Irrigation and Drainage Engineering

(Soil Water Regime Management)

(ENV-549, A.Y. 2025-26)

4ETCS, Master option

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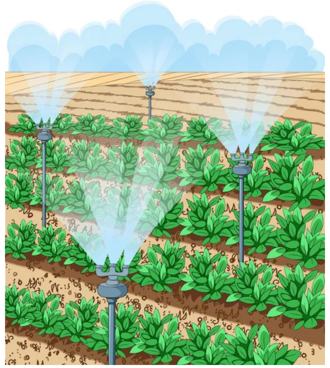
Lecture 2-1: Determination of plant water needs

Why determining plant water needs?

- planning, e.g. the use of water resources: volume of water required for irrigation, irrigable areas in relation to resources, etc.

- management of irrigation networks: short-term forecasting

- design of irrigation networks: calculation of the design flow rate of structures (prediction)



How water is (naturally) removed from soil?

- Direct evaporation

- Extraction from plant activity
  - Constitutive water (e.g., contained in tissues)
  - Transpired water (released into the atmosphere)

Approximative % of constitutive water

Arbres	60%
Céréales	75%
Plantes fourragères	80%
Légumes	90%
Fruits	90 à 95%

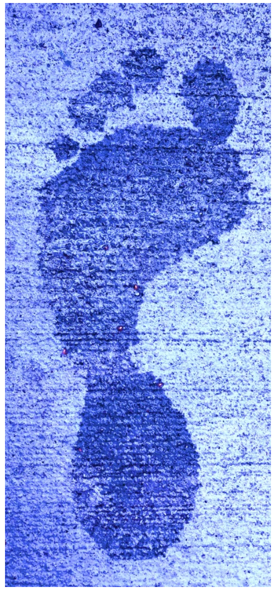
Total water consumption = évapotranspiration ET

Coton	**5 000 - 25 000**
Riz	**2 000 - 5 000**
Céréales (blé, maïs, etc.)	**500 - 2 000**
Pommes de terre	**100 - 500**

Average quantity of water (in litres) needed to produce one kg

Link to blue, green and gray water

$$WF_{proc} = WF_{proc,green} + WF_{proc,blue} + WF_{proc,grey}$$



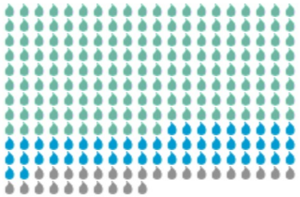
= Eau bleue + Eau verte + Eau grise

Hoekstra et al., WFP assessment Manual, 2011

Global average water footprint

2497 litre/kg

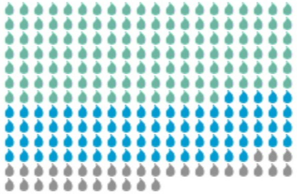
68% green, 20% blue, 11% grey



Global average water footprint

2495 litre for a shirt of 250 gram

54% green, 33% blue, 13% grey



Global average water footprint

1222 litre/kg

77% green, 7% blue, 16% grey

Global average water footprint

287 litre/kg

66% green, 11% blue, 22% grey

https://tools.waterfootprint.org/product-gallery/

Evapotranspiration

Evapotranspiration ET* is the sum of the volumes of water removed from the soil over a given time and area by :

- Plants
- Direct evaporation from bare soil

ET* = f
- climate
- crop species
- soil

Crop water needs

Part of the requirements can be met by rainfall or water initially stored in the soil.

Irrigation water amount is calculated on the basis of a water balance

* ET in m3/m2 for a given period (mm/d, mm/month, etc.)

Calcululus of net water need from irrigation

Based on a water balance in the root zone over a given period (day, decade, month).

A comparison is made between the amount of water naturally available to plants and the water taken by the same plants under optimum water supply conditions (irrigated crops).

Available water: **- fraction of precipitation reaching the root zone: Pe (effective rainfall)**

- possible reserve R* (i.e. remaining from previous period)

Consumption and losses : **- maximum evapotranspiration ETM**

Net water need B_n : B_n = ETM - Pe - R

*** Any water reserves available in the soil at the start of the period for which water needs are calculated.**

Estimate of plant water consumption

In view of the large number of parameters likely to influence evapotranspiration, conceptual models have been introduced to estimate water abstraction by plants in the root zone and the evaporation at the soil surface. Such models build on the following key quantities

- **reference evapotranspiration ET_0**
- **maximum evapo-transpiration for specific plants, ETM**

Reference evapotranspiration ET_0

Definition

ET_0 represents the maximum quantity of water consumed by a reference crop (turf grass) covering the entire soil and having a uniform height of a few centimetres, under the dual hypothesis :

- **maximum stage of vegetative development**
- **soil with sufficient water content (retention capacity)**

Calculus of ET_0*

- Formula of Blaney Criddle
- Formula of Thornthwaite
- Formula of Turc
- Formula of Penman
- Formula of Doorenbos et Pruitt
- Formula of Brochet-Gerbier
- Formula of Priestley-Taylor
- Formula of Penman-Monteith, etc.

