WP5
Deliverable 5.4.2
Recycled water DSS development

Interreg V- A
Greece-Italy
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2014 2020

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IR2MA
Large Scale Irrigation Management Tools for Sustainable Water Management in Rural Areas and Protection of Receiving Aquatic Ecosystems

Subsidy Contract No: I1/2.3/27

Project co-funded by
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Deliverable 5.4.2 – Recycled water DSS development
Progress report and final report on recycled water DSS development and testing

Involved partners:
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Summary

One of the outputs or IR2MA includes the development and testing of a DSS tool for irrigation under different cropping patterns and water quantity/quality scenarios. This aims the development, testing, and validation of the decision support system for irrigation with saline water named EXCEL–IRR. The first part of the report is tackling the development of a daily soil water balance model. The core of the model is presented throughout a set of the equation used to develop the model to run under ''normal'' conditions, conditions of water stress, conditions of salinity stress, and both conditions of salinity and water stress. In the second part of the report, a case study is presented running the model in the irrigation district 17, Trinitapoli, Puglia region. The input parameters used for running the model are given through a set of local climate, soil, crop, and irrigation water conditions, whereas the output parameters are given utilizing relative yields, crop evapotranspiration, irrigation requirements, drainage, number of days crops were under stress and leaching requirements. The simulations were conducted for peach and tomato crops for the three years, 2014–2016. Several different irrigation management options were tested. The model was tested for full irrigation and deficit irrigation scenarios, as well as for conditions of saline irrigation water. The third part of the report consists of the main facts agricultural producers are required to know about irrigation water, irrigation with saline water, crop tolerance to salinity, yield reduction, and management practices used in saline soils.

Keywords: DSS; salinity; wastewater, irrigation management, crop growth

Riassunto

Uno dei obiettivi di IR2MA include lo sviluppo e il collaudo di uno strumento DSS per l'irrigazione con diversi modelli di coltivazione e scenari di quantità e qualità dell'acqua. Questo studio tratta lo sviluppo, il test e la convalida del sistema di supporto decisionale per l'irrigazione con acqua salina denominato EXCEL – IRR. La prima parte del rapporto affronta lo sviluppo di un modello quotidiano di bilancio idrico del suolo. Una serie di equazioni sono sviluppate per far funzionare il modello in condizioni "normali", condizioni di stress idrico, condizioni di stress da salinità ed entrambe le condizioni di salinità e stress idrico. Nella seconda parte viene presentato un caso studio condotto a schema di irrigazione Trinitapoli, in Puglia. I parametri di input utilizzati per l'esecuzione del modello sono forniti attraverso una serie di condizioni locali di clima, suolo, coltura e irrigazione, mentre i parametri di output sono forniti utilizzando le rese relative, l'evapotraspirazione delle colture, i requisiti di irrigazione, il drenaggio, il numero di giorni in cui le colture erano sotto requisiti di stress e lisciviazione. Le simulazioni sono state condotte per le colture di pesco e pomodori per i tre anni, 2014-2016. Sono state testate diverse opzioni di gestione dell'irrigazione. Il modello è stato testato per scenari di irrigazione completa e di irrigazione deficitaria, nonché per le condizioni dell'acqua di irrigazione salina. La terza parte del rapporto è costituita dai fatti principali che i produttori agricoli devono conoscere sull'acqua di irrigazione, l'irrigazione con acqua salata, la tolleranza delle colture alla salinità, la riduzione della resa e le pratiche di gestione utilizzate nei suoli salini.

Parole chiave: IR2MA; DSS; salinità; acque reflue, gestione dell'irrigazione, sviluppo delle colture

1.Model set up

1.1 Calculation procedures in Excel-IRR

Excel-IRR model runs on a daily soil water balance basis. Under standard conditions without water stress, it uses reference evapotranspiration (ET_o) and crop coefficients (K_c) to estimate crop evapotranspiration (ET_c). The ET_o can be computed from meteorological data and the FAO Penman-Monteith method is recommended as the sole standard method for the definition and computation of the reference evapotranspiration. This method requires radiation, air temperature, air humidity, and wind speed data. Excel-IRR computes FAO Penman-Monteith method ET_o, and provides an opportunity to estimate ET_o FAO Penman-Monteith method also in the case of missing climatic data, as well as to use Hargreaves equation, or simply insert measured ET_o data. Excel-IRR also runs on a daily soil water balance basis for the conditions of water stress, salinity stress, combined stress, or saline water application for irrigation.

