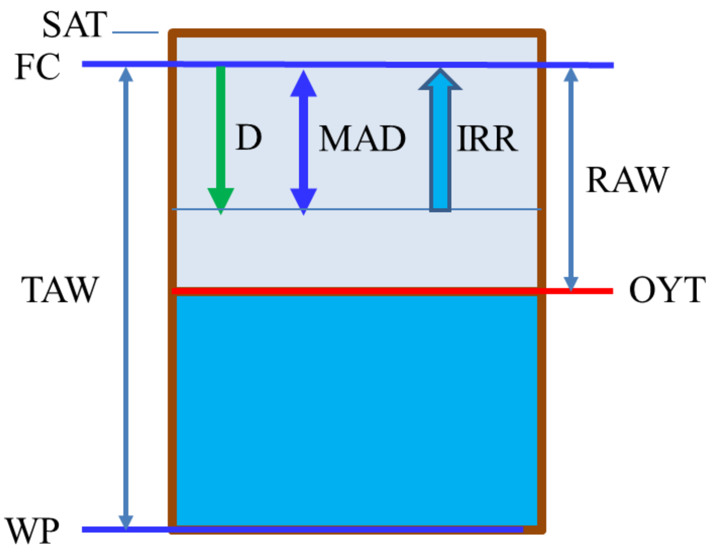
If soil water content is at FC, ETc = 5 mm/day
and MAD = RAW = 30 mm then
irrigation should start after 6 days because
30 mm / 5 mm/day = 6 days

Irrigation input depends on application efficiency
EFF_{app} = 0.9 for drip irrigation method
EFF_{app} = 0.75 for sprinkler irrigation method
Hence, if we should refill the root zone to FC level
$IRR_{gross}=IRR_{net}/EFF_{app}$
For drip, IRR = 30/0.9 = 33.3 mm
For sprinkler, IRR = 30/0.75 = 40 mm

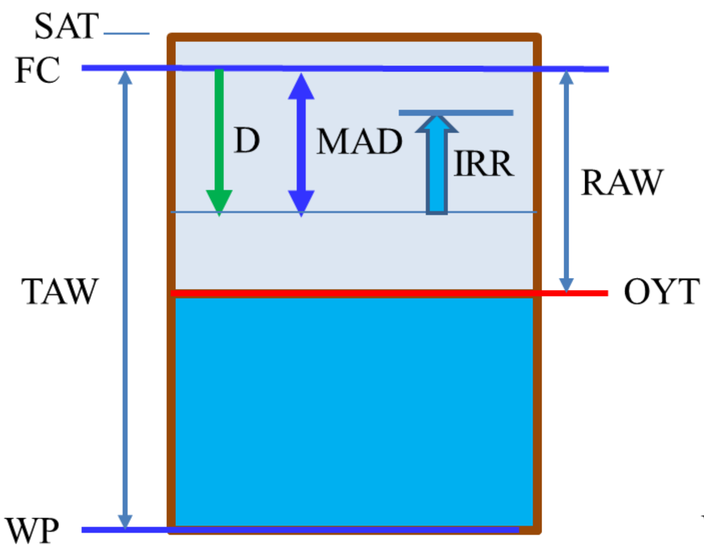
If irrigated land is 0.3 ha
then volume of water to supply is
For drip, IRR = 333 m^3/ha * 0.3 ha = 100 m^3
For sprinkler, IRR = 400 m^3/ha * 0.3 ha = 120 m^3

IRRIGATION : BASIC MANAGEMENT CONCEPTS

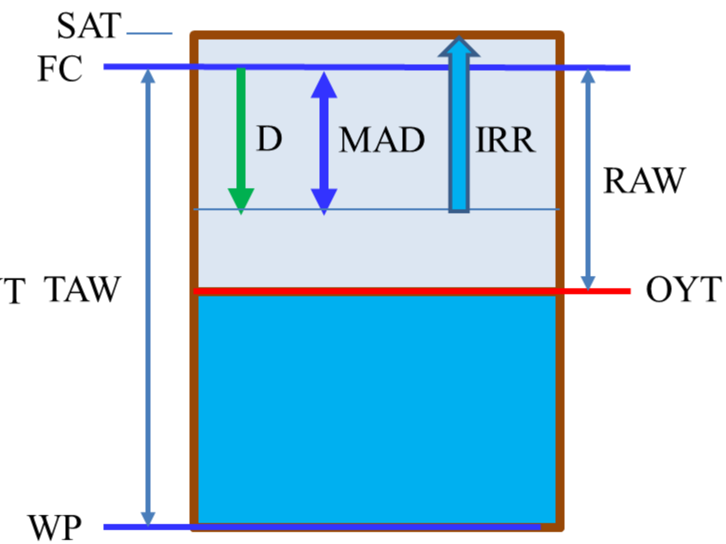
Irrigation starts when D < RAW, no water stress



Return back to FC



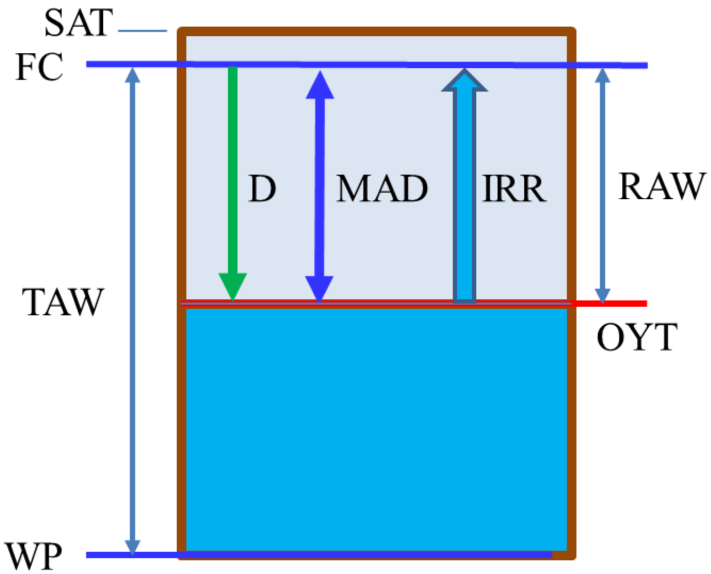
Refill to a level below FC



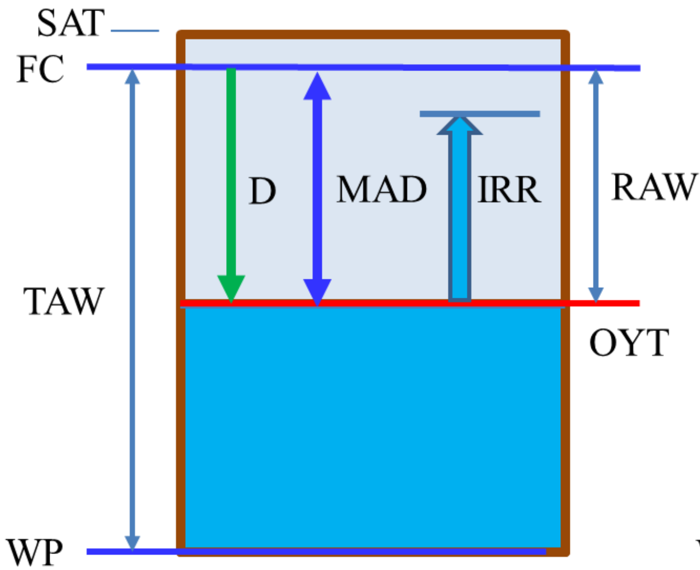
Refill to a level above FC

IRRIGATION : BASIC MANAGEMENT CONCEPTS

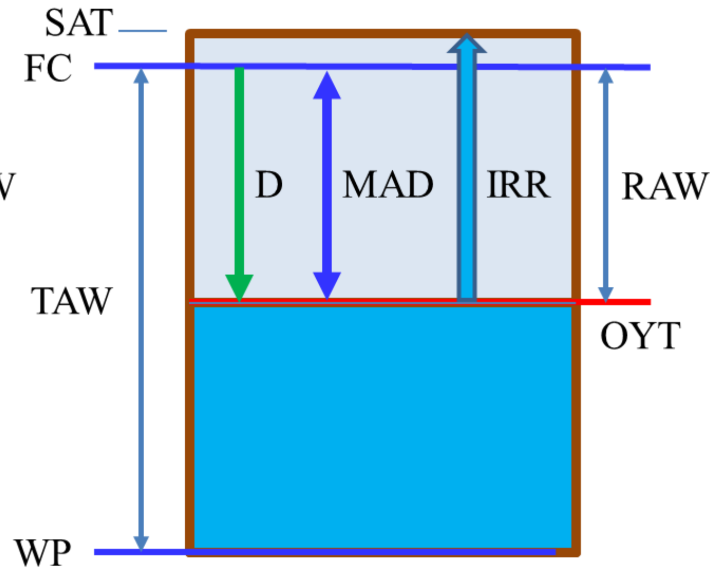
Irrigation starts when D = RAW, no water stress



Return back to FC



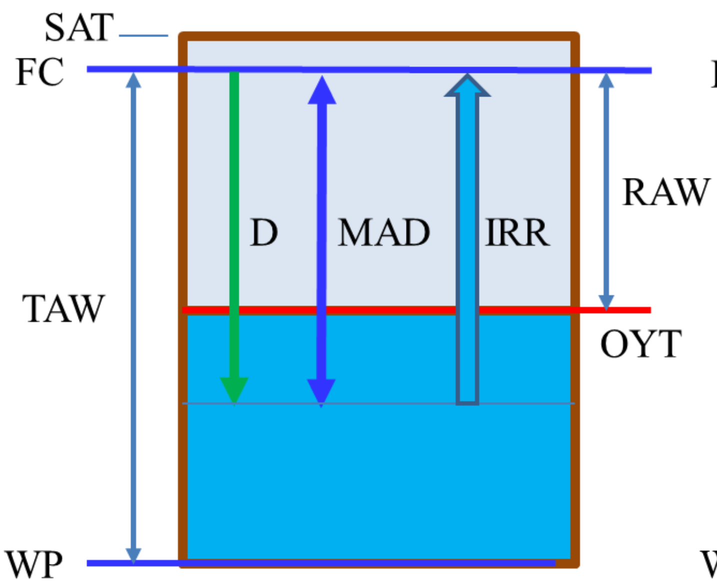
Refill to a level below FC



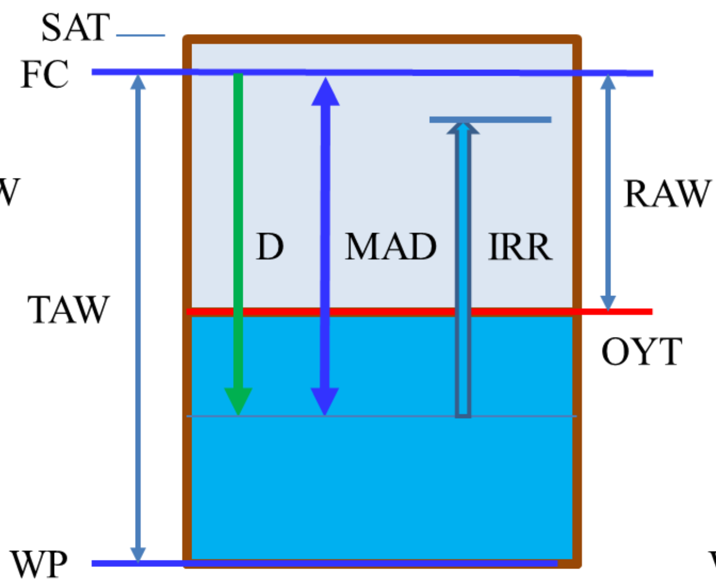
Refill to a level above FC

IRRIGATION : BASIC MANAGEMENT CONCEPTS

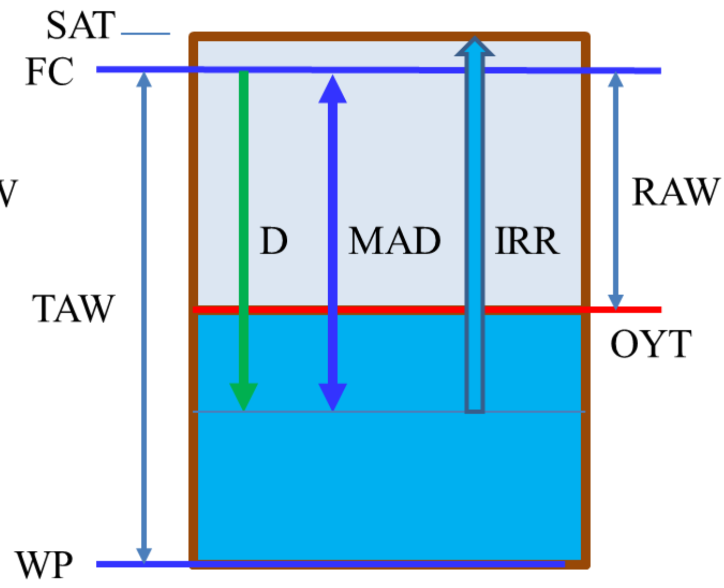
Irrigation starts when D > RAW, water stress → ETc reduction → biomass reduction



Return back to FC

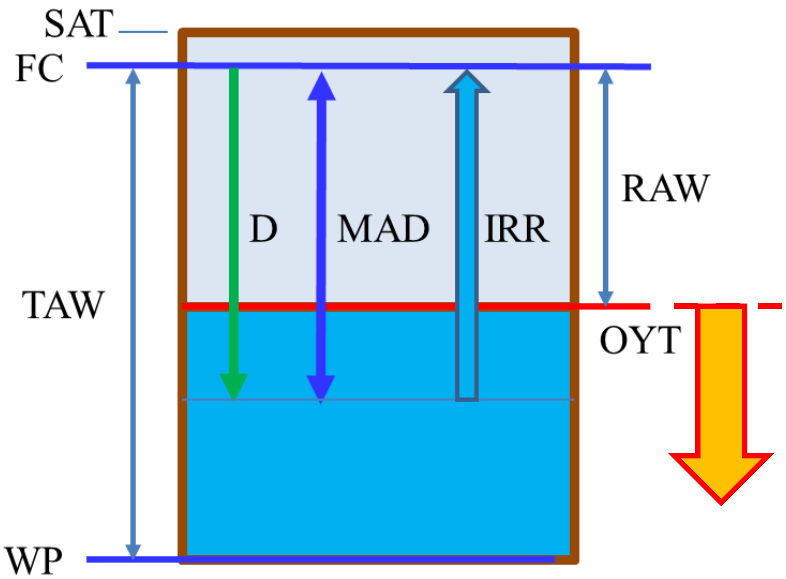


Refill to a level below FC

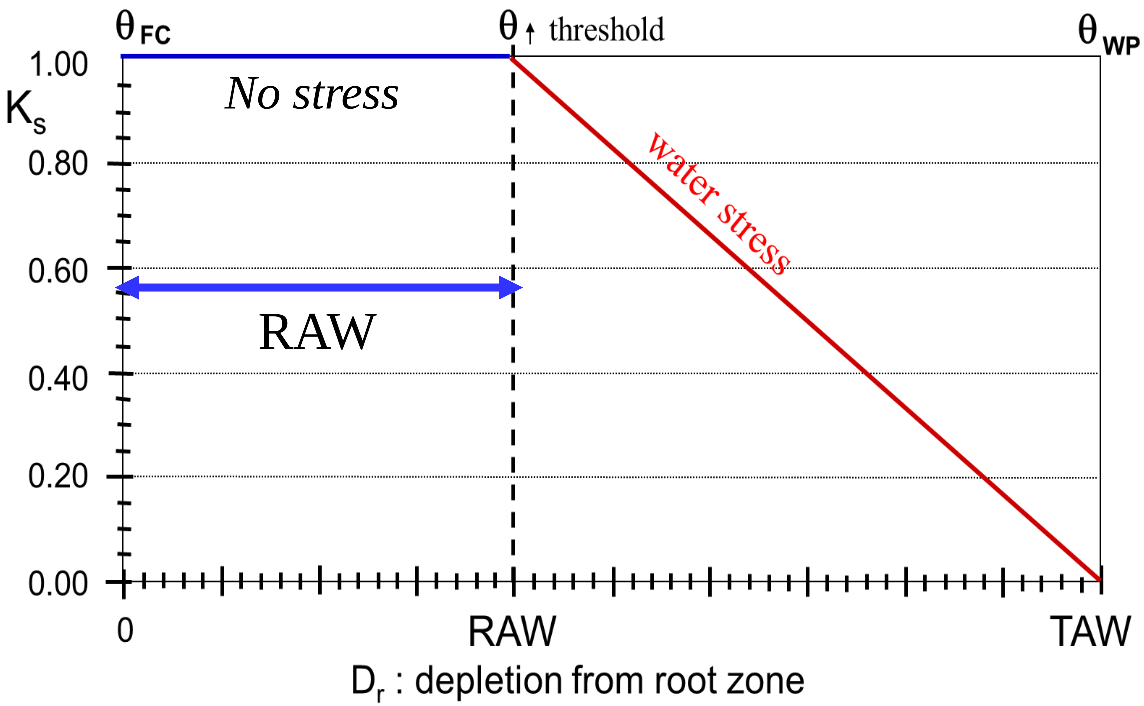


Refill to a level above FC

IRRIGATION : BASIC MANAGEMENT CONCEPTS



When depletion > RAW soil water in the root zone drops below OYT. Root's capacity to extract water from the soil is reduced and stomata are going to close, thus, ETc will be reduced.



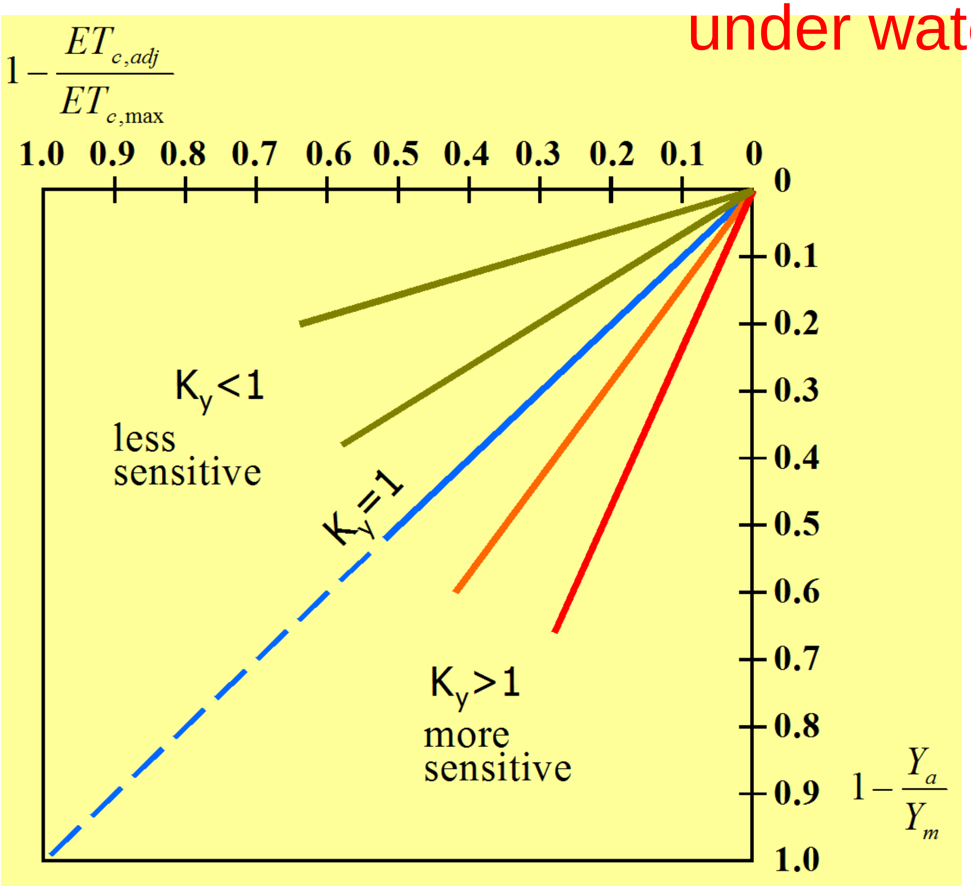
K_s - Water Stress Coefficient, $K_s<1$

Crop ET adjusted for water stress

$$ET_{c,adj}=K_s*K_c*ET_o$$

$$ET_{c,adj} < ET_c$$

Relative yield estimation for the whole growing season under water stress conditions



Ya : actual yield;

Ym : maximum expected yield;

Ky : yield response factor (crop specific and varies during the growing season);

ETc,max : ETc for optimal water supply

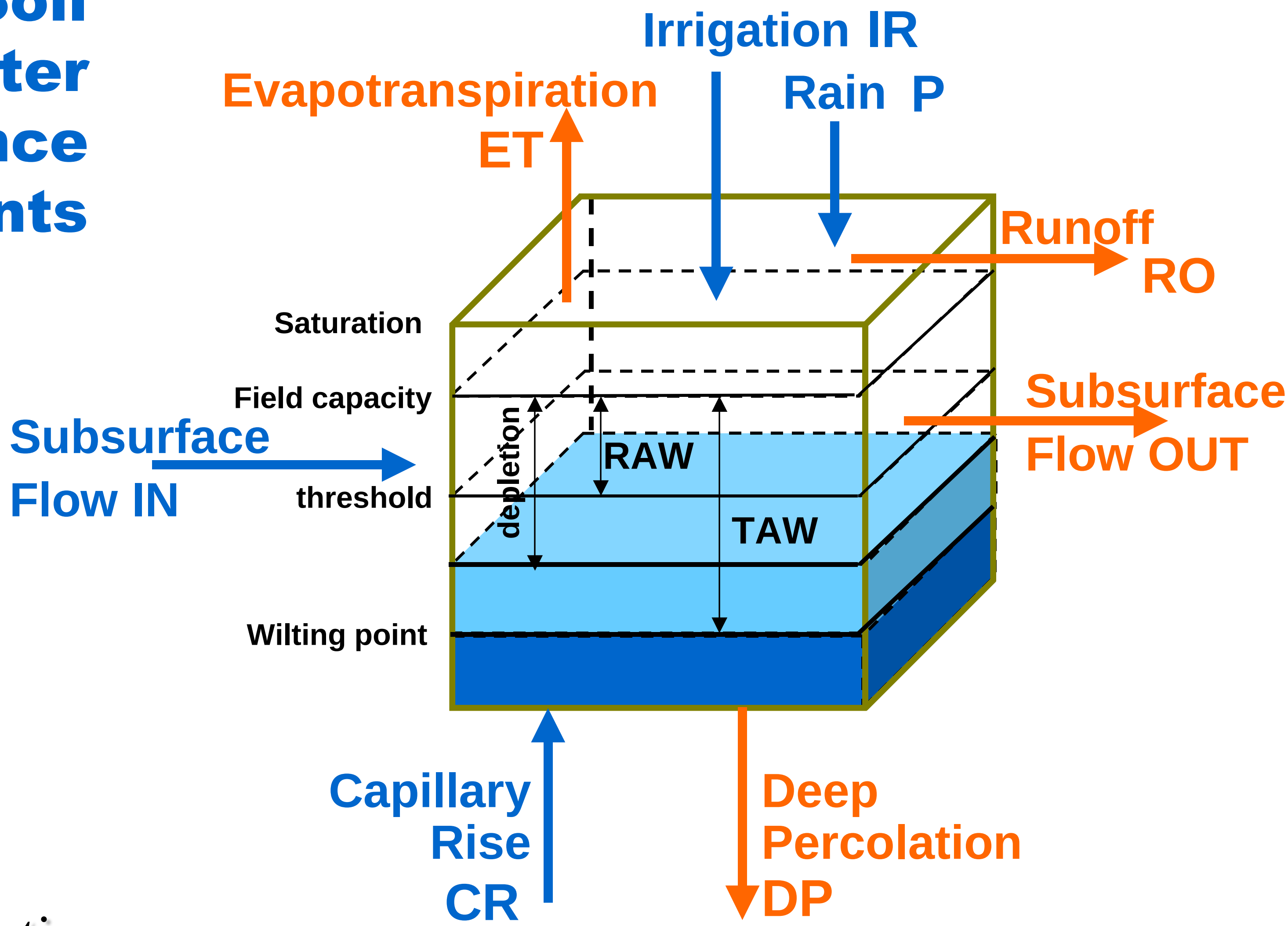
ETc,adj : actual crop ET adjusted for water stress

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_{c,adj}}{ET_{c,\max}}\right)$$

Crop	K_y
Alfalfa	1.1
Beans	1.2-1.35
Cabbage	0.95
Citrus	1.1-1.3
Cotton	0.85
Grape	0.85
Maize	1.25
Onion	1.1
Peas	1.15
Pepper	1.1
Potato	1.1
Sorghum	0.9
Soybean	0.85
Spring Wheat	1.15
Sugarbeet	1.0
Sugarcane	1.2
Sunflower	0.95
Tomato	1.05
Watermelon	1.1
Winter Wheat	1.05