***ET_0 depends on climate, essentially**

Examples of formulas to calculate ET_0

Blaney-Criddle's formula

$$ET_o = (8.13 + 0.46\,t)\,p$$

ET_o : reference evapotranspiration, in mm/month

t : mean monthly temperature, in °C

p : clear-sky percentage, f (latitude)

Turc's formula

$$ET_o = 0.4(R_s + 50)\frac{t}{t+15}$$

R_s : radiation globale, en cal/cm^2 j

If R_s is unknown:

$$R_s = R_a\left(0.18 + 0.62\frac{n}{N}\right)$$

R_a : extra-terrestrial radiation, in cal/cm^2 j

N : possible astronomical sunshine duration (h/month)

n : effective sunshine duration (h/month)

R_a et N : function of location and latitude, only

Clear-sky percentage (Blaney-Criddle's formula)

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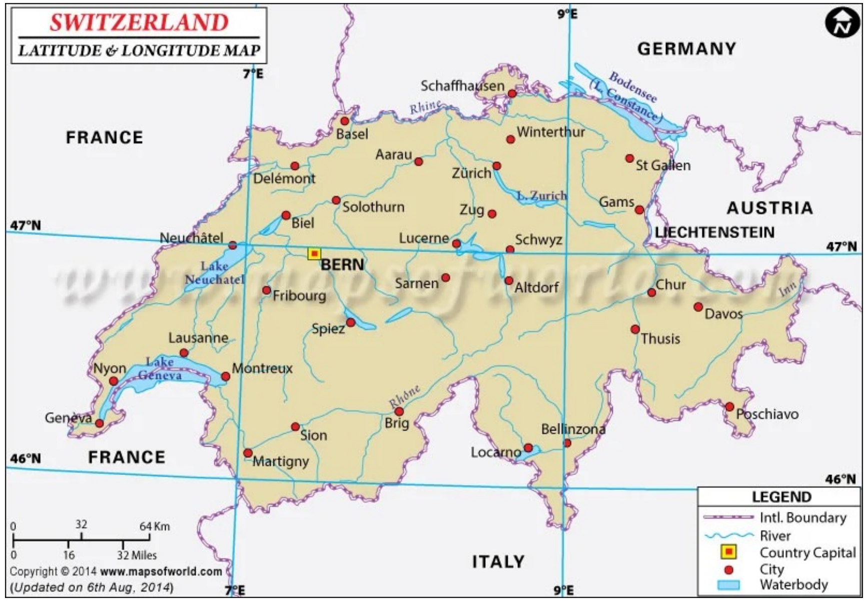
Mean daily percentage values, p, of clear-sky

Latitude Nord	Jan.	Fév.	Mars	Avr.	Mai	Juin	Juil.	Août	Sept.	Oct.	Nov.	Déc.
Latitude Sud	Juil.	Août	Sept.	Oct.	Nov.	Déc.	Jan.	Fév.	Mars	Avr.	Mai	Juin
60°	0.15	0.20	0.26	0.32	0.38	0.41	0.40	0.34	0.28	0.22	0.17	0.13
58°	0.16	0.21	0.26	0.32	0.37	0.40	0.39	0.34	0.28	0.23	0.18	0.15
56°	0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.16
54°	0.18	0.22	0.26	0.31	0.36	0.38	0.37	0.33	0.28	0.23	0.19	0.17
52°	0.19	0.22	0.27	0.31	0.35	0.37	0.36	0.33	0.28	0.24	0.20	0.17
50°	0.19	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.20	0.18
48°	0.20	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.21	0.19
46°	0.20	0.23	0.27	0.30	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.20
44°	0.21	0.24	0.27	0.30	0.33	0.35	0.34	0.31	0.28	0.25	0.22	0.20
42°	0.21	0.24	0.27	0.30	0.33	0.34	0.33	0.31	0.28	0.25	0.22	0.21
40°	0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
35°	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.25	0.23	0.22
30°	0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.30	0.28	0.26	0.24	0.23
25°	0.24	0.26	0.27	0.29	0.30	0.31	0.31	0.29	0.28	0.26	0.25	0.24
20°	0.25	0.26	0.27	0.28	0.29	0.30	0.30	0.29	0.28	0.26	0.25	0.25
15°	0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.25
10°	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.26
5°	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27
0°	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

e.g., Latitude Lausanne: 46°30



Note: for monthly calculations, multiply the values in the table by the number of days in the month in question.

Penman's formula

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$$ET_o = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \left(1 - \frac{\Delta}{\Delta+\gamma}\right)(e_s - e_a)\, f(U_2)$$

ET_0	:	reference evapotranspiration(mm d^{-1})
D	:	slope of vapour pressure curve, at mean air temperature (mbar $^oC^{-1}$)
R_n	:	net radiation, expressed as equivalent evaporation (mm d^{-1})
G	:	soil heat flux (mm d^{-1}); often neglected
g	:	psychrometric constant (0.66 mbar $^oC^{-1}$)
e_s	:	saturation vapour pressure at mean air temperature (mbar)
e_a	:	vapour pressure in air, at 2 m height (mbar)

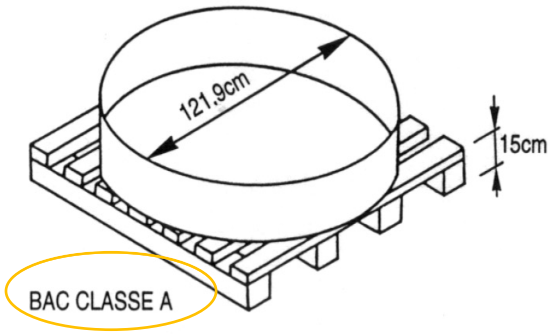
For a cultivated area in our region: $f(U_2) = 0.26\,(1 + 0.54\, U_2)$

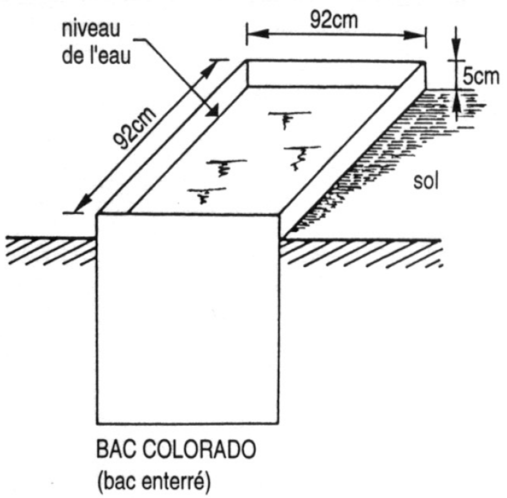
U_2 : average wind speed at 2 m height (m s^{-1})

