Irrigation and Drainage Engineering

(Soil Water Regime Management)

(ENV-549, A.Y. 2024-25)

4ETCS, Master option

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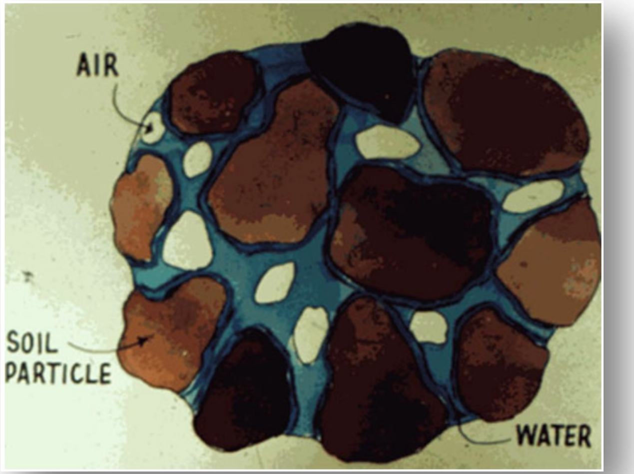
Platform of Hydraulic Constructions



Source: Waller & Ytayew, 2017

Lecture 2-1: Elements of soil physics and water quality

Gravimetric vs volumetric soil water content

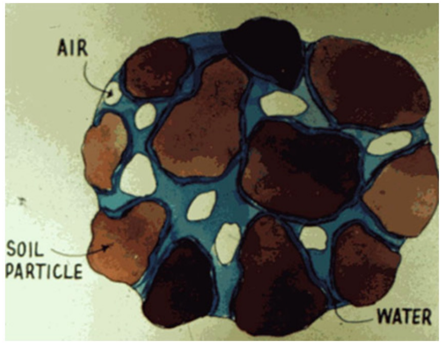
Soil porosity

$$n = \frac{V_a + V_w}{V_s}$$

Where

$$V_s = V_a + V_w + V_m$$

(air+water+mineral)



Gravimetric soil moisture (weight based)*

$$\theta_{grav} = \frac{m_{water}}{m_{dry\ \ soil}} = \frac{m_{wet\ \ soil} - m_{dry\ \ soil}}{m_{dry\ \ soil}}$$

where

θ_{grav} = gravimetric water content, gm/gm
m_{water} = mass of water, gm.
$m_{dry\ soil}$ = mass of soil after drying, gm.
$m_{wet\ soil}$ = mass of soil before drying, gm.

* Dry soil: drying in owen for 24h at 105°C

Volumetric soil moisture

$$\theta_V = \frac{V_w}{V_s} = \frac{V_w}{V_a + V_w + V_m}$$

Volumetric vs gravimetric

$$\theta_V = \frac{V_w \rho_W \rho_b}{V_s \rho_W \rho_b} = \frac{m_w \rho_b}{m_{dry\,soil} \rho_W} = \theta_{grav} \frac{\rho_b}{\rho_W}$$

Relative soil moisture

$$s = \frac{V_w}{V_a + V_w} = \frac{\theta_V}{n}$$

Example(s)

A soil sample collected before irrigation weighs 1.73 kg, and the soil collected just after irrigation weights 1.94 kg. Both soils are placed in an oven and dried at 100 °C for 24 hours. After drying, the soil collected just before irrigation weighs 1.49 kg and the soil collected just after irrigation weighs 1.52 kg. What are the volumetric water contents just before and just after irrigation?

Solution:
Gravimetric water content just before irrigation

$$\theta_{grav} = \frac{1.79\ \ kg - 1.49\ \ kg}{1.49\ \ kg} = 0.20 = 20\%$$

Gravimetric water content just after irrigation

$$\theta_{grav} = \frac{1.94\ \ kg - 1.52\ \ kg}{1.52\ \ kg} = 0.27 = 27\%$$

Water content collected two days after irrigation is close to field capacity because the soil has drained, but there has been little evaporation after drainage.

The soils described in previous Example have bulk density 1.3 g/cm^3. Find the volumetric water contents and porosity of the two samples.

Solution:
Volumetric water content just before irrigation

$$\theta_v = \theta_{grav}\rho_b = (0.20\ \ g/g)\left(1.3\ \ g/cm^3\right) = 0.26 = 26\%$$

Volumetric water content just after irrigation

$$\theta_v = \theta_{grav}\rho_b = (0.27\ \ g/g)\left(1.3\ \ g/cm^3\right) = 0.36 = 36\%$$

The bulk density is 1.3 g/cm^3 and soil particle density is 2.65 g/cm^3.

$$\phi = 100 - \left(\frac{1.3}{2.65}\right)\ (100) = 51\%$$

This means that 51 % of the soil volume is filled with air or water.