SOIL WATER BALANCE

Soil Water Balance Components



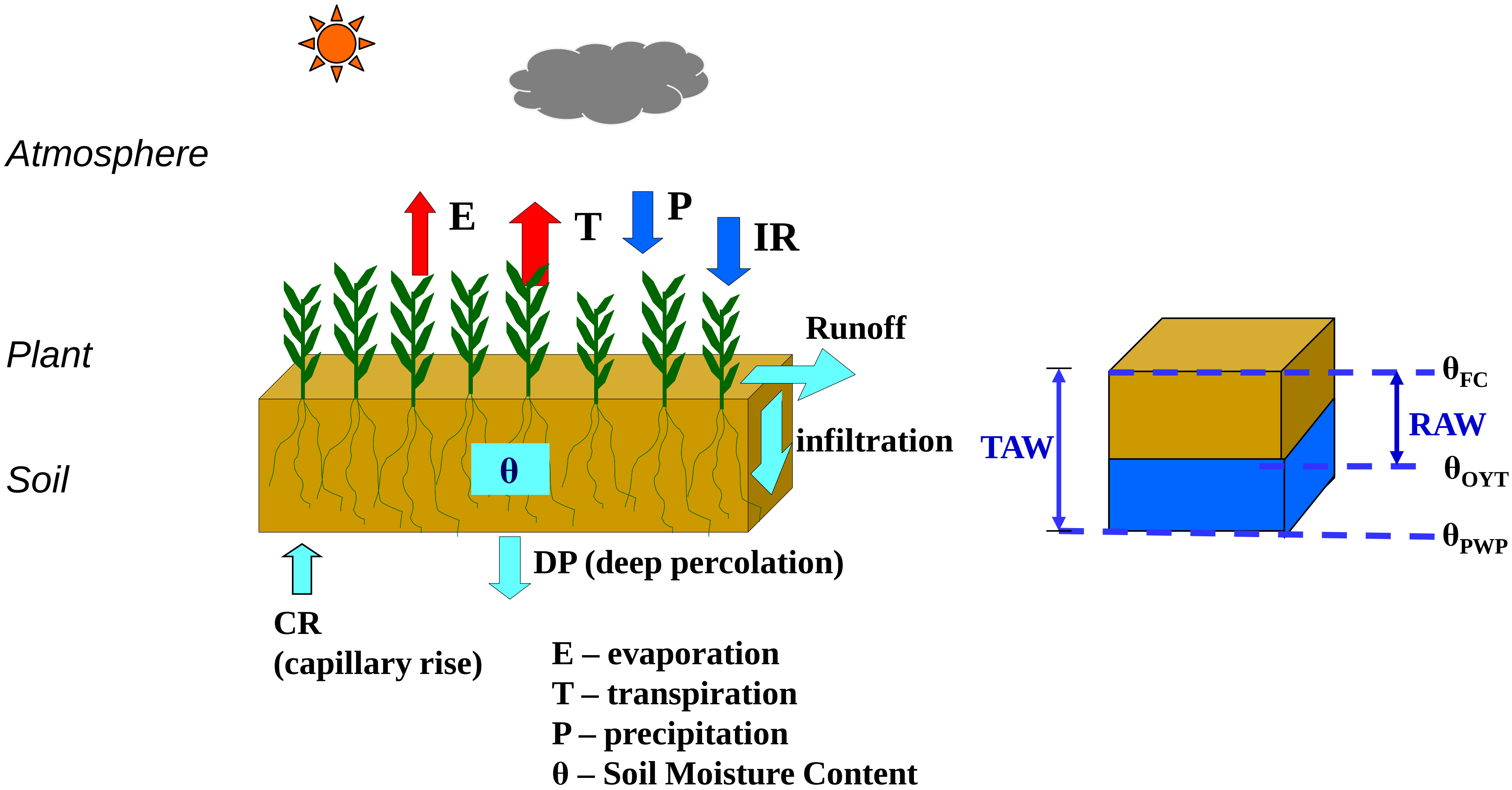
Root zone depletion:

$$D_{r,i} = D_{r,i-1} - P_i - IR_i - CR_i + ET_{c,i} + RO_i + DP_i$$

Soil moisture content:

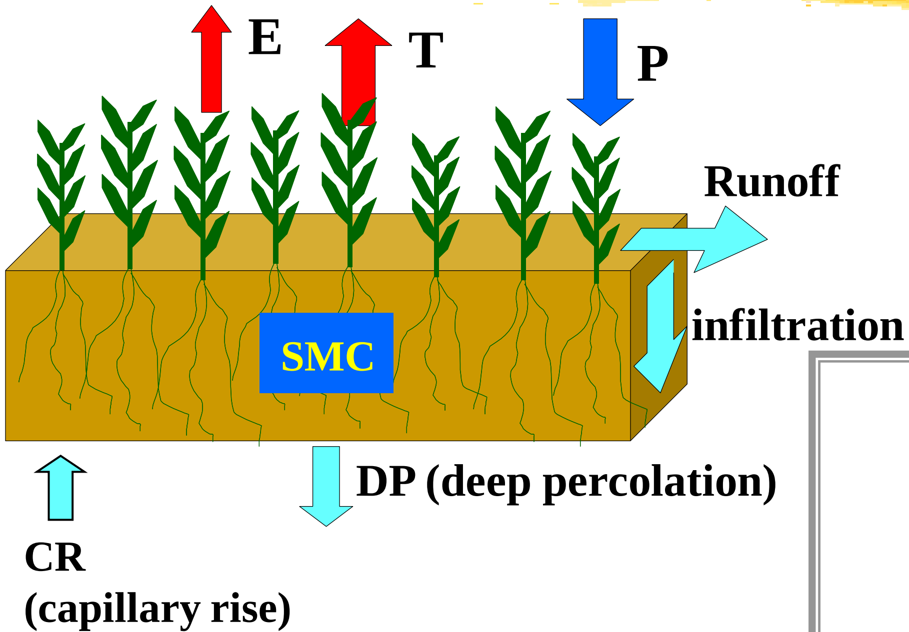
$$\Theta_{r,i} = \Theta_{r,i-1} + P_i + IR_i + CR_i - ET_{c,i} - RO_i - DP_i$$

Soil – Plant – Atmosphere Continuum

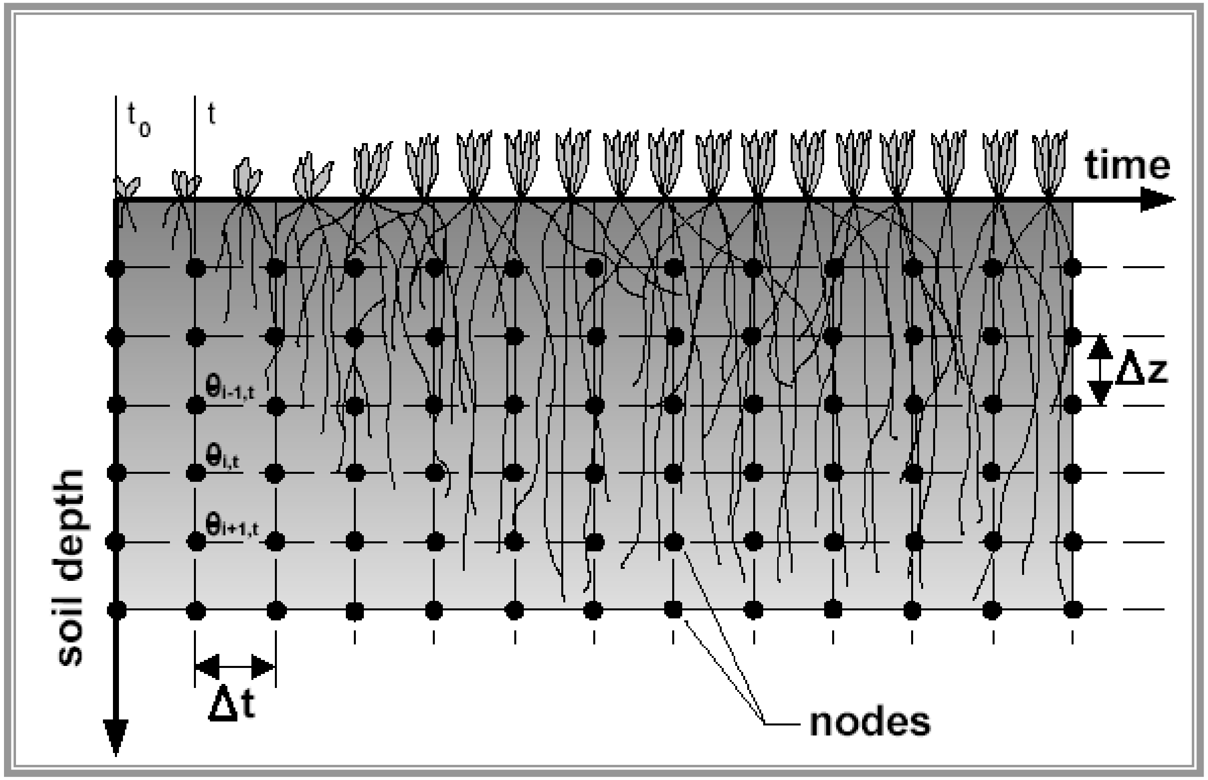


DYNAMIC SIMULATION MODEL

Time (t) – soil depth (z) – space grid

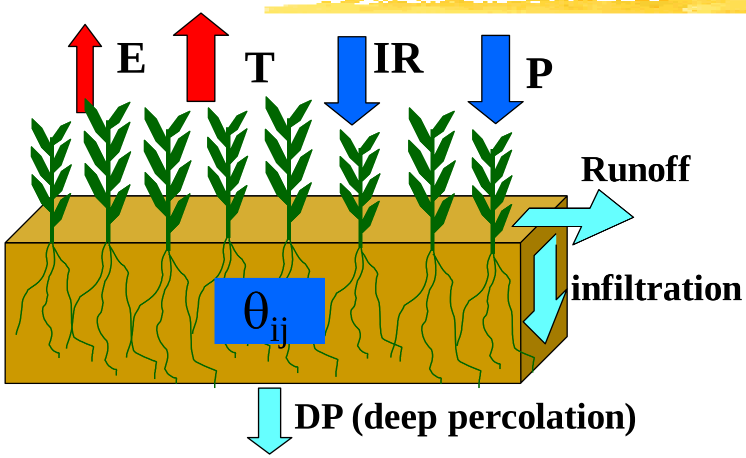


E – evaporation
T – transpiration
P – precipitation
SMC – Soil Moisture Content

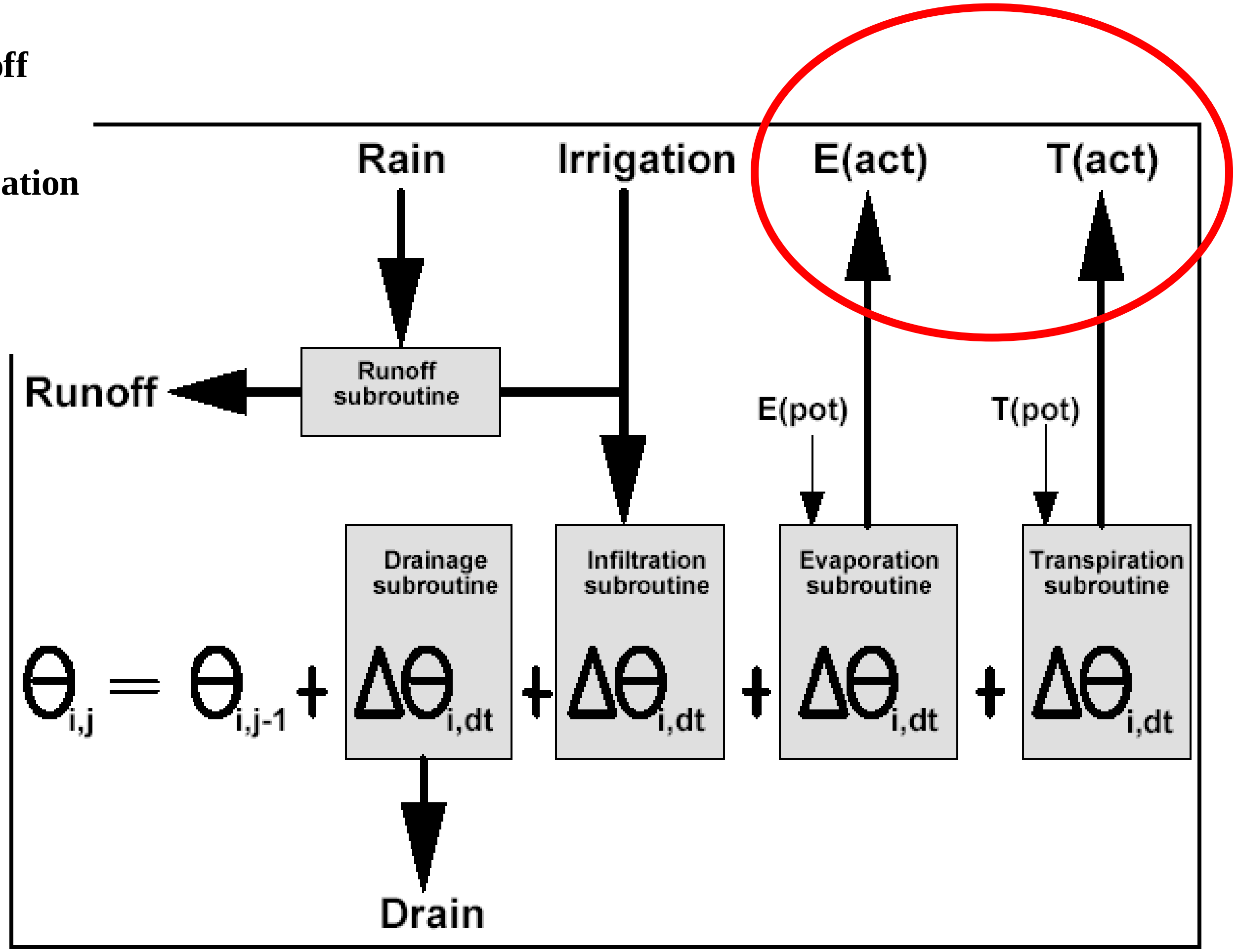


Soil Water Balance – common calculation scheme

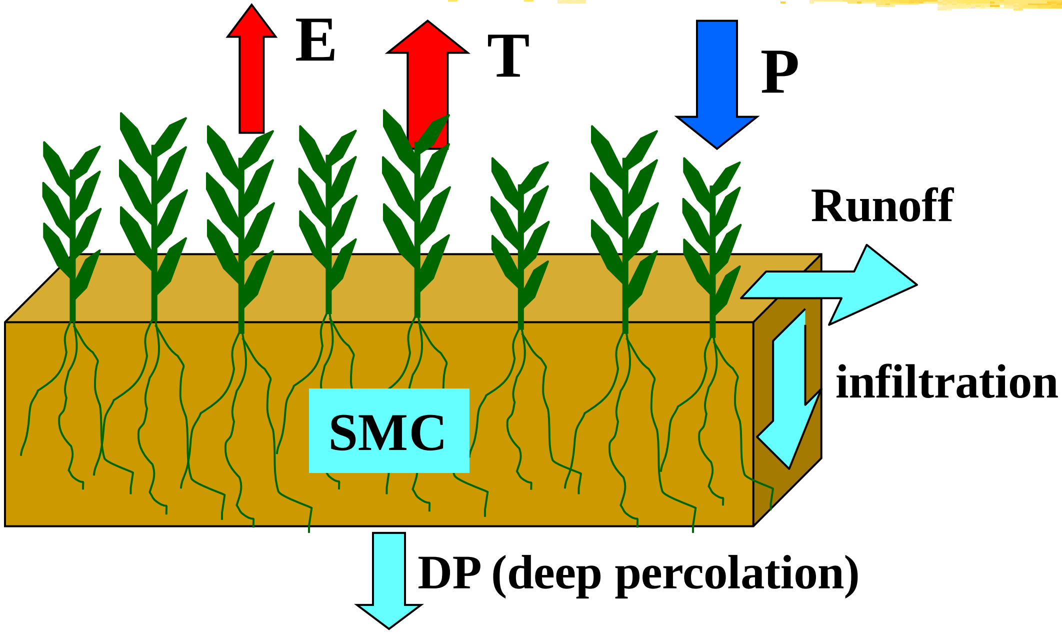
The greatest components of SWB in the Mediterranean

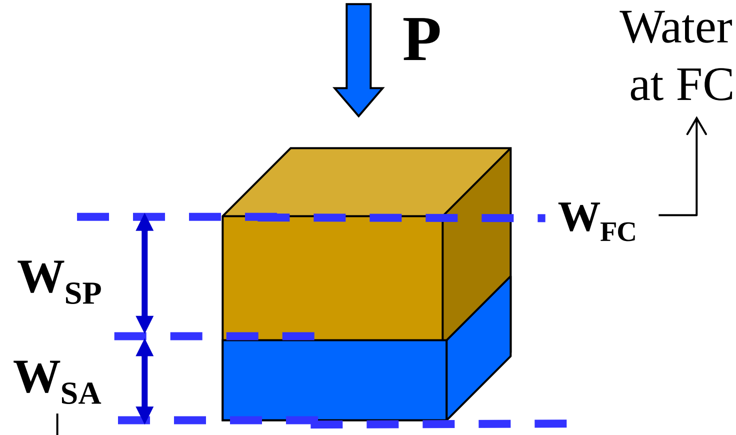


θ_{ij} - soil moisture content at depth z_i and at time level t_j



Simplified Soil Water Balance for a rainfall event



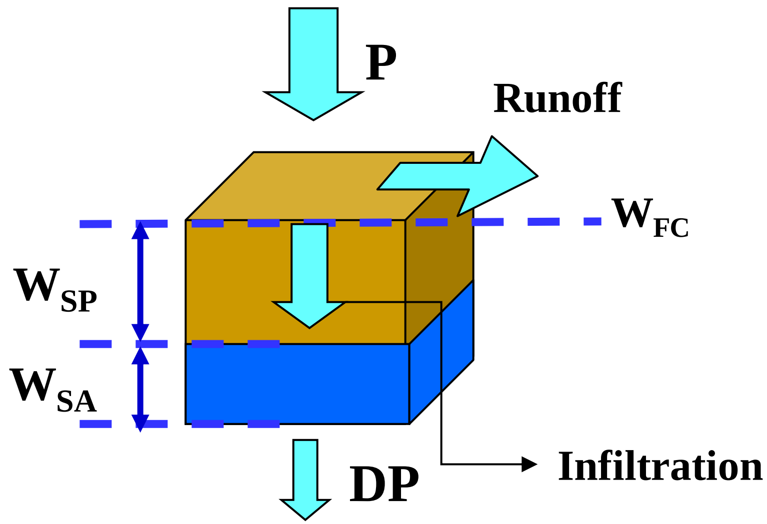


$$W_{SP} = W_{FC} - W_{SA}$$

- ❑ For a rainfall event, the water infiltrated into the soil (W_{inf}) is given by : $W_{inf} = P - Runoff$
- ❑ Thus, water stored in the soil (W_{ST}) is obtained in the following way:
  - if $W_{inf} \leq W_{SP}$ then $W_{ST} = W_{inf}$ and $DP = 0$
  - if $W_{inf} > W_{SP}$ then $W_{ST} = W_{SP}$ and $DP = W_{inf} - W_{SP}$

Simplified Soil Water Balance for a rainfall event – an example of calculation

- Assume:
  - $P = 50$ mm
  - $W_{SA} = 20$ mm
  - $W_{FC} = 40$ mm
  - Runoff = 15 mm
- Calculate water stored in the soil W_{ST} !



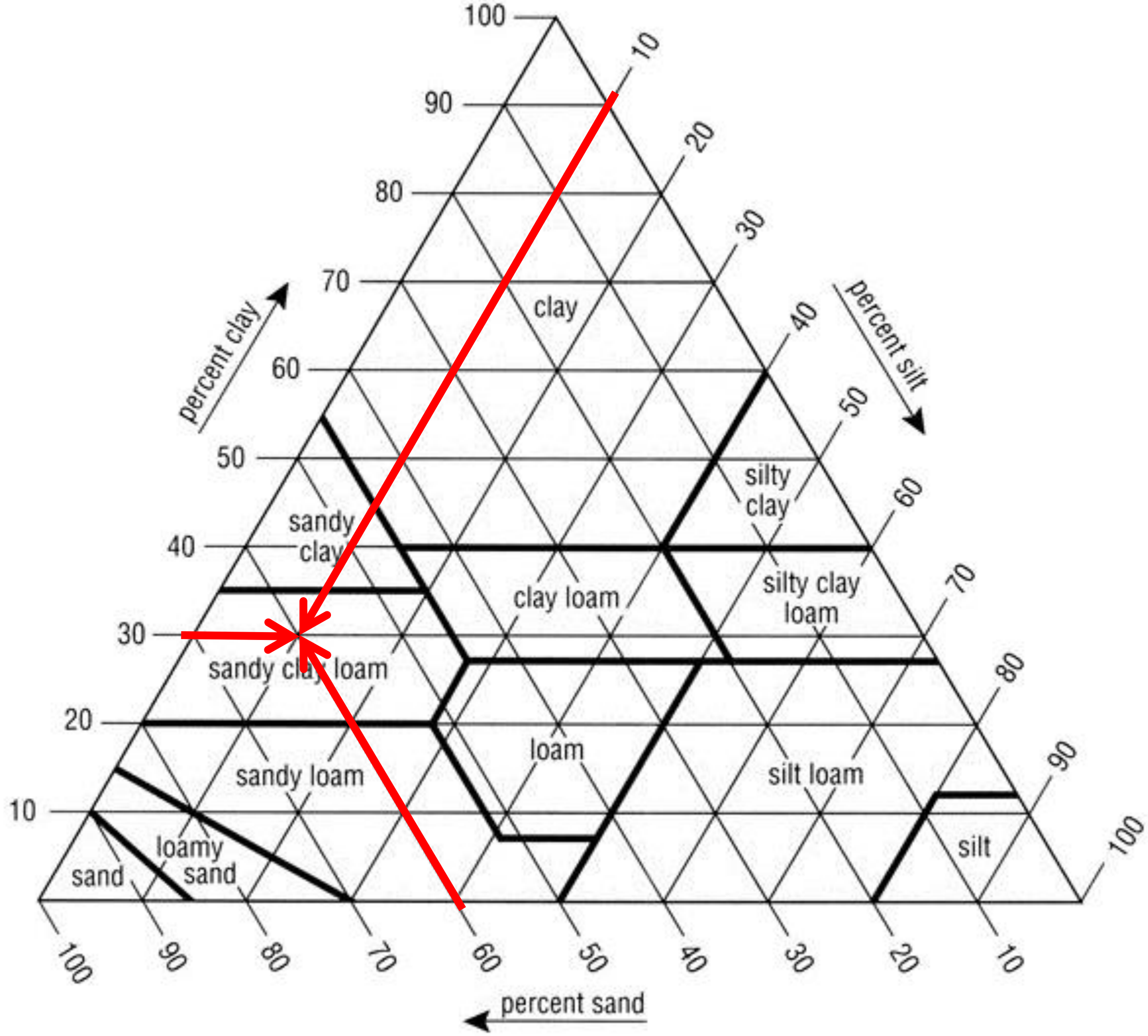
- Calculation:
  - Water infiltrated into the soil is W_{inf} = P - Runoff = 50 – 15 = 35 mm
  - Potential water storage is $W_{SP} = W_{FC} - W_{SA} = 40 - 20 = 20$ mm
  - Since $W_{inf} > W_{SP}$, then water stored in the soil is $W_{ST} = W_{SP} = 20$ mm
  - Deep percolation is $DP = W_{inf} - W_{ST} = 35 - 20 = 15$ mm

Soil classification – from granulometric soil characteristics & soil triangle

Example:
Sand 60%
Clay 30%
Silt 10%

From the soil triangle
this soil can be classified as
Sandy Clay Loam

Soil triangle



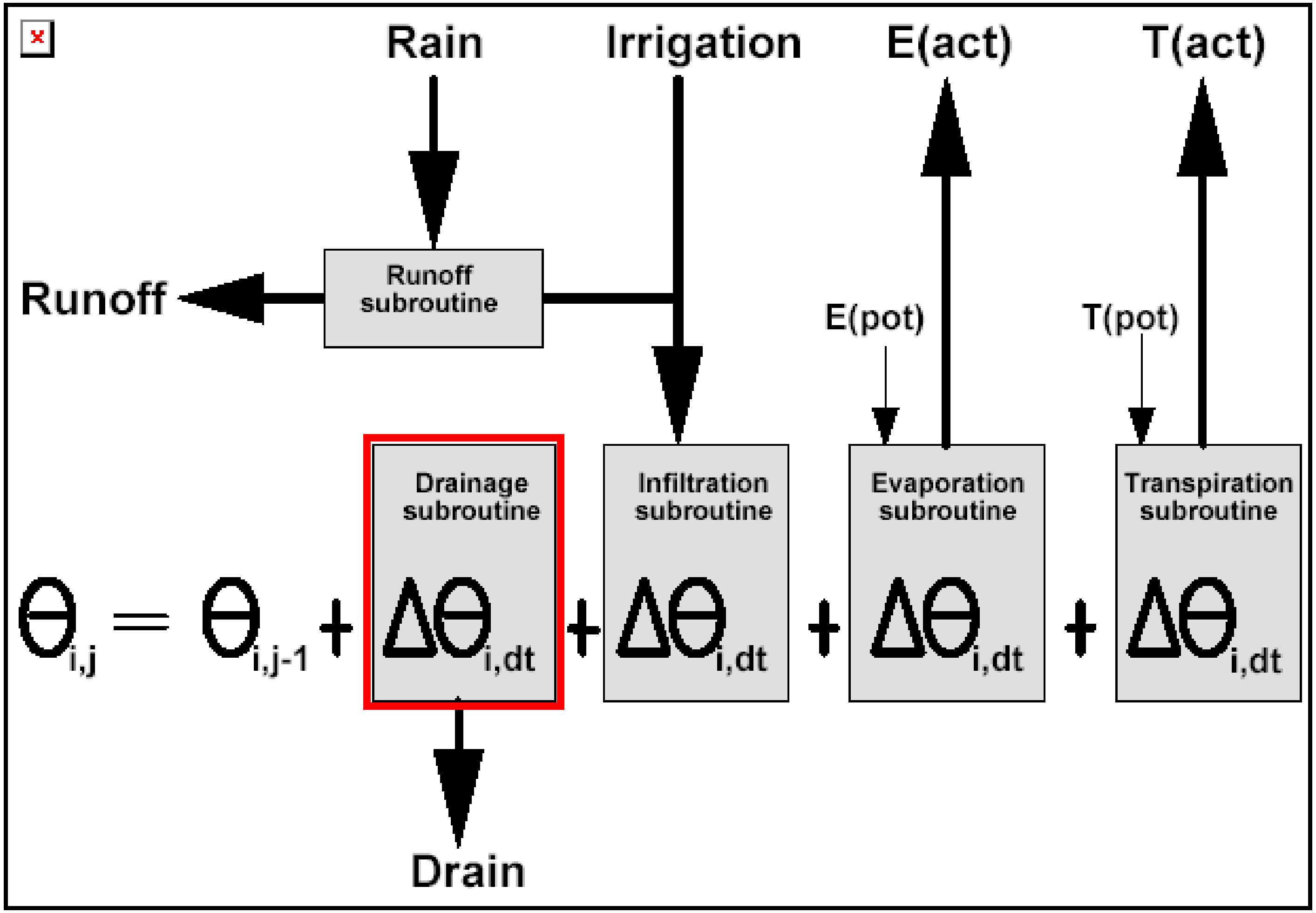
Soil hydraulic properties
- function of soil type

SAT	FC	WP	tau	Ksat	Soil type
vol%	vol%	vol%	-	mm/day	-
36	13	6	1.00	1500	Sand
38	16	8	0.95	800	Loamy sand
41	22	10	0.75	500	Sandy loam
46	31	15	0.60	250	Loam
46	33	13	0.50	150	Silt loam
43	33	9	0.35	50	Silt
47	32	20	0.45	125	Sandy clay loam
50	39	23	0.40	70	Clay loam
52	44	23	0.30	20	Silty clay loam
50	39	27	0.42	75	Sandy clay
54	50	32	0.20	15	Silty clay
55	54	39	0.10	2	Clay

The *characteristics* of the soil layer are the following hydraulic properties:

SAT : soil water content [vol%] at saturation;
FC : soil water content [vol%] at field capacity;
WP : soil water content [vol%] at wilting point;
tau : drainage characteristic (value between 1 and 0);
Ksat : infiltration rate [mm/day] at saturation.

