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Soil salinization and sodification processes 1

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SALINITY AND WATER BALANCE UNDER IRRIGATED CONDITIONS

INDICES AND MODELS FOR PREDICTIVE EVALUATION OF SOIL SALINIZATION AND SODIFICATION PROCESSES

by

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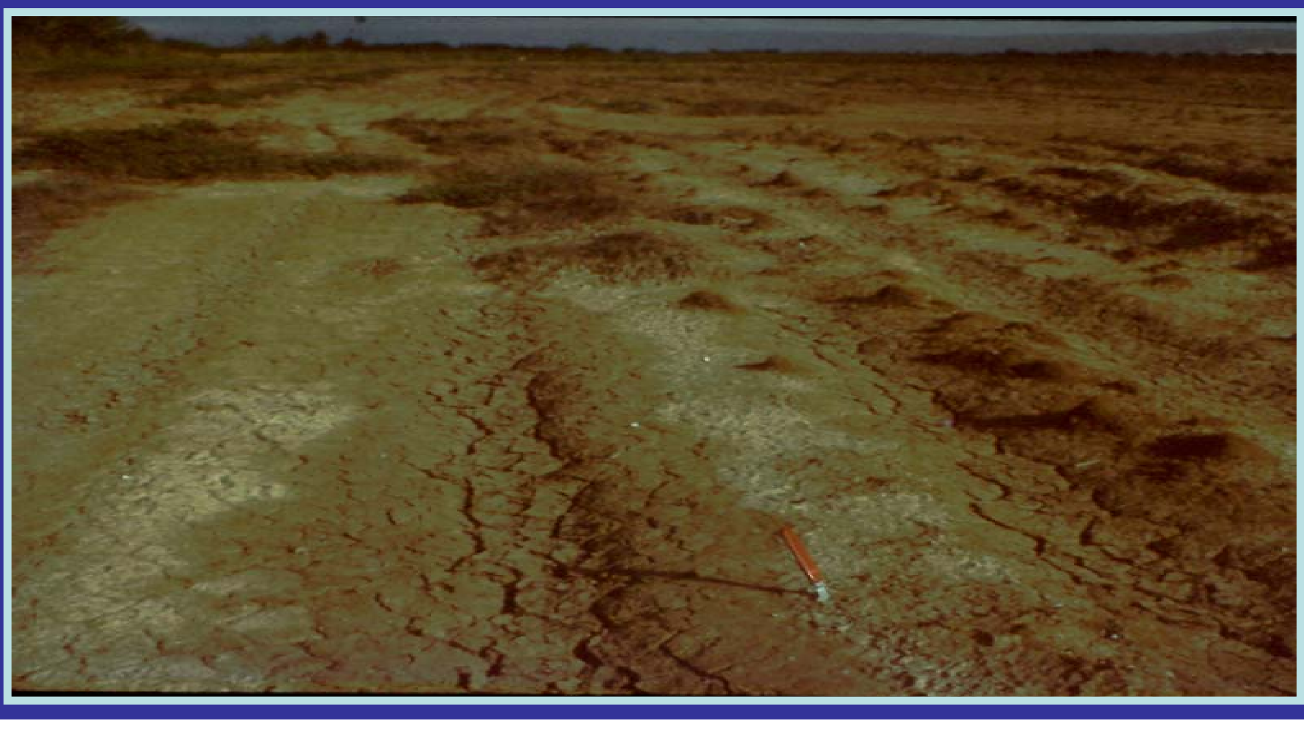
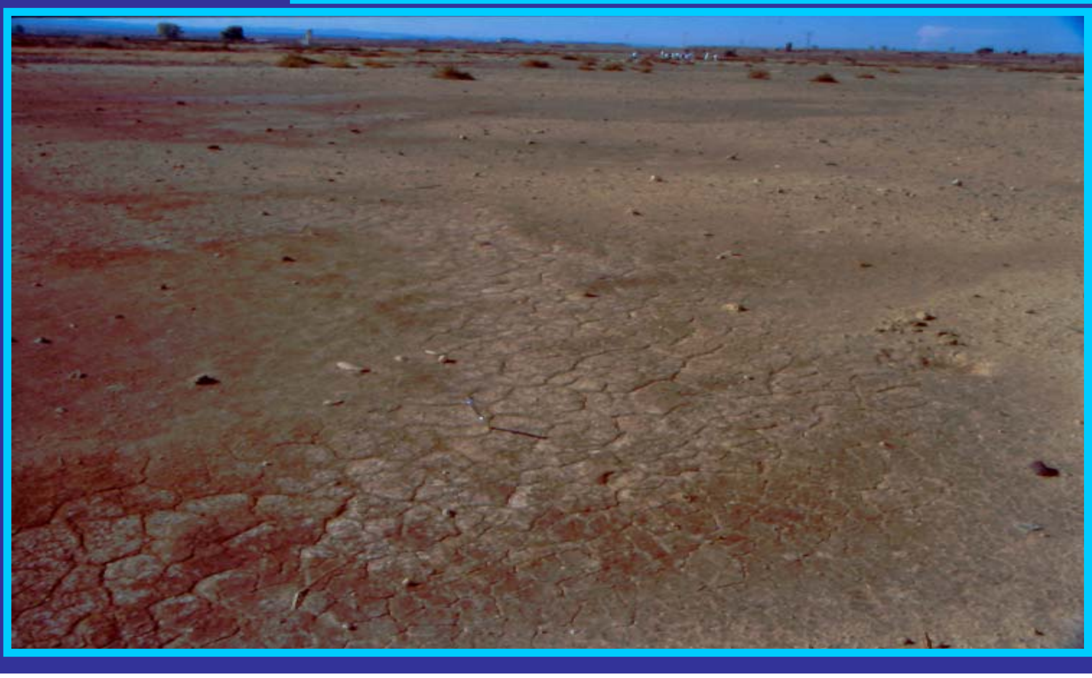
INTRODUCTION

The secondary soil salinization, induced by men, is mainly due to an inappropriate management of irrigation and drainage water in relation to each particular combination of climate, soil, crop, fertilization practices, groundwater depth and salinity, quality of irrigation water, and irrigation system.







The reclamation of soils already affected by salinity cannot generally be justified by strictly economical reasons

It is more convenient to preestablish, using predictive indices and models, the best alternatives for the management of irrigation and drainage waters in order to prevent and to control salinization and sodification problems for each combination of climate, soil and available irrigation water

This is even more necessary when :

. there is a high competence for the use of the available high quality water

. the quality of the available water is poor

. it is required to reduce the volume of effluents of salinized or contaminated drainage water

QUALITY OF IRRIGATION WATER

The quality of irrigation water is a relative term, and it is defined as the water characteristics determining its possibilities of being used for some specific purposes

In irrigation waters, the characteristics generally considered are the presence and content of:

- **CHEMICAL contaminants: Salts, certain ions and other contaminants in solution**
- **PHYSICAL contaminants: Sediments and temperature**
- **BIOLOGICAL contaminants: Pathogens**

The qualification of irrigation waters would be determined by their potential to cause problems, more or less reversible, leading to:

- **Diminishing yields and quality of crops and their products**
- **Problems of contamination of crops, soils, groundwaters, and effluents**
- **Requirements of special practices, equipments and structures for the management of irrigation and drainage water, of soils and of crops**

The qualification of waters in relation to potential problems of soil salinization and sodification is mainly based in the absolute and relative content of salts and certain ions

(HCO3-, Cl-, SO4=, NO3-, Ca++, Mg++, Na+, K+).

These contents are interpreted in relation to potential problems of salinity (limitations in the use of the soil water by plants), and of sodicity (deterioration of the soil physical properties) in relation to particular conditions of:

- Soils
- Climate
- Crops
- Limited available irrigation water
- Difficulties in the management of irrigation and drainage

In the last decades there have been developed several systems for qualifying irrigation waters in relation to potential problems of salinization and sodification, including:

- **General schemes for average conditions, which cannot be applied to solve practical problems due to their qualitative nature and inability to be adjusted to specific situations**

- **Empirical indices developed for very specific conditions of soils and crops in a specific area, which cannot be used or adapted to different conditions.**

Among the general schemes the most known is the one proposed by the USSL-USDA (1954), which was developed for the predominant conditions in the SW of USA.