Saturated vs unsaturated soils

Saturated soils*: θ_{sat}
Almost all voids are full of water

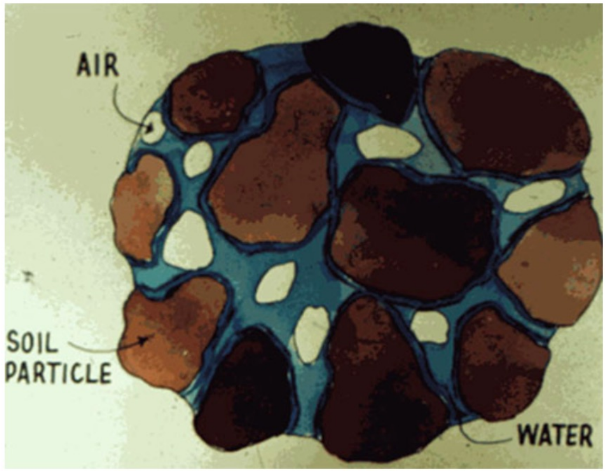
Soil moisture (at saturation)=porosity

$$\theta_{sat} = n$$

*Note: High water content is not desirable because it restricts oxygen diffusion from the atmosphere into the soil because most of the soil pores are occupied by water: oxygen diffusion is approximately 1,000 times greater in a gas than it is in water. This lack of oxygen restricts oxygen uptake by plant roots during respiration.

Field capacity: θ_{FC}
Saturated soil freely drained by gravity only

Soil texture	Time to Field capacity
Coarse	Few hours
Medium	1 day
Fine	Several days

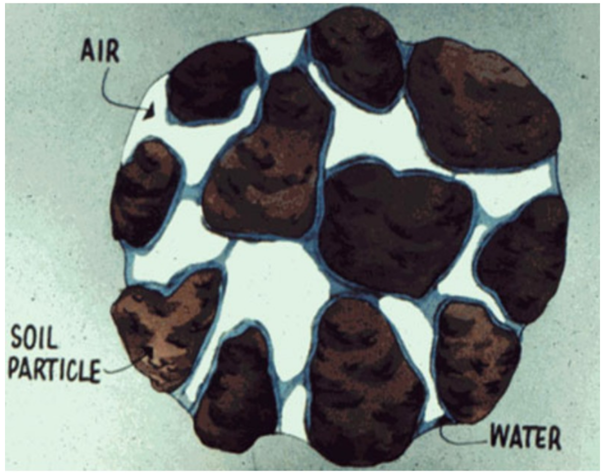


Source: Waller & Ytayew, 2017

Permanent wilting point: θ_{PWP}
Water content at which (a given) crop cannot remove water without preventing wilting of the stomata

Plant water stress

Generically assumed to happen when
~-1.5 Mpa = -15 bar



Source: Waller & Ytayew, 2017

Soil Water Potential

Matric (hydraulic) potential energy, elevation (gravitation), and chemical (osmotic), are all components of the total energy of water in soils, H*

$$H = \frac{P}{\rho g} + z + \psi_s = \psi_p + z + \psi_s$$

where

ψ_s = osmotic potential, m
ψ_p = capillary or hydraulic (pressure) potential (also equal to h_c in m
z = elevation, m
P = pressure, N/m^2
ρ = density of water, kg/m^3
g = gravity, 9.8 m/sec^2

*Note: thermal energy contributes as well to flow magnitude and direction (through viscosity but is not considered here. Kinetic energy is usually neglected

Water cohesion and evaporation energy

Water cohesion* is an important water property in soils and plants since water must flow from the soil to the plant root and then upward in the plant at extremely negative water potentials.