Soil Water Balance –
common calculation scheme in crop growth models



θ_{ij} - soil moisture content at depth z_i and at time level t_j

Drainage – amount of water lost by free drainage as a function of time for any SWC between saturation and FC

$$\frac{\Delta\theta_i}{\Delta t} = \tau(\theta_{sat} - \theta_{FC})\frac{e^{\theta_i - \theta_{FC}} - 1}{e^{\theta_{sat} - \theta_{FC}} - 1}$$

$\Delta\theta_i/\Delta t$: decrease in soil water content at depth i, during time step Δt [$m^3m^{-3}day^{-1}$]

τ : drainage characteristics, from 0 to 1, non-dimensional

θ_i : actual soil water content at depth *i* [m^3m^{-3}]

θ_{SAT} : soil water content at saturation [m^3m^{-3}]

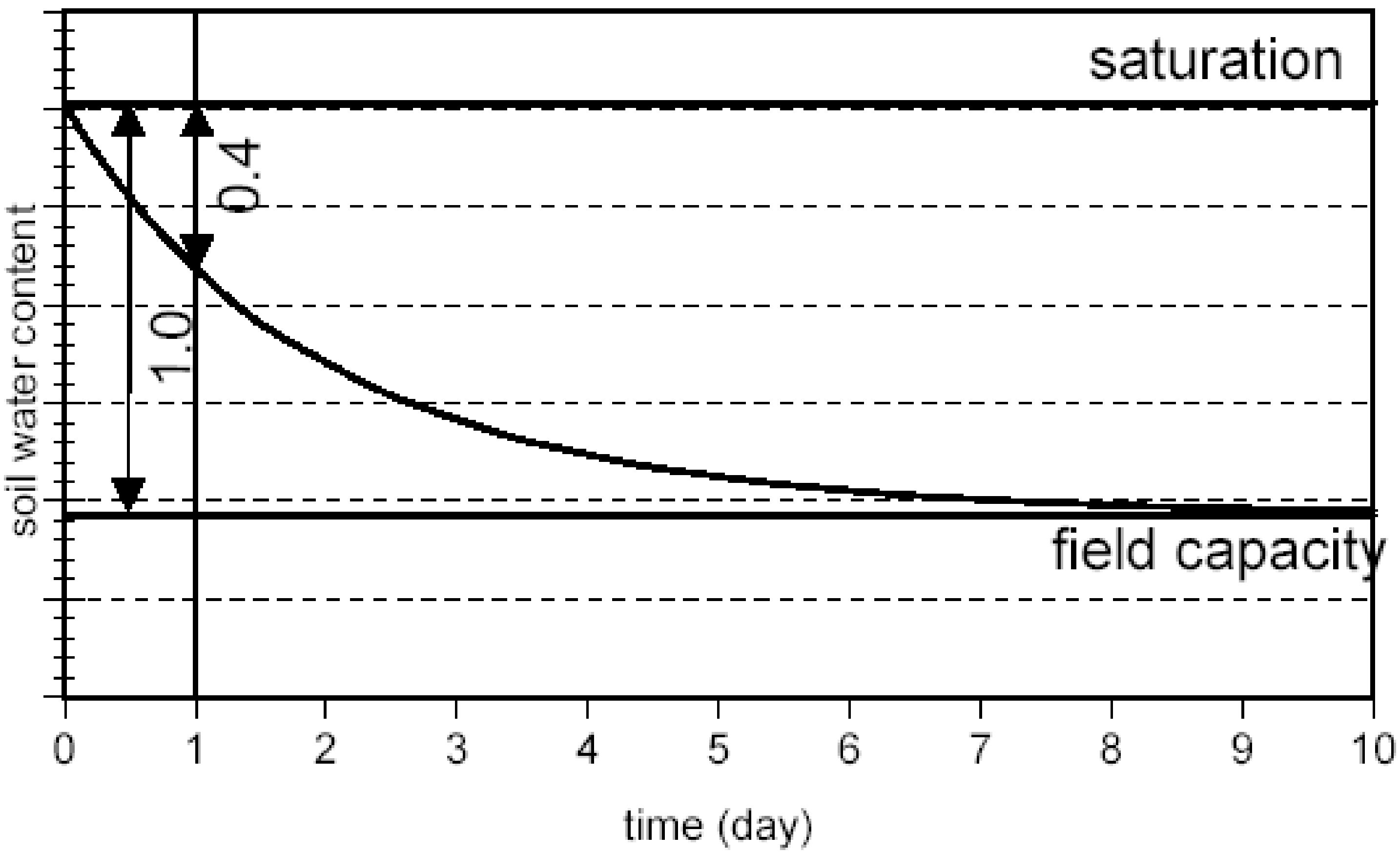
θ_{FC} : soil water content at field capacity [m^3m^{-3}]

Δt : time step

If $\theta_I \leq \theta_{FC}$ than $\Delta\theta_i/\Delta t = 0$

If $\theta_I = \theta_{SAT}$ than $\Delta\theta_i/\Delta t = \tau(\theta_{SAT} - \theta_{FC})$

Variation of soil water content in function of time in a free draining soil layer with a drainage characteristics of τ = 0.4

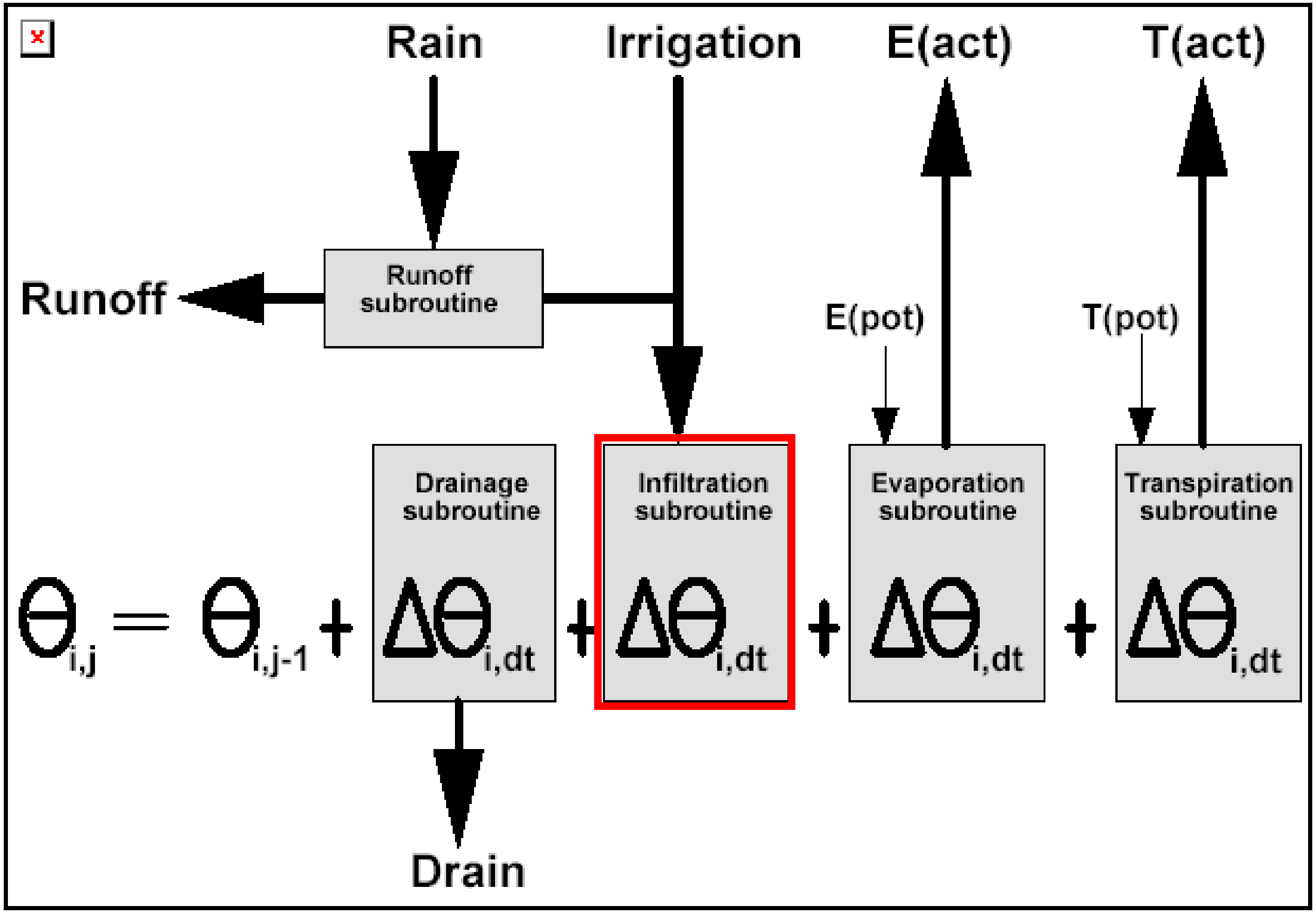


τ : drainage characteristics – expresses the decrease in soil water content of a soil layer, originally at saturation, at the end of the first day of free drainage.

τ = 0 : when soil layer is impermeable

τ = 1 : when complete drainage happens after one day

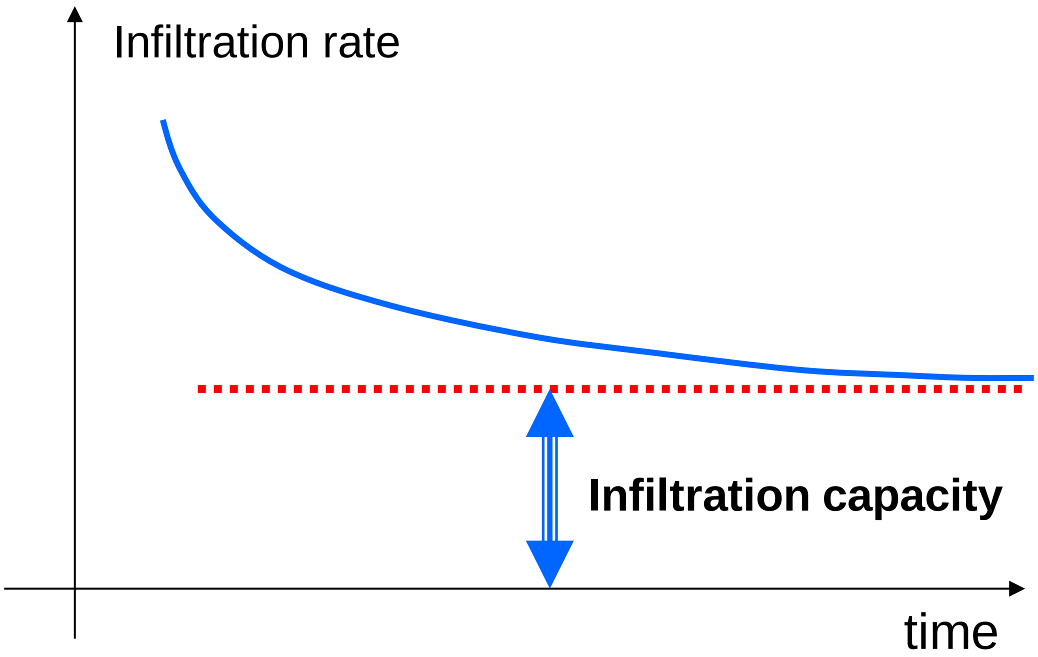
Soil Water Balance –
common calculation scheme in crop growth models



θ_{ij} - soil moisture content at depth z_i and at time level t_j

Infiltration

- **Infiltration** refers to the downward flow of water from surface into the soil.
- **Percolation** refers to the movement of water through the soil profile



Indicative values of infiltration capacity [mm/hr] as a function of soil texture and vegetation cover

Texture	Vegetative soil	Bare soil
Loamy sand	50	25
Loam	25	13
Silt loam	15	8
Clay loam	5	3

Source: Khonkeo, 1968

Runoff – basic considerations

- From the hydrological (engineering) point of view, the runoff from a drainage basin can be considered as a product (gain) in a hydrological cycle.
- Main climatic factors affecting runoff:
  - precipitation: form, duration, intensity, time and areal distribution, frequency of occurrence, antecedent precipitation, antecedent soil moisture, interception (vegetation species, composition, age, density of canopy, season of the year) …
- Main physiographic factors affecting runoff:
  - basin characteristics: size, shape, slope, orientation, elevation, stream density
  - physical factors: land use and cover, soil type, infiltration conditions, permeability conditions, capacity of groundwater formations …
- From the agronomic point of view, the runoff can be considered as precipitation losses in a rainfall-runoff analysis.

Runoff – SCS-USDA Curve Number (CN) method

- A Curve Number is an empirical value assigned to each watershed or portion of watershed based on:
  - Soil type;
  - Land use and treatment;
  - Antecedent moisture conditions (AMC).
- Antecedent moisture conditions are divided into:
  - AMC-I – soils are dry close to the wilting point, and satisfactory plowing or cultivation takes place;
  - AMC-II – average soil moisture conditions and management practices
  - AMC-III – the soil is nearly saturated – heavy rainfall or light rainfall and low temperatures occurred during the five days previous to the given storm

SCS-USDA method – CN values

Description	Average % Impervious	Curve Number by Hydrologic Soil Group				Typical Land Uses
		A	B	C	D	
Residential (High Density)	65	77	85	90	92	Multi-family, Apartments, Condos, Trailer Parks
Residential (Med. Density)	30	57	72	81	86	Single-Family, Lot Size ¼ to 1 acre
Residential (Low Density)	15	48	66	78	83	Single-Family, Lot Size 1 acre and Greater
Commercial	85	89	92	94	95	Strip Commercial, Shopping Ctrs, Convenience Stores
Industrial	72	81	88	91	93	Light Industrial, Schools, Prisons, Treatment Plants
Disturbed/Transitional	5	76	85	89	91	Gravel Parking, Quarries, Land Under Development
Agricultural	5	67	77	83	87	Cultivated Land, Row crops, Broadcast Legumes
Open Land – Good	5	39	61	74	80	Parks, Golf Courses, Greenways, Grazed Pasture
Meadow	5	30	58	71	78	Hay Fields, Tall Grass, Ungrazed Pasture
Woods (Thick Cover)	5	30	55	70	77	Forest Litter and Brush adequately cover soil
Woods (Thin Cover)	5	43	65	76	82	Light Woods, Woods-Grass combination, Tree Farms
Impervious	95	98	98	98	98	Paved Parking, Shopping Malls, Major Roadways
Water	100	100	100	100	100	Water Bodies, Lakes, Ponds, Wetlands

SCS-USDA Curve Number (CN) method

Soil hydrological groups by means of infiltration rate

- ***A*** Soils having **high infiltration rates**, even when thoroughly wetted and consisting chiefly of deep, well to excessively-drained sands or gravels. These soils have a high rate of water transmission.
- ***B*** Soils having **moderate infiltration rates** when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
- ***C*** Soils having **slow infiltration rates** when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
- ***D*** Soils having **very slow infiltration rates** when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay-pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

SCS-USDA Curve Number (CN) method

Soil hydrological groups by means of potential runoff

- ***A*** **Lower Runoff Potential –** Includes deep sands with very little silt and clay, also deep, rapidly permeable loess.
- ***B*** **Moderately Low Runoff Potential –** Mostly sandy soils less deep than A, and less deep or less aggregated than A, but the group as a whole has above-average infiltration after thorough wetting.
- ***C*** **Moderately High Runoff Potential –** Comprises shallow soils and soils containing considerable clay and colloids, though less than that of group D. The group has below-average infiltration after thorough wetting.
- ***D*** **Highest Runoff Potential –** Includes mostly clays of high swelling percentage, but the group also includes some shallow soils with nearly impermeable sub-horizons near the surface.

Runoff – SCS-USDA Curve Number (CN) method

Range of variation (possible error?!)

CN values for Antecedent Moisture Classes (AMC) II and their corresponding values for AMC I (dry) and III (wet).

AMC	Soil water content	CN value			
I	Wilting point	45	56	63	70
II	**Default value**	**65**	**75**	**80**	**85**
III	Field capacity	84	88	91	93

$$S = 254\left(\frac{100}{CN} - 1\right)$$

$$RO = \frac{(P - 0.2S)^2}{P + S - 0.2S}$$

S : potential maximum storage (soil retention)

(0.2)*S : initial abstraction [mm] – the amount of water that can infiltrate before runoff occurs

CN : curve number

RO : amount of water lost by surface runoff [mm]

P : precipitation [mm]

Initial abstraction 0.2S

CN45 → 62 mm — **Initially dry soil**

CN65 → 27 mm — **Initially moderately wet soil**

CN85 → 9 mm — **Soil is nearly saturated**

Runoff starts when P>0.2S

Runoff – SCS-USDA Curve Number (CN) method

Example of calculation

- **Assume:**
  - **P = 50 mm**
  - **CN = 75 (agricultural land, moderate infiltration rate)**

- **Calculate runoff and initial water abstraction in the soil !**

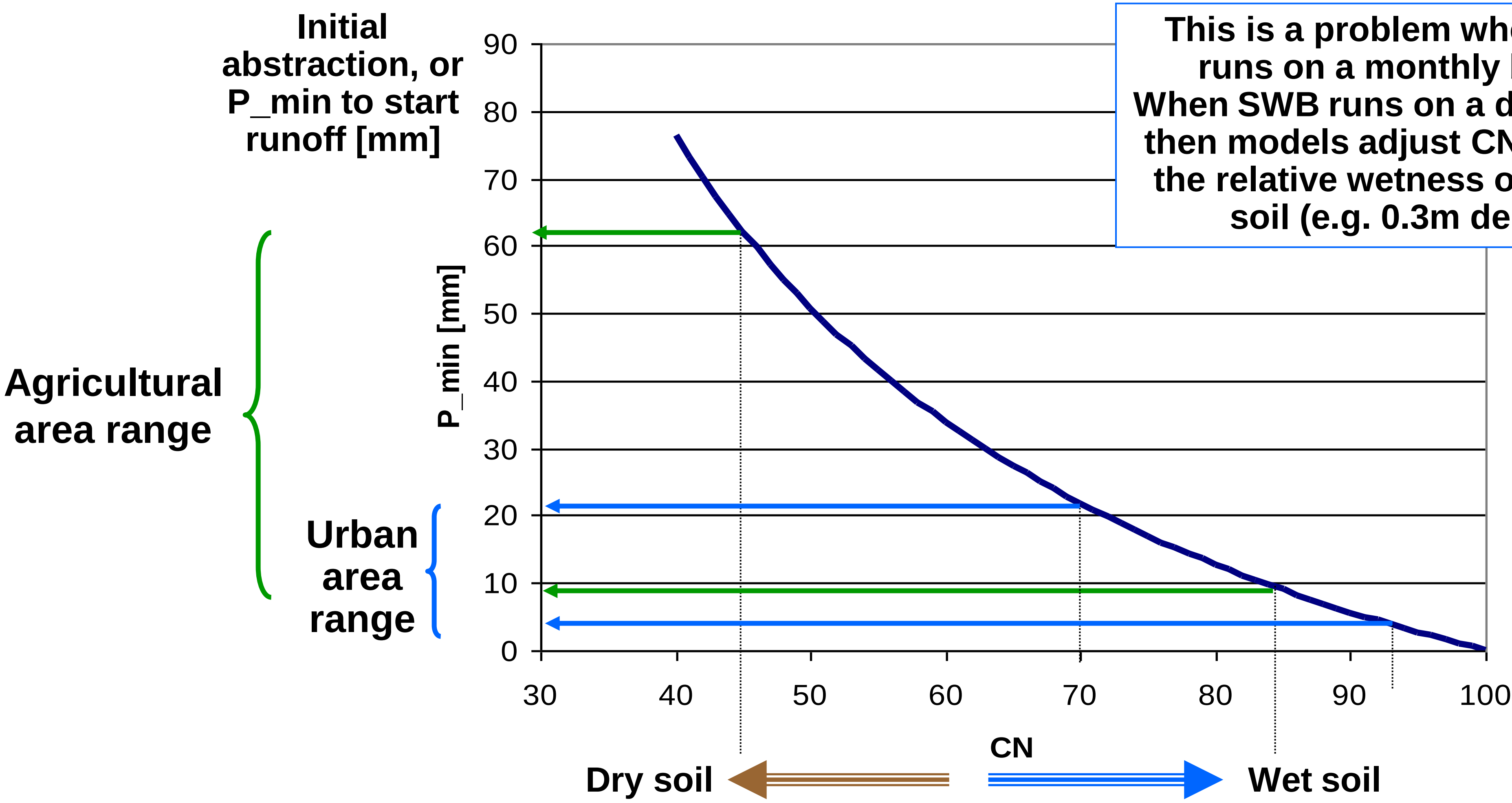
$$S = 254\left(\frac{100}{CN} - 1\right) = 84.7 \text{ mm – potential maximum storage}$$

*Initial abstraction 0.2*S = 16.9 mm*

$$RO = \frac{(P - 0.2S)^2}{P + S - 0.2S} = 9.2 \text{ mm – runoff}$$

Runoff – SCS-USDA Curve Number (CN) method

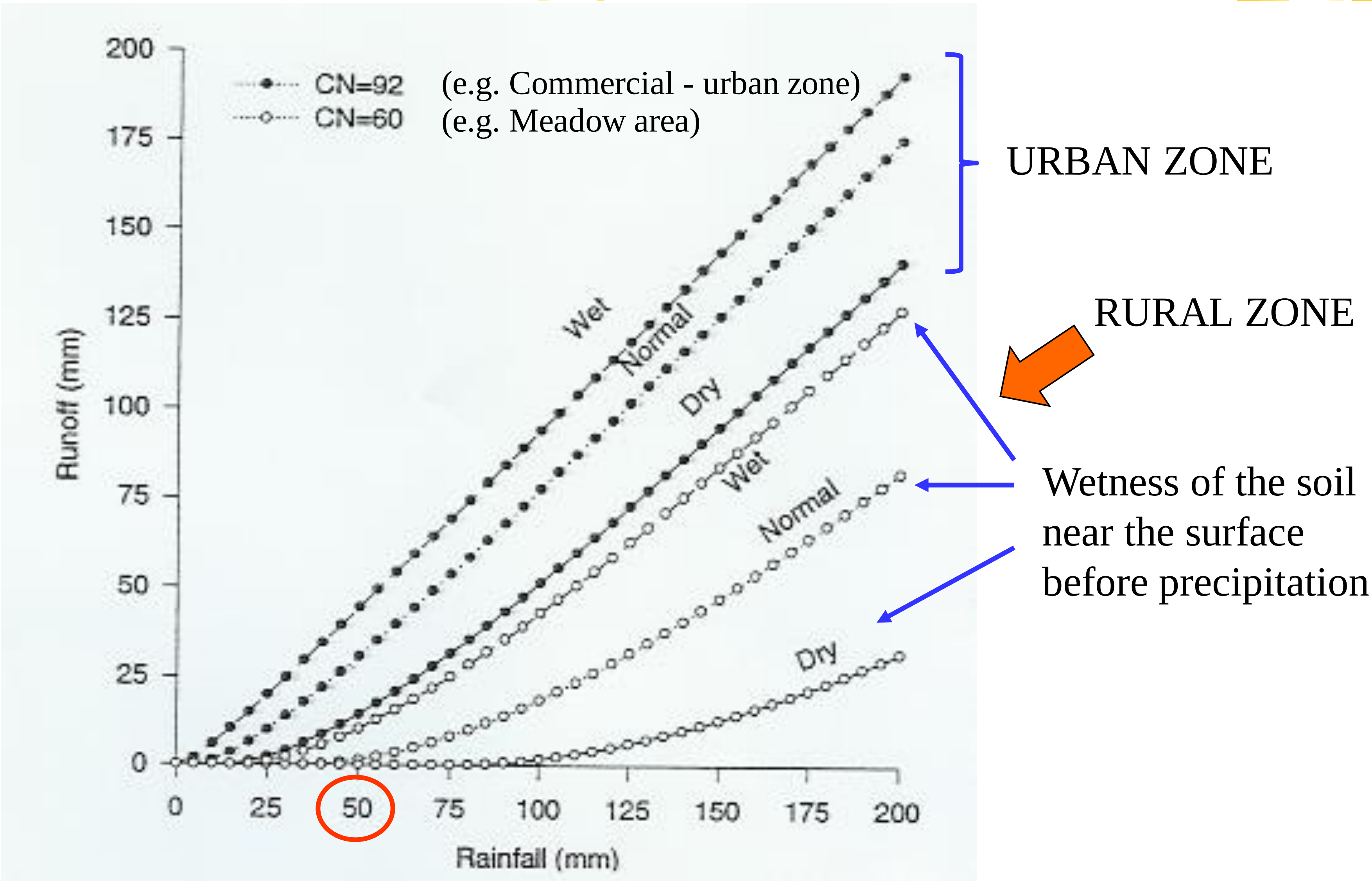
Range of variation as a function of AMC (possible error?!)