Required data:

Net radiation
Air temperature
Vapour pressure
Wind speed

Estimate of ET_0 from PAN evaporimeter





$$ET_0 = k_p \, ET_{PAN}$$

Bac classe A	Cas A - Bac environné d'une culture verte courte				Cas B * - Bac environné d'une jachère sèche			
HR moyenne %		Faible < 40	Moy. 40-70	Forte > 70		Faible < 40	Moy. 40-70	Forte > 70
Vent [km/jour]	Distance de la culture verte du côté exposé au vent [m]				Distance de la jachère sèche du côté exposé au vent [m]			
Léger < 175	0	0.55	0.65	0.75	0	0.70	0.80	0.85
	10	0.65	0.75	0.85	10	0.60	0.70	0.80
	100	0.70	0.80	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.50	0.60	0.70
Modéré 175 - 425	0	0.50	0.60	0.65	0	0.65	0.75	0.80
	10	0.60	0.70	0.75	10	0.55	0.65	0.70
	100	0.65	0.75	0.80	100	0.50	0.60	0.65
	1000	0.70	0.80	0.80	1000	0.45	0.55	0.60
Fort 425 - 700	0	0.45	0.50	0.60	0	0.60	0.65	0.70
	10	0.55	0.60	0.65	10	0.50	0.55	0.65
	100	0.60	0.65	0.70	100	0.45	0.50	0.60
	1000	0.65	0.70	0.75	1000	0.40	0.45	0.55
Très fort > 700	0	0.40	0.45	0.50	0	0.50	0.60	0.65
	10	0.45	0.55	0.60	10	0.45	0.50	0.55
	100	0.50	0.60	0.65	100	0.40	0.45	0.50
	1000	0.55	0.60	0.65	1000	0.35	0.40	0.45

Maximal evapotranspiration ETM

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Actual evapotranspiration depends on many factors (type of crop, vegetative stage, state of health, water availability, soil fertility, etc.).

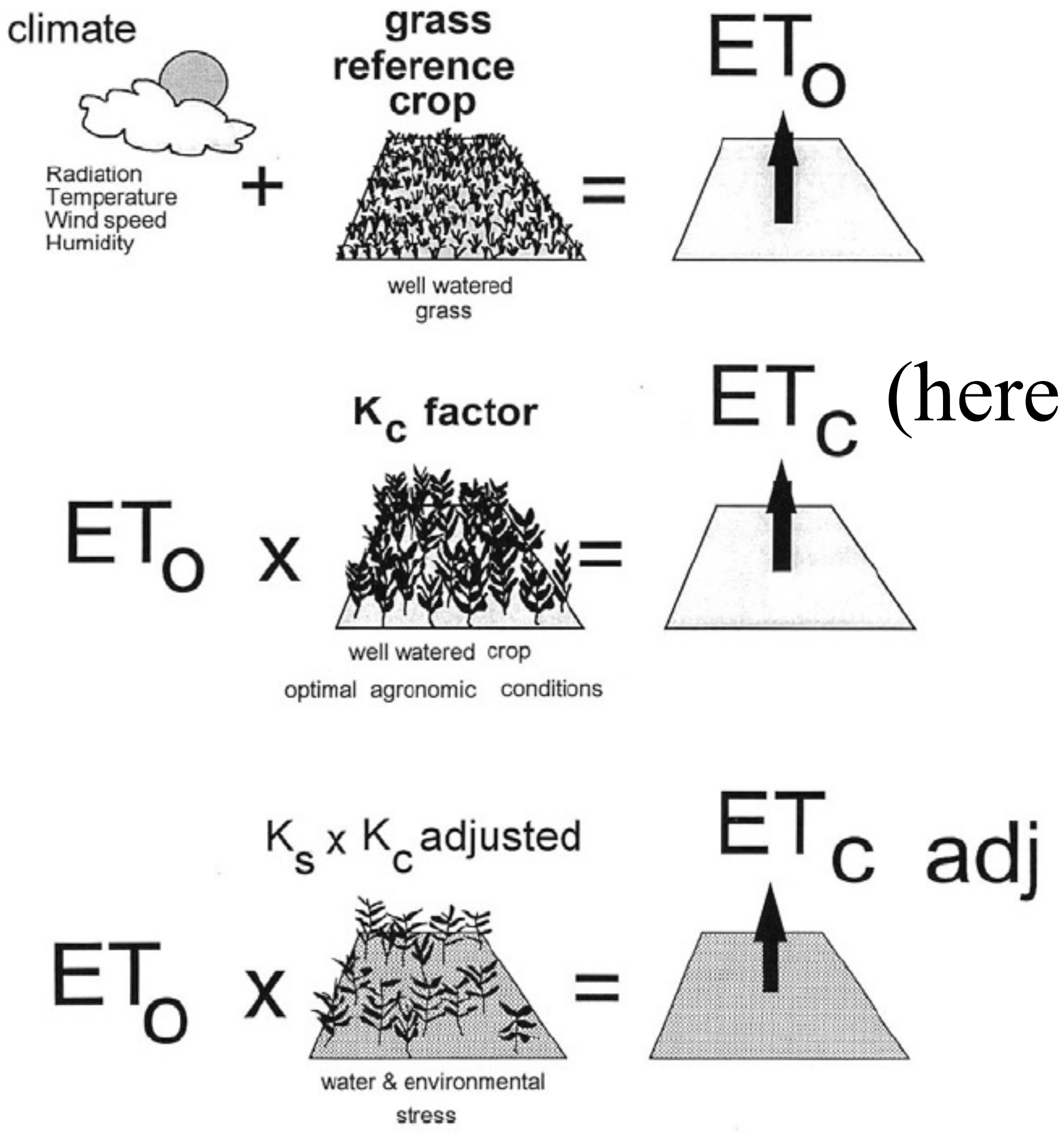
When it comes to irrigation, the aim is to place plants in optimum production conditions, and irrigation is based on the value of maximum evapotranspiration (ETM).