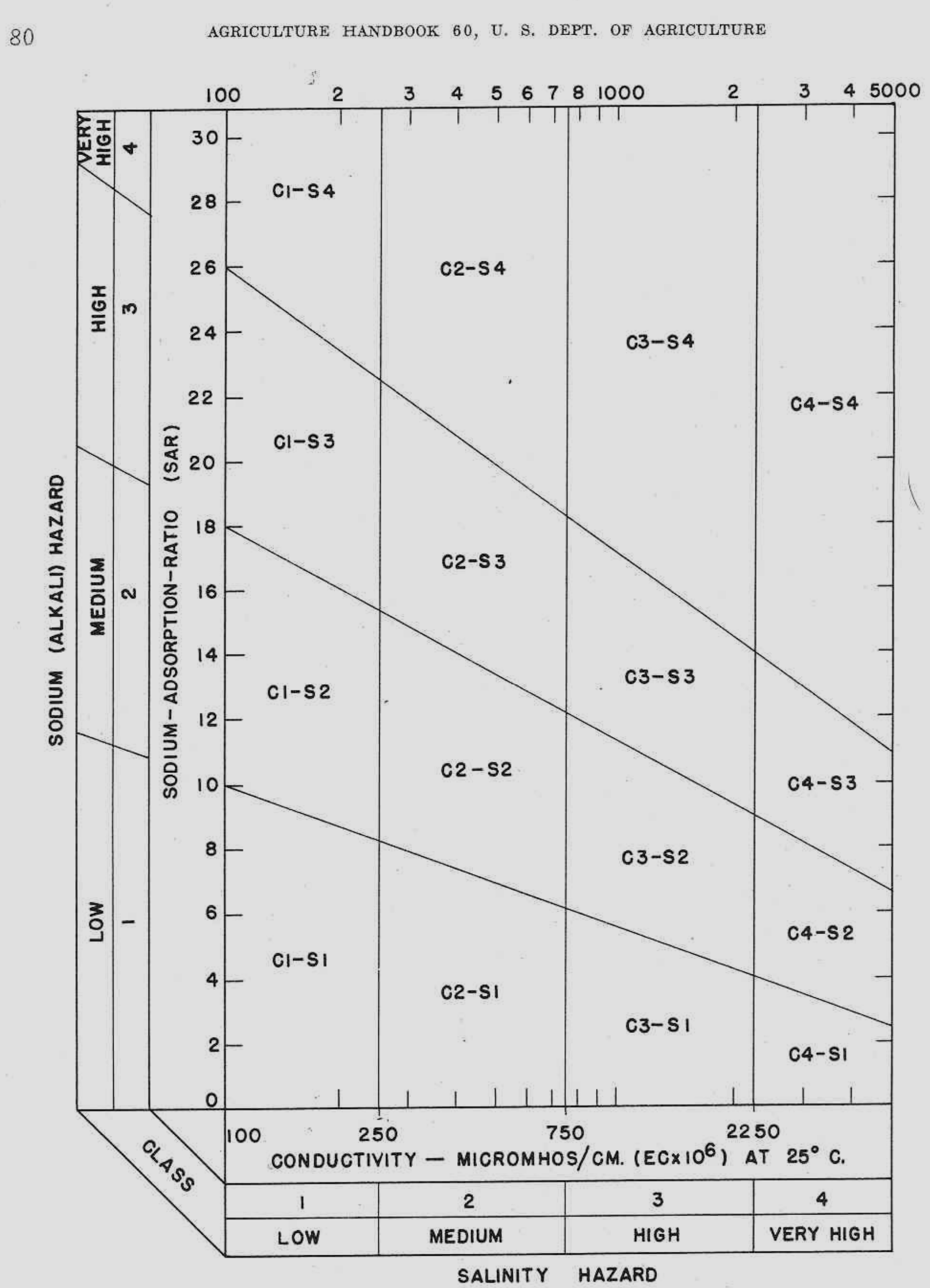
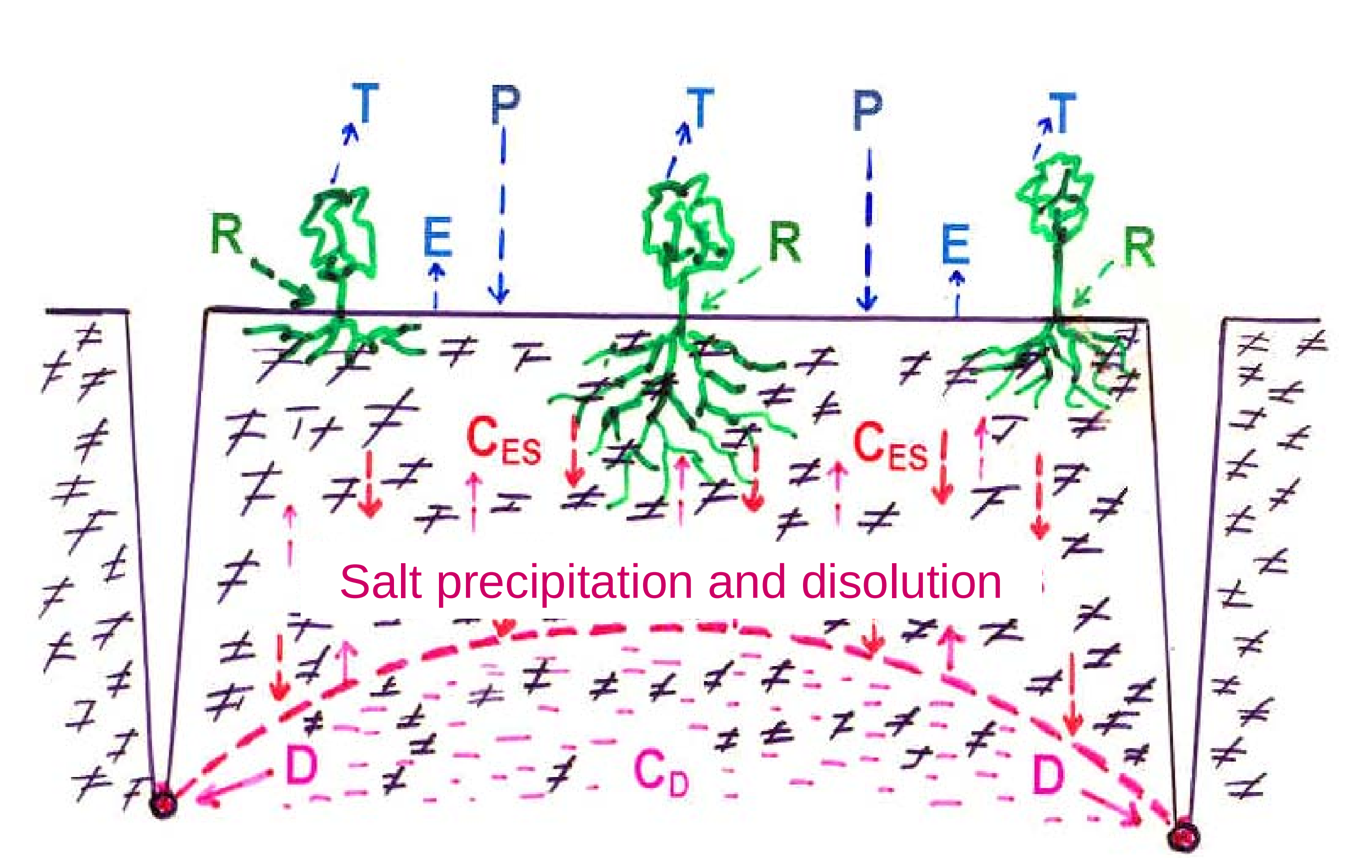


FIGURE 25.—Diagram for the classification of irrigation waters.

BALANCES AND REACTIONS OF SALTS IN SOIL SOLUTION (SOIL WATER)

The accumulation of salts in the soil occurs when the input of them with the irrigation water, required to replace the water losses by evaporation and transpiration, exceeds the losses by precipitation, leaching and internal drainage

Besides, the salt concentration in the soil solution increases in between of those additions by irrigation water, when the soil moisture decreases due to the temporal losses of water by evaporation and transpiration