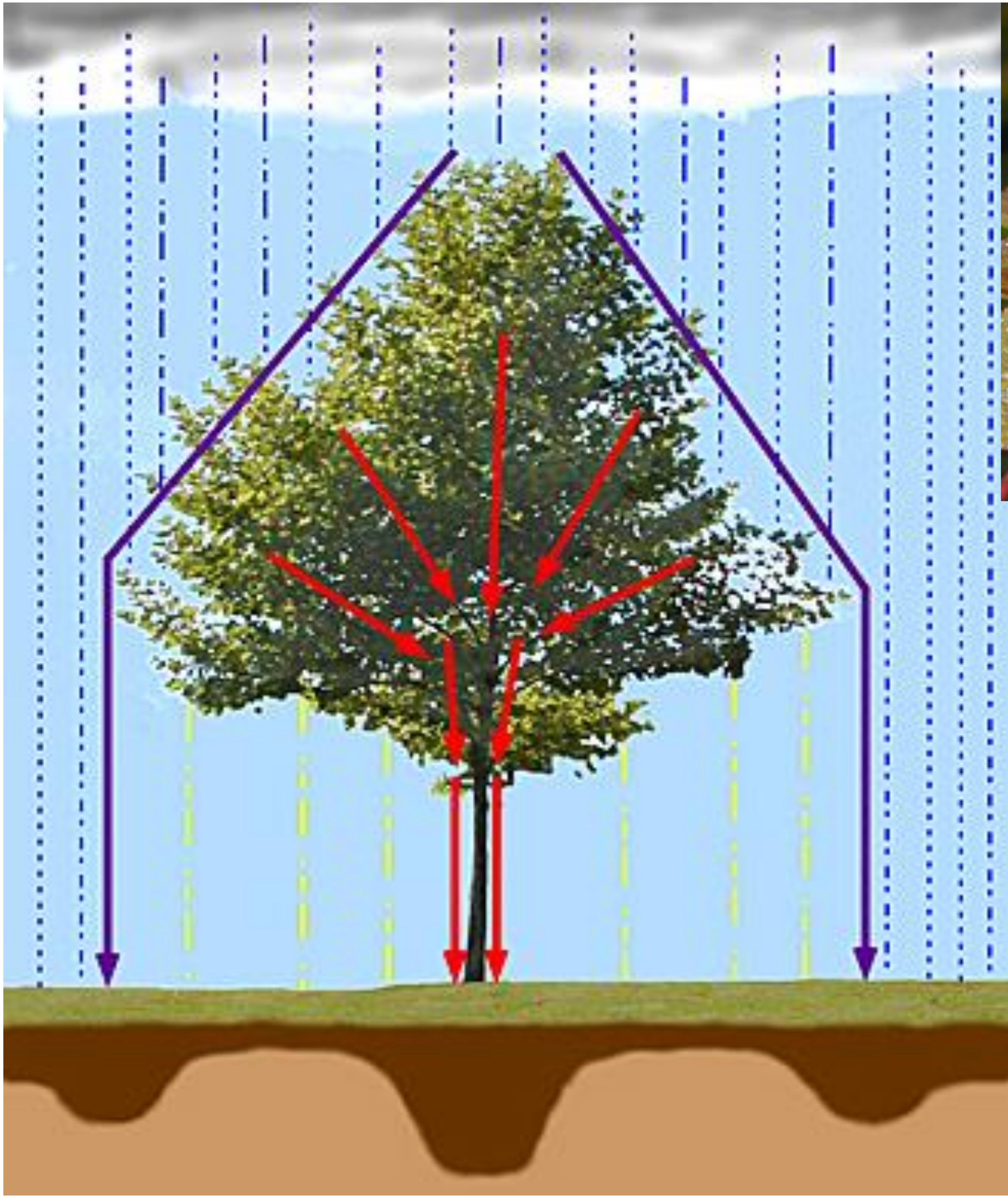
This is a problem when SWB runs on a monthly basis. When SWB runs on a daily basis then models adjust CN value to the relative wetness of the top soil (e.g. 0.3m depth)

Higher CN → smaller S → greater runoff (smaller infiltration)

SCS USDA Curve number method – discussion



However, sometimes runoff can represent almost 100% of P even from agricultural fields

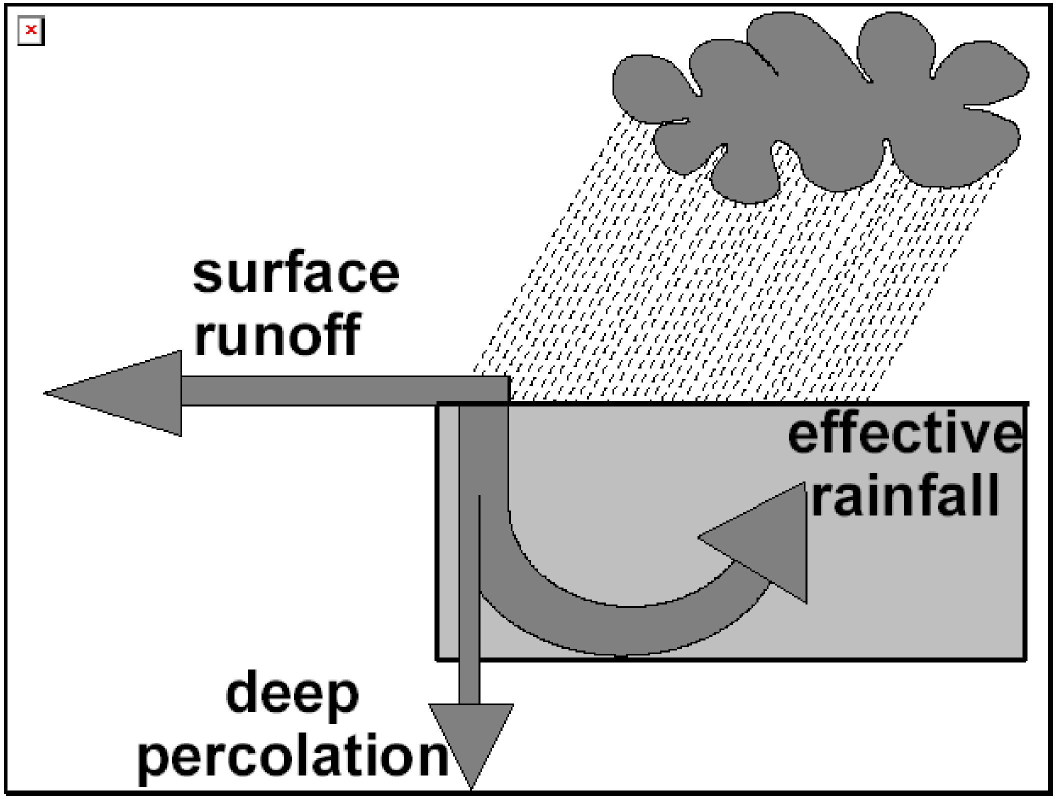


Interception and Effective Rainfall Concept

Effective Rainfall (P_{eff})

a part of P stored in the root zone and not lost by surface runoff or deep percolation

(to be used over the total growing season, or on a monthly basis)



Total rainfall is used (and not P_{eff}) in the water balance calculations for irrigation scheduling on a daily basis - the intake of rain into soil is determined and rainfall losses due to deep percolation and surface runoff are estimated according to actual soil moisture content in the root zone.

- Fixed % of P

$$P_{eff} = P_{coeff} * P$$

- FAO/AGL Empirical Equation for design purposes where 80% probability of exceedance is required

$$P_{eff}=0.6*P_{tot}-10 \quad \text{for } P_{tot}<70mm$$

$$P_{eff}=0.8*P_{tot}-24 \quad \text{for } P_{tot}>70mm$$

- USDA Soil Conservation Method

$$P_{eff}=P_{tot}(125-0.2P_{tot})/125 \quad \text{for } P_{tot}<250mm$$

$$P_{eff}=125+0.1P_{tot} \quad \text{for } P_{tot}>250mm$$

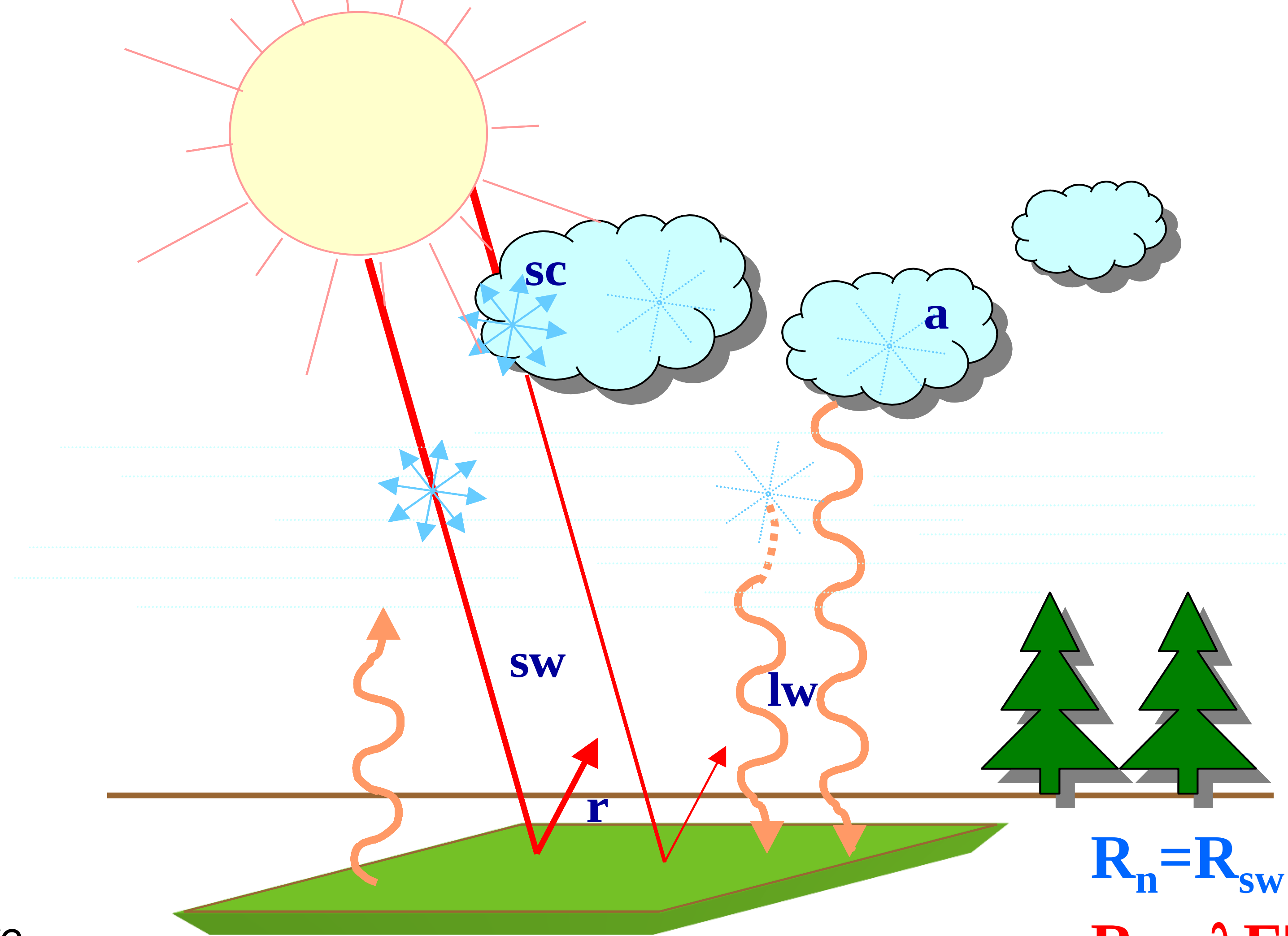
Interception, Effective Rainfall and percentage of ground cover by vegetation

27 January

2 March

17 March

Surface radiation (and energy) balance

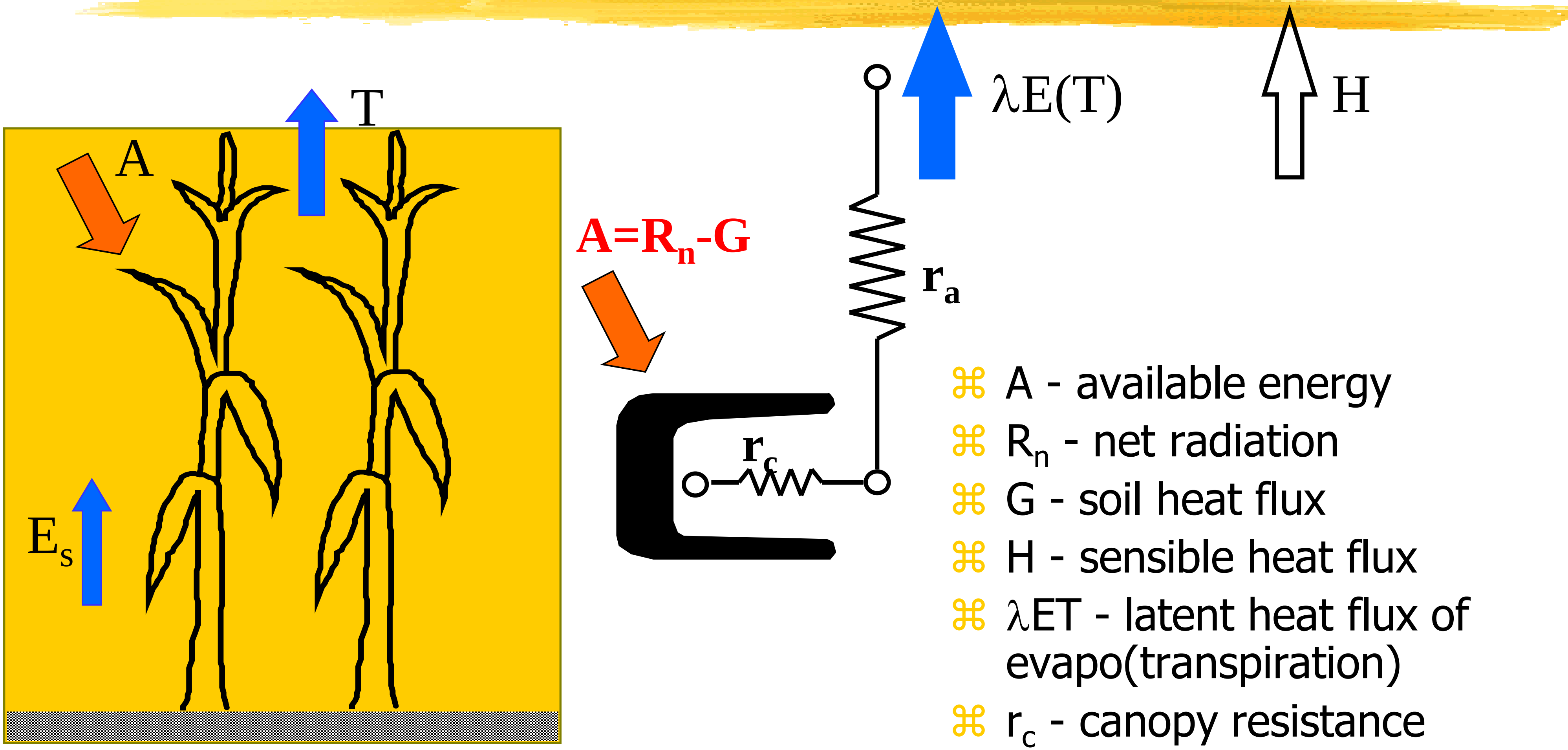


a=absorption
r=reflection
sc=scattering
sw=short-wave
lw=long-wave

$$R_n = R_{sw} + R_{lw}$$

$$R_n = \lambda ET + H + G$$

Plant-Atmosphere Relationship
Crop Evapo-transpiration

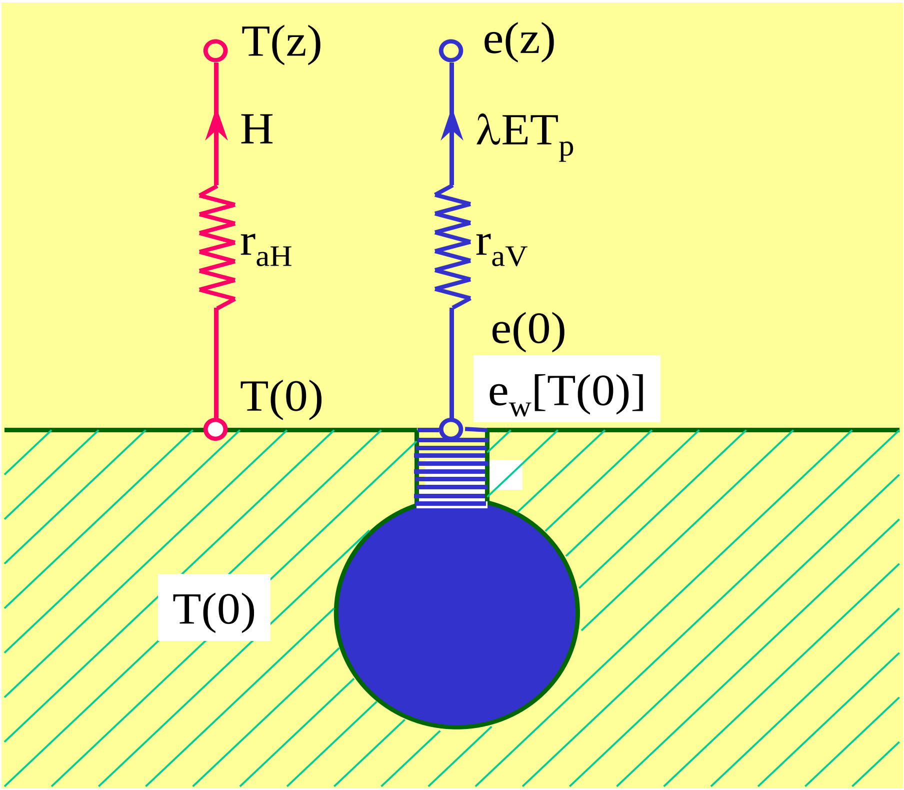


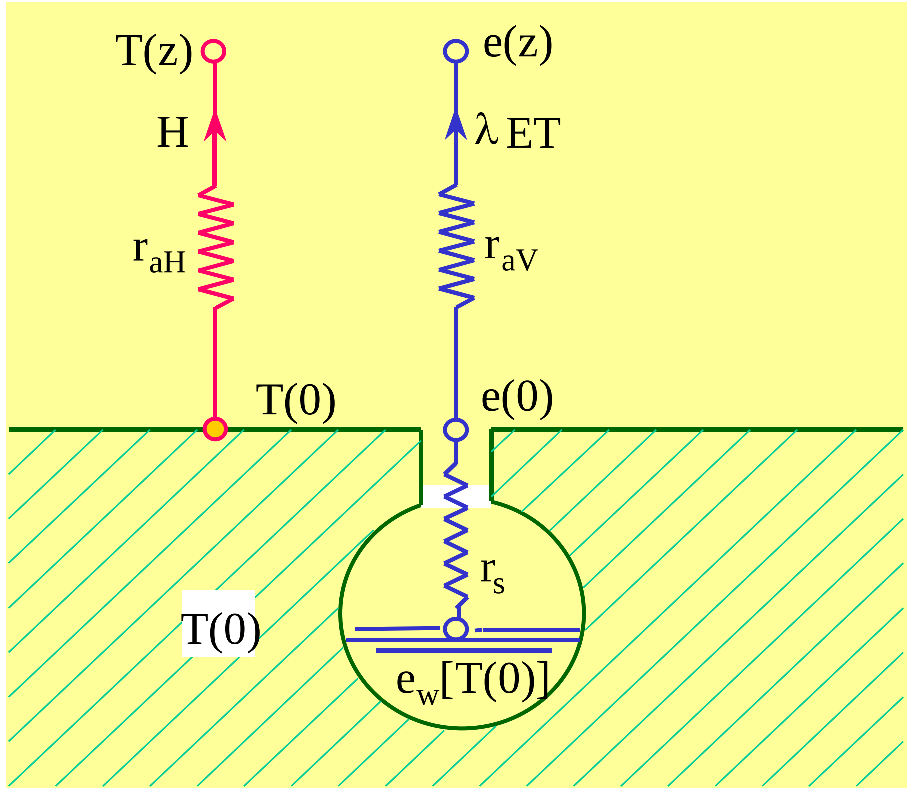
$$\lambda ET_p = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)}$$

- A - available energy
- R_n - net radiation
- G - soil heat flux
- H - sensible heat flux
- λET - latent heat flux of evapo(transpiration)
- r_c - canopy resistance
- r_a - aerodynamic resistance

Reference Evapotranspiration
From Penman to Penman-Monteith

$$\lambda ET_p = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma} \quad \Rightarrow \quad \lambda ET_p = \frac{\Delta A + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma (1 + r_s / r_a)}$$





Source: Todorovic, 1998

FAO - Penman-Monteith method for ETo

- On daily basis:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

- where
  - ET_o is the reference evapotranspiration, (mm day^{-1}),
  - R_n is the net radiation, (MJ m^{-2} day^{-1}),
  - G is the soil heat flux density, (MJ m^{-2} day^{-1}),
  - T is the mean daily air temperature at 2 m height, (^{o}C),
  - Δ is the slope of the saturated vapour pressure curve, (kPa ^{o}C^{-1}),
  - γ is the psychrometric constant, 66 Pa ^{o}C^{-1},
  - e_s is the saturated vapour pressure at air temperature (kPa),
  - e_a is the prevailing vapor pressure (kPa), and
  - U_2 is the wind speed measured at 2 m height (m s^{-1})
- On hourly basis:
  - replace 900 by 37(=900/24) and
  - express the net radiation and the soil heat flux on hourly basis

Hargreaves-Samani method for ETo estimate

- On daily basis:

$$ETo = 0.0023\frac{R_a}{\lambda}(T + 17.8)(T_{max} - T_{min})^{0.5}$$

- where
  - ET_o is the reference evapotranspiration, (mm day^{-1}),
  - R_a is the extraterrestrial radiation, (MJ m^{-2} day^{-1}),
  - T is the average air temperature (^oC),
  - Tmin is the minimum air temperature (^oC),
  - Tmax is the maximum air temperature (^oC),
  - λ is the latent heat of vaporization (MJ kg^{-1}),

$$\lambda = 2.501 - \left(2.361 * 10^{-3}\right)T$$

FAO method with only measured T_{air} data

- Wind speed is fixed to 2 m/s (average value of 2000 weather stations around the globe), more accurate data could be used when available
- Solar radiation is estimated as:

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a$$

k_{Rs} is empirical radiation adjustment coefficient, 0.16 for "interior" and 0.19 for "coastal" areas

- Assuming that T_{dew} is close to T_{min} at a reference site (at sunrise), actual vapour pressure is estimated as:

$$e_a = e^o(T_{min}) = 0.611 \exp\left[\frac{17.27\, T_{min}}{T_{min} + 237.3}\right]$$

Pan evaporation method: ETo=Kp*Epan

TABLE 5
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	.55	.65	.75	1	.7	.8	.85
< 2	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	1	.5	.6	.65	1	.65	.75	.8
2-5	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	1	.45	.5	.6	1	.6	.65	.7
5-8	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	1	.4	.45	.5	1	.5	.6	.65
> 8	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

ETo Estimate methods

Method	Temperature	Humidity	Wind speed	Sunshine or Radiation	Evaporation	Time scale			
						hour	day	week	month
Blaney-Criddle	+	-	-	*	-				x
Hargreaves	+	-	-	*	-				x
Pan evaporation	-	-	-	-	+			x	x
Radiation	+	-	-	+	-			x	x
Penman	+	+	+	+	-		x	x	x
Penman-Monteith	+	+	+	+	-	x	x	x	x
PM-Temperature	+	*	*	*	-	x	x	x	x

+ : must be measured
- : is not necessary

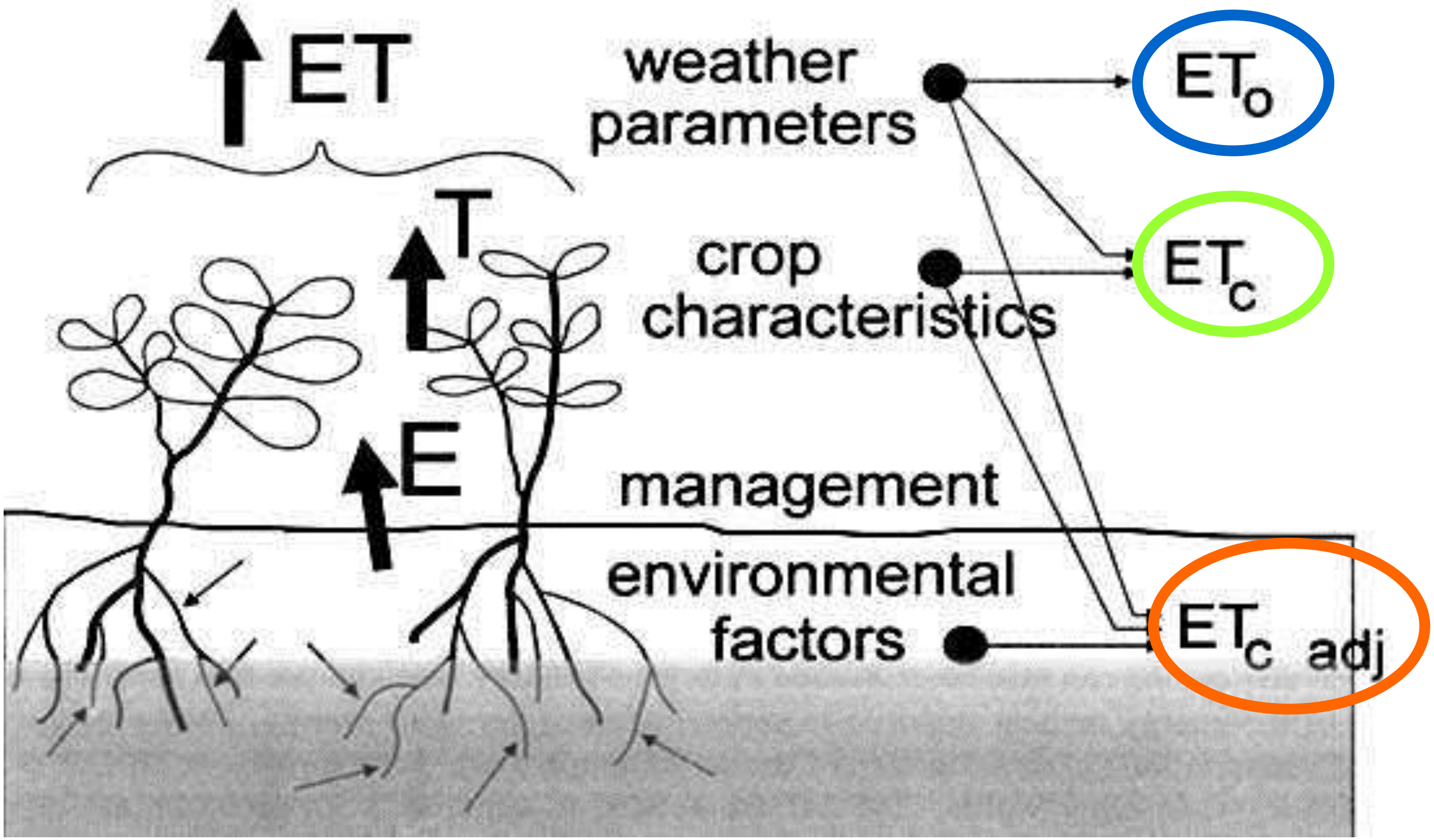
* : estimation required
x : recommended time scale of application

Source: Todorovic, 2004

Performances of various ETo methods

- FAO-PM shows the best performances under both humid and arid conditions, although a slight underestimation is observed in arid zones during the summer months. FAO-PM is recommended as the standard method for ETo estimate.
- Penman method requires local calibration of wind function to achieve satisfactory results
- Hargreaves method shows reasonable results with under different conditions, although the coefficients used in Eq. could require local calibration. Underestimates ET under high wind conditions and overestimates in humid areas.
- Pan evaporation method is susceptible to the local climatic conditions under which the pans are evaporating.
- Radiation and Priestley-Taylor methods show good results in humid climates where the aerodynamic term is relatively small, but they tend to underestimate ET under arid conditions and high wind.