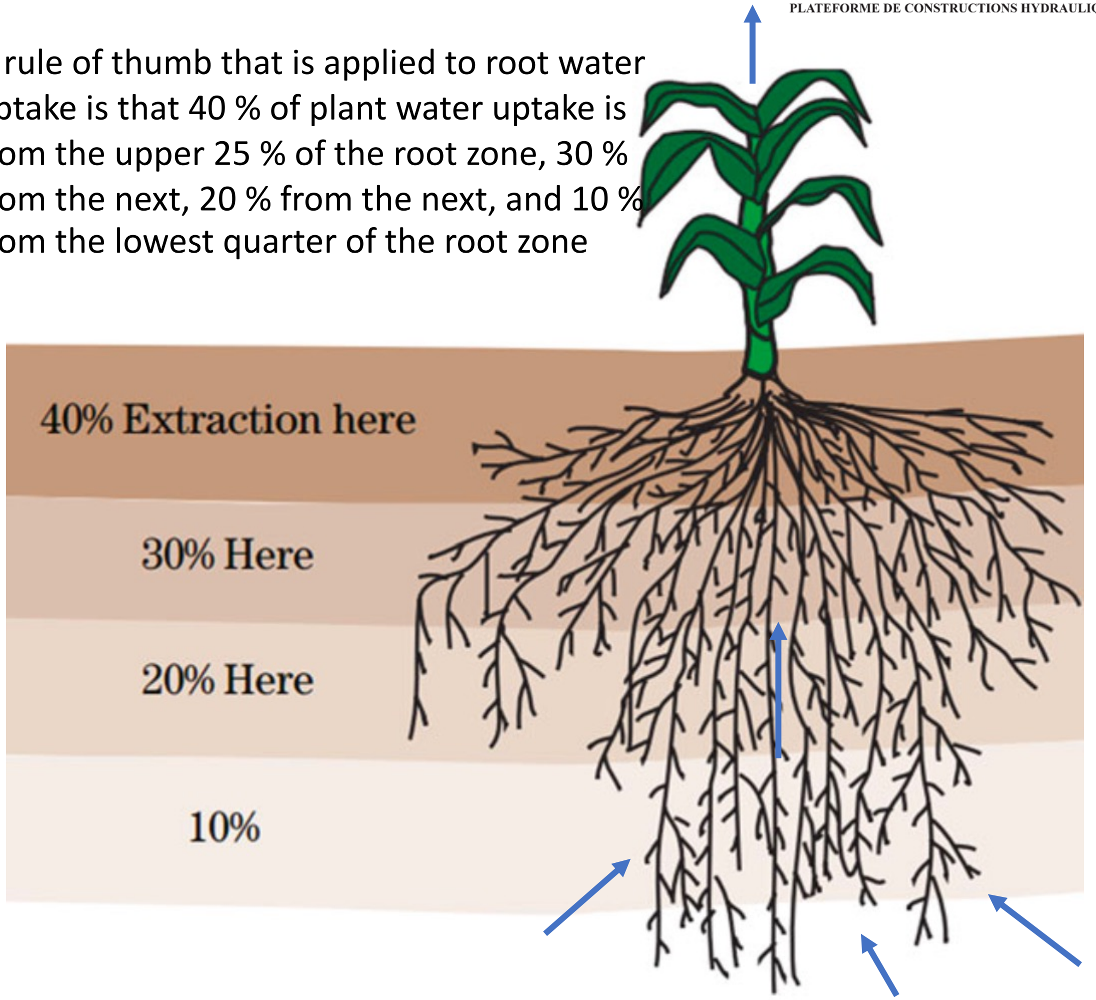
Water cohesion is the force of attraction due to polarity of the water molecule and has several names: hydrogen bonds, Van der Waal's force, or electrostatic attraction.

In the liquid state, water demonstrates cohesion up to a suction of approximately 30 MPa or 30,000 kPa (300 atmospheres or ca. 300 bar)

The energy in hydrogen bonds between water molecules is approximately 20 kJ/mole of water or 1100 kJ/kg;

The energy required to evaporate water, the latent heat of vaporization, is 2,450 kJ/kg. Thus, significant part of the energy used to evaporate water is used to break hydrogen bonds.

A rule of thumb that is applied to root water uptake is that 40 % of plant water uptake is from the upper 25 % of the root zone, 30 % from the next, 20 % from the next, and 10 % from the lowest quarter of the root zone



Source: Waller & Ytayew, 2017

* Cohesion: attraction vs same material

Adhesion: attraction vs other materials

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

Plant root depth-to-water extraction

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Table 3.2 Depth to which roots of mature crops will extract available water from a deep uniform, well-drained soil under average unrestricted conditions (depths shown are 80 % of the entire root zone depth). (Credit NRCS NAM 504-4)

Crop	Depth (m)	Crop	Depth (m)
Alfalfa	1.5	Milo	0.6–1.2
Asparagus	1.5	Mustard	0.6
Bananas	1.5	Onions	0.3–0.6
Beans, dry	0.6–0.9	Parsnips	0.6–0.9
Beans, green	0.6–0.9	Peanuts	0.6–0.9
Beets, table	0.6–0.9	Peas	0.6–0.9
Broccoli	0.6	Peppers	0.3–0.6
Berries, blue	1.2–1.5	Potatoes, Irish	0.6–0.9
Berries, cane	1.2–1.5	Potatoes, sweet	0.6–0.9
Brussels sprouts	0.6	Pumpkins	0.9–1.2
Cabbage	0.6	Radishes	0.3
Cantaloupes	0.9	Safflower	1.2
Carrots	0.6	Sorghum	1.2
Cauliflower	0.6	Spinach	0.3–0.6
Celery	0.3–0.6	Squash	0.9–1.2
Chard	0.3–0.6	Strawberries	0.3–0.6
Clover, Ladino	0.6–0.9	Sudan grass	0.9–1.2
Cranberries	0.3	Sugar beets	1.2–1.5
Corn, sweet	0.6–0.9	Sugarcane	1.2–1.5
Corn, grain	0.9–1.2	Sunflower	1.2–1.5
Corn, seed	0.9–1.2	Tobacco	0.9–1.2
Corn, silage	0.9–1.2	Tomato	0.9
Cotton	1.2–1.5	Turnips	0.6– 0.9
Cucumber	0.3–0.6	Watermelon	0.9– 1.2
Eggplant	0.6	Wheat	1.2
Garlic	0.3–0.6	Trees	
Grains and flax	0.9–1.2	Fruit	1.2–1.5
Grapes	1.5	Citrus	0.9–1.2
Grass pasture/hay	0.6–1.2	Nut	1.2–1.5
Grass seed	0.9–1.2		
Lettuce	0.3–0.6		
Melon	0.6–0.9		