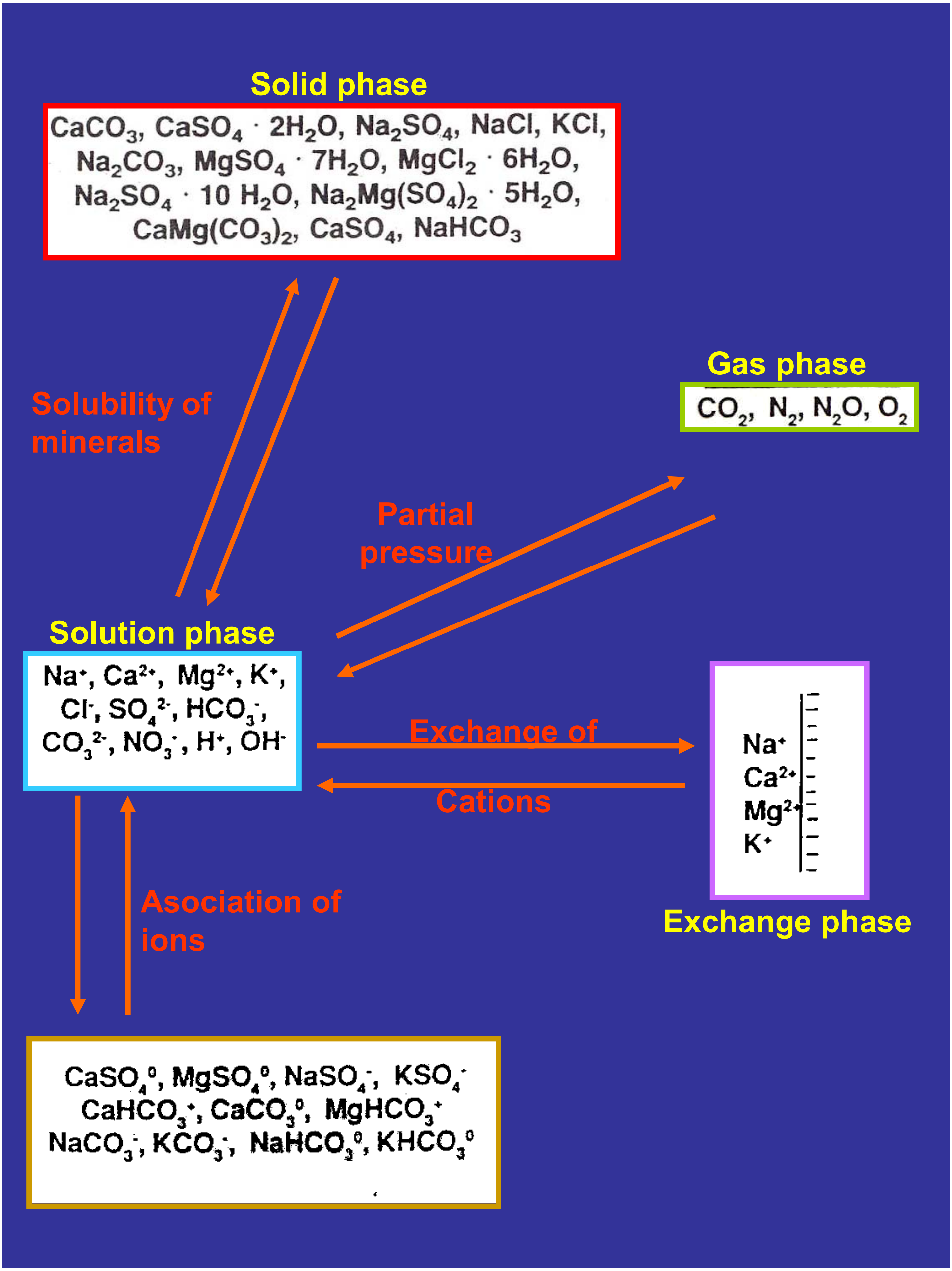


The levels and composition of salts in the soil will be determined by the:

Composition of salts in the applied irrigation water

Possibilities of the different salts to reach determinate concentrations before they precipitate in the soil

Additionally, the composition of cations in the soil exchange phase is determined by the composition and relative concentration of the different cations in soil solution


Solid phase
CaCO3, CaSO4 · 2H2O, Na2SO4, NaCl, KCl, Na2CO3, MgSO4 · 7H2O, MgCl2 · 6H2O, Na2SO4 · 10 H2O, Na2Mg(SO4)2 · 5H2O, CaMg(CO3)2, CaSO4, NaHCO3
Solubility of minerals
Gas phase
CO2, N2, N2O, O2
Partial pressure
Solution phase
Na+, Ca2+, Mg2+, K+, Cl-, SO42-, HCO3-, CO32-, NO3-, H+, OH-
Exchange of
Cations
Na+
Ca2+
Mg2+
K+
Exchange phase
Asociation of ions
CaSO40, MgSO40, NaSO4-, KSO4-
CaHCO3+, CaCO30, MgHCO3+
NaCO3-, KCO3-, NaHCO30, KHCO30

In the soil salinisation process, the changes that my happen in the composition of the soil solution derived of the precipitation of some salts of limited solubility, like bicarbonates (carbonates) of Ca and Mg, and Ca sulfates, are very important.

Conditions leading to such precipitation, like:

Predominion of bicarbonates among the anions in the irrigation water, specially with the relation:

$(HCO_3^-/(Ca^{++} + Mg^{++})>1$

Losses of CO_2

Defficient drainage

would contribute to a relative enrichment of Na in the soil solution and at the same time in the exchange complex, and to a decrease in total salinity in the soil solution.


·2
·4
·6
·8
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Conditions					
IRRIGATION WATER					
Concentration:	(High)	(Medium)	(Low)		
EC:	>2 dS/m	1-2 dS/m	< 1 dS/m		
Composition:	Cl>S>B Na>=CA	S>=Cl>B CA>Na	B>=S>Cl CA>=Na		B>S>Cl (B>CA) Na>=CA
DRAINAGE	(Variable)		(Very restricted)		(Restricted)
Soil Perm.(I):	1-50 mm/hour		< 1 mm/hour		< 5 mm/hour
Groundwat.depth:#	< 1.5 m		< 0.5 m		< 1.0 m
CLIMATE	(Ar.-DSAr.)		(Ar.-DSAr.)	(DSAr.-SH.)	(Ar.-HSAr.)
IMA (P/ETP):	< 0.5		< 0.5	0.5-1.0	< 0.8
LGP (P>(ETP/2)):	< 120 days		< 120 days	120-270 days	< 180 days
Resulting problem					
SOIL SOLUTION	(Very saline)		(Mod.saline)	(Sligh.saline)	(Var.salin.)
Concentration (EC):	>8 dS/m		>4 dS/m	<4 dS/m	>2 dS/m
Composition:	Cl>>S>>B Na>CA	Cl>=S>>B Na>=CA	S>Cl>B Na>CA	(*)S>=B>Cl Na>>CA	B>=S>Cl Na>>CA
	(A)	(B)	(C)	(D)	(E)
pH	< 8.5		< 8.5	> 7.5	> 8.5
PRECIPIT. SALTS:	CAC + CaS		CAC + CaS	CAC	CAC
POTENTIAL KIND OF PROBLEM:	"SALINITY"			"SODICITY"	

(*) Change of composition under anaerobic conditions ($2Na^{+} + SO_4^{=} + 2C + 2H_2O = S^{=} + 2NaHCO_3$)

Condiciones

AGUA DE RIEGO				
Concentración:	(Alta)	(Mediana)	(Baja)	
CE:	> 2dS/m	1-2 dS/m	< 1dS/m	
Composición:	Cl>S>B Na≥CA	S≥Cl>B CA>Na	B≥S>Cl CA ≥ Na	B>S>Cl (B>CA) Na ≥ CA
DRENAJE	(Variable)		(Muy restringido)	(Restringido)
Perm. Suelo (I):	1-50 mm/hora		< 1 mm/hora	< 5 mm/hora
Prof. Freática (#):	< 1,5 m		< 0,5 m	< 1,0 m
CLIMA	(Ar. - SAr. S)	(Ar.-SAr.S)	(SAr.S.-SH.)	(Ar.-SAr.H)
IDA (P/ETP):	< 0,5	< 0,5	0,5-1	< 0,8
LPC (P>(ETP/2)):	< 120 días	< 120 días	120-270 días	< 180 días

Problema resultante

SOLUCIÓN DEL SUELO (ES)	(Muy salina)	(Med.salina)	(Lig.salina)	(Var.salin.)
Concentración(CE):	> 8 dS/m	> 4 dS/m	< 4 dS/m	> 2 dS/m
Composición:	Cl>>S>>B Na>CA Cl≥S>>B Na≥CA	S>Cl>B Na>CA	(*)S≥B>Cl Na>>CA	B≥S>Cl Na>>CA
pH:	< 8,5	< 8,5	> 7,5	> 8,5
SALES PRECIP:	CAC + CaS	CAC + CaS	CAC	CAC
PROBLEMA POTENCIAL:	**"SALINIDAD"**		**"SODICIDAD"**	

(#) Nivel freático permanente o presencia de estratos que impidan o restrinjan el drenaje interno

(*) Cambio de composición bajo condiciones anaeróbicas $(2Na^+ + SO_4^= + 2C + 2H_2O = S^= + 2NaHCO_3)$

LEACHING REQUIREMENTS

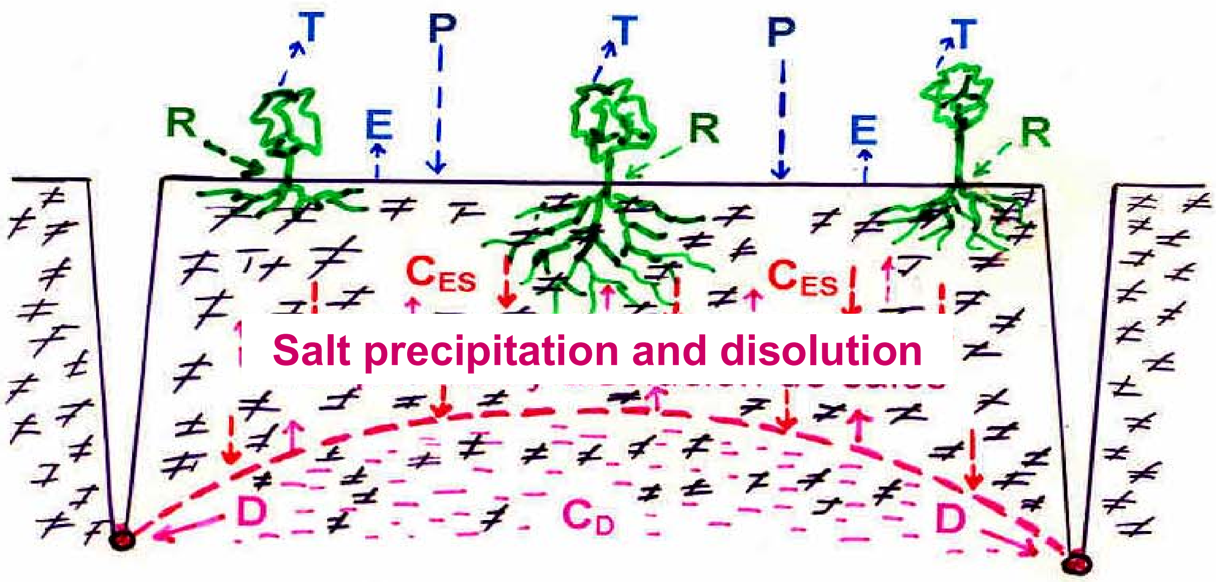
The plants do not take salts in the same proportion as they absorb soil water, and the losses of water by evaporation and transpiration leave the salts in solution behind.