Factors affecting ETc

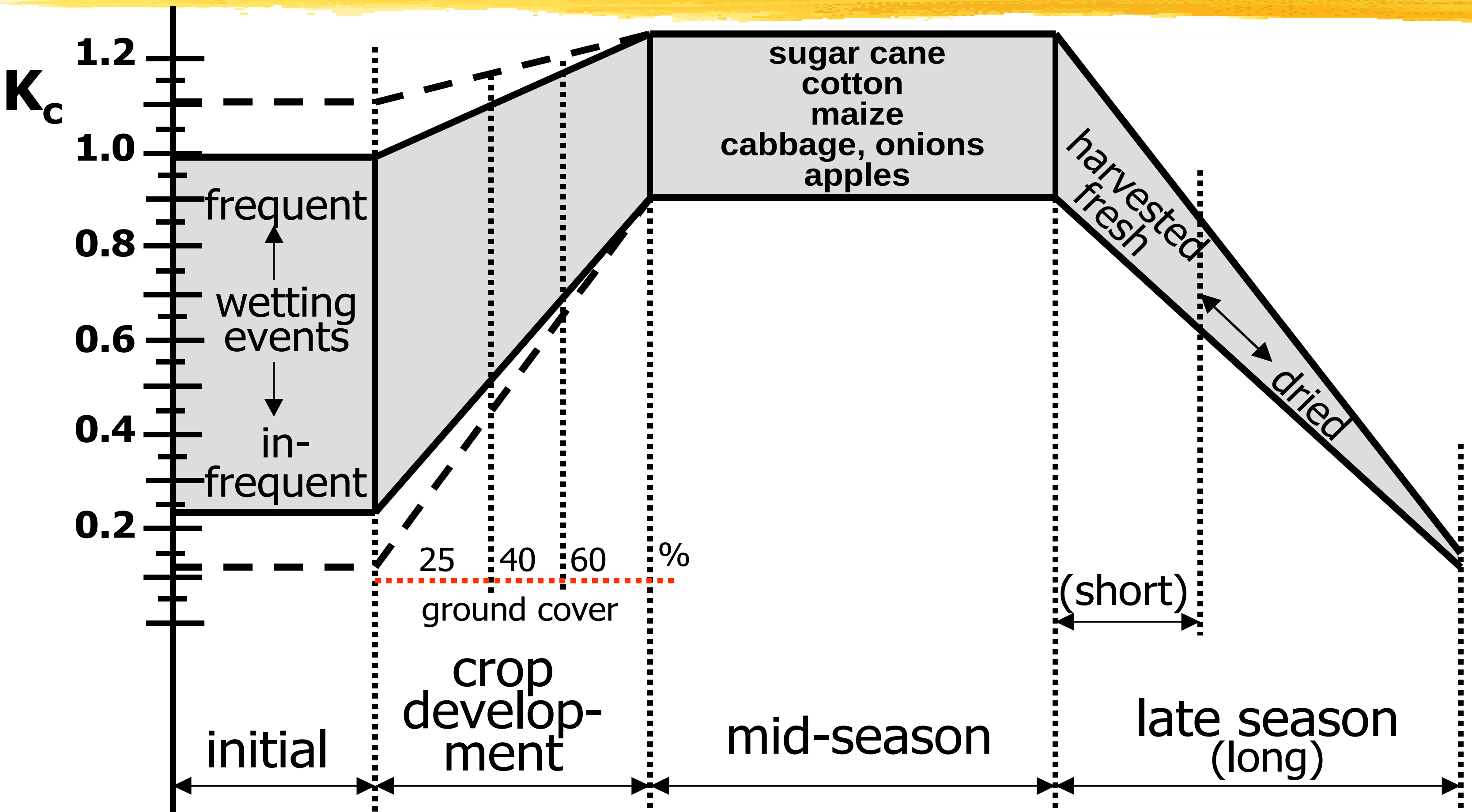


Source: FAO 56, 1998

Crop coefficient Kc: definition and factors affecting it

- Kc is the ratio of the crop ETc to the reference ETo and it represents the integration of four primary characteristics that distinguish the crop from reference grass:
  - crop height (influences r_a)
  - albedo (reflectance) of the crop soil surface (influences Rn)
  - canopy resistance (affected by LAI, leaf age and conditions, etc.)
  - evaporation from soil (especially from exposed soil)
- Factors determining the crop coefficient
  - crop type (height taller crops and close spacing mean greater Kc)
  - climate (more arid climate and higher windspeed mean greater Kc)
  - soil evaporation (depends on soil wetness)
  - crop growth stages (initial, crop development, mid-season and late season)

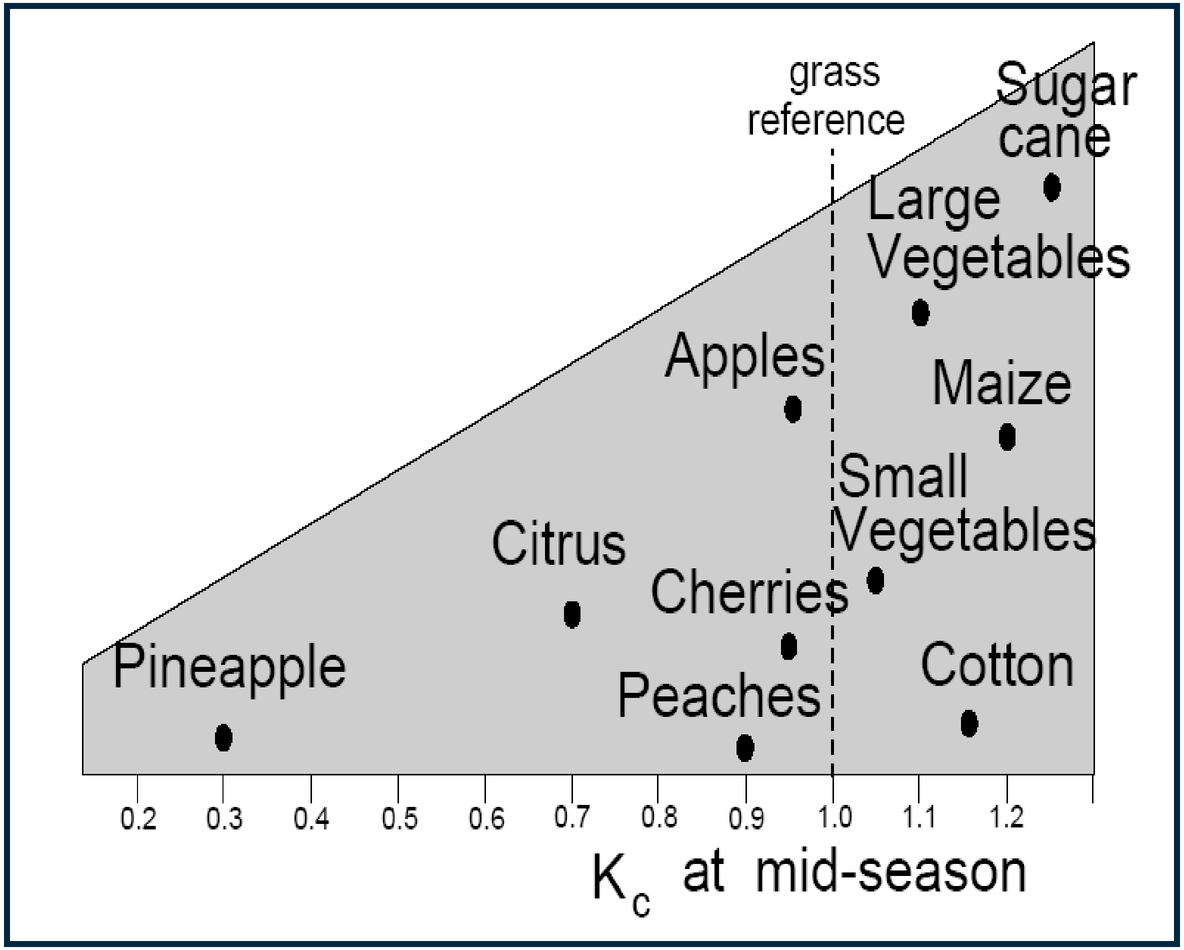
Main factors affecting Kc & typical ranges expected in Kc for the four growth stages



main factors affecting K_c in the 4 growth stages

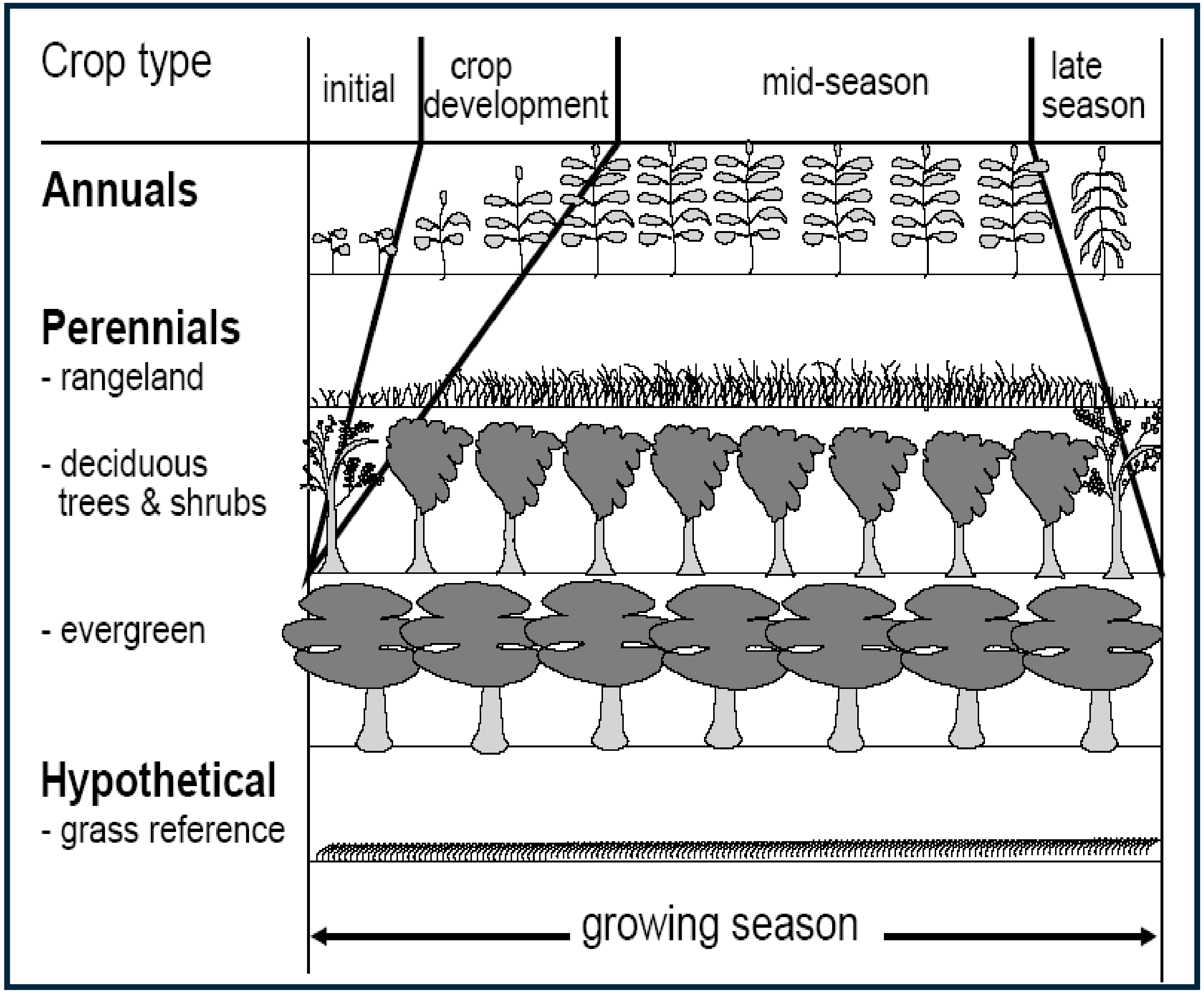
soil evapo-ration	**ground cover plant development**	**crop type (humidity) (wind speed)**	**crop type harvesting date**

Crop coefficient Kc:
a function of crop type



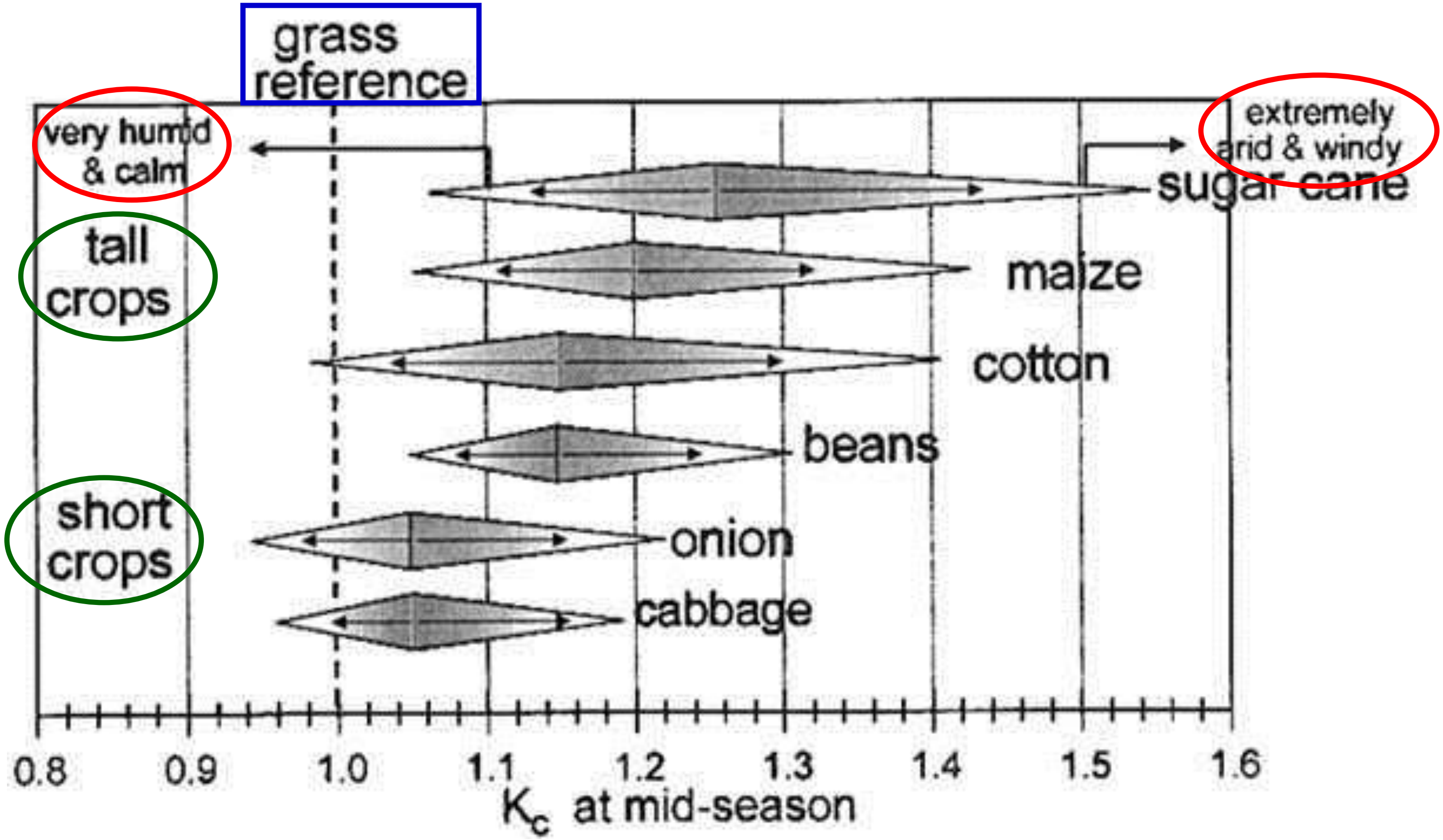
Source: FAO 56, 1998

Crop coefficient Kc:
a function of crop type and growing stages



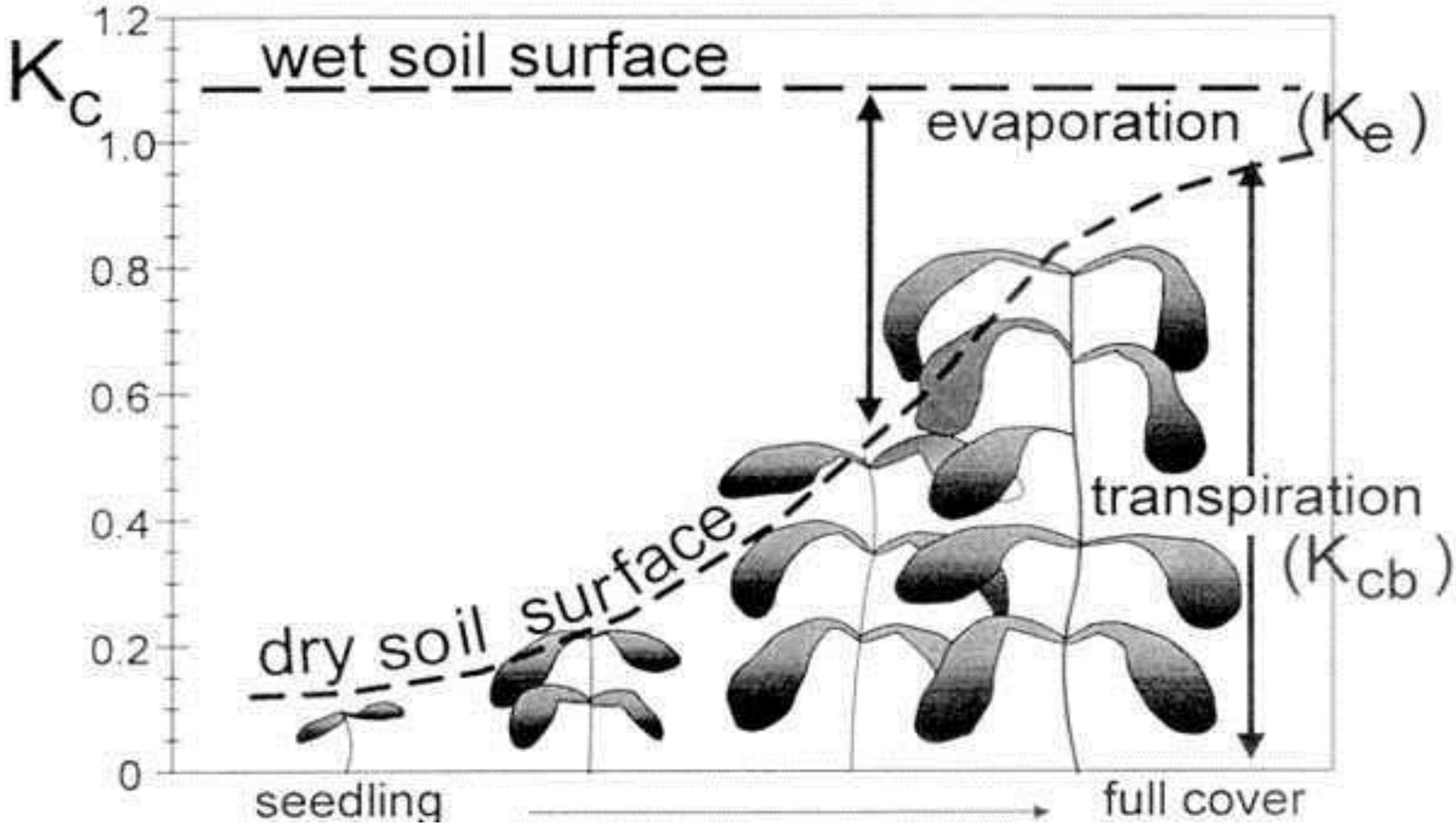
Source: FAO 56, 1998

Extreme ranges expected in Kc for full grown crops as climate and weather change



Source: FAO 56, 1998

Dual Kc approach – the effect of surface wetting on Kc



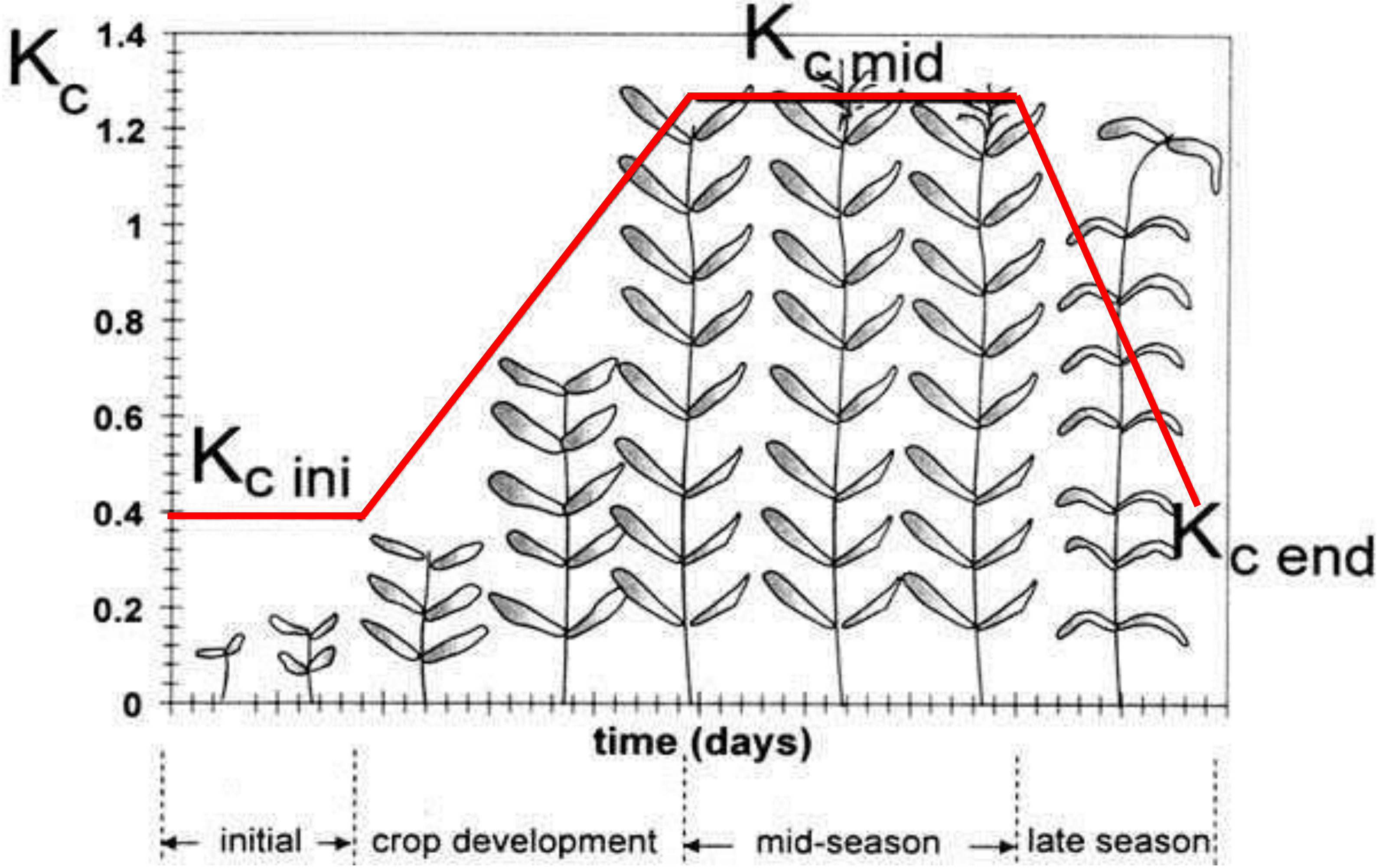
Source: FAO 56, 1998

Dual crop coefficient approach

$K_c = K_{cb} + K_e$

- The basal crop coefficient (Kcb)
  - describes plant transpiration
  - represents the ratio of ETc to ETo when the soil surface layer is dry but where the average soil water content of the root zone is adequate to sustain full plant transpiration
- The soil water evaporation coefficient (Ke)
  - describes evaporation from the soil surface
  - if the soil is wet following rain or irrigation, Ke may be large
  - as the soil surface becomes drier, Ke becomes smaller and falls to zero
- The sum (Kcb+Ke) can never exceed a maximum value Kc,max, determined by the energy available for evapotranspiration at the soil surface.