1.1.1 Crop evapotranspiration under non-standard conditions

Crop evapotranspiration under standard conditions (ET_c) assumes evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. If the conditions encountered in the field differ from the standard conditions, ET_c estimation should be corrected. This correction refers to low soil fertility and poor fertilizer management, soil salinity, and irrigation with low-quality water, soil waterlogging, pests, diseases, and the presence of an impermeable layer within the root zone. The correction is also viable for specific management concerning soil water balance (i.e mulching, intercropping). Soil water shortage and soil salinity also reduce soil water uptake by plants. Therefore, the assumption of crop evapotranspiration under non-standard conditions is derived through the introduction of water stress coefficients over the adjustment of crop coefficients to the field conditions, and through the inclusion of the effects of salts.
The Excel-IRR model employs meteorological, soil, and crop data for a day-by-day estimation of the soil water balance in the effective root zone. The soil water balance is expressed in terms of water depletion in the effective root zone $D_{r,i}$ (mm) at the end of each day through the following equation:

$$D_{r,1} = D_{r,i-1} - P_i - IR_i - CR_i + ET_{C,i} + RO_i + DP_i \quad \text{Eq. 1}$$

Where: $D_{r,i-1}$ – the rhizosphere depletion at the end of the previous day i-1 (mm); P_i – effective precipitation on the day i (mm); IR_i –net irrigation supply on the day i (mm); CR_i – capillary rise on the day i (assumed to zero); $ET_{c,i}$ – crop evapotranspiration on the day i (mm); RO_i – runoff on the day i (mm); DP_i – deep percolation on the same day (mm).

The crop evapotranspiration in the Excel-IRR model is estimated from reference evapotranspiration (ETo) and the single crop coefficient approach. Reference evapotranspiration (ET_O) is calculated using the Penman-Monteith (PM) equation presented below or with several other ET_O equations, including different

versions of the modified PM equation with a lack of input parameters, or Hargreaves equation. Also, Excel-IRR allows for inserting daily measured values of ETo.

$$ET_O = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \chi \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \chi \cdot (1 + 0.34 \cdot u_2)} \quad \text{Eq. 2}$$

Where: ET_o – grass reference evapotranspiration (mmday^{-1}); Rn – net radiation at the crop surface (MJm^{-2}day^{-1}); G – soil heat flux density (MJm^{-2}day^{-1}); T – mean daily air temperature at 2 m height (^{0}C); u_2 – wind speed at 2 m height (ms^{-1}); e_s – saturation vapor pressure (kPa); e_a – actual vapor pressure (kPa); e_s-e_a – saturation vapor pressure deficit (kPa); Δ – slope of the vapor pressure curve (kPa^{0}C^{-1}); χ – psychometric constant (kPa^{0}C^{-1}).

The crop evapotranspiration is estimated from reference evapotranspiration (ETo) and single crop coefficient approach:

$$ET_C = ET_O \cdot K_C \quad \text{Eq. 3}$$

Where: ET_c – crop evapotranspiration (mm day^{-1}); K_c – crop coefficient (K_c values changes according to crop development stages).

The crop coefficient varies during the growing period. K_C is presented by values at the initial stage ($K_{C\ ini}$), the mid-season stage ($K_{C\ mid}$), and the end of the late-season stage ($K_{C\ end}$). K_C trends during the growing period are represented in the crop coefficient curves. Table 12 of FAO 56 IDP (FAO, 1998) lists typical values for $K_{C\ ini}$, $K_{C\ mid}$, and $K_{C\ end}$ for various crops.

1.1.2 ET_c under soil water stress conditions

On one side, in the conditions of wet soils, water in the soil relatively freely moves and it is relatively easily absorbed by plants. On the other side, when the soils are dry, soil water is more strongly bound by capillary and absorptive forces to the soil matrix and is less easily extracted by the crop. Forces acting on the soil water decrease its potential energy and make it less available for plant root extraction. When the potential energy drops below a threshold value, the crop is said to be water-stressed. The effects of soil water stress are described by using by water stress coefficient, K_s. ET_c is adjusted by multiplying the crop coefficient with K_s in the common equation of ET_c estimation:

$$ET_{C\,adj} = K_S \cdot K_c \cdot ET_O \quad \text{Eq. 4}$$

Where: $ET_{c\ adj}$ – adjusted crop evapotranspiration (mm/day); K_s – water stress coefficient (–);K_c – crop coefficient ; ET_o – reference evapotranspiration (mm/day).

For soil water stress-free conditions, $K_s = 1$, whereas for soil water limiting conditions, $K_s < 1$.