From Musy et al (book)

Cultures maraîchères, en général	0.3	à	0.6 m
Pommes de terre	0.3	à	0.7 m
Carottes	0.5	à	1.0 m
Tomates	0.7	à	1.3 m
Herbe	0.4	à	0.6 m
Céréales, en général	0.6	à	1.5 m
Maïs	0.8	à	1.6 m
Orge	1.0	à	1.5 m
Riz	0.5	à	0.7 m
Coton	0.75	à	1.7 m
Betterave à sucre	0.6	à	1.2 m
Canne à sucre	0.8	à	1.8 m
Tabac	0.5	à	0.9 m
Vigne	1	à	2.0 m
Arbres fruitiers	1	à	2.0 m

Total available water and Depletion

The difference between field capacity and permanent wilting point is called available water capacity

$$AWC = \theta_{FC} - \theta_{PWP}$$

The Soil Water Holding Capacity (SWHC) or Total Available Water (TAW) is the depth of water in the soil available for growth

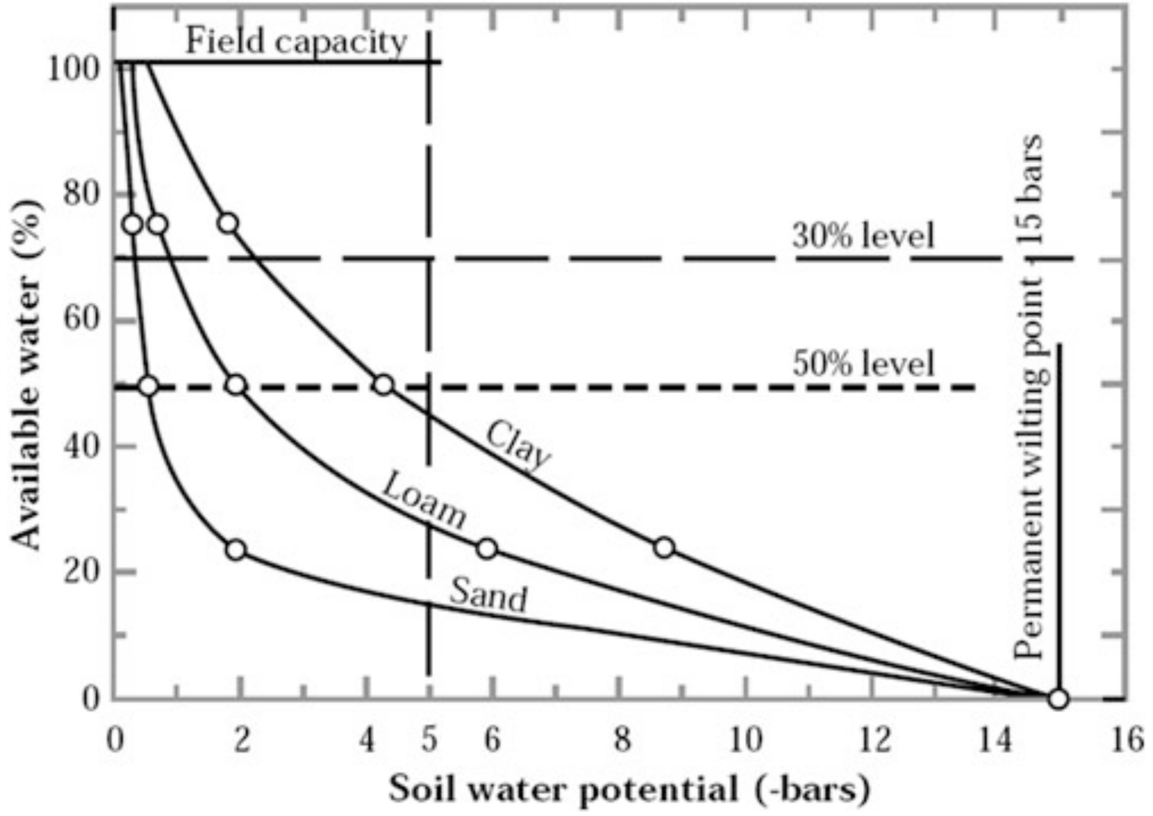
$$SWHC = TAW = (\theta_{FC} - \theta_{PWP})z_R{}^*$$