Therefore, it is not possible to control salinity in irrigated soils without an adequate leaching of the salts and drainage of the leaching water, which requires a net flux of water below the soil root zone

This can be achieved applying an excess of irrigation water above the plant water requirements.

When the original soil, before being irrigated, contains an excessive amount of salts in soil solution, there would also be necessary to apply an excess of water for leaching them.

In any case, the amount of excess water to apply will depend on the content and kind of salts present in the irrigation water, on the original content of salts in the soil solution, on the climate, and on the crops.



$H_R = (H_{ET} - H_P) + H_D$ $\quad$ $H_R C_R = H_D C_D$ $\quad$ $(C_{ET} = 0;\ C_P \approx 0)$

$H_D/H_R = C_R/C_D = L$ $\quad$ $C_D/C_{ES} = F \ (\leq 1)$

$C_D = C_{ES} \times F$ $\quad$ $C_R/(C_{ES} \times F) = L$

$$LF = C_R/C_{ES}$$

Salts that can precipitate : : $CaCO_3$, $MgCO_3$, $CaSO_4$

Salts that can disolve : " " "

If precipitation of Ca and Mg carbonates and of Ca sulfate :

$$LF_{ST} = (Na + Mg + CaCl)/(ST_{ES} - 40)$$

$$LF_{Na} = \frac{[(RAS_{ES}^2 \times (Mg + CaCl^2) + (320\ Na^2)]}{80\ RAS_{ES}} - \frac{(Mg + CaCl)}{80}$$

$(Ca + Mg)\ C_p = B - 10\ LF$ $\quad$ $CaS_p = CaS - 30\ LF$

The fraction of irrigation water applied in excess of the crop water requirements, and that infiltrates and finally is lost as drainage water after percolation through the soil rooting zone, is called leaching fraction (L)

L = HD / HR = CR / CD

L: Leaching fraction

HD: Drainage water in depth

HR: Irrigation water in depth

CR: Salt concentration in the irrigation water

CD: Salt concentration in the drainage water

The calculation of L has been changing through the years (Pla, 1968: 1983: 1988: 1996, 1997) (Rhoades, 1968, 1984), (Pla & Dappo, 1977), (FAO, 1976, 1986), and its use has been extended to the control of soil sodicity. L, integrating in a unique figure the present and required balances of water, salts and sodium in the soil, may be used as a basis for the predictive indices and models for salinity and sodicity in irrigated soils.

Calculation of the leaching requirements and of the concentration and composition of salts in the resulting soil solution (Pla, 1997)

$$C_D / C_{ES} = F \ (\leq 1)$$

$$LF = C_R / C_{ES}$$

C_D: Salt concentration in drainage water

C_{ES} : Salt concentration in saturation extract

F: Leaching efficiency

C_R: Salt concentration in irrigation water

LF: Leaching requirement

L : Effective leaching requirement

Required information

- **Cations and anions more common in irrigation waters (meq / liter) :**

Ca^{++} **(Ca)**, Mg^{++} **(Mg)**, Na^{+} **(Na)**,
$CO_3^{=} + HCO_3^{-}$ **(B)**, $SO_4^{=}$ **(S)**, Cl^{-} **(Cl)**

- **Salts in irrigation water:**

NaB = B - Ca - Mg ***si NaB*** $\geq$ ***0*;**
MgB = B - Ca - NaB ***si MgB*** $\geq$ ***0*;**

CaCl = Ca - B - S ***si CaCl*** $\geq$ ***0*;**
CaS = Ca - B - CaCl ***si CaS*** $\geq$ ***0***

- **Critical levels of total salts (STES), chlorides (ClES), sodium (NaES) and other toxic elements in the soil saturation extract (ES) for different crops.**

When the calculations show the possibility of precipitation of Ca carbonates and sulfates in the soil, the critical levels of STES may be increased by 20 meq/l.



Tolerance of different crops to total salinity (and to chlorides) in the soil saturation extract (STES and ClES)

TOLERANT CROPS (ST$_{ES}$: 80-160 meq/l)

Guayule — *Cártamo*
Cebada — *Sorgo*
Algodón — *Dátil*
Remolacha azucarera — *Olivo*
Pasto Bermuda — *Higuera*
Trigo

MODERATELY TOLERANT CROPS (ST$_{ES}$: 40-80 meq/l)

Soja — *Alfalfa*
Tomate — *Caña de azúcar*
Espinaca — *Maíz*
Girasol — *Arroz*
Pepino — *Patata*
Melón — *Viña*

MODERATELY SENSIBLE CROPS (ST$_{ES}$: 20-40 meq/l)

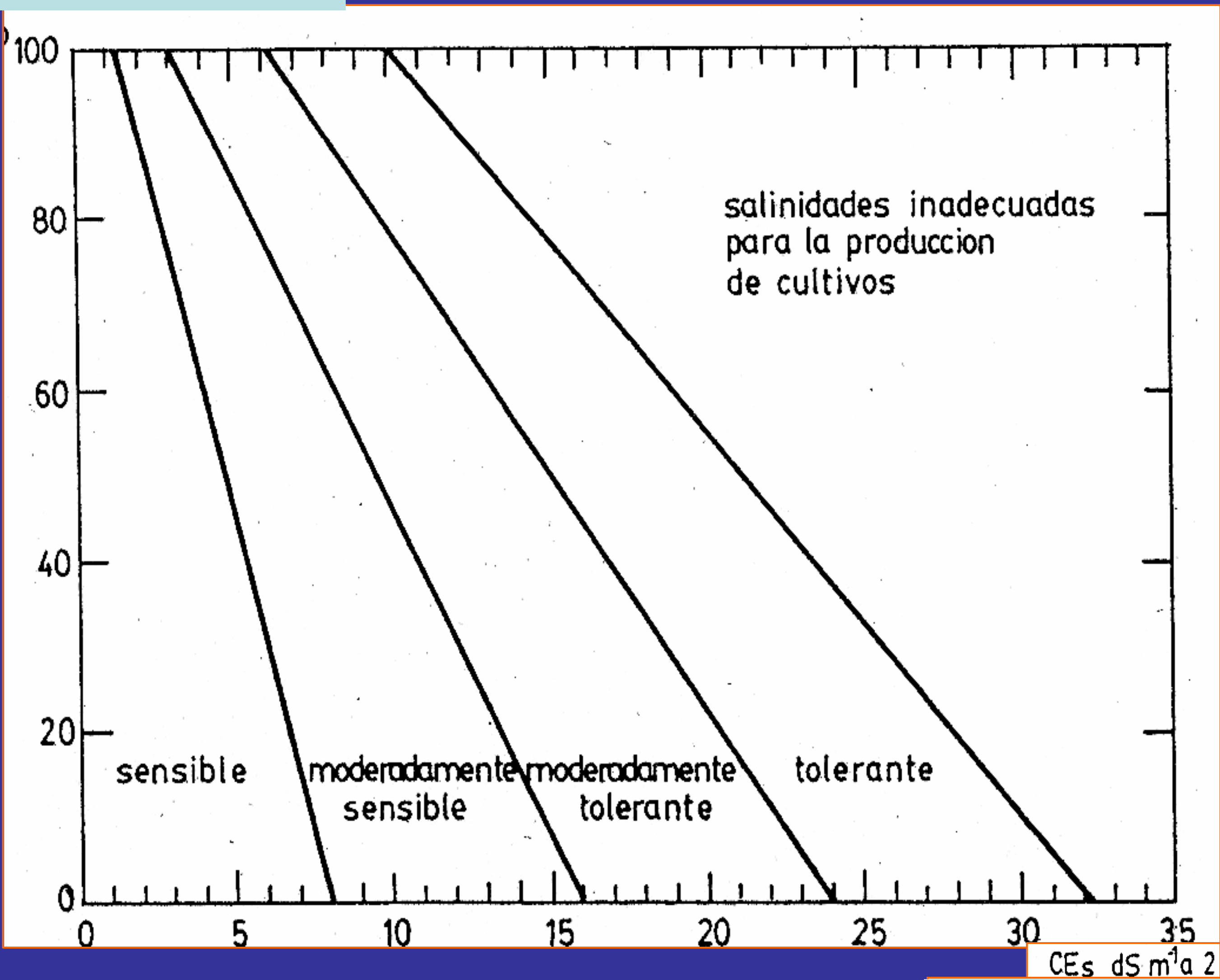
Cebolla — *Col*
Pimiento — *Cacahuete*
Lechuga — *Zanahoria (Cl < 10 meq/l)*

SENSIBLE CROPS (máx. ST$_{es}$: < 20 meq/l)

Ciruelo — *Peral*
Limonero — *Aguacate (Cl < 12 meq/l)*
Naranjo (Cl < 20 meq/l) — *Melocotonero*
Judía (Cl < 10 meq/l) — *Berenjena*
Manzano — *Fresal (Cl < 10 meq/l)*