1.1.3 Soil water availability

Total available water (TAW) in the soil is the amount of water located in the range between water content at field capacity (FC) and water content at wilting point (WP). FC is the amount of soil water held in the soil after excess water has drained away and the rate of downward movement has decreased. Field capacity is the bulk water content retained in the soil at −0.33 bar of the hydraulic head or suction pressure. Wilting point is the water content at which plants will permanently wilt, and it refers to suction pressure of -15 bar.

The water content in the root zone changes daily as a result of changes in soil water balance components, such as crop transpiration, evaporation from the soil surface, rainfall, runoff, deep percolation, irrigation. When the water content in the soil is decreasing because of low water input, the remaining water in the soil is held to the soil particles with greater force. This water becomes more difficult for the plant to be extracted. The plant water uptake becomes zero when the wilting point is reached. Therefore, TAW in the root zone is the difference between the water content at field capacity and wilting point and it is computed from the following equation:

$$TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot z_r \qquad \text{Eq. 5}$$

Where: TAW – total available soil water in the root zone (mm); θ_{FC} – water content at field capacity ($m^3\ m^{-3}$); θ_{WP} – water content at wilting point ($m^3\ m^{-3}$); Z_r – rooting depth (m).

Crop water uptake is reduced well before the wilting point is reached because water is held with higher and higher forces when decreasing in content. When the soil is sufficiently water uptake equals ET_C, whereas when the soil water content decreases, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a threshold value, soil water can not respond fast enough to the transpiration demand and the crop begins to experience stress. Readily available water (RAW) is defined as the fraction of TAW that a crop can extract from the root zone without suffering water stress:

$$RAW = p \cdot TAW \qquad \text{Eq. 6}$$

Where: RAW – readily available soil water in the root zone (mm); p – an average fraction of TAW that can be depleted from the root zone before moisture stress occurs (0 – 1).

Depletion fraction differs from one crop to another (FAO, 1998), which varies with crop growth stages, and it is also a function of evaporative demand and soil texture. RAW is very similar to the term Management Allowed Depletion (MAD), which is influenced by management and economic factors.

1.1.3.1 Water stress coefficient (K_s)

Soil water stress affects crop ET by reducing the value of the water stress coefficient (Equation 4). Water content in the root zone in the Excel-IRR model is expressed by root zone depletion (D_r) which present water shortage relative to FC. Important facts referring to D_r are:

At FC water content, Dr = 0.

Dr = RAW, water stress threshold water content is reached.

Dr > RAW, water content drops below the threshold and crop evapotranspiration begins to decrease in proportion to the amount of water remaining in the root zone (Fig. **1**).