Depletion is the depth of water removed from the soil by evapotranspiration (starting from θ_{FC})

$$D_r = (\theta_{FC} - \theta)z_R$$

Percent Depletion %Dep

$$\%Dep = \frac{D_r}{TAW} * 100 = \frac{(\theta_{FC} - \theta)}{(\theta_{FC} - \theta_{PWP})} * 100$$



*z_R is the root zone depth

Management Allowable Depletion and Readily Available Water

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Percent depletion with no yield reduction for specific crop is called Management Allowable Depletion (MAD)

In general, soil water content should remain above the 30 % depletion line (MAD 1⁄4 30 %) for drought sensitive crops and above 50 % depletion for drought tolerant crops in order to avoid yield reduction.

The Readily Available Water (RAW) is the depth of water available to the plant between irrigation events

$$RAW = TAW * MAD$$

Table 3.3 Recommended Management Allowed Depletion (MAD) values for loamy soils (Credit NRCS)

	Establishment	Vegetative	Flowering	Ripening
Alfalfa hay	50	50	50	50
Alfalfa seed	50	60	50	80
Beans, green	40	40	40	40
Beans, dry	40	40	40	40
Citrus	50	50	50	50
Corn, grain	50	50	50	50
Corn, seed	50	50	50	50
Corn, sweet	50	40	40	40
Cotton	50	50	50	50
Cranberries	40	50	40	40
Garlic	30	30	30	30
Grains, small	50	50	40	60
Grapes	40	40	40	50
Grass pasture/hay	40	50	50	50
Grass seed	50	50	50	50
Lettuce	40	50	40	20
Milo	50	50	50	50
Mint	40	40	40	50
Nursery stock	50	50	50	50
Onions	40	30	30	30
Orchard, fruit	50	50	50	50
Peas	50	50	50	50
Peanuts	40	50	50	50
Potatoes	35	35	35	50[4/]
Safflower	50	50	50	50
Sorghum, grain	50	50	50	50
Spinach	25	25	25	25
Sugar beets	50	50	50	50
Sunflower	50	50	50	50
Vegetables				
30–60 cm root depth	35	30	30	35
90–120 cm root depth	35	40	40	40

Example

The root depth of an orange tree is z_R =1.5 m. The soil has 56 % solid particles, and 44 % voids. After drainage, the 50 % of the void volume contains water and 50 % holds air. At the wilting point, the void volume is 25 % water. What is the soil water holding capacity (SWHC)?

Solution

$$\theta_{FC} = 0.44 \ * \ 0.5 = 0.22 \rightarrow 22\%$$

$$\theta_{PWP} = 0.44 * 0.25 = 0.11 \rightarrow 11\%$$

$$AWC = \theta_{FC} \text{-} \ \theta_{PWP} = 0.22 - 0.11 = 0.11$$

$$TAW = SHWC = AWC * z_R = 0.11 * 1.5 = 0.165 \text{ m}^*$$

If the soil water content is θ=0.18, then

$$D_r = (\theta_{FC} - \theta) * z_R = (0.22 - 0.18) * 1.5 = 0.06 \text{ m}$$

and

$$\%Dep = \frac{(\theta_{FC} - \theta)}{(\theta_{FC} - \theta_{PWP})} * 100 = 54.5\%$$

If the crop has a MAD=0.4, then

$$RAW = TAW * MAD = 0.165 * 0.3 = 0.049 \text{ m}$$

$$= 4.9 \text{ cm}$$

*Note: Actually, only about half of the SWHC or TAW (total available water) is available to the plant so only about 8 cm of water would be available between irrigation events. This means that if the evapotranspiration rate was 1 cm/day, then the field would need to be irrigated every 8 day

Quality of the water used for irrigation purposes

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Physical quality

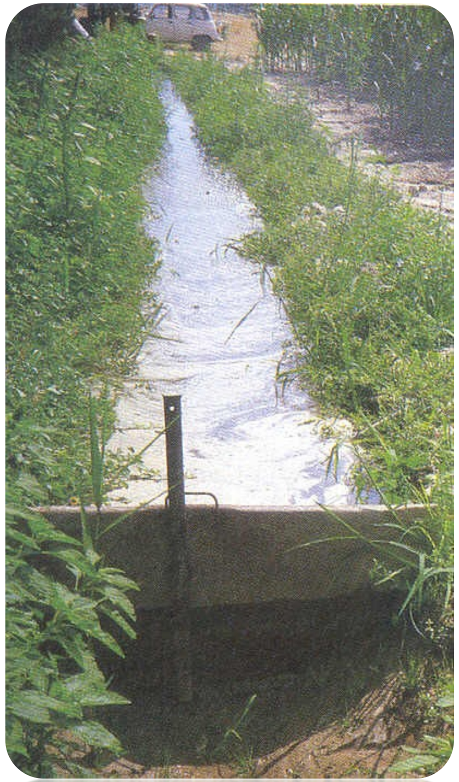
- Sediment content and vegetation particles and debris
- Temperature
- pH, etc.