Crop salt tolerance

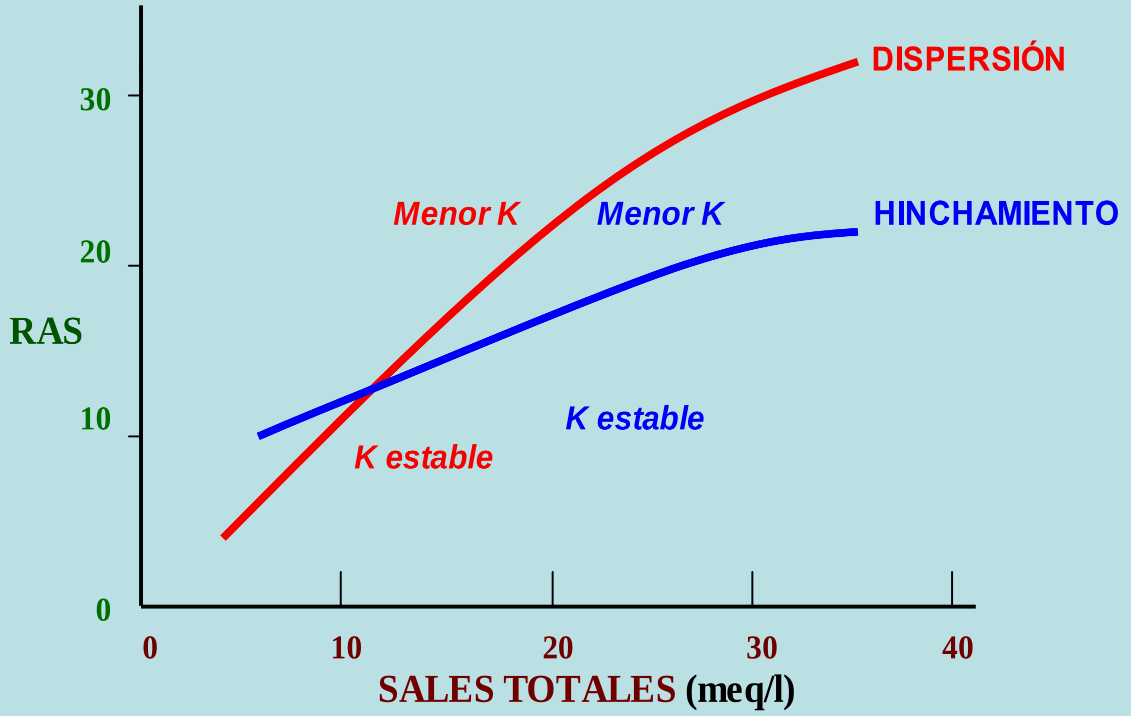
Relative yield
Y%

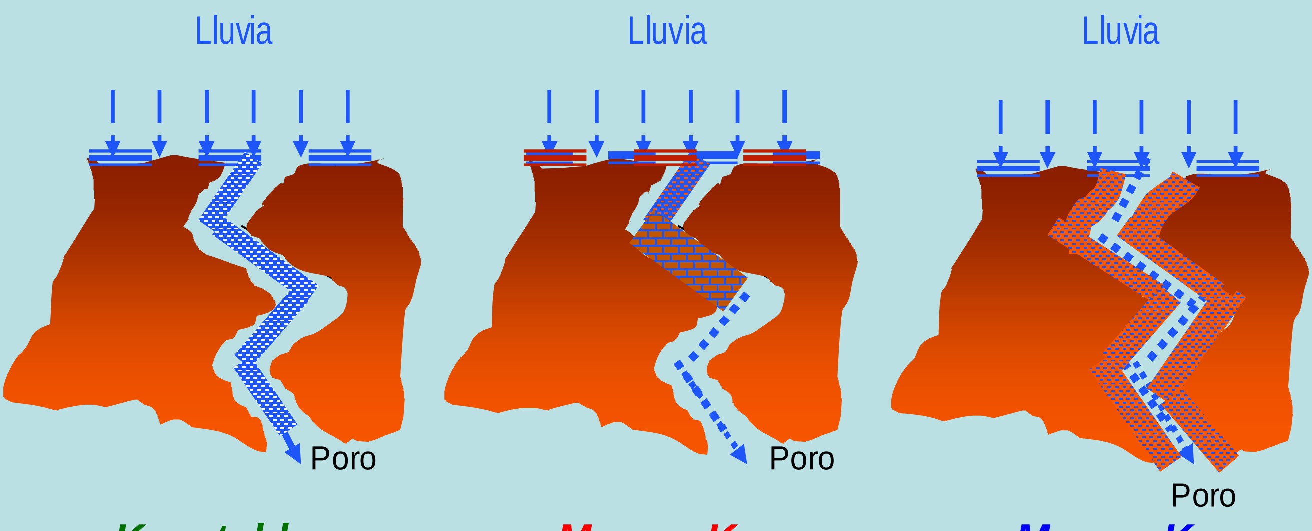


Electrical conductivity

Critical values of "Sodium Adsorption Ratio" (SARES = NaES / ((CaES + MgES)/2)1/2)) in the saturation extract (ES) of the soil, for different soils and concurrent levels of STES.

EFECTOS DEL SODIO (RAS) Y SALES TOTALES EN LA SOLUCIÓN DEL SUELO SOBRE LA CONDUCTIVIDAD HIDRÁULICA SATURADA (K)





K estable

Menor K

DISPERSIÓN

(Clogging of pores)

(Irreversible)

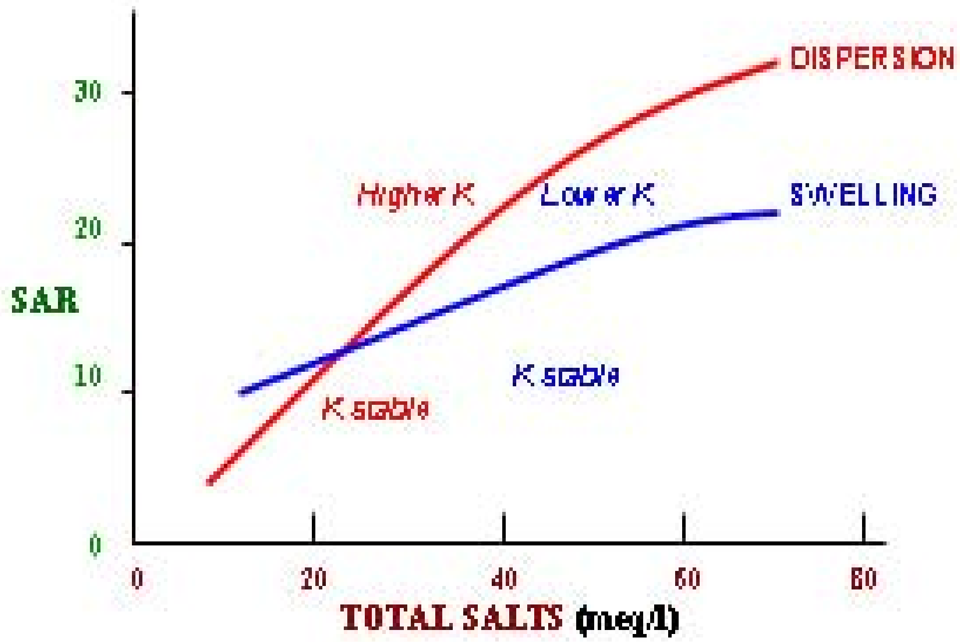
Menor K

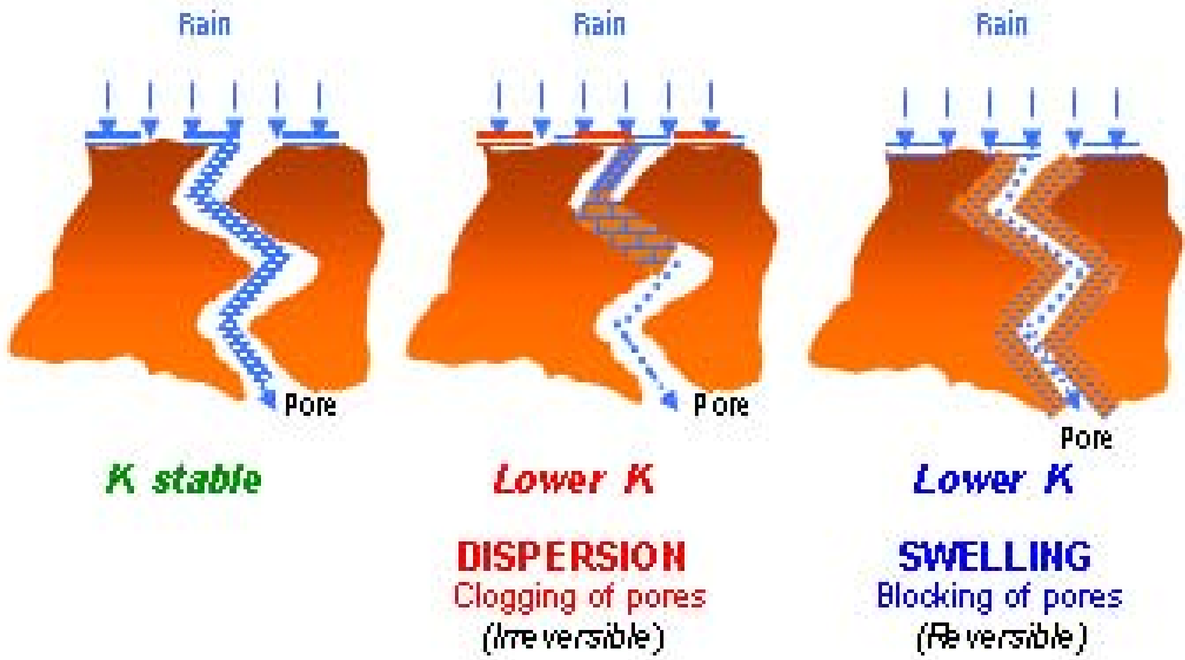
SWELLING

(Blocking of pores)