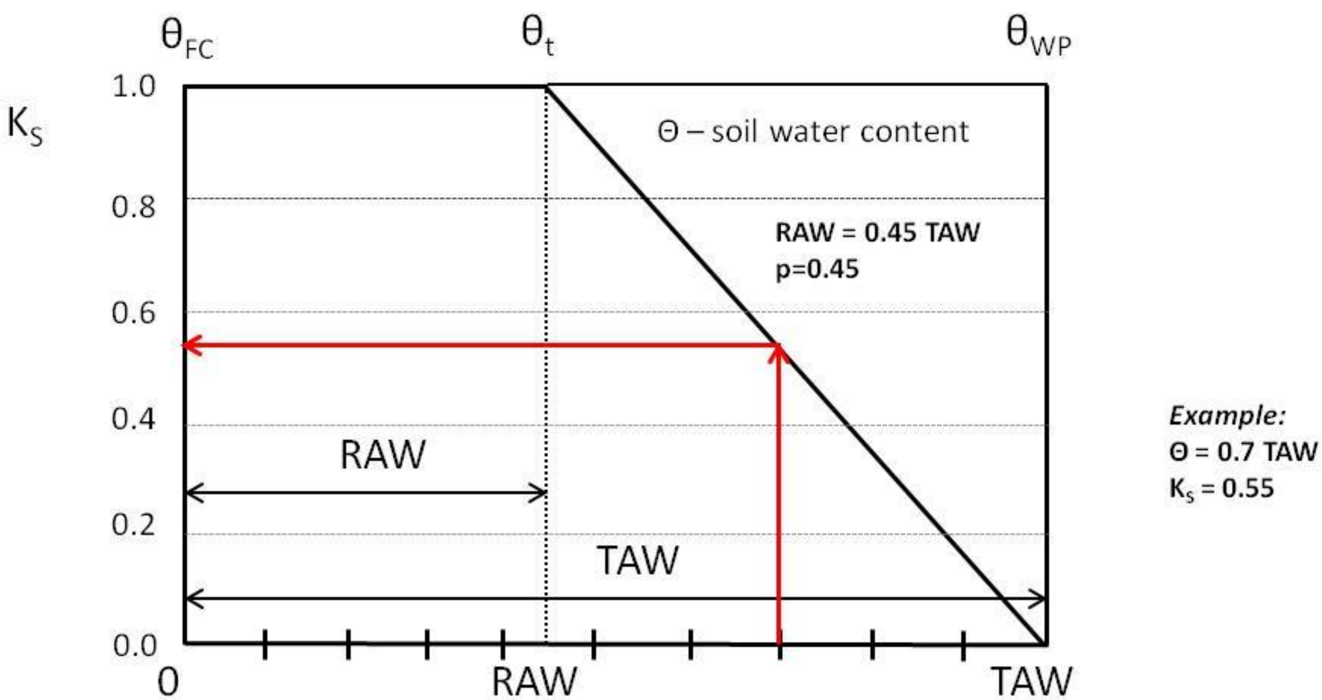

Fig. 1. Water stress coefficient in relation to total and readily available water, as well as to water content at field capacity and wilting point, and depletion fraction (adapted from FAO, 1998, and adjusted) (red arrows indicate an example of soil water content in relation to TAW and K_s value that corresponds to this water content).

For Dr > RAW, Ks is given by:

$$K_S = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p) \cdot TAW} \quad \text{Eq. 7}$$

Where: K_S – transpiration reduction factor dependant on soil available water (0-1)

After the computation of Ks, the adjusted evapotranspiration $ET_{c\ adj}$ is computed using Equation 4 $ET_{C\,adj} = K_S \cdot K_c \cdot ET_O$ Eq. 4. When the root zone depletion is smaller than RAW, K_S = 1.

1.1.3.2 Effects of soil salinity

When salts appear in the soil, soil water becomes less available to the plants. This is related to the fact that salts have an affinity for water and that they decrease osmotic potential. Therefore, the presence of salts in the soil can reduce evapotranspiration by making soil water more bind to soil particles. Also, some salts can cause toxicity and plant metabolism and growth.
The Excel-IRR model utilizes the function that predicts the reduction of crop evapotranspiration caused by soil salinity. This function is derived by combining yield-salinity equations from the FAO Irrigation and Drainage Paper No. 29 (FAO, 1985) with yield-ET equations from FAO Irrigation and Drainage Paper No 33. (FAO, 1979).
Soil salinity is usually measured and expressed based on the electrical conductivity of the saturation extract of the soil (EC_e). This is done because salt concentration changes with soil water content changes. The EC_e is defined as the electrical conductivity of the saturated soil water solution. The solution is saturated after the addition of a sufficient quantity of distilled water. It is typically expressed in deciSiemens per meter (dS m^{-1}). In respect to EC values and soil moisture content, crop yields remain at the potential level in the conditions when crop-specific water stress threshold is not reached and when a specific threshold for electrical conductivity of the saturation soil water extract ($EC_{e\ threshold}$) is not reached. Above the threshold values, the yield begins to decrease linearly in proportion to the increase in salinity. This rate of decrease is expressed as a slope, b, having units of percentage of reduction in yield per dS/m increase in EC_e. All plants do not similarly respond to salinity, and the response of crops to salinity is presented in FAO Irrigation and Drainage Papers No. 33 and 48, as well as in FAO Irrigation and Drainage Papers No. 56.

1.1.3.3 Yield-moisture stress relationship

Excel-IRR model utilizes a simple, linear crop-water production function which was introduced in the FAO Irrigation and Drainage Paper No. 33 (FAO, 1979). This function predicts the reduction in crop yield when crop stress was caused by a shortage of soil water and it was proposed by Stewart et al. (1977):

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \cdot \left(1 - \frac{ET_{C\,adj}}{ET_C}\right) \qquad \text{Eq. 8}$$

Where: Y_a – actual crop yield; Y_m – maximum expected crop yield; K_y – yield response factor (–); $ET_{C\ adj}$ – adjusted (actual) crop evapotranspiration (mm day-1); ET_c – crop evapotranspiration for no water stress conditions (mm day^{-1}).

K_y describes the reduction in relative yield according to the reduction in ET_{Cc} caused by soil water shortage. A list of seasonal K_y values for specific crops is given in the table below.

Table 1. Seasonal yield response functions from FAO IDP No. 33 (FAO, 1979).