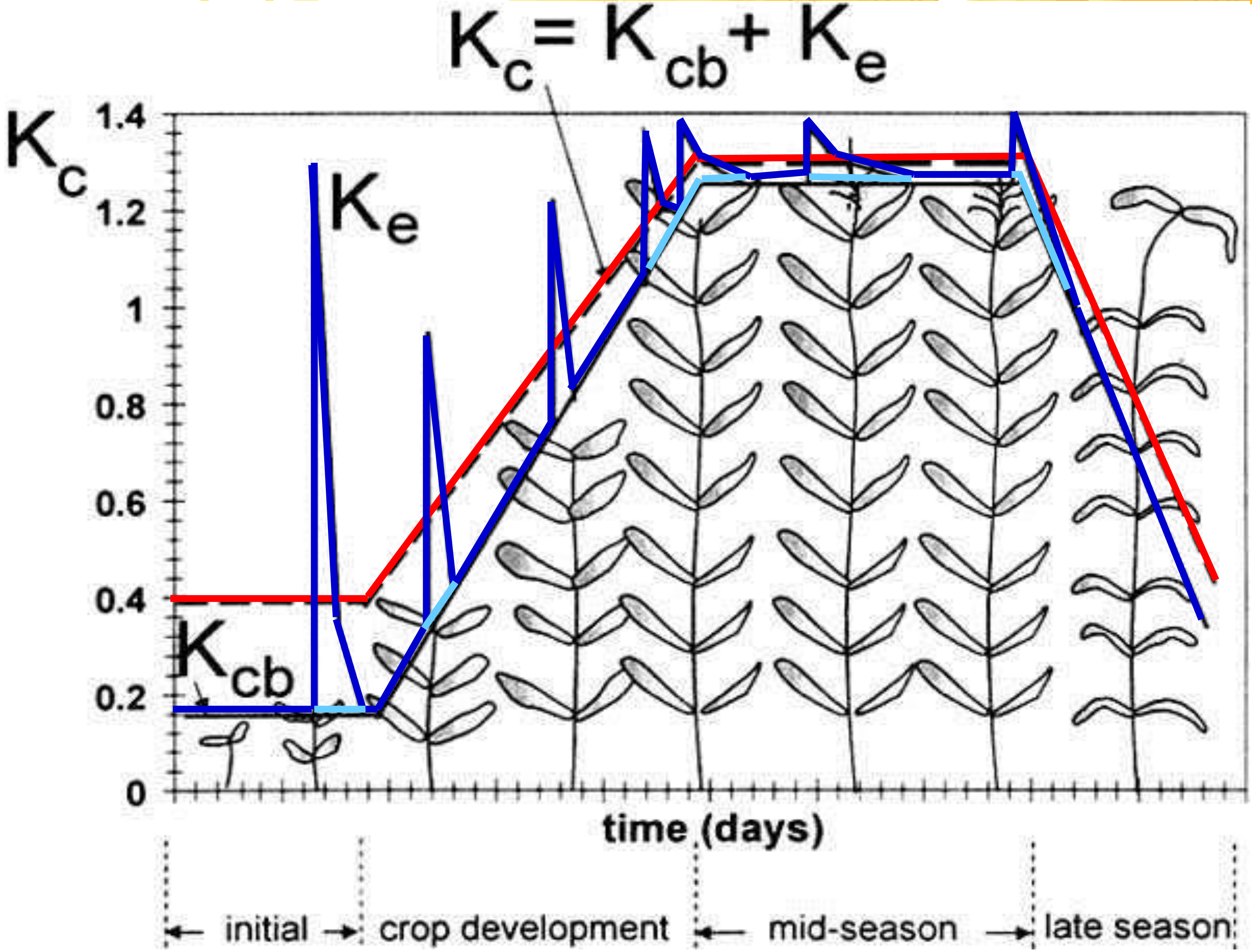
Generalized Kc curve for the single crop coefficient approach



Source: FAO 56, 1998

The Kc curves

for single and dual Kc approaches



General selection criteria for the single and dual crop coefficient approaches

	Single crop coefficient K_c	Dual crop coefficient $K_{cb}+K_e$
Purpose of calculation	- Irrigation planning and design - Irrigation management - Basic irrigation scheduling - Real time irrigation scheduling for non-frequent water applications (surface and sprinkler irrigation)	❑ Research ❑ Real time irrigation scheduling ❑ Irrigation scheduling for high frequency water application (micro-irrigation and automated sprinkler irrigation) ❑ Supplemental irrigation ❑ Detailed soil and hydrologic water balance studies
Time step	❑ Daily, 10-days, monthly	❑ Daily
Solution method	❑ Graphical ❑ Pocket computer ❑ PC	❑ PC

Source: adapted after FAO 56, 1998

Management factors affecting ETc

Ploughed or grassy

- For a deciduous orchard in frost-free climates, the Kc,ini can be as high as 0.8 or 0.9, where grass ground cover exists, and as low as 0.3 or 0.4 when the soil surface is kept bare and wetting is infrequent.

Water saving: Mulching – cultivation under controlled conditions

Impact of mulching on Kc

TABLE 25

Approximate reductions in K_c and surface evaporation and increases in transpiration for various horticultural crops under complete plastic mulch as compared with no mulch using trickle irrigation

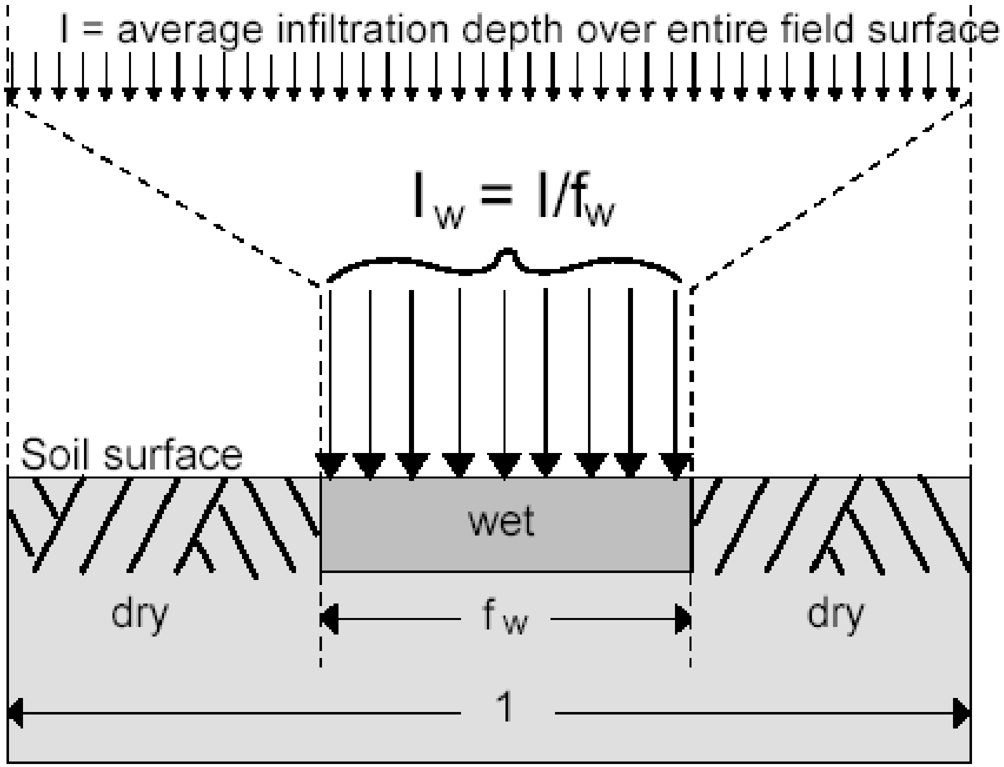
Crop	Reduction[1] in K_c (%)	Reduction[1] in evaporation (%)	Increase[1] in transpiration (%)	Source
Squash	5-15	40-70	10-30	Safadi (1991)
Cucumber	15-20	40-60	15-30	Safadi (1991)
Cantaloupe	5-10	80	35	Battikhi and Hill (1988)
Watermelon	25-30	90	-10	Battikhi and Hill (1986), Ghawi and Battikhi (1986)
Tomato	35	not reported	not reported	Haddadin and Ghawi (1983)
Average	10-30	50-80	10-30	

[1] Relative to using no mulch

Source: FAO 56, 1998

- Kc,mid and Kc,end for the horticultural crops should be reduced by 10-30%, depending on the frequency of irrigation (higher value for frequent trickle irrigation).
- When the plastic mulch does not entirely cover the soil wetted by the drip emitters, or where substantial rainfall occurs, then the reduction in Kc,mid or Kc,end will be less, in proportion to the fraction of wet surface covered by the mulch.
- In the case of organic mulching, the reduction of Kc will be much lower (about 50%)

$K_{c,ini}$ adjustment for partial wetting by irrigation



$$K_{c,ini\_adj}=f_w*K_{c,ini}$$

f_w= fraction of surface wetted by irrigation

$$I_w = \frac{I}{f_w}$$

I_w= irrigation depth for the part of the surface that is wetted [mm]

I = the irrigation depth for the field [mm]

When irrigation of part of the soil surface and precipitation over the entire soil surface both occur during the initial period, f_w should represent the average of f_w for each type of wetting, weighted according to the total infiltration depth received by each type.

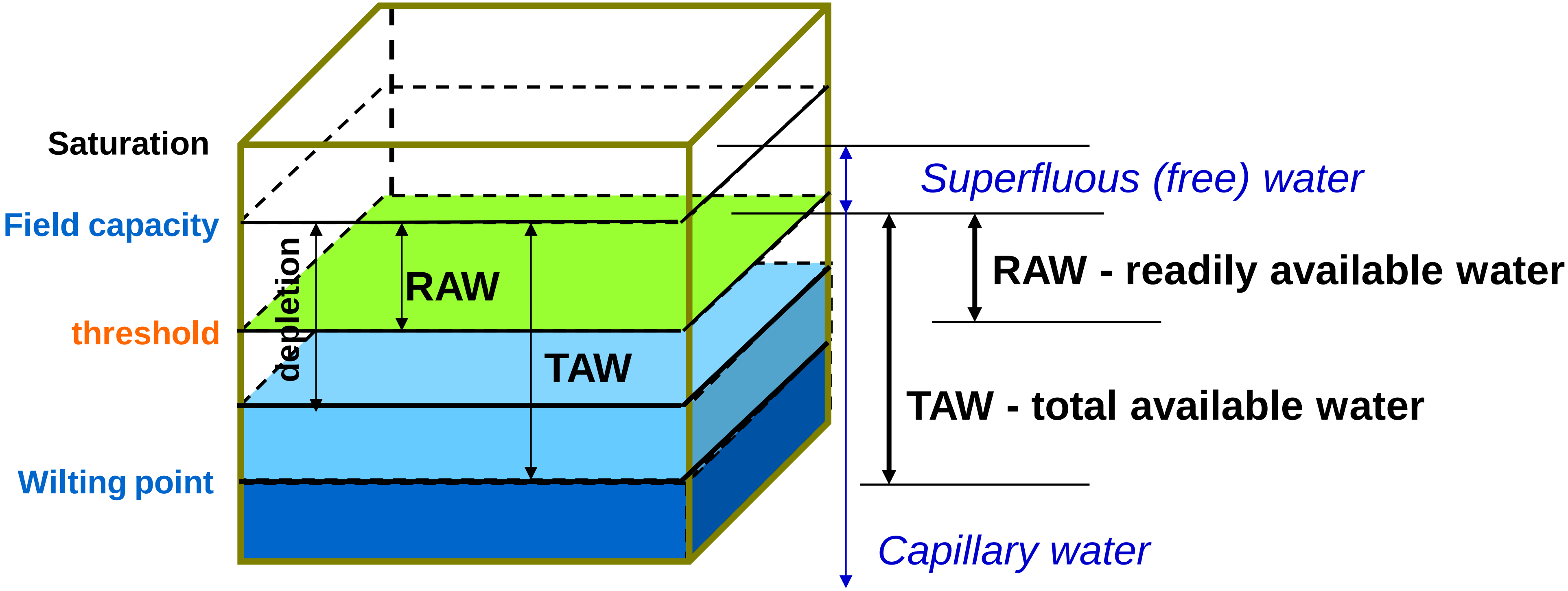
Common values of fraction f_w of soil surface wetted for different wetting events

Wetting event	f_w fraction of soil surface wetted
Precipitation	1.0
Sprinkler irrigation	1.0
Basin irrigation	1.0
Border irrigation	1.0
Furrow irrigation (every furrow), narrow bed	0.6 … 1.0
Furrow irrigation (every furrow), wide bed	0.4 … 0.6
Furrow irrigation (alternated furrows)	0.3 … 0.5
Trickle irrigation	0.3 … 0.4

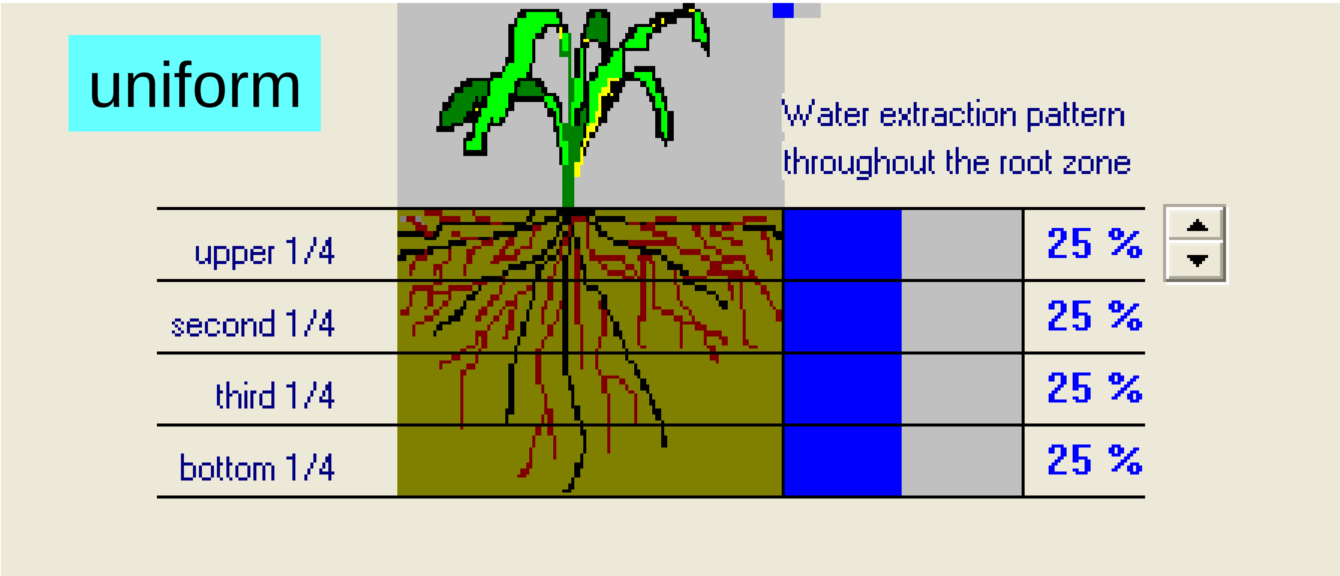
Source: FAO 56, 1998

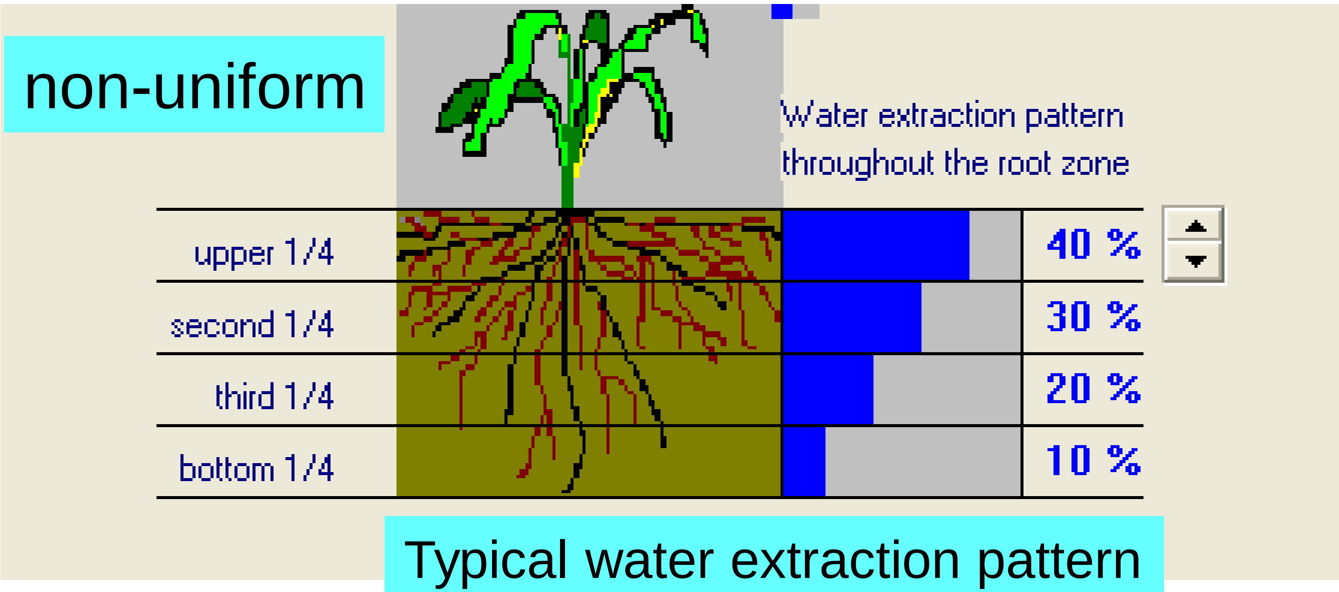
IRRIGATION SCHEDULING

Soil Water Retention



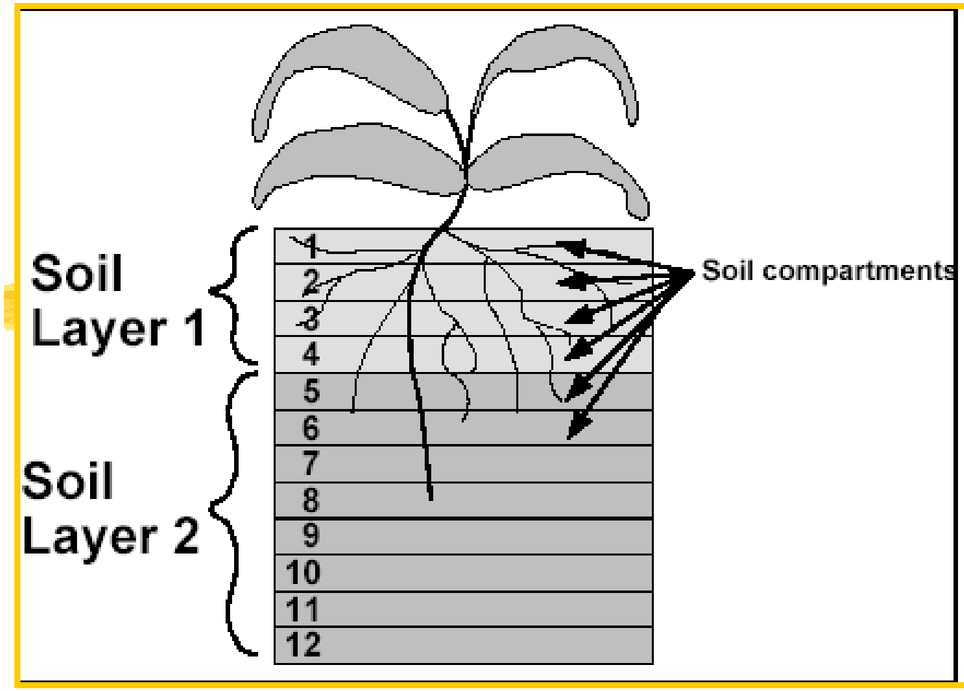
Water extraction pattern throughout the root zone



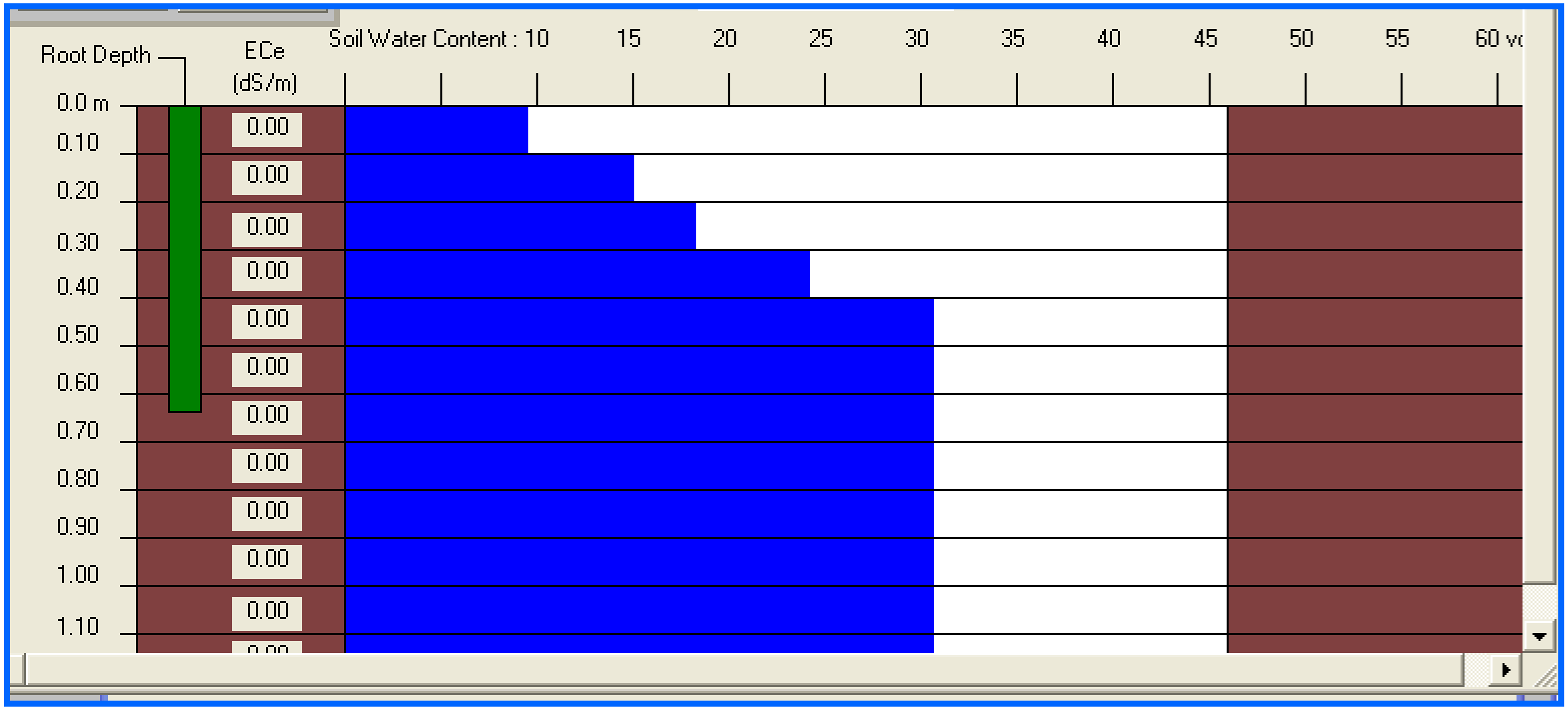


Typical water extraction pattern

Soil layers and soil compartments



Soil water content



Source: Raes, 2002

APPLICATION EFFICIENCY OF IRRIGATION METHODS

Irrigation Method	Range† (Per cent)	Design (Per cent)
Gravity - Undeveloped		30
Gravity - Developed	40 - 80	62
Sprinkler - Solid Set		72
Sprinkler - Hand-Move	60 - 85	67
Sprinkler - Wheel-move - 2 Laterals	60 - 85	68
Sprinkler - Wheel-move - 4 Laterals	60 - 85	70
Sprinkler - Pivot - High pressure	75 - 90	73
Sprinkler - Linear - High pressure	75 - 90	73
Sprinkler - Pivot - Low pressure	75 - 95	84
Sprinkler - Linear - Low pressure	75 - 95	84
Sprinkler - Volume gun - Stationary	55 - 75	65
Sprinkler - Volume gun - Traveller	55 - 75	66
Micro - Spray - Sprinkler	70 - 95	82
Micro - Drip - Trickle	70 - 95	88

surface

sprinkler

micro-sprinkler

drip

† Source: Howell, T.A. 2003. Irrigation Efficiency, in Encyclopedia of Water Science. Marcel Dekker, Inc. New York, New York. 1076 pp.