Chemical quality

- Concentration of dissolved substances (CE, SAR)
- Ions potentially toxic at high concentrations (B, Cl, Na, HCO_3, etc.)
- Other substances possibly leading to precipitates (carbonates, Fe and Mn oxydes, sulfures, etc.)

Bacteriological quality

- Algaes, bacteria, fungi, spores, etc.



Presence of dissolved solutes

The presence of solutes (e.g., salt) dissolved in water causes several drawbacks

- increased osmotic pressure, making it harder for plants to mobilise water $\Psi = M + \Pi + \Omega + G$
- toxicity of certain ions to plants (B, Cl, Na, etc.)
- soil degradation (changes in structural state, reduced hydraulic conductivity, etc.)

Waters can be classified on the basis of the solutes concentration alone :

From electrical condutivity measures one can go back to the total salinity

$$C_{iw} = EC_{iw} \cdot 640$$

C_{iw} = total salinity of water, mg/L
EC_{iw} = electrical conductivity of the irrigation water, dS/m.

- Freshwater < 0.5 g/l
- Saline water from 0.5 to 1 g/l
- Very saline water from 1 to 3 g/l
- Brackish water > 3 g/l

(Sea water ranges between 33-37 g/l)

Salinity and osmotic potential energy

The osmotic potential energy in saturated soils can be calculated with the following equation:

$$\psi_s = -3.6 * EC_e \qquad (4.2)$$

where

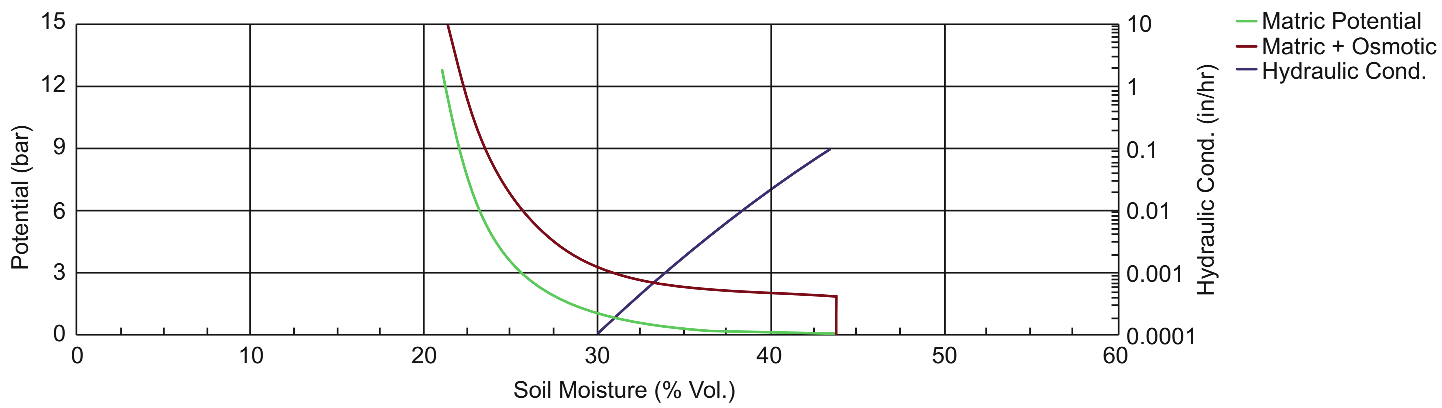
EC_e = electrical conductivity of the saturated paste extract, dS/m
ψ_s = Osmotic potential, m.

As the soil dries, the salinity increases. The osmotic potential as a function of water content is

$$\psi_s = -3.6 * EC_e * \frac{\theta_{sat}}{\theta} \qquad (4.3)$$

where

θ_{sat} = saturated water content (by volume), ml/ml
θ = actual water content (by volume), ml/ml



Appreciation indexes (salinity risk)

Risk of salinity

Electrical conductivity EC (CE) at 25 °C

Classes de risque :

CE ≤ 250 mS/cm	Risque faible
250 < CE ≤ 750	Risque moyen
750 < CE ≤ 2250	Risque élevé
CE > 2250	Risque très élevé