Crop	K_y	Crop	K_y
Alfalfa	1.1	Potato	1.1
Banana	1.2-1.35	Safflower	0.8
Beans	1.15	Sorghum	0.9
Cabbage	0.95	Soybean	0.85
Citrus	1.1-1.3	Spring Wheat	1.15
Cotton	0.85	Sugarbeet	1
Grape	0.85	Sugarcane	1.2
Groundnut	0.7	Sunflower	0.95
Maize	1.25	Tomato	1.05
Onion	1.1	Watermelon	1.1
Peas	1.15	Winter wheat	1.05
Pepper	1.1		

1.1.3.4 Yield-salinity relationship

A model utilizes a well-known approach for predicting the crop yield reduction due to salinity (FAO, 1985) which is described in the FAO Irrigation and Drainage Paper No. 29. This approach presumes that there is a specific threshold electrical conductivity of the soil water solution. When salinity increases beyond this threshold, crop yield is decreased and it is presumed to decrease linearly in proportion to the increase in salinity. The soil water salinity is expressed as the electrical conductivity of the saturation extract, EC_e, and the following function (Ayers and Wescot, 1985) is used:

$$\frac{Y_a}{Y_m} = 1 - (EC_e - EC_{e,threshold}) \cdot \frac{b}{100} \quad \text{Eq. 9}$$

Where: Y_a – actual crop yield; Y_m – maximum expected crop yield when $EC_e < EC_{e\ threshold}$; EC_e – mean electrical conductivity of the saturation extract for the root zone (dS m^{-1}); EC_e – threshold electrical conductivity of the saturation extract at the threshold of EC_e; when crop yield first reduces below Ym (dS m^{-1}); b – reduction in yield per increase in ECe [%/(dS m^{-1})].

Equation 9 is valid for conditions where $EC_e > EC_{e\ threshold}$. Values for $EC_{e,threshold,}$ and b are given in FAO Irrigation and Drainage Papers No. 29 (FAO, 1985), No. 48 (Rhoades et al; 1992), and No. 56 (FAO, 1998) for many crops.

Table 2. Salt tolerance of common crops expressed as the electrical conductivity of the soil saturation extract at the threshold when crop yield first reduces below the full potential (EC_e,threshold) and as the slope (b) of reduction in crop yield with increasing salinity beyond Ece, threshold (adopted from FAO, 1979; FAO,1998)

Crop [1]	$EC_{e,treshold}$ [2] ($dS\ m^{-1}$) [3]	b [4] ($\%/dS\ m^{-1}$)	Rating [5]
Alfalfa	2	7.3	MS
Banana	-	-	MS
Beans	1	19	S
Cabbage	1.0-1.8	9.8-14.0	MS
Citrus (orange)	1.7	16	S
Cotton	7.7	5.2	T
Grape	1.5	9.6	MS
Groundnet	3.2	29	MS
Maize	1.7	12	MS
Onion	1.2	16	S
Peas	1.5	14	S
Pepper	1.5-1.7	12-14	MS
Potato	1.7	12	MD
Safflower	-	-	MT
Sorghum	6.8	16	MT
Soybean	5	20	MT
Sugarbeet	7	5.9	T
Sugarcane	1.7	5.9	MS
Sunflower	-	-	MS
Tomato	0.9-2.5	9	MS
Watermelon	-	-	MS
Winter wheat	6	7.1	MT

[1]The data serve only as a guideline - Tolerance varies depending upon climate, soil conditions, and cultural practices. Crops are often less tolerant during the germination and seedling stage.
[2]$EC_{e,\ threshold}$ means the average root zone salinity at which yield starts to decline
[3]Root zone salinity is measured by the electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre ($dS\ m^{-1}$) at 25°C
[4]b is the percentage reduction in crop yield per 1 dS/m increase in EC_e beyond $EC_{e,threshold}$
[5]Ratings are: T = Tolerant, MT = Moderately Tolerant, MS = Moderately Sensitive and S = Sensitive

1.1.3.5 Combined salinity-ET reduction relationship

Excel-IRR utilizes combined salinity vs. evapotranspiration reduction relationship. On one side, it covers salinity effects on yield with no water stress (Dr < RAW), whereas on the other side, it covers the combined effect of salinity and water shortage on yield (Dr < RAW).

When salinity stress occurs without water stress, Equation 8 and Equation 9 can be combined and solved for an equivalent K_s, where $K_s = ET_{c\ adj}/ET_c$:

$$K_S = 1 - \frac{b}{K_y \cdot 100} \cdot \left(EC_e - EC_{e,threshold}\right) \qquad \text{Eq. 10}$$

Equation 10 is valid for conditions when $EC_e > EC_{e\ threshold}$ and Dr < RAW.