Field application efficiency of irrigation methods as a function of soil texture

Irrigation method	**APPLICATION PRACTICES**	Field application efficiency in %		Average deep percolation as fraction of irrigation water applied to the field	
		Soil texture		Soil texture	
		fine	coarse	fine	Coarse
Sprinkler	*Daytime application, moderately strong wind*	60	60	0.3	0.3
	Nighttime application	70	70	0.25	0.25
Trickle		80-85	80-85	0.10-0.15	0.10-0.15
Basin	*Poorly leveled and shaped*	60	45	0.30	0.40
	Well leveled and shaped	75	60	0.20	0.30
Furrow	*Poorly graded and sized*	55	40	0.30	0.40
Border	*Well graded and sized*	65	50	0.25	0.35

Source: FAO 38, 1980

Irrigation Scheduling Management Terms

- TAW - total available water
  - water stored in the root zone between the field capacity and wilting point:

$$TAW = 1000 * (\theta_{FC} - \theta_{WP}) * Rd$$

where TAW is in *mm* , θ_{FC} and θ_{WP} are given in $m^3\ m^{-3}$, and the effective root depth Rd in *m*

- RAW - readily available depletion
  - a fraction (p) of TAW that can be extracted by crops without suffering water stress:

$$RAW = p * TAW$$

Readily allowable water depletion (RAW)

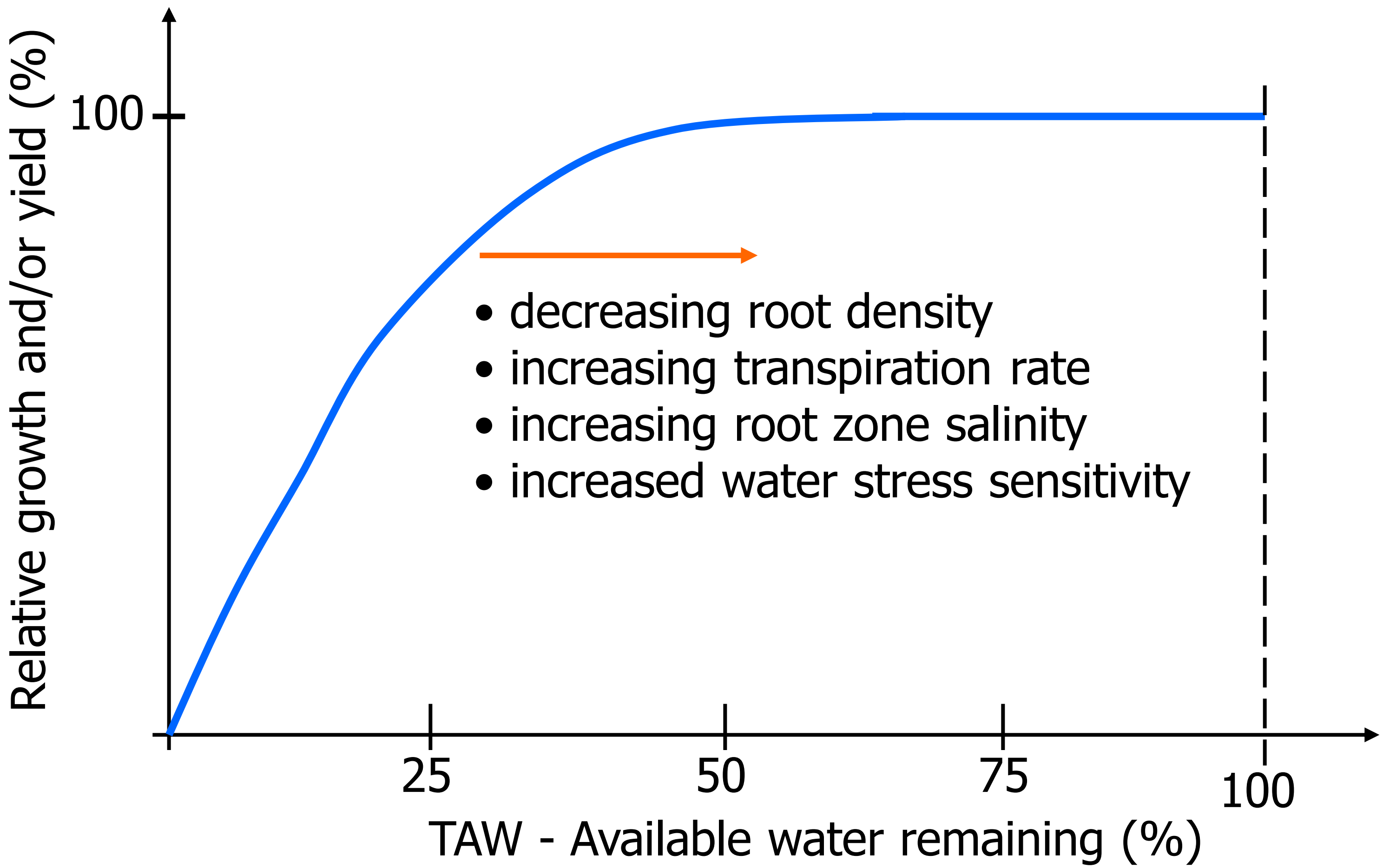
- The percentage of available soil water which can be depleted between irrigations without serious water stress
- Values of RAW (as percentage of TAW) are typically:
  - 25-40% for shallow or sparsely rooted crops
  - 50% for deep-rooted crops
  - 60-65% for deep-rooted crops with dense rooting system
  - may decreased by 5-10% when ETo>6 mm/day
- FAO 33 recommended:
  - 50% of TAW as an average "safe" level
  - increase/decrease of 15% in when ETo<3mm/day or ETo>8mm/day

Management allowable depletion (MAD)

- The percentage of available soil water which can be depleted between irrigations
- MAD should be less than or equal to RAW except when deficit irrigation is applied
- MAD may change during the season
  - to account for sensitivity to water stress during critical developmental periods and for changes in rooting depth and evaporative demand
  - Some crops require greater soil-water depletion directly before harvest to enhance the quality of fruit or grain
- MAD may depend also on irrigation method, crop value, water delivery...
  - it is lower for drip than for sprinkler irrigation method
  - it is lower for high-value than for low-value crops

Range of root zone available water

that can be utilized before growth and/or yield is reduced



Allowable root zone water depletion

for various crops according to sensitivity to water stress

Crop groups	Maximum evapotranspiration rate ET_m [mm/day]								
	2	3	4	5	6	7	8	9	10
1	0.50	0.43	0.35	0.30	0.25	0.23	0.20	0.20	0.18
2	0.68	0.58	0.48	0.40	0.35	0.33	0.28	0.25	0.23
3	0.80	0.70	0.60	0.50	0.45	0.43	0.38	0.35	0.30
4	0.88	0.80	0.70	0.60	0.55	0.50	0.45	0.43	0.40

Group	Crops
1	Onion, pepper, potato
2	Banana, cabbage, pea, tomato
3	Alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat
4	Cotton, sorghum, olive, grape, safflower, maize, soybean, sugarbeet, tobacco

Source: FAO 33, 1986

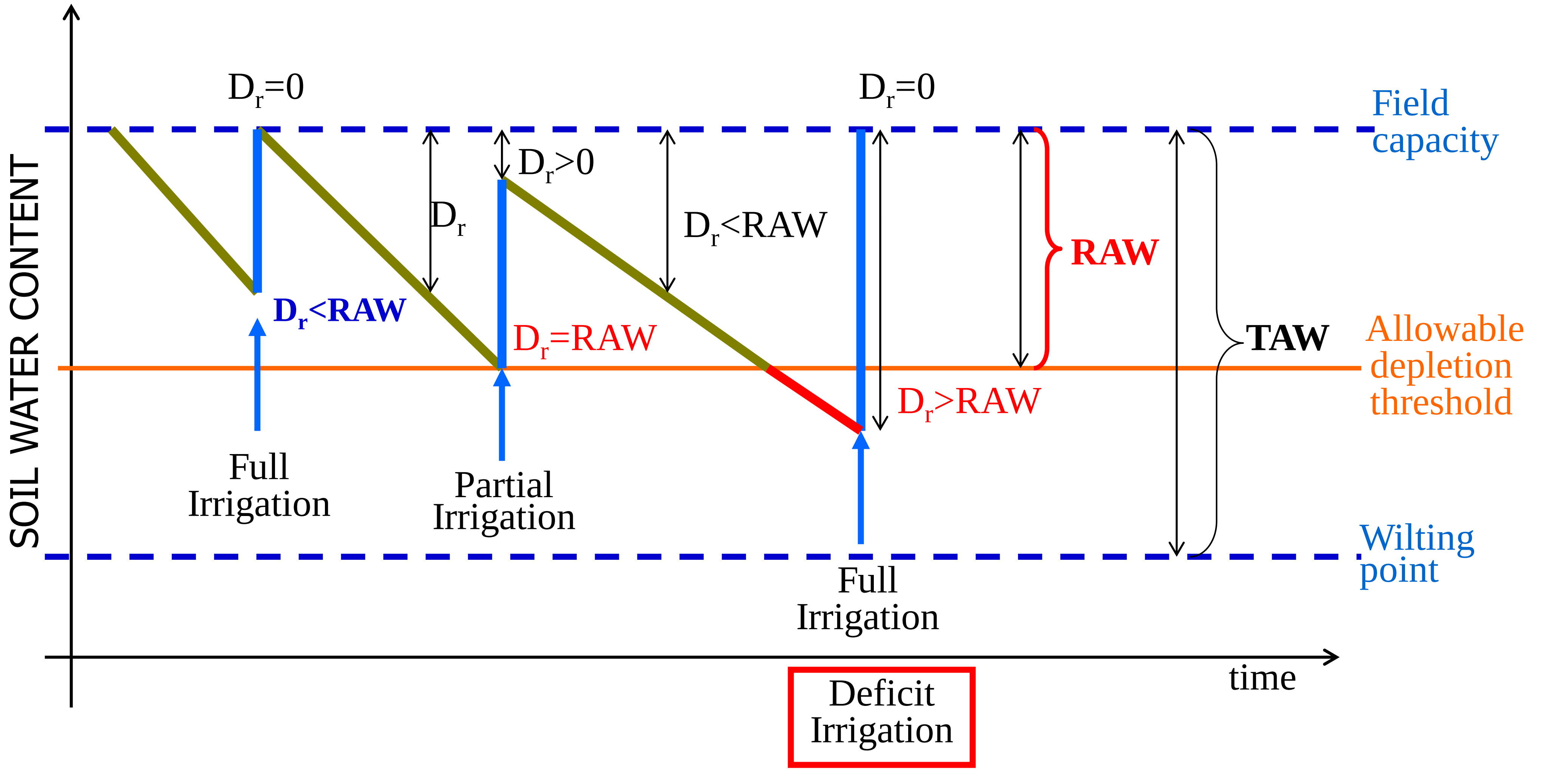
Timing Irrigation Criteria

- Allowable depletion of TAW (fraction)
  - irrigation is applied whenever Dr drops below a predetermined fraction of TAW
- Allowable depletion of RAW (fraction)
  - irrigation is applied whenever Dr drops below a predetermined fraction of RAW
- Allowable daily stress
  - irrigation is applied whenever the actual ET rate drops below a predetermined fraction of potential ET rate
- Allowable depletion amount
  - irrigation is applied whenever a predetermined amount of water below field capacity is depleted
  - particularly useful in the case of high frequency irrigation systems (drip)
- Fixed/variable calendar
  - irrigation is applied 4 days, every week, etc. depending on growing stage

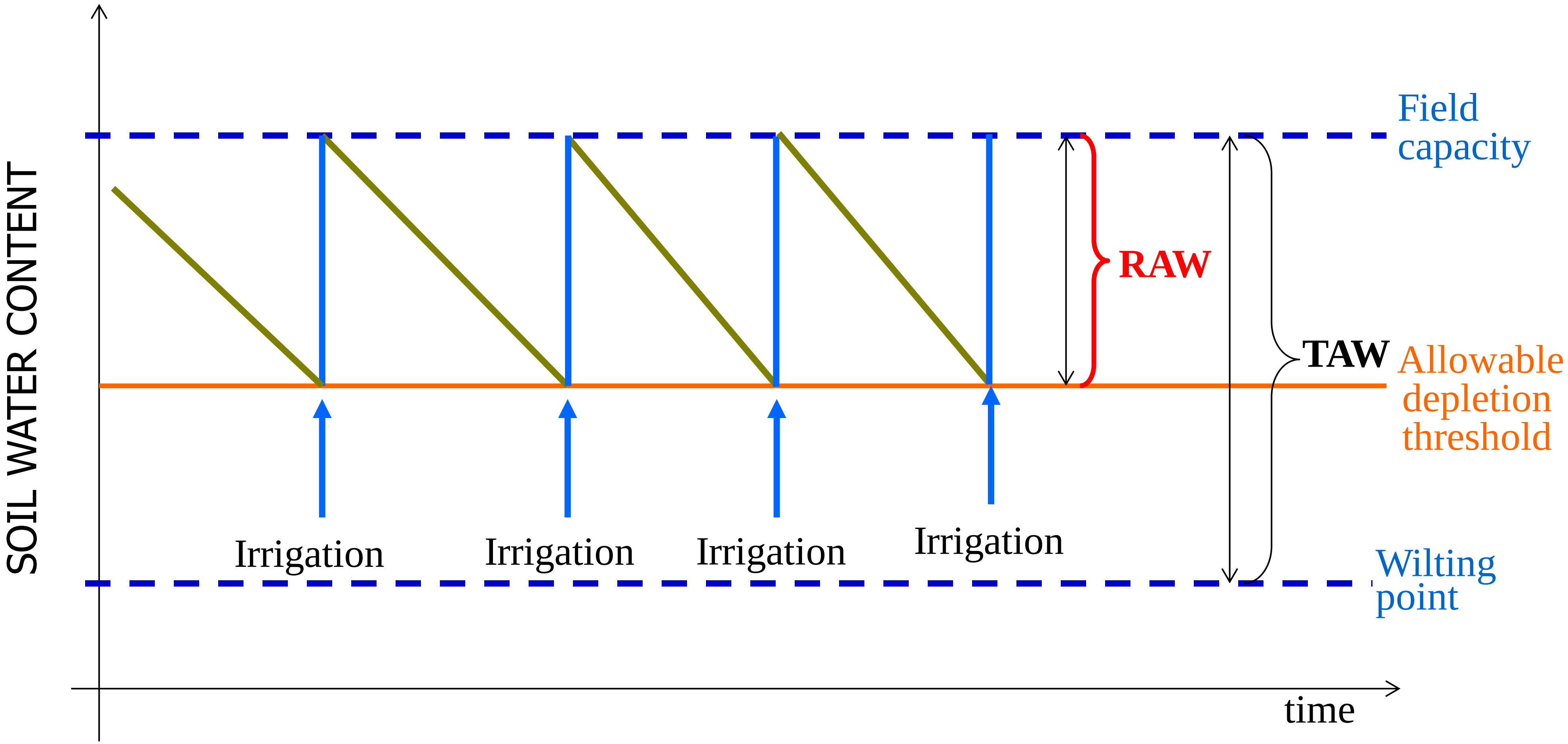
Depth Irrigation Criteria

- Back to field capacity (+/-)
  - the soil water content in the root zone is brought back to field capacity plus or minus a specified depth for salt leaching purposes or rainfall allowance respectively.
- Fixed depth
  - a predetermined amount of water is applied (adapted to specific irrigation method)
  - for high frequency irrigation there is no water stress risk but there is water excess risk (aeration problems)

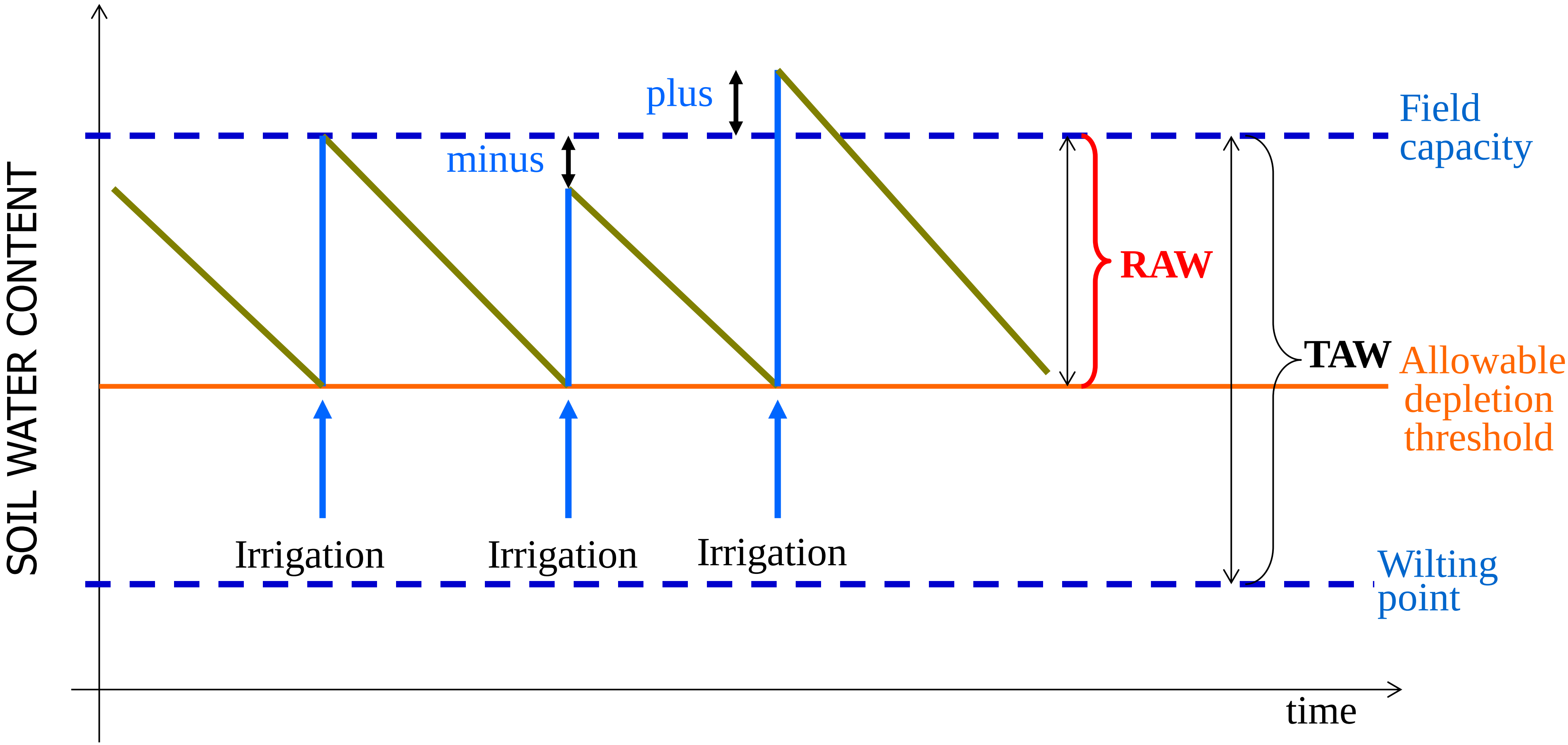
Root zone water depletion (Dr) and irrigation water supply strategies



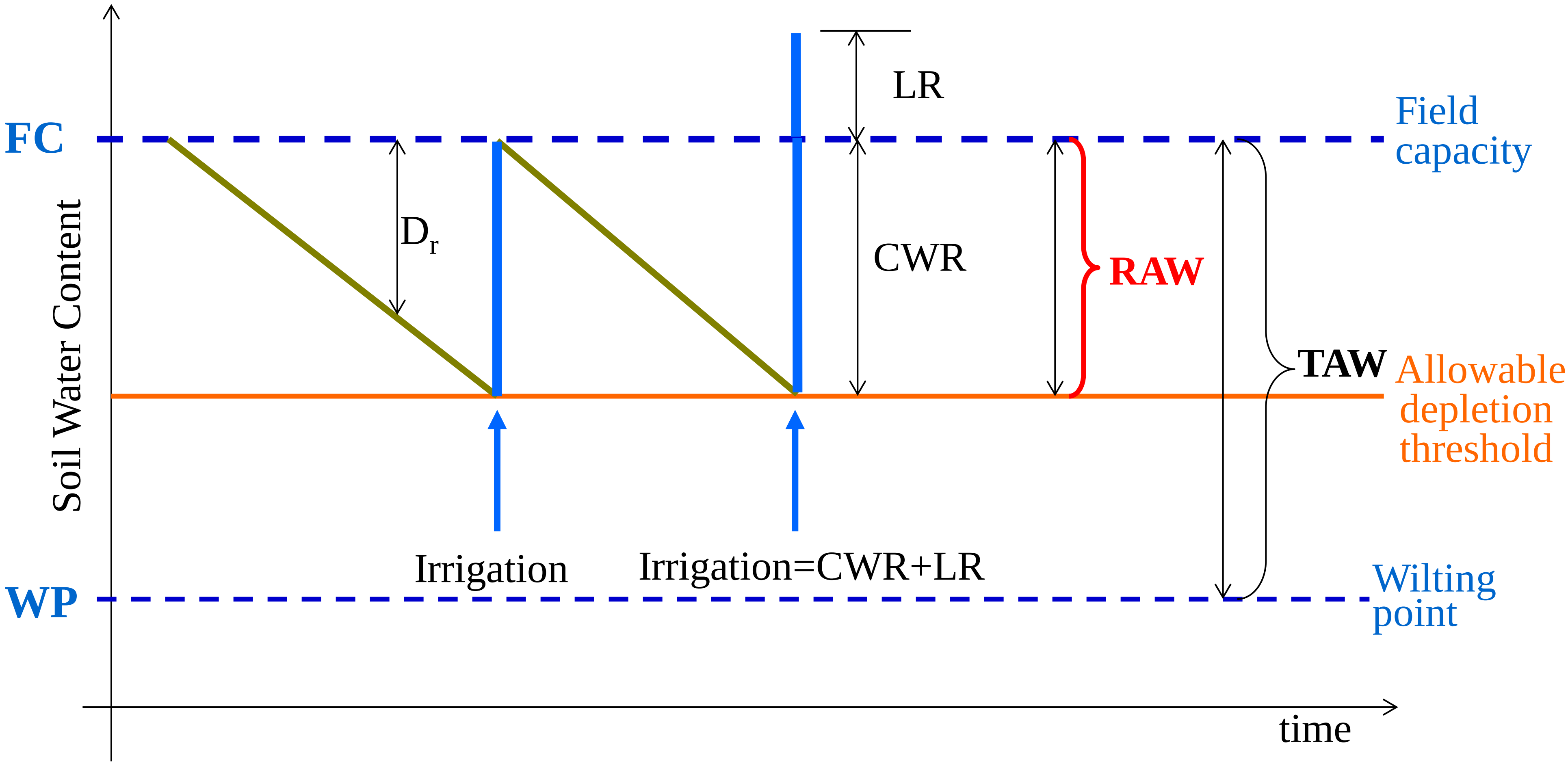
Fixed depth irrigation



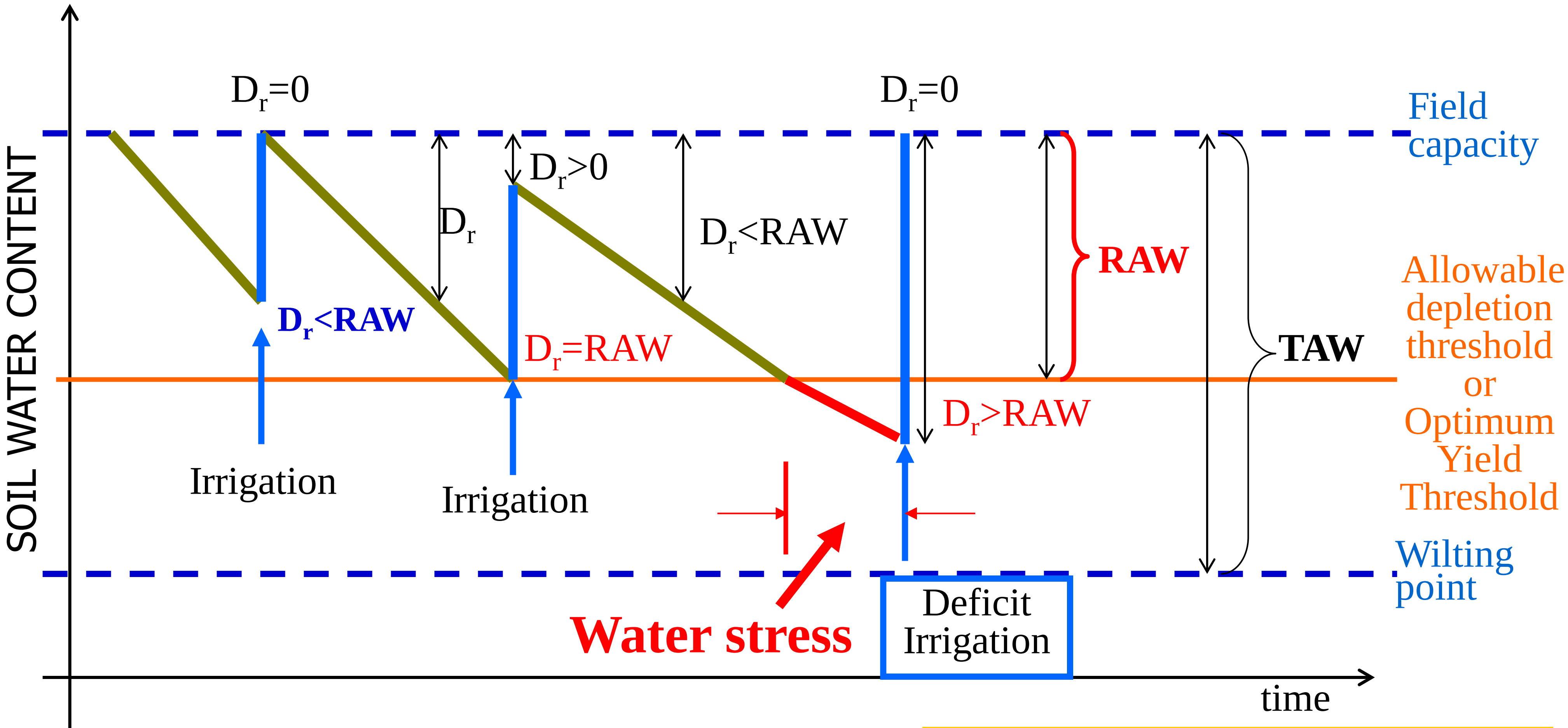
Back to field capacity (+/-) irrigation



Irrigation with leaching



Root zone water depletion (Dr) and irrigation water supply strategies

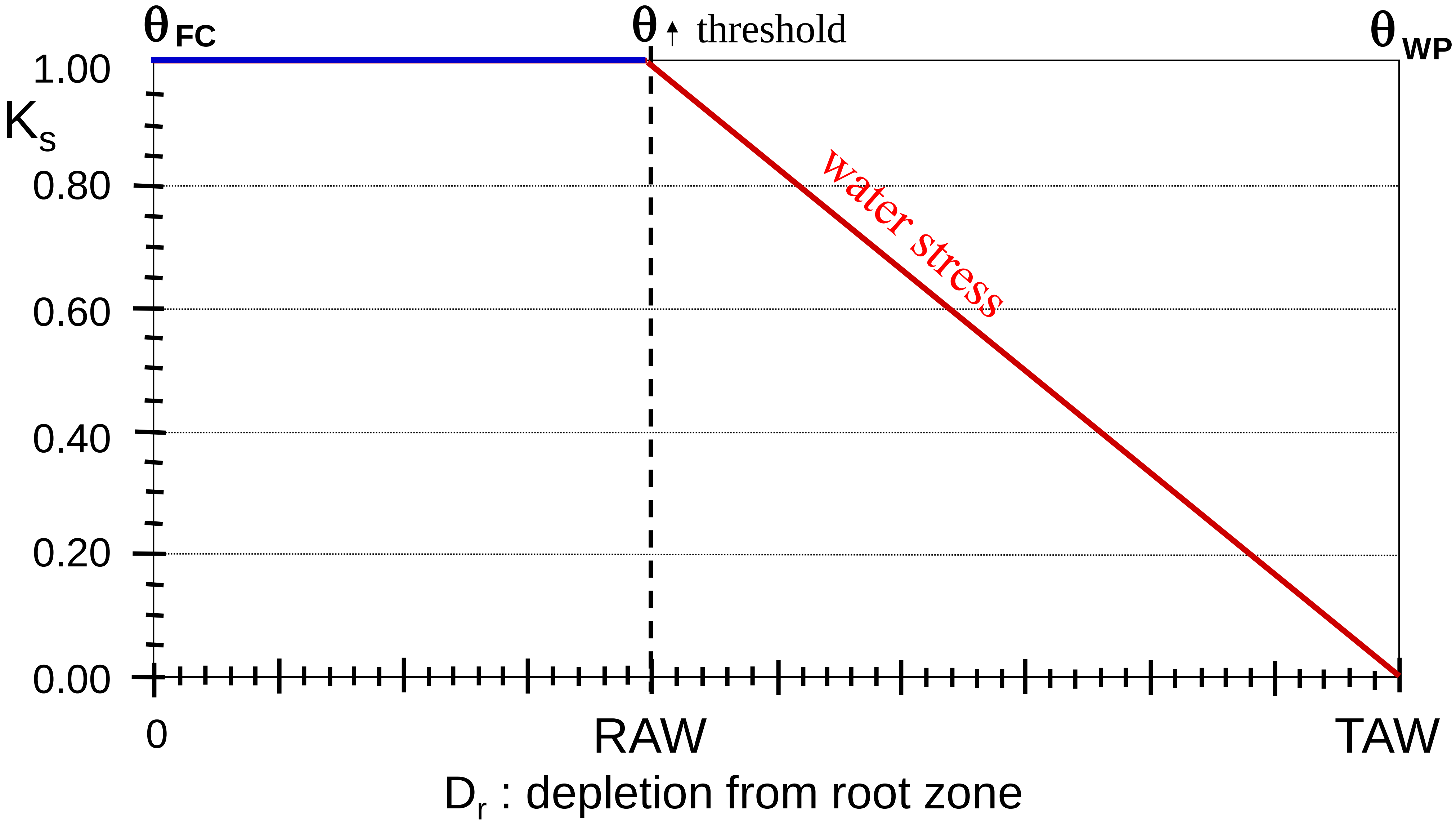


Ks – reduction coefficient for ETc :