Risk of alcalinity

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

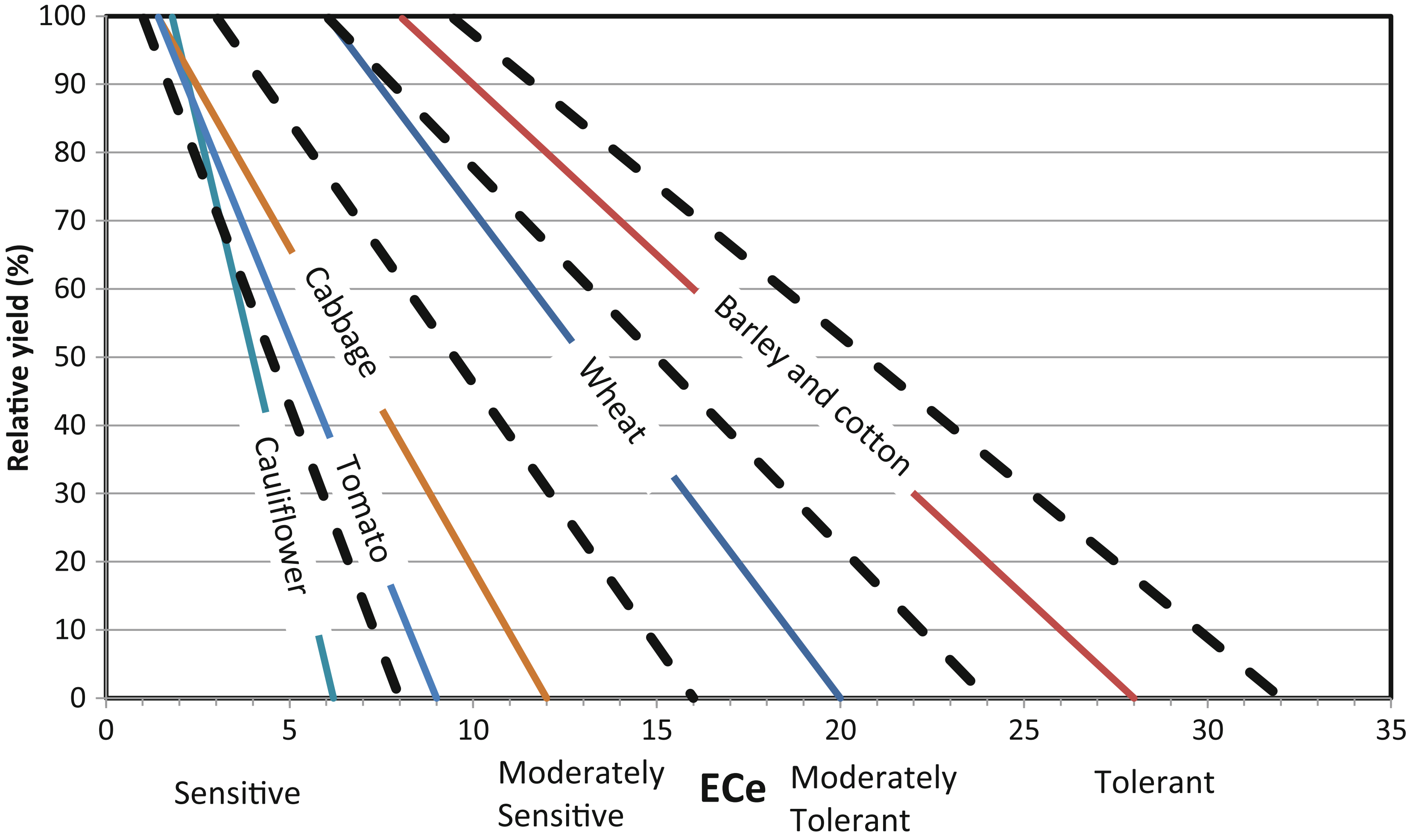
Na, Ca et Mg in $mmol_c/l$

Classes de risque :