When salinity stress occurs with water stress (Dr > RAW) following function is used:

$$K_S = \left[1 - \frac{b}{K_y \cdot 100} \cdot \left(EC_e - EC_{e,threshold}\right)\right] \cdot \left(\frac{TAW - D_r}{TAW - RAW}\right) \qquad \text{Eq. 11}$$

Equation 11 is valid for conditions when $EC_e > EC_{e\ threshold}$ and Dr > RAW. Fig. **2.** shows the impact of soil salinity on water stress coefficient, and accordingly ET_c reduction.

1.1.3.6 Useful equations for conditions of water stress and salinity

Water balance computed daily assumes an exponential decrease for ET_c when the soil water depletion fraction exceeds the depletion fraction p, which is crop-specific. Thus, the factor p should be corrected, becoming smaller when EC_e is larger than $EC_{e,threshold}$, and depending upon the crop sensitivity to salinity through the parameter b of Equation 9. The fraction p corrected for salinity (p_{cor}) is then estimated from the equation:

$$p_{cor} = p - \left[b \cdot \left(EC_e - EC_{e\ threshold}\right)\right] \cdot p \qquad \text{Eq. 12}$$

This equation indicates that p decreases with increasing salinity and with increasing crop sensitivity to salts. Decreasing p means that a smaller soil water depletion is required for the crop to evapotranspire at a rate $ET_a < ET_m$ at higher soil water contents than without salinity effects. The limit $p \geq 0.1$ proposed by Allen et al. (1998) is kept since soil evaporation is not affected.

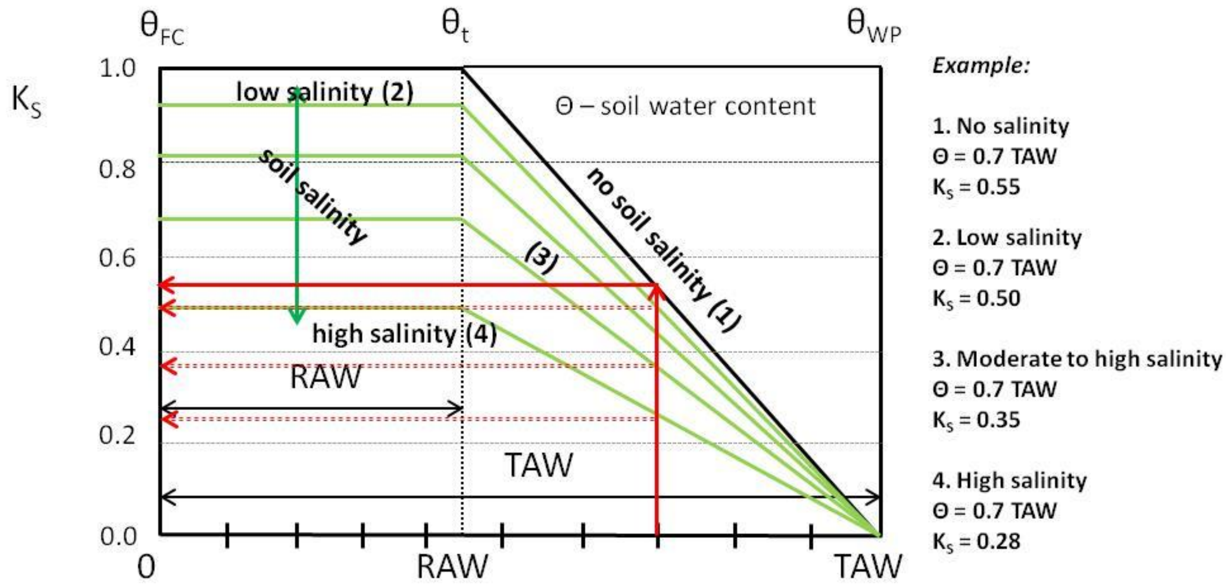

Fig. 2. Soil salinity and water shortage effects of water stress coefficient (adopted from Allen et al., 1998 and adjusted).

Salinity increases the soil water content at the wilting point because crop roots have to overcome the combined matric potential and increased osmotic potential (Beltrao and Ben Asher, 1997). When salts are present the value for θ_{WP} is corrected through:

$$\theta_{WP\ salt} = \theta_{WP} + b \cdot \left(\frac{EC_e - EC_{e\ threshold}}{100} \right) \cdot \left(\theta_{FC} - \theta_{WP} \right) \qquad \text{Eq. 13}$$

Where:
θ_{WP} – soil water content at the wilting point under non-saline conditions; θ_{FC} – soil water content at field capacity ($m^3\ m^{-3}$); $\theta_{WP,salt}$ – soil water content at wilting point ($m^3\ m^{-3}$) for saline conditions.