The ETM characterises the evapotranspiration of a given crop, at different stages of growth, when :

- **water is not a limiting factor**
- **agronomic conditions are optimal (good soil fertility, sufficient fertiliser inputs, good health, etc.)**

$$ETM = K_c \, ET_o$$

Correction factor for crop evapotranspiration (FAO method)



(here ETM)

Reference conditions

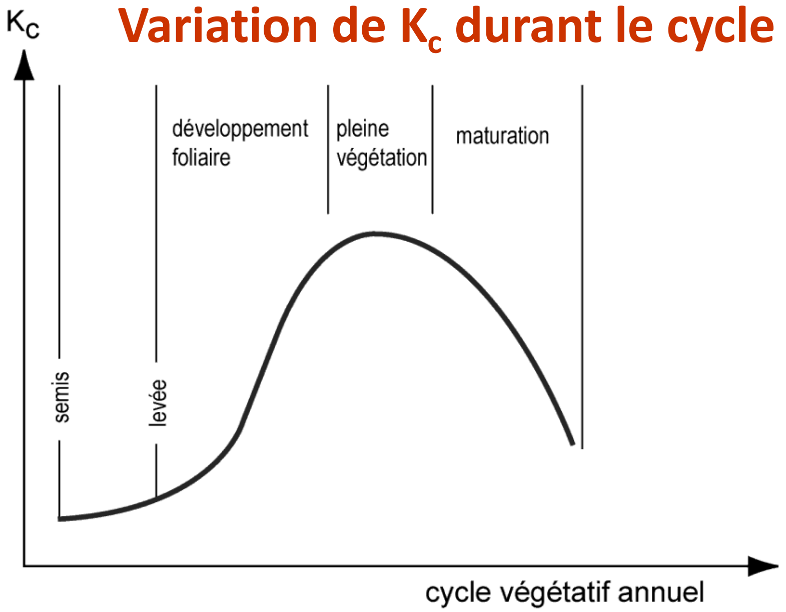
Standard conditions

Non-standard conditions

Crop coefficient K_c

Cultures	Amplitude totale	Période de pointe
Céréales(blé, avoine, orge, maïs, mil, sorgho)	0.2 - 1.2	1.05 - 1.2
Luzerne, trèfle, fourrage	0.3 - 1.25	1.05 - 1.25
Riz	0.95 - 1.35	1.05 - 1.35
Coton	0.2 - 1.25	1.05 - 1.25
Betteraves à sucre	0.2 - 1.2	1.05 - 1.2
Carottes, céleris, pommes de terre	0.2 - 1.15	1.0 - 1.15
Melons, épinards	0.2 - 1.05	0.55 - 1.05
Oignons, crucifères	0.2 - 1.1	0.95 - 1.1
Tomates	0.2 - 1.25	1.05 - 1.25