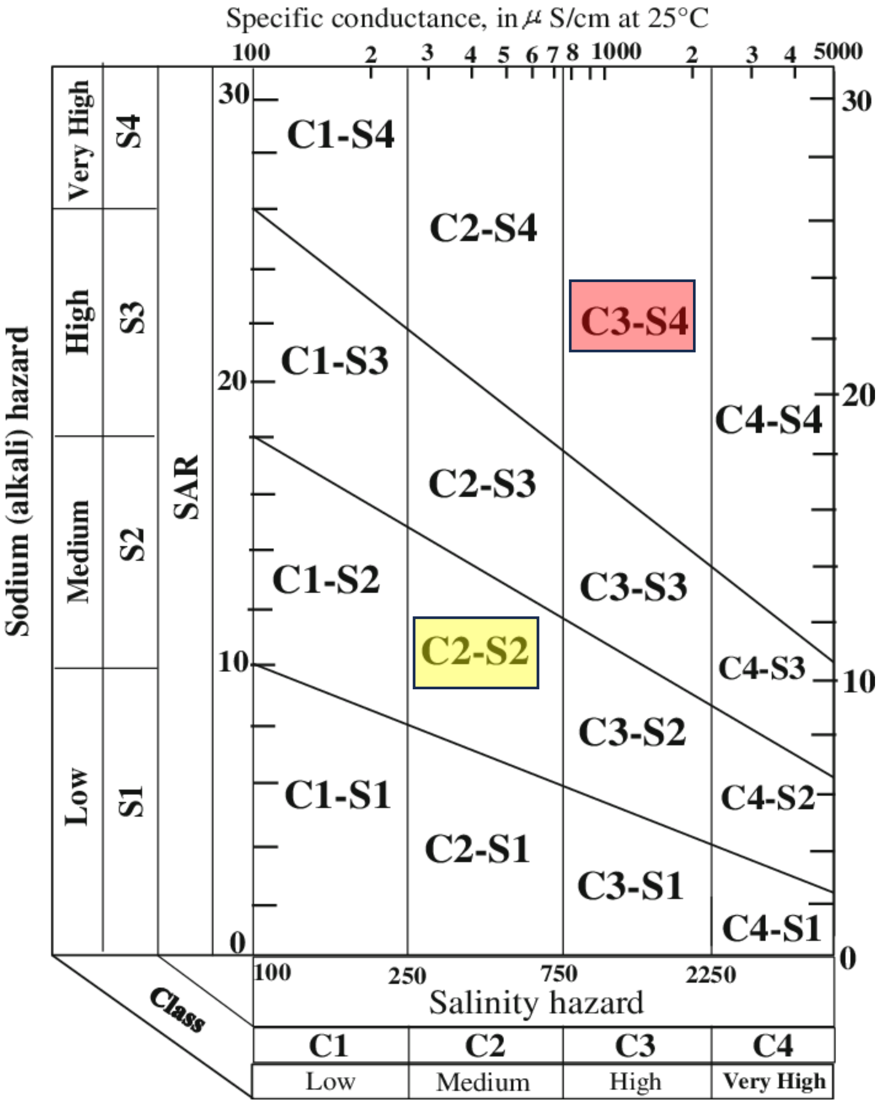
SAR* ≤ 10	Risque faible
10 < SAR ≤ 18	Risque moyen
18 < SAR ≤ 26	Risque élevé
SAR > 26	Risque très élevé

* SAR : sodium adsorption ratio

Salinity tolerance of some crops



Classification diagram for irrigation water quality



USA Soil salinity Laboratory

Interpretation of classes corresponding to saline risks - alkaline risks

C1 S1 *Good quality water.* Precautions with sensitive plants.

C1 S2 *Average to good quality.* Use with caution in heavy, poorly
C2 S1 drained soils and for sensitive plants (fruit trees).

C2 S2 *Average to poor quality*.
C1 S3 Use with caution. Need for drainage with doses of leaching
C3 S1 and/or addition of gypsum.

C1 S4 *Poor to mediocre quality*.
C2 S3 Exclude sensitive plants and heavy soils. Can be used with great
C3 S2 precautions in light and well drained soils with doses of leaching
C4 S1 and/or addition of gypsum.

C2 S4 *Poor quality*. To be used with great care,
C4 S2 only in light, well-drained soils and for resistant plants.
C3 S3 High risk. Leaching and addition of gypsum essential.

C3 S4 *Very poor quality*. Use only in exceptional
C4 S3 exceptional circumstances.

C4 S4 *Not recommended for irrigation*

Water quality assessment for irrigation use

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Nature des problèmes potentiels	Sans problème	Problèmes légers à modérés	Problèmes sérieux
Disponibilité de l'eau pour la plante			
CE (mS·cm^{-1})	< 750	750 - 3000	> 3000
Concentration totale (mg·l^{-1})	< 500	500 - 2000	> 2000
Toxicité spécifique			
Absorption par les racines			
Sodium (mg·l^{-1})	< 70	70 - 200	> 200
Chlorure (mg·l^{-1})	< 150	150 - 350	> 350
Bore (mg·l^{-1})	< 0.75	0.75 - 2	> 2
Absorption par les feuilles (aspersion)			
Sodium (mg·l^{-1})	< 70	> 70	
Chlorure (mg·l^{-1})	< 100	> 100	
Nuisances diverses			
Azote total (mg·l^{-1})	< 5	5 - 30	> 30
Bicarbonate (asp.) (mg·l^{-1})	< 90	90 - 500	> 500
pH	6.5 - 8.4	< 6.5 et > 8.4	
Goutte à goutte			
Pop. bactérienne (nbre par ml)	< 10'000	10'000 - 50'000	> 50'000
Manganèse (mg/l)	< 0.1	0.1 - 1.5	> 1.5
Fer (mg/l)	< 0.1	0.1 - 1.5	> 1.5
H_2S (mg/l)	< 0.5	0.5 - 2.0	> 2.0

Evaluation de la qualité de l'eau d'irrigation