Following this approach, the total available soil water (TAW) is corrected for salinity effects by

$$TAW_{salt} = 1000 \cdot \left(\theta_{FC} - \theta_{WP\ salt} \right) \cdot z_r \qquad \text{Eq. 14}$$

Where:
TAW_{salt} – the corrected value of the total available soil water (mm); θ_{FC} – water content at field capacity ($m^3\ m^{-3}$); $\theta_{WP,salt}$ – water content at wilting point corrected for salinity ($m^3\ m^{-3}$); Z_r – rooting depth (m).

It is assumed that a crop would not be grown on saline soil that would produce a relative yield Ya/Ym < 0.50.

Correction of the wilting point value because of the effects of salinity is given in the Equation below:

$$\Delta\theta_{WP} = b \cdot \left(\frac{EC_e - EC_{e\,threshold}}{100} \right) \cdot \left(\theta_{FC} - \theta_{WP}\right) \qquad \text{Eq. 15}$$

Where:

$\Delta\theta_{WP}$ – correction of wilting point because of the presence of salts ($m^3\ m^{-3}$)

Accordingly, the corrected value of total available water because of the presence of salts is:

$$TAW_{salt} = 1000 \cdot \left(\theta_{FC} - \theta_{WP} - \Delta\theta_{WP}\right) \cdot z_r \qquad \text{Eq. 16}$$

Where: TAW_{salt} – the corrected value of the total available soil water (mm); θ_{FC} – water content at field capacity ($m^3\ m^{-3}$); θ_{WP} – water content at wilting point ($m^3\ m^{-3}$); $\Delta\theta_{WP}$ – correction of wilting point because of the presence of salts ($m^3\ m^{-3}$); Z_r – rooting depth (m).

1.1.3.7 Irrigation management in Excel-IRR

Excel–IRR offers different irrigation options. Important input parameters in the model are irrigation threshold, Irrigation supply (1 – referring to the fraction/percentage to supply in respect to depletion), Irrigation supply (2 – referring to water amount below or above that fraction), irrigation efficiency, irrigation wetting coefficient, irrigation water quality, ECe threshold for a designed relative yield of a specific crop, and ECw threshold of irrigation water for a specific crop. As a result, Excel-IRR computes daily soil water content in the soil as well as crop evapotranspiration, drainage, leaching requirements, and daily and seasonal irrigation amounts.

The irrigation threshold is the management defined threshold at which depletion value (from 0 to 1) irrigation event starts. It is sometimes the same as depletion fraction, but also it can be lower than RAW, and it means that plants will suffer mild to moderate water stress, or higher than RAW, which means that the user's wat to have frequently high water content in the soil. Irrigation threshold, therefore, allows to user to set deficit irrigation as an irrigation strategy.

Irrigation efficiency differs depending on the irrigation method applied. For practical purposes, users can utilize values from the literature. Irrigation efficiency is used to obtain gross irrigation requirements.

Irrigation wetting coefficient has values lower than 1 in the conditions when the irrigation method does not cover the entire surface by watering, but narrow strips of non-irrigation land appear in the field. This is mainly related to drip irrigation and conditions of young plant establishment, or orchards.

Irrigation water quality parameters in the model are EC_w - electrical conductivity of irrigation water, which triggers salinity water stress if it is higher than mean electrical conductivity of the saturation extract for the root zone (EC_e), higher than $EC_{e,threshold}$ for a specific crop, or higher than $EC_{w,threshold}$ – threshold electrical conductivity of irrigation water above which crop yield is reduced.

Designed relative yield in the model is adopted for EC_e targeted value (at least 90% of the yield) from the FAO Irrigation and drainage paper No. 29 Rev. 1. Table 4 in the mentioned document provides irrigation

water EC threshold values for a specific crop, as well as ECe threshold values for specific relative yield (50–100%)

Leaching requirements are computed using $LR = \frac{EC_W}{5 \cdot EC_{e-} EC_W}$

Eq. 18Equation 18 taking into account threshold electrical conductivity of irrigation water above which crop yield is reduced ($EC_{w,threshold}$) and threshold electrical conductivity of the saturation extract for the specific crop ($EC_{e,threshold}$).