Variation de K_c durant le cycle végétatif



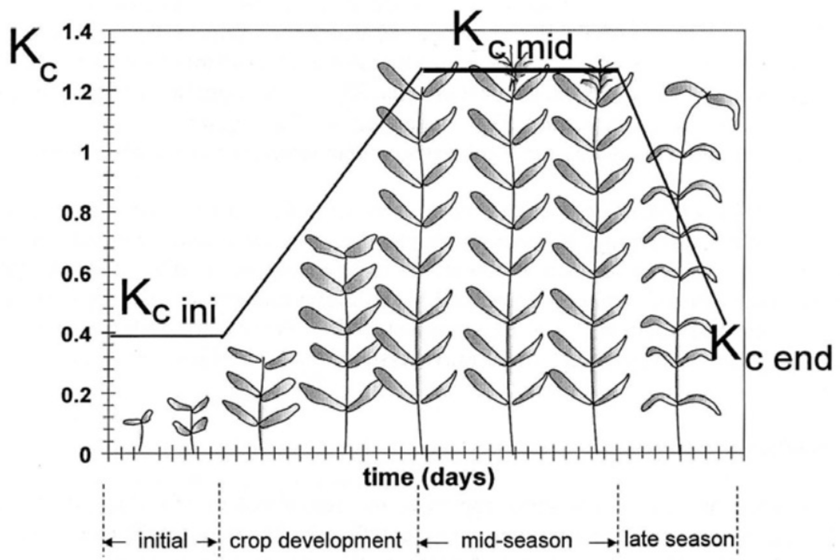
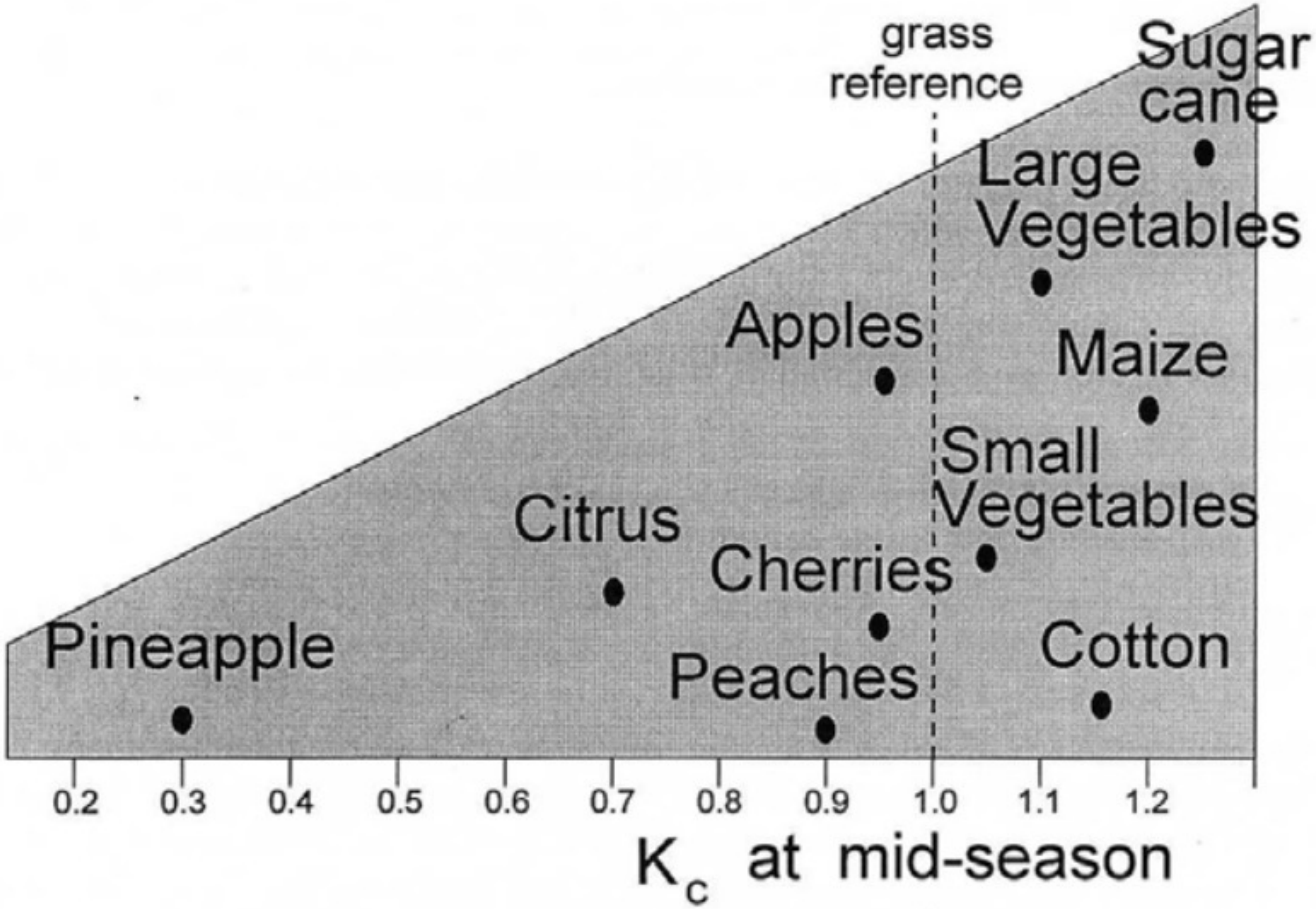
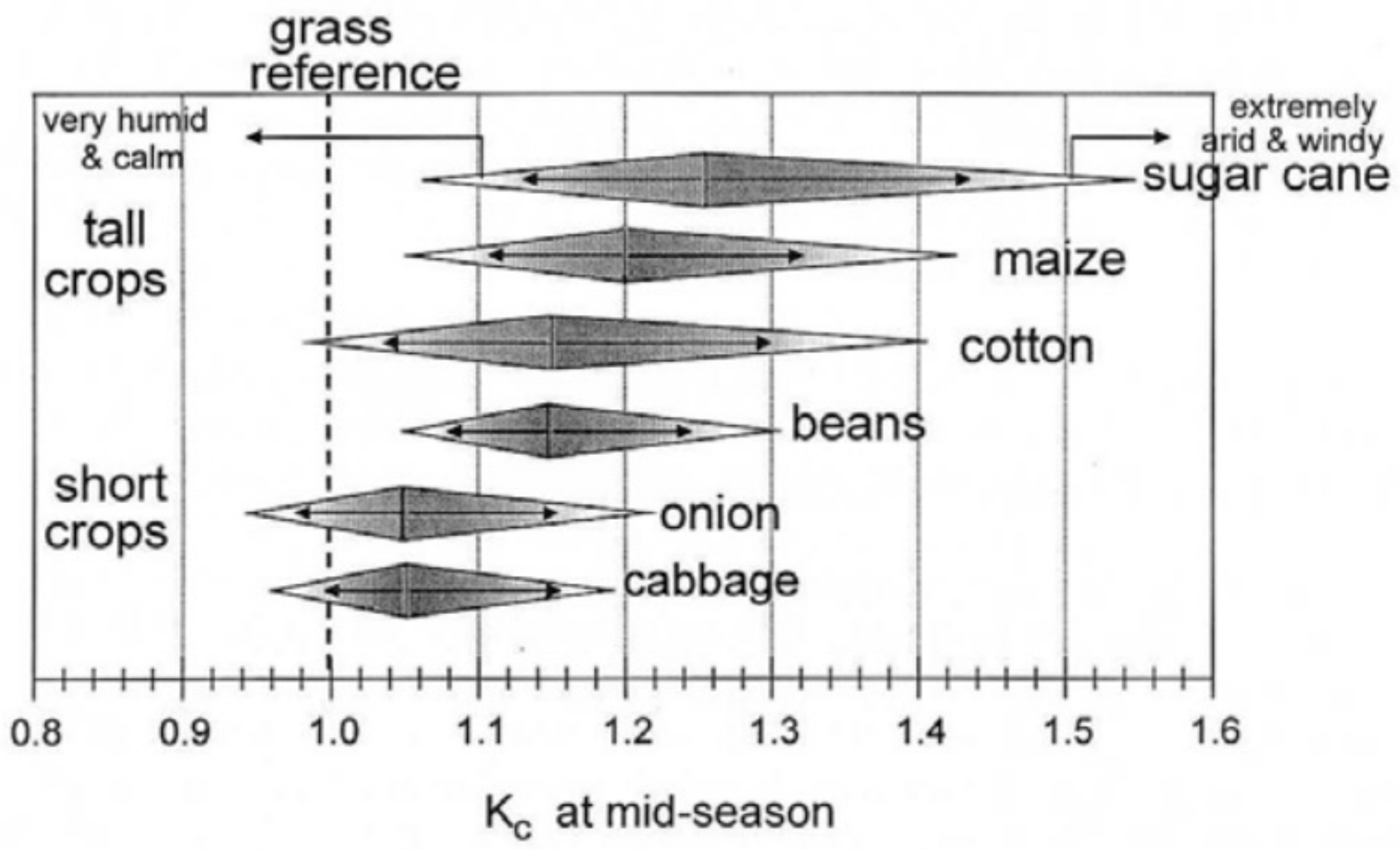