(Reversible)

EFFECTS OF SODIUM (SAR) AND TOTAL SALTS IN SOIL SOLUTION ON THE SATURATED HYDRAULIC CONDUCTIVITY (K) OF THE SOIL





- Amounts of monthly, daily… effective rainfall (HP) and evapotranspiration (HET) for each climate, crop, variety, development period of the crop… in mm

-Leaching efficiency

(F = STD / STES: F = NaD / NaES)

(D: drainage water)

for each soil and irrigation method

Soil characteristics and properties:

-Effective depth (R) in mm

-Bulk density (DA) in g/cc

-Field Capacity (CC) in g/cc

-Infiltration

If in the irrigation water $B < (Ca + Mg)$ (a)

$$LF(ST) = (Na + Ca + Mg) / (ST_{ES})$$
$$LF(Cl) = Cl / Cl_{ES}$$
$$LF(Na) = (2Na^2) / ((RAS_{ES}{}^2 \times (Ca + Mg))$$

$LF(a) = LF(ST)$ si $LF(ST) > LF(Cl)$ y $LF(ST) > LF(Na)$

$LF(a) = LF(Cl)$ si $LF(Cl) > LF(ST)$ y $LF(Cl) > LF(Na)$

$LF(a) = LF(Na)$ si $LF(Na) > LF((ST)$ y $LF(Na) > LF(Cl)$

$Na_{ES} = Na / LF(a)$ $Ca_{ES} = Ca / LF(a)$ $Mg_{ES} = Mg / LF(a)$ $Cl_{ES} = Cl / LF(a)$

$(Ca + Mg)Cd = 10\ LF(a) - B$ $CaSd = 30\ LF(a) - CaS$

If: $10\ LF(a) < B$ y $30\ LF(a) \geq CaS$ (b)

$$LF(ST) = (Na + Ca + Mg - B) / (ST_{ES} - 10)$$
$$LF(Cl) = Cl / Cl_{ES}$$
$$LF(Na) = \frac{((RAS_{ES}{}^2 \times (Ca + Mg - B)^2) + (80\ Na^2))^{1/2}}{20\ RAS_{ES}} - \frac{(Ca + Mg - B)}{20}$$

$LF(b) = LF(ST)$ si $LF(ST) > LF(Na)$ y $LF(ST) > LF(Cl)$

$LF(b) = LF(Cl)$ si $LF(Cl) > LF(ST)$ y $LF(Cl) > LF(Na)$

$LF(b) = LF(Na)$ si $LF(Na) > LF(ST)$ y $LF(Na) > LF(Cl)$

$$Na_{ES} = Na / LF(b) \qquad Ca_{ES} = \frac{10\ (Ca + Mg - MgB)}{(Ca + Mg)} + \frac{(CaS + CaCl)}{LF(b)}$$

$$Mg_{ES} = 10 + \frac{(Ca + Mg - B)}{LF(b)} - Ca_{ES} \qquad Cl_{ES} = Cl / LF(b)$$

$(Ca + Mg)Cp = B - 10\ LF(b)$ $CaSd = 30\ LF(b) - CaS$

If: LF(a) < B y 30 LF(a) < CaS **(c)**

$$LF(ST) = (Na + Mg + CaCl) / (ST_{ES} - 40)$$

$$LF(Cl) = Cl / Cl_{ES}$$

$$LF(Na) = \frac{((RAS_{ES}{}^2 \times (Mg + CaCl)^2) + (320\ Na^2))^{1/2}}{80\ RAS_{ES}} - \frac{(Mg + CaCl)}{80}$$

LF(c) = LF(ST) si LF(ST) > LF(Cl) y LF(ST) > LF(Na)
LF(c) = LF(Cl) si LF(Cl) > LF(ST) y LF(Cl) > LF(Na)
LF(c) = LF(Na) si LF(Na) > LF(ST) y LF(Na) > LF(Cl)

$Na_{ES} = Na / LF(c)$ $Ca_{ES} = 40 + (CaCl / LF(c))$ $Mg_{ES} = Mg / LF(c)$

$Cl_{ES} = Cl / LF(c)$

$(Ca + Mg)Cp = B - 10\ LF(c)$ $CaSp = CaS - 30\ LF(c)$

If: 10 LFa ≥ B y 30 LFa < CaS **(d)**

$$LF(ST) = (Na + Ca + Mg - CaS) / (ST_{ES} - 30)$$

$$LF(Cl) = Cl / Cl_{ES}$$

$$LF(Na) = \frac{((RAS_{ES}{}^2 \times (Ca + Mg - CaS)^2) + (240\ Na^2))^{1/2}}{60\ RAS_{ES}} - \frac{(Ca + Mg - CaS)}{60}$$

LF(d) = LF(ST) si LF(ST) > LF(Cl) y LF(ST) > LF(Na)
LF(d) = LF(Cl) si LF(Cl) > LF(ST) y LF(Cl) > LF(Na)
LF(d) = LF(Na) si LF(Na) > LF(ST) y LF(Na) > LF(Cl)

$Na_{ES} = Na / LF(d)$ $Ca_{ES} = 30 + ((Ca - CaS) / LF(d))$ $Mg_{ES} = Mg / LF(d)$

$Cl_{ES} = Cl / LF(d)$

$(Ca + Mg)Cd = 10\ LF(d) - B$ $CaSp = CaS - 30\ LF(d)$

If in the irrigation **water** : $B > (Ca + Mg)$ (e)

$LF(ST) = Na / (ST_{ES} - Ca - Mg)$
$LF(Cl) = Cl / Cl_{ES}$
$LF(Na) = Na / (RAS_{ES} \times ((Ca + Mg)/2)^{1/2})$

$LF(e) = LF(ST)$ si $LF(ST) > LF(Cl)$ y $LF(ST) > LF(Na)$
$LF(e) = LF(Cl)$ si $LF(Cl) > LF(ST)$ y $LF(Cl) > LF(Na)$
$LF(e) = LF(Na)$ si $LF(Na) > LF(ST)$ y $LF(Na) > LF(Cl)$

$Na_{ES} = Na / LF(e)$ $Ca_{ES} = Ca$ $Mg_{ES} = Mg$ $Cl_{ES} = Cl / LF(e)$
$NaB_{ES} = NaB / LF(e)$
$(Ca + Mg)Cp = (Ca + Mg) \times (1 - LF(e))$

REQUIREMENTS OF IRRIGATION AND DRAINAGE MANAGEMENT

Departing from and adequate evaluation of the leaching requirements, taking into consideration the previewed salt precipitation or dissolution in the soil profile, and the possibilities of sodification besides salinization, it is possible a more precise calculation of the irrigation and drainage requirements:

$$H_R = (H_{ET} - H_P) / (1 - L)$$

$$H_D = (L (H_{ET} - H_P)) / (1 - L)$$

$$T_R / T_{ER} = (H_{ET} - H_P) / (720\, I\, (1-L))$$

$$T_{ER} \leq T_{ER}\,(máx.)$$

$$T_{ER}\,(máx.) = (15 \times DA \times P \times CC) / (H_{ET} - H_P)$$

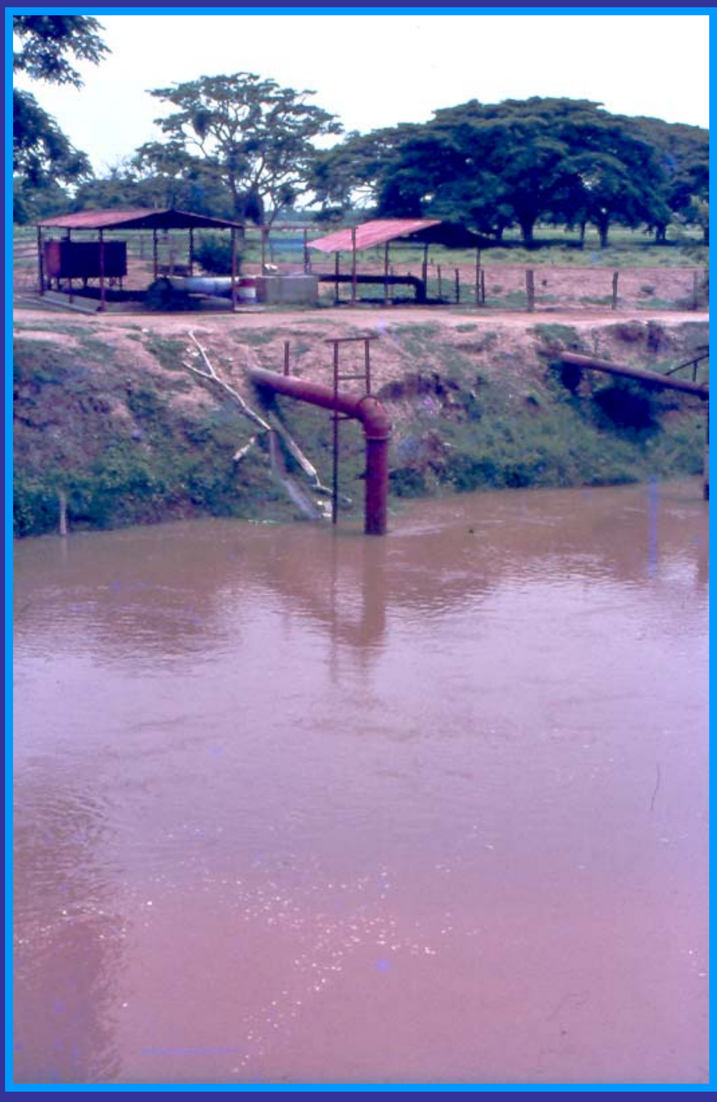
Irrigation requirements (HR) and drainage requirements (HD) in mm/month, mm/day…., in order to satisfy the crop water requirements and to control at the same time the levels of salts, chlorides, sodium …. in the soil solution and drainage waters under the pre selected critical levels

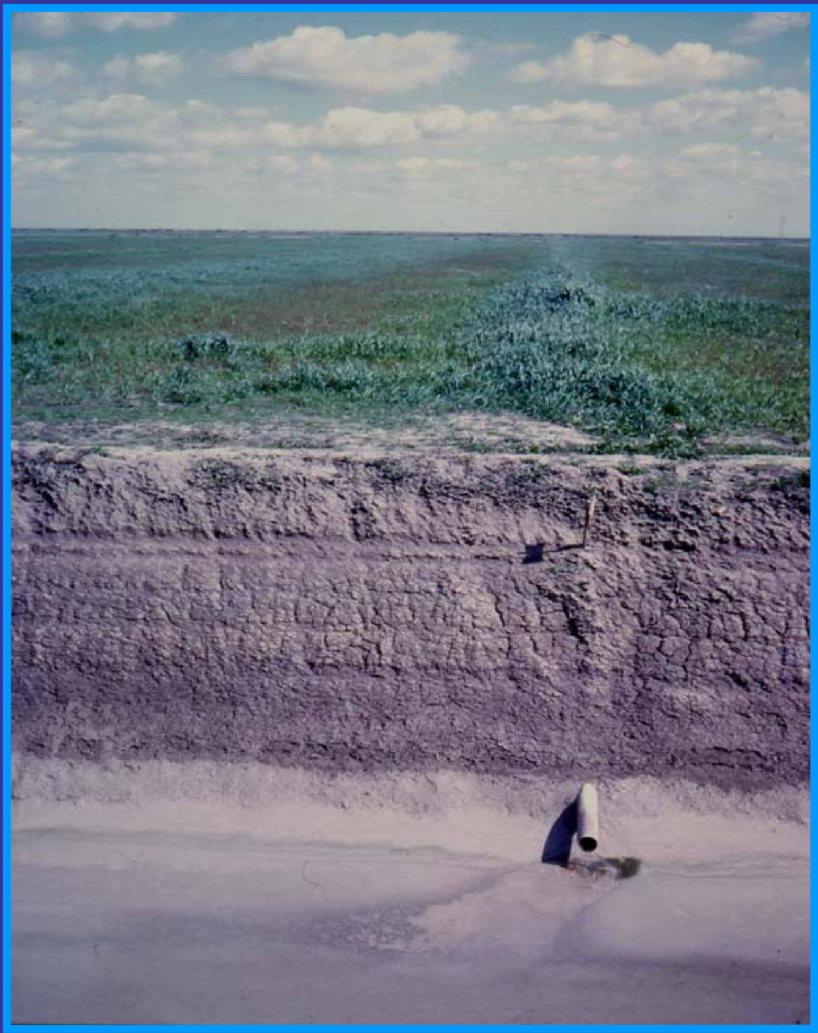
Requirements for the irrigation management (TR /TER) in order to be able to fill the irrigation and drainage requirements (HR, HD), derived from the relation between the duration of irrigation (TR: time in hours or days required for the infiltration in the soil of the irrigation water) and the maximum interval in hours or days among irrigations (TER) for each soil (P, DA, CC and I).

The requirements for irrigation and drainage management are the basis for précising the best possible alternatives for irrigation and drainage management.

The final selection of a determinate alternative will depend on practical, economical and environmental limitations, such as

- availability and cost of the irrigation water,
- soil hydrological properties,
- groundwater depth,
- natural drainage capacity and requirements of artificial drainage,
- costs of the irrigation system,
- limitations in the volume and salinity of the effluent drainage waters, etc.



MODEL SALSODIMAR

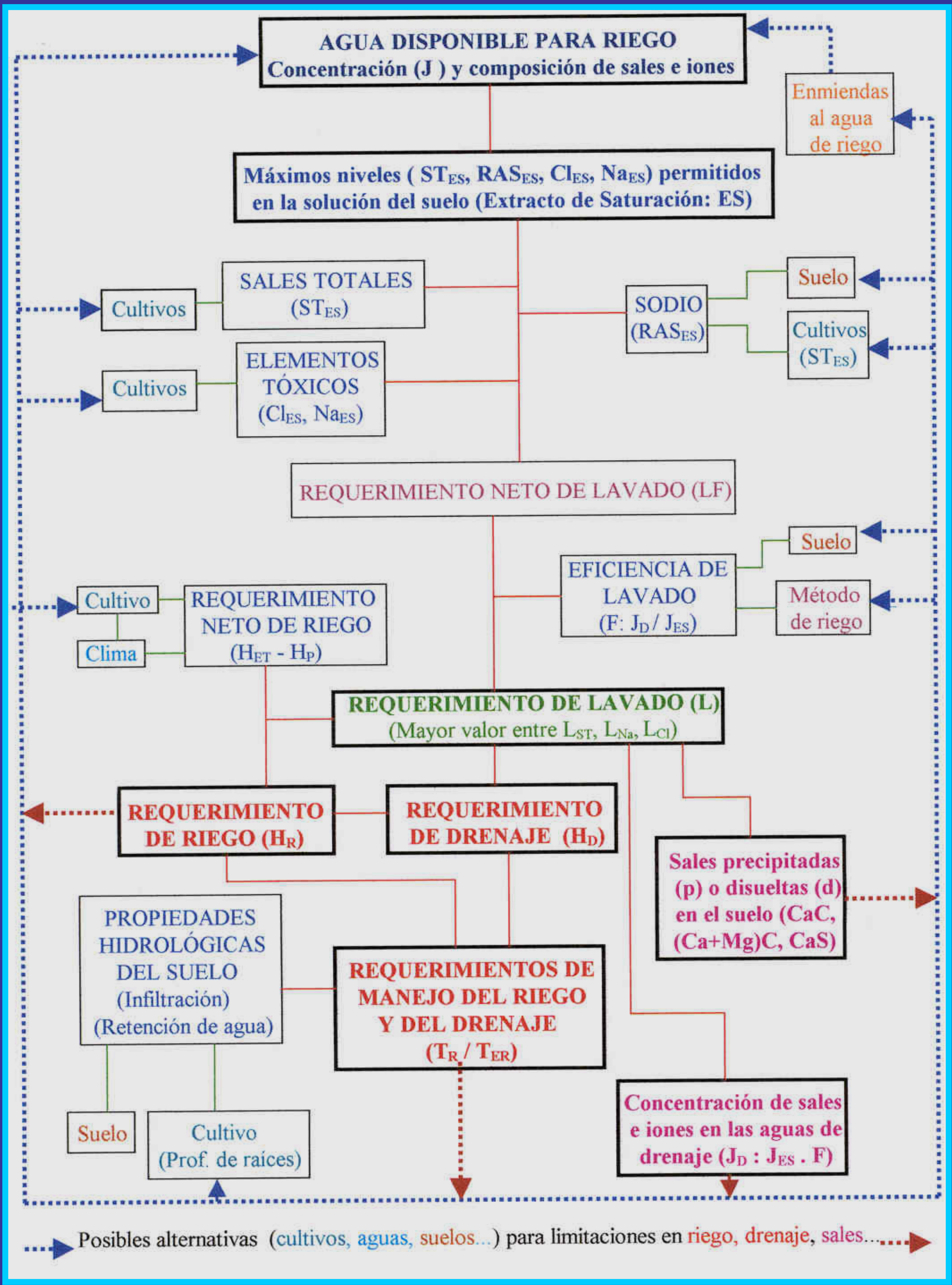
The model "SALSODIMAR" is based on an independent balance of the more common ions in the irrigation water and in the soil solution, until reaching equilibrium, according to an effective leaching fraction and to the maximum solubility of the different salts under different conditions.