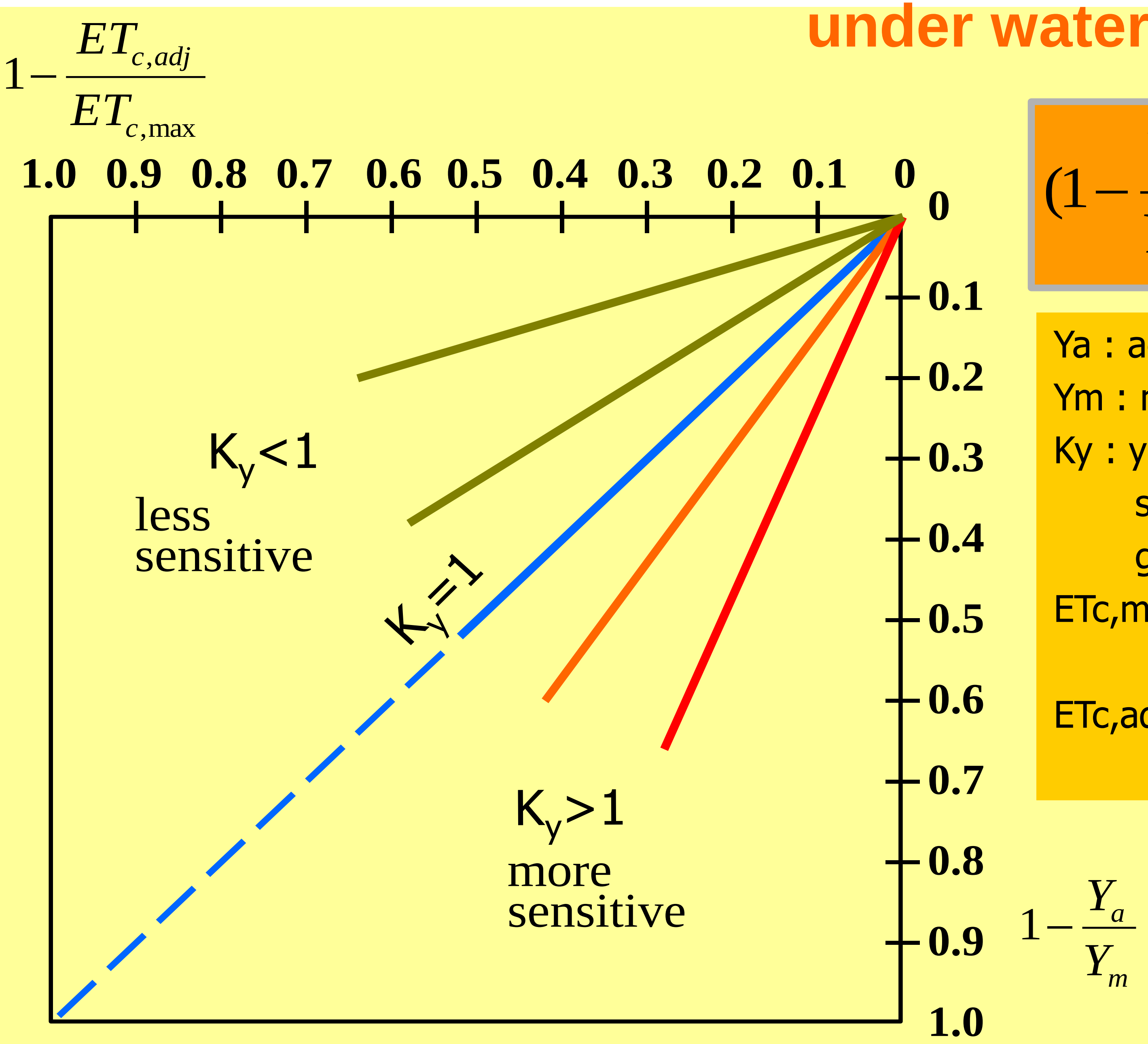
$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW}$$

ETc adjusted for water stress :

$$ET_{c,adj} = K_s K_c ET_o$$



Relative yield estimation for the whole growing season under water stress conditions



$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_{c,adj}}{ET_{c,\max}}\right)$$

Ya : actual yield;

Ym : maximum expected yield;

Ky : yield response factor (crop specific and varies during the growing season);

ETc,max : ETc for optimal water supply

ETc,adj : actual crop ET adjusted for water stress

Source: Stewart et al., 1977

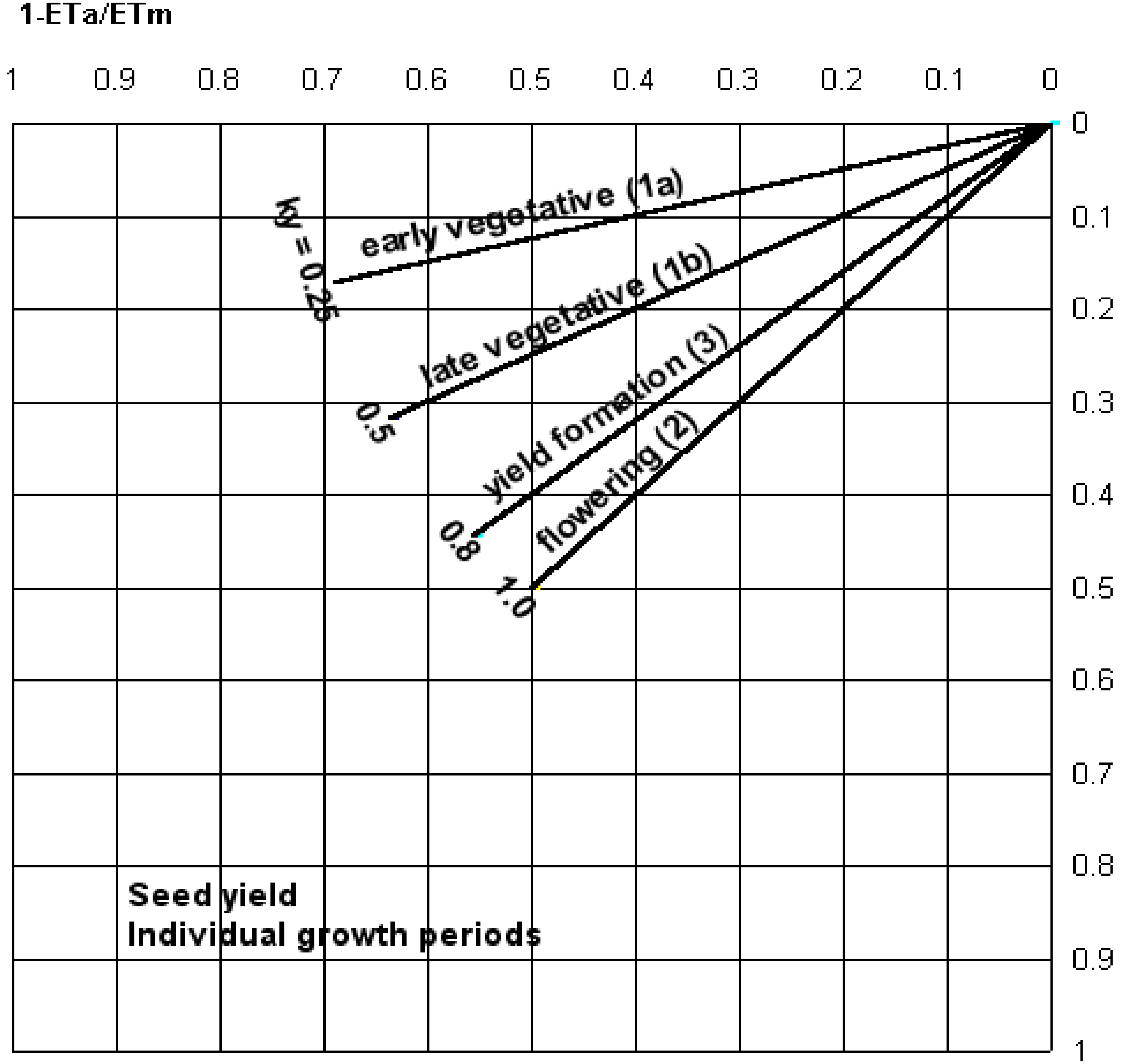
Ky (yield response factor to water stress) values for some crops

Crop	K_y
Alfalfa	1.1
Beans	1.2-1.35
Cabbage	0.95
Citrus	1.1-1.3
Cotton	0.85
Grape	0.85
Maize	1.25
Onion	1.1
Peas	1.15
Pepper	1.1

Crop	K_y
Potato	1.1
Sorghum	0.9
Soybean	0.85
Spring Wheat	1.15
Sugarbeet	1.0
Sugarcane	1.2
Sunflower	0.95
Tomato	1.05
Watermelon	1.1
Winter Wheat	1.05

Source: FAO, 1998

Relative yield estimation for individual growth periods : a multiplicative approach

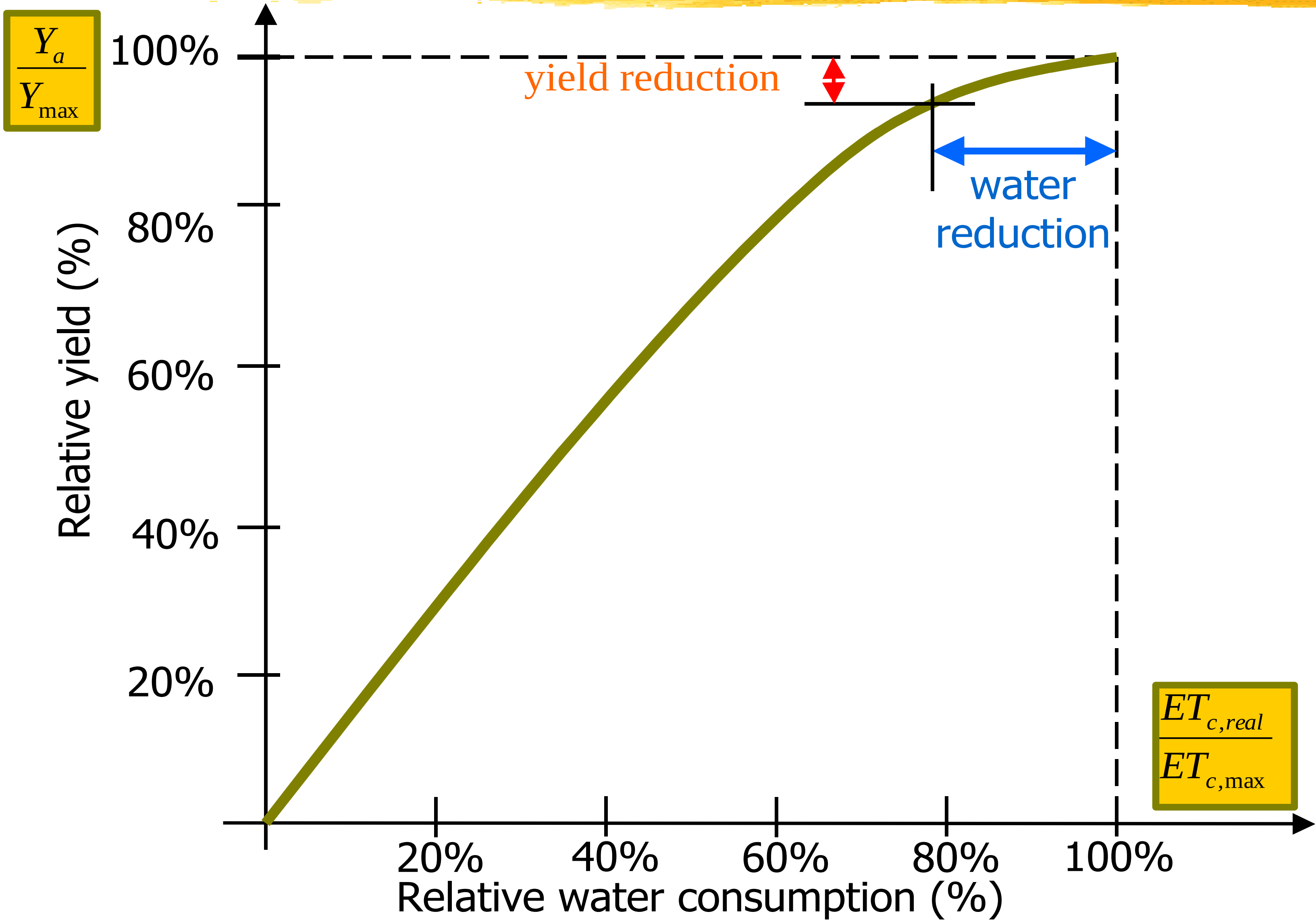


Multiplicative approach for N growing (sensitivity) stages:

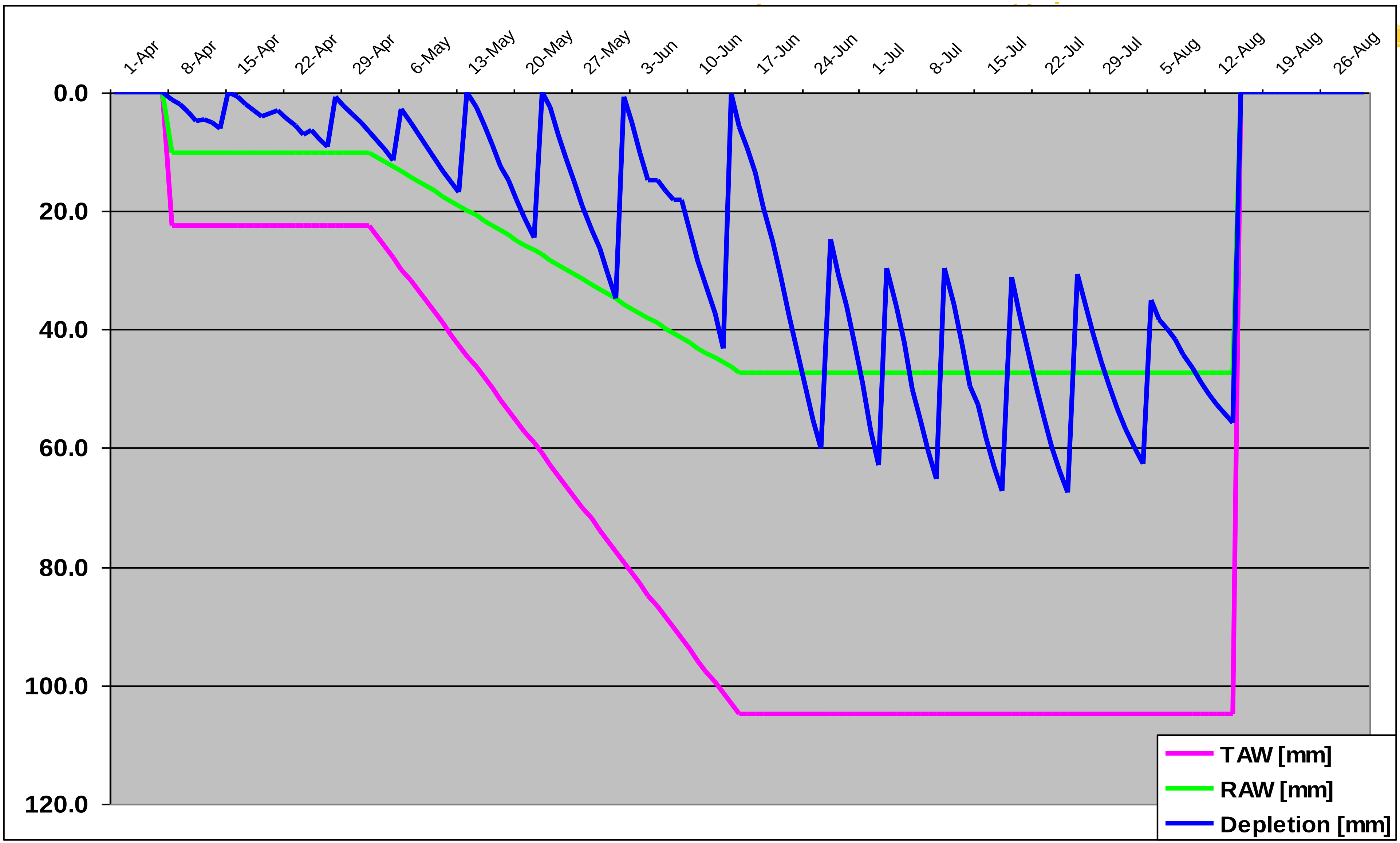
$$\frac{Y_a}{Y_m} = \prod_{i=1}^{N}\left[1 - K_{y,i}\left(1 - \frac{ET_{c,adj,i}}{ET_{c,i}}\right)\right]$$

Source: FAO 33, 1979; Rao et al., 1988

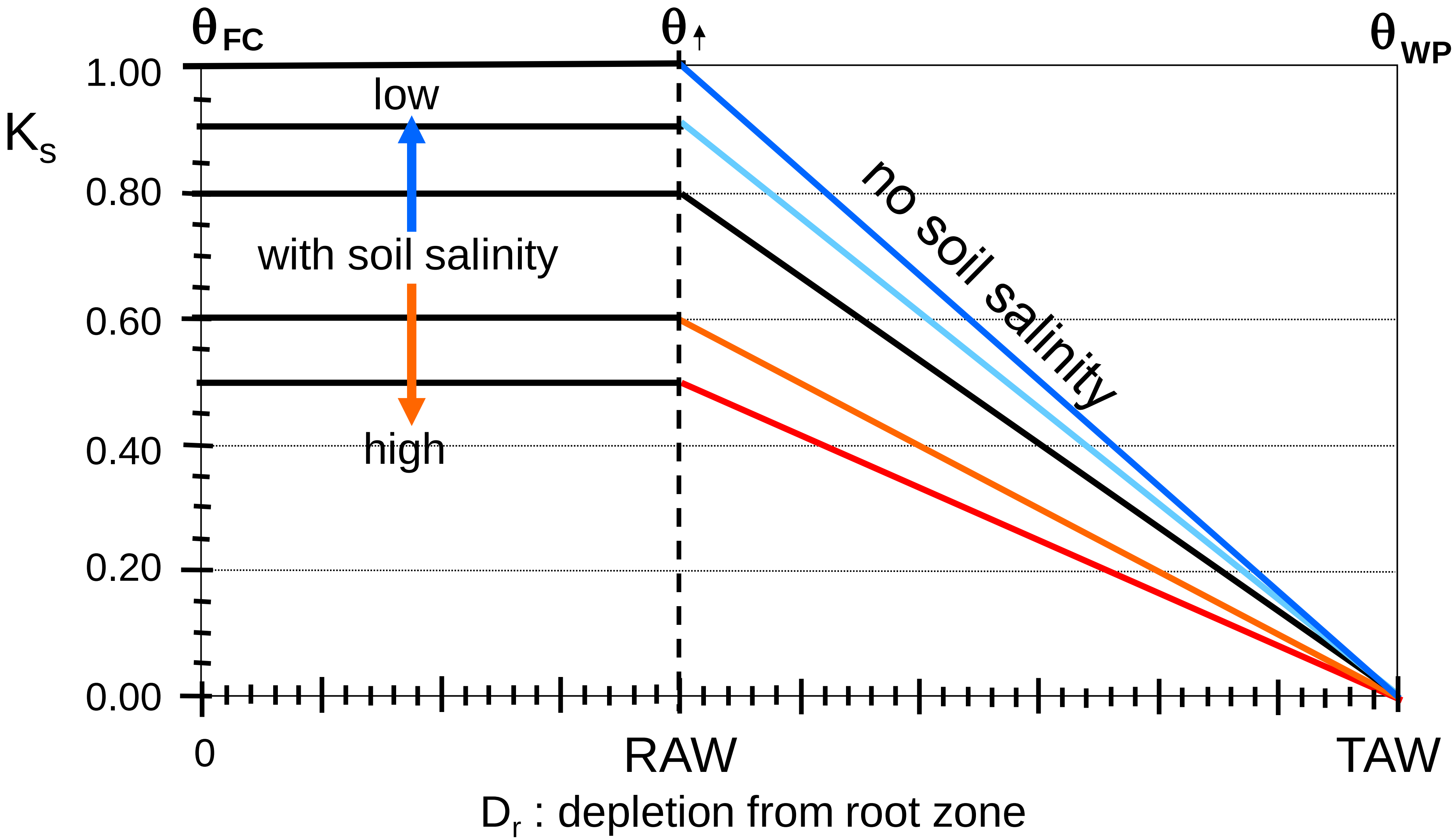
Deficit Irrigation Strategy:
minimizing Yield reduction while
maximizing ET reduction (water saving)



Example of RDI applied on a field crop during the phase tolerant to water stress



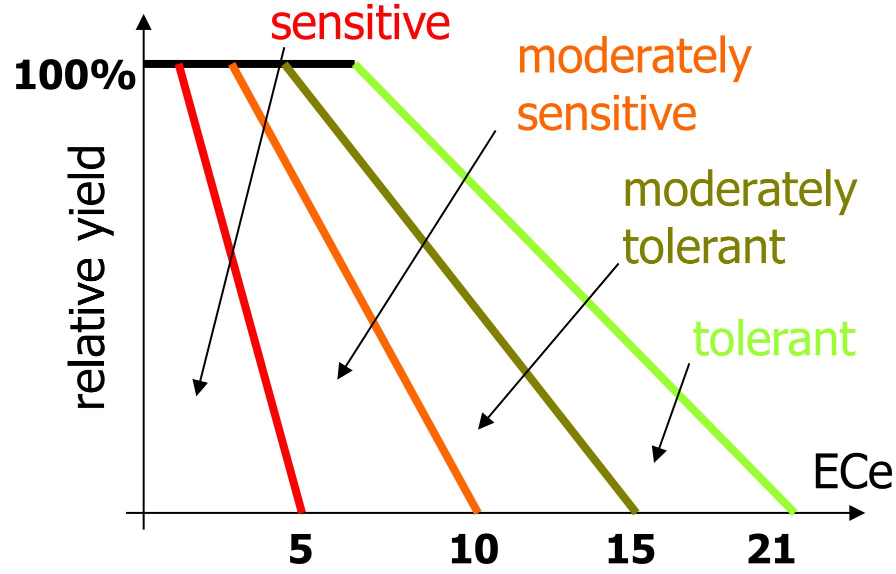
The effect of soil salinity on the Ks and reduction of ETc



Yield-salinity relationship and salinity-ET reduction relationship

- Assumption:
  - crop yield decreases linearly with salinity increase which may be expressed through ECe

$$\frac{Y_a}{Y_m} = 1 - (EC_e - EC_{e,thres})\frac{b}{100}$$



- Y_a - the actual crop yield,
- Y_m - the maximum crop yield expected when there is no salt stress,
- EC_e is the mean electrical conductivity of the saturation extract for the root zone,
- $EC_{e,thres}$ - the threshold value of EC_e when yield reduction occurs;
- b is the is the factor of yield reduction (slope of the curve) in respect to increase of EC_e (%/dS m^{-1})

Salinity stress without water stress

- $EC_e > EC_{e,threshold}$ and Dr<RAW
- Salinity stress

$$\frac{Y_a}{Y_m} = 1 - (EC_e - EC_{e,thres})\frac{b}{100}$$

- The reduction of yield

$$(1 - \frac{Y_a}{Y_m}) = K_y(1 - \frac{ET_{c,adj}}{ET_{c,\max}})$$

$$K_s = \frac{ET_{c,adj}}{ET_{c,\max}}$$

$$1 - 1 + (EC_e - EC_{e,thres})\frac{b}{100} = K_y(1 - K_s)$$

- Reduction coefficient Ks for salinity stress

$$K_s = 1 - \frac{b}{K_y 100}(EC_e - EC_{e,thres})$$

Water and salinity stress

- Water stress Dr>RAW

$$K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW}$$

- Salinity stress $EC_e > EC_{e,threshold}$

$$K_s = 1 - \frac{b}{K_y 100}(EC_e - EC_{e,thres})$$

- Both, water (Dr>RAW) and salinity stress ($EC_e > EC_{e,threshold}$)

$$K_s = K_{s,water} * K_{s,salinity}$$

$$K_s = (1 - \frac{b}{K_y 100}(EC_e - EC_{e,thres}))\frac{TAW - D_r}{TAW - RAW}$$

Instead of conclusions

- Certain:
  - measured climatic variables
  - measured average soil characteristics
  - quality of irrigation water
  - quantity of water applied and timing
  - irrigation method (and its performances)
  - some crop parameters (crop height, development stage, DAP, LAI, root depth…)
- Uncertain:
  - estimate of reference evapotranspiration and Kc values
  - estimate of crop water requirements
  - readily available water (total available water)
  - crop water uptake pattern
  - crop response function to deficit irrigation and/or excessive salt accumulation
  - spatial and temporal variability