FIGURE 20
Typical K_C for different types of full grown crops



Typical range values of k_c

FIGURE 21
Extreme ranges expected in K_c for full grown crops as climate and weather change



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	45	15	125	April	Mediterranean
	30	55	105	20	210	Jan	(Semi)Arid
Crucifers[1]	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan.	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	October	Arid Region
	30	55	55	40	180	March	Calif., USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean
	20	30	40	10	100	November	Arid Region
Radish	5	10	15	5	35	Mar/Apr	Medit.; Europe
	10	10	15	5	40	Winter	Arid Region
b. Vegetables – Solanum Family *(Solanaceae)*							
Egg plant	30	40	40	20	130\1	October	Arid Region
	30	45	40	25	40	May/June	Mediterranean
Sweet peppers (bell)	25/30	35	40	20	125	April/June	Europe and Medit.
	30	40	110	30	210	October	Arid Region
Tomato	30	40	40	25	135	January	Arid Region
	35	40	50	30	155	Apr/May	Calif., USA
	25	40	60	30	155	Jan	Calif. Desert, USA
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
c. Vegetables – Cucumber Family *(Cucurbitaceae)*							
Cantaloupe	30	45	35	10	120	Jan	Calif., USA
	10	60	25	25	120	Aug	Calif., USA
Cucumber	20	30	40	15	105	June/Aug	Arid Region
	25	35	50	20	130	Nov; Feb	Arid Region
Pumpkin, Winter squash	20	30	30	20	100	Mar, Aug	Mediterranean
	25	35	35	25	120	June	Europe
Squash, Zucchini	25	35	25	15	100	Apr; Dec.	Medit.; Arid Reg.
	20	30	25	15	90	May/June	Medit.; Europe

continued...

* Lengths of crop development stages provided in this table are indicative of general conditions, but may vary substantially from region to region, with climate and cropping conditions, and with crop variety. The user is strongly encouraged to obtain appropriate local information.

1 Crucifers include cabbage, cauliflower, broccoli, and Brussel sprouts. The wide range in lengths of seasons is due to varietal and species differences.

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
b. Vegetables – Solanum Family (*Solanaceae*)	**0.6**	**1.15**	**0.80**	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables – Cucumber Family (*Cucurbitaceae*)	**0.5**	**1.00**	**0.80**	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber – Fresh Market	0.6	1.00[2]	0.75	0.3
– Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	**0.5**	**1.10**	**0.95**	
Beets, table		1.05	0.95	0.4
Cassava – year 1	0.3	0.80[3]	0.30	1.0
– year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70[5]	0.5

continued...

1 These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\ ini}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30, or Equation 7-3 in Annex 7, or using the dual $K_{cb\ ini} + K_e$.

2 Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_c values need to be taken. For green beans, peppers and cucumbers, 1.15 can be taken, and for tomatoes, dry beans and peas, 1.20. Under these conditions h should be increased also.

3 The midseason values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\ end}$ values account for dormancy during the dry season.

4 The $K_{c\ end}$ value for potatoes is about 0.40 for long season potatoes with vine kill.

5 This $K_{c\ end}$ value is for no irrigation during the last month of the growing season. The $K_{c\ end}$ value for sugar beets is higher, up to 1.0, when irrigation or significant rain occurs during the last month.

Determination of the effective precipitation

- heavy rainfall can lead to significant runoff
- very light rainfall (less than 5 or 10 mm) does little to replenish the soil
- part of the rain may percolate deep into the soil (macropores or retention capacity exceeded)

$$P_e = \alpha P$$

The abatement coefficient α can be estimated on the basis of a frequency study of rainfall compared with the initial moisture content of the soil and its hydrodynamic properties (infiltration capacity, storage capacity of the root zone, etc.).

Normally, it is considered: $0.5 < \alpha < 0.8$

Estimation of the reserve, R

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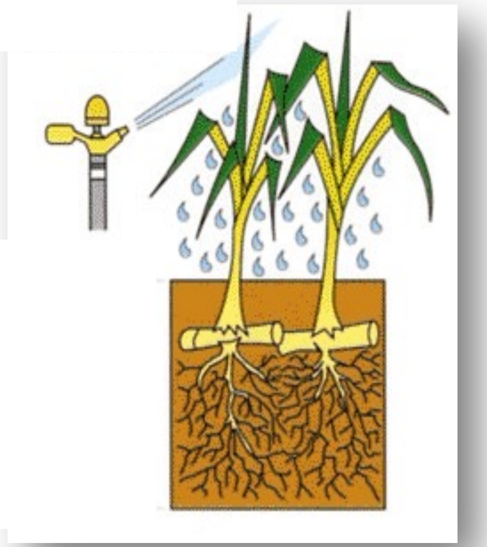
The reserve, R, is the amoint of water in the soil (moisture) that may be available to plants at the start of the period for which water requirements are calculated.