Besides there are taking into consideration

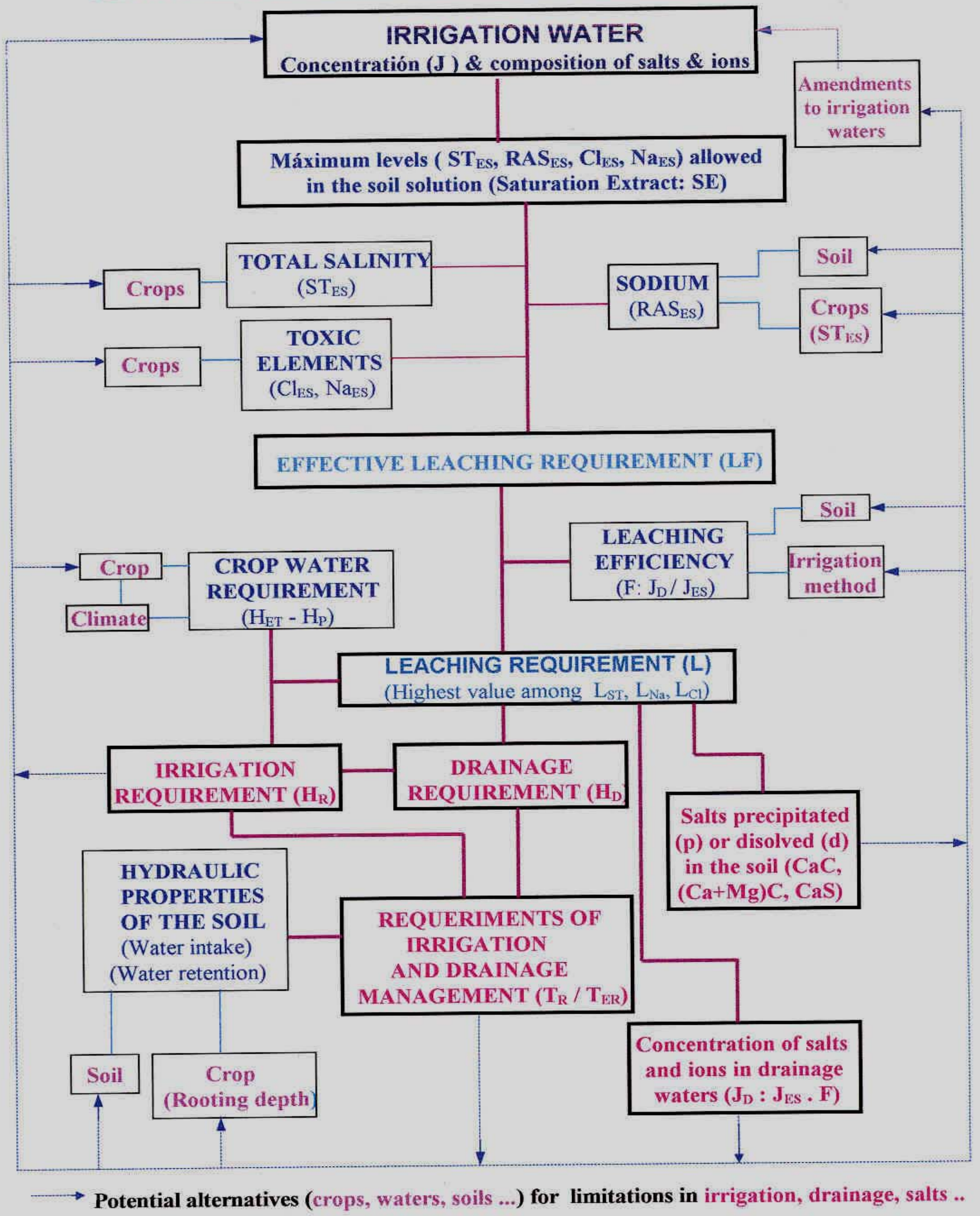
- the critical levels of salinity and of toxic elements as chlorides for different crops and climate

- the critical levels of Na for different soils and concurrent salinity levels.

MODEL SALSODIMAR



FLOW DIAGRAM OF THE SIMULATION MODEL "SALSODIMAR"



The model SALSODIMAR allows:

* To preview the conditions under which there would develop salt affected soils, “saline” or “sodic”, and their variants

* To predict the accumulation of certain elements as Cl-, Na+, Mg++ etc. which may cause some specific problems

*To determine under which conditions, and at what levels, there is favored the precipitation or dissolution in the soil of low solubility salts (Ca and Mg carbonates, and Ca sulfates)

*Calculate the requirements of irrigation and drainage waters for controlling the salinity and sodicity in relation to the requirements of water by the crop under a determinate climate, and from them to deduce the best or possible alternatives for the irrigation water management in each soil.

When the simulation of a given condition leads to:

-Excessive drainage requirements in relation to the existence, possibilities and capacity of the natural or artificial internal drainage, and in relation to the possibilities and limitations derived of the contamination of surface or subsurface waters that have to be used again

-Technical difficulties in the irrigation water management, derived of excessive values of calculated irrigation and drainage requirements, or derived of limitations in the hydrological soil properties

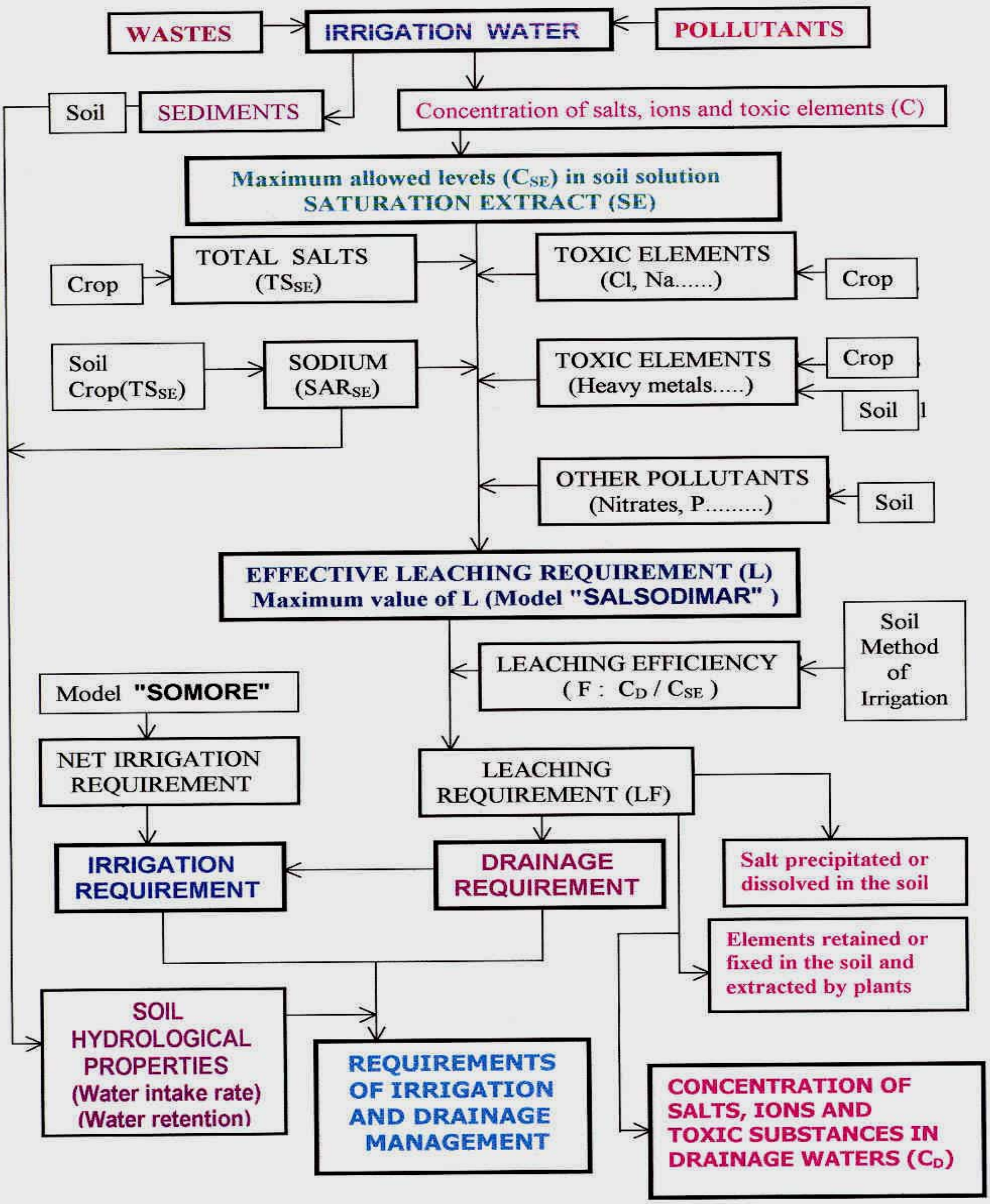
-Excessive levels and amounts of salts and other toxic elements in the drainage water which may contaminate surface or subsurface water to be used for other purposes

the model permits to deduce:

* Alternatives to change or modify (treatments, amendments) the irrigation water

* Changes in the crops,looking for crops more tolerant to salts or other toxic elements

*Changes, or use of amendments in the irrigated soils



Scheme 2. Flow diagram of a conceptual model of a balance of salts and toxic substances in irrigated soils (SAR: Sodium Adsorption Ratio) (Model "SOMORE": Pla, 1997a; Model "SALSODIMAR": Pla, 1997b)