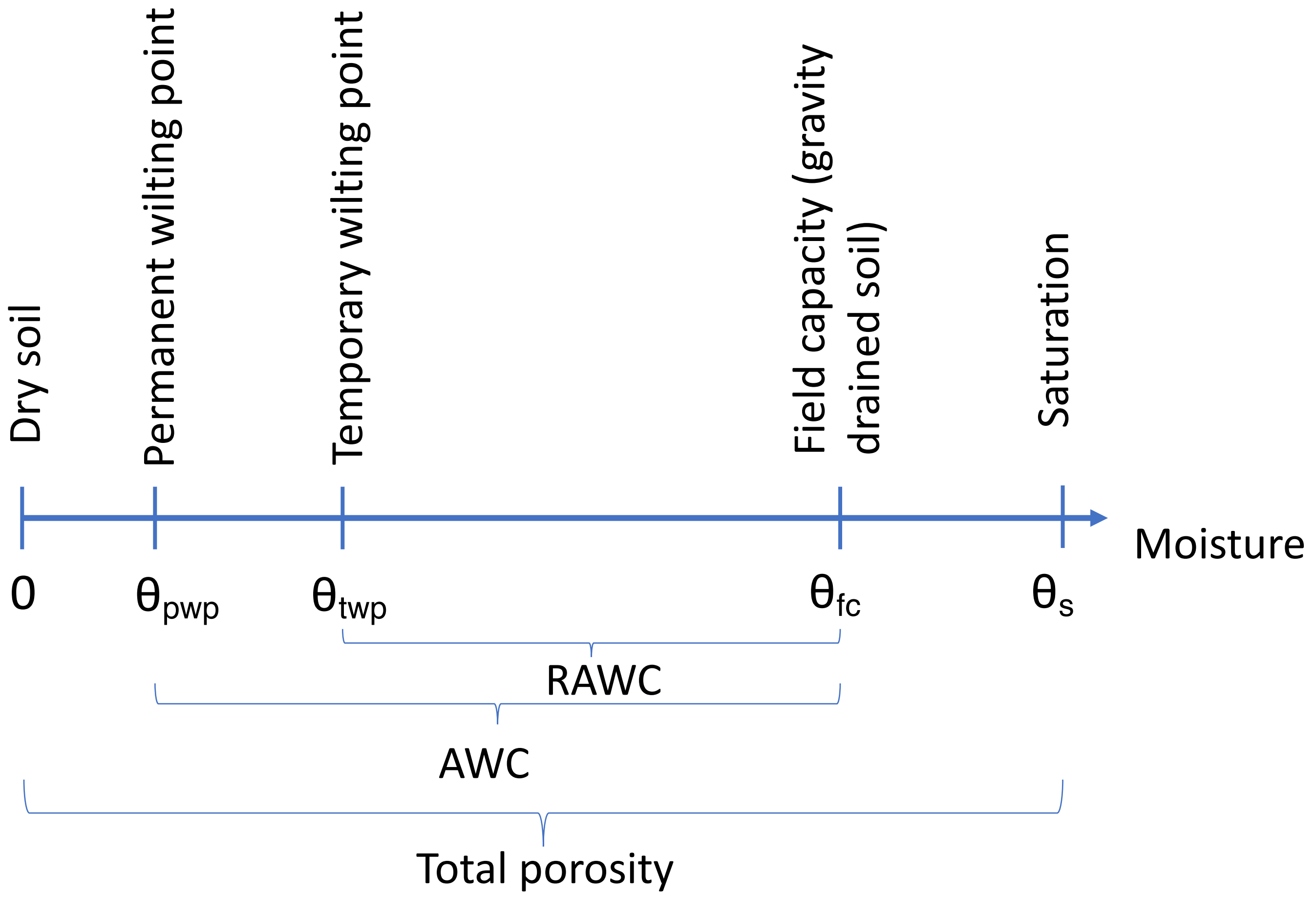
Estimating R is tricky because it depends on many factors (rainfall regime, soil type, root depth, etc.).

Different approaches are possible :

- Calculate the water balances starting at a period when the reserve can be reasonably estimated (e.g. late summer, when it can often be considered negligible).
- Adopt a pessimistic hypothesis (zero reserve), which will lead to a slight oversizing of the network
- Adopt a plausible assumption, if sufficient data are available, often is



$$R = f\,RAW \qquad (0 < f < 1)$$



TAW: Total Available Water [mm]

RAW: Readable Usable Water [mm]

θ_{fc}: retention capacity (field capacity)
θ_{twp} : temporary wilting point
θ_{pwp} : permanent wilting point [$m^3\ m^{-3}$]

z_r= rooting depth [mm]

$$TAW = (\theta_{fc} - \theta_{pwp}) * z_r = AWC * z_r$$

$$RAW = (\theta_{fc} - \theta_{twp}) * z_r = RAWC * z_r$$

Empirical assumptions in the absence of measured data

$$\theta_{pwp} = 0.55 * \theta_{fc}$$

$$RAWC = 0.66 * AWC$$

Estimation of net water need from irrigation

$$B_n = ETM - Pe - R$$

B_n: net irrigation water requirements

ETM: maximum evapotranspiration

P_e: effective precipitation

R: reserve available at the start of the calculation period

$$B_n = K_c\, ET_o - \alpha\, P - R$$

ET0 also from PAN evaporimeter (see notes)

K_c: crop coefficient

ET_0: reference evapotranspiration

α : rainfall reduction coefficient

P: total rainfall

Prediction[1] of net water needs from irrigation

- On the basis of a record of historical data (acquired in the past), the needs that have arisen in the past and for which the necessary data are available are calculated.
- The series of values for past needs (statistical sample) is used to predetermine future needs by means of a frequency analysis (be careful to non-stationary effects, e.g. climate change!).
- This sample is then linked to a statistical model (frequency model) which provides information on all possible values of requirements with a certain probability of occurrence. The frequency model can be used to determine the probability of occurrence of a given event[2].
- The value of requirements corresponding to a given frequency or return time can be deduced from this.

[1] used for dimensioning structures or planning developments

[2] greater than or less than a specified value or between any 2 values

Return period (basic notions)

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Irrigation projects are designed on the basis of water requirements associated with a probable frequency of occurrence.

For example, we want to determine the probability $F(x_i)$ that requirements are < than a given value x_i :

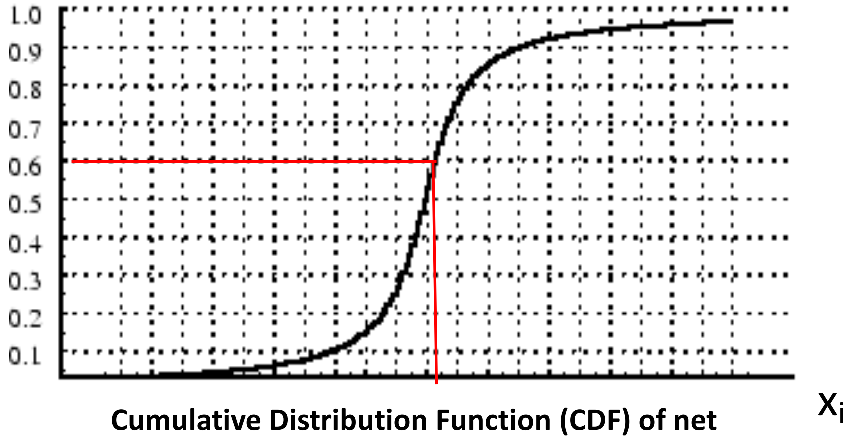
$$F(x_i) = P(B_n \leq x_i)$$

$F(x_i)$: cumulative distribution function = probability of not being exceeded

$1 - F(x_i)$: probability of being exceeded or frequency of occurrence

The return period T of an event is the inverse of the frequency of occurrence of the event (at the chosen time unit) :

$$T = \frac{1}{1 - F(x_i)}$$



Cumulative Distribution Function (CDF) of net requirements in a given place and for a given period

Water needs with a return time T will only be exceeded, on average, once every T years..

Example of calculus

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

$$B_n = K_c\, ET_o - \alpha\, P - R$$

Année	Paramètres climatiques			ET_o	$K_c\, ET_o$	$\alpha\, P$	R	Bn
	Temp.	Rayon.	etc.					
1940								
1941								
1942								
1943								
1944								
……								
1998								
1999								
2000								
2001								
2002								
2003								

Exemple de calculs des besoins en eau en vue d'une analyse fréquentielle

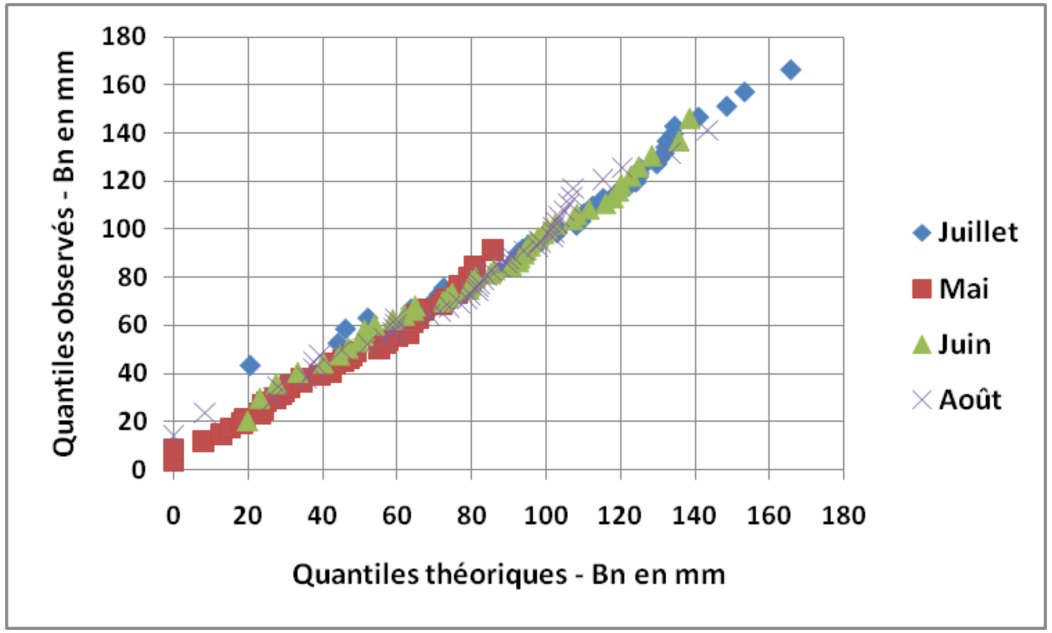
This is valid for a given crop and a given month.

The Return period will therefore be in years and referring to that specific month

Example of comparison with a gaussian statistical model

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

Quantiles-Quantiles chart of net requirement values



Example of comparing monthly net irrigation needs to a normal distribution

Q - Q graph: graphical representation of the tested variable plotted on the ordinate (observed quantiles of the sample) versus the inverse function of the statistical model being tested (theoretical quantiles of the law under consideration). If the points are aligned on a straight line, we can accept that the data comes from the model being tested.

Theoretical quantiles: values of the inverse distribution model tested for the experimental frequency under consideration.