The user can specify different irrigation management options using the model:

1. Full irrigation and
2. Deficit irrigation with water replenishment up to field capacity

2.Testing and validation of the model

2.1 Input parameters

The model requires a set of different climates, soil, crop, irrigation water, and management parameters.

2.1.1 Climate input parameters

Climate data for the model are obtained from agro-meteorological station in Trinitapoli (Latitude Nord 41° 19' 16.22'''; Longitude East 16° 07' 45.25''; elevation: 16 m a.s.l.), South Italy (Puglia region), for the period 2014-2016. The agrometeorological station provides daily measurements of minimum, mean and maximum temperature, precipitation, and minimum, maximum, and means relative humidity, incoming solar radiation, and wind speed. These measurements are used to estimate daily reference evapotranspiration (ET_0). The model offers several possibilities in estimating ET_0, and in this case, the original Penman-Monteith equation was used. Fig. **3.** and Fig. **4.** present monthly averages of reference evapotranspiration and the sum of monthly rainfalls for the three observed years.

In the year 2016, mean summer months reference evapotranspiration was higher compared with the other two years. Nevertheless, in the year 2015, reference evapotranspiration during May, June, and July was also much higher compared with the year 2014. Therefore, regarding the demand of the atmosphere, the year 2016 was much demanding, followed by 2015, whereas the year 204 was much less demanding. Total annual rainfall in the years 2016 and 2015 were similar (540.6 mm and 544.4 mm respectively), whereas the amount of rainfall in the year 2014 was almost 100 mm lower (447.6 mm). In the vegetation period (March-October) the amount of rainfall was the highest in the year 2016 (403.0 mm), and a bit lower in the year 2015 (379.4 mm). In the year 2014, the amount of rainfall recorded in the vegetation period was significantly lower, 293.8 mm.

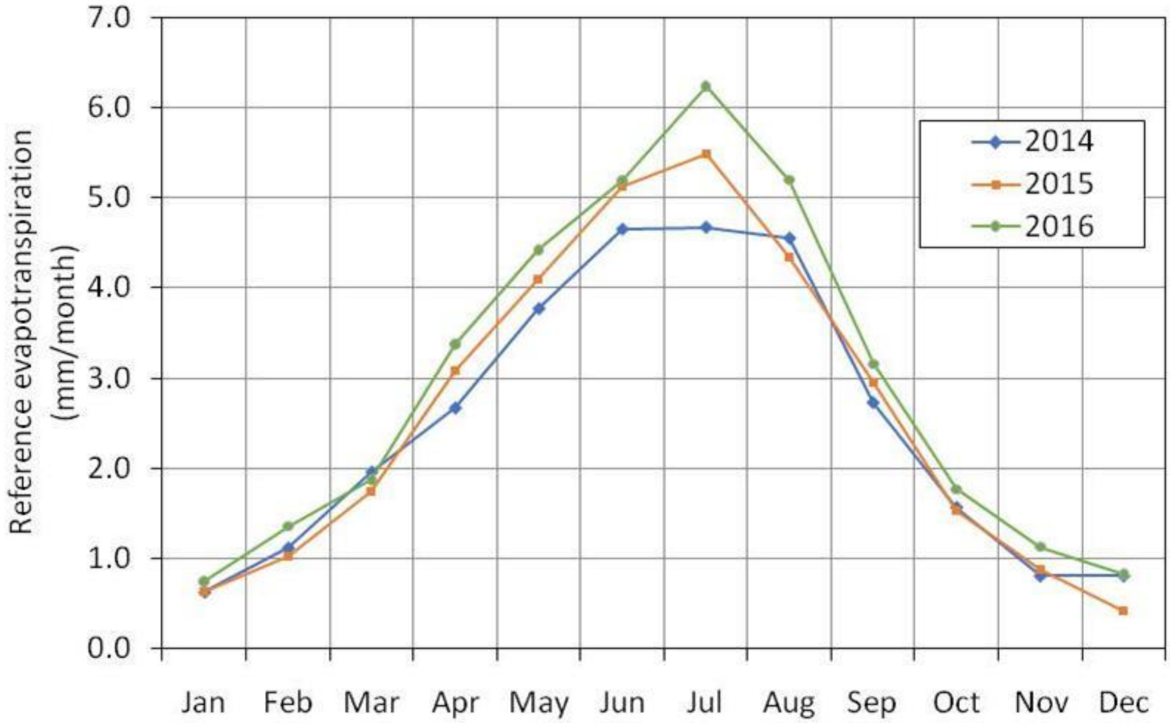

Fig. 3. Mean monthly reference evapotranspiration at Trinitapoli agro-meteorological station for the period 2014-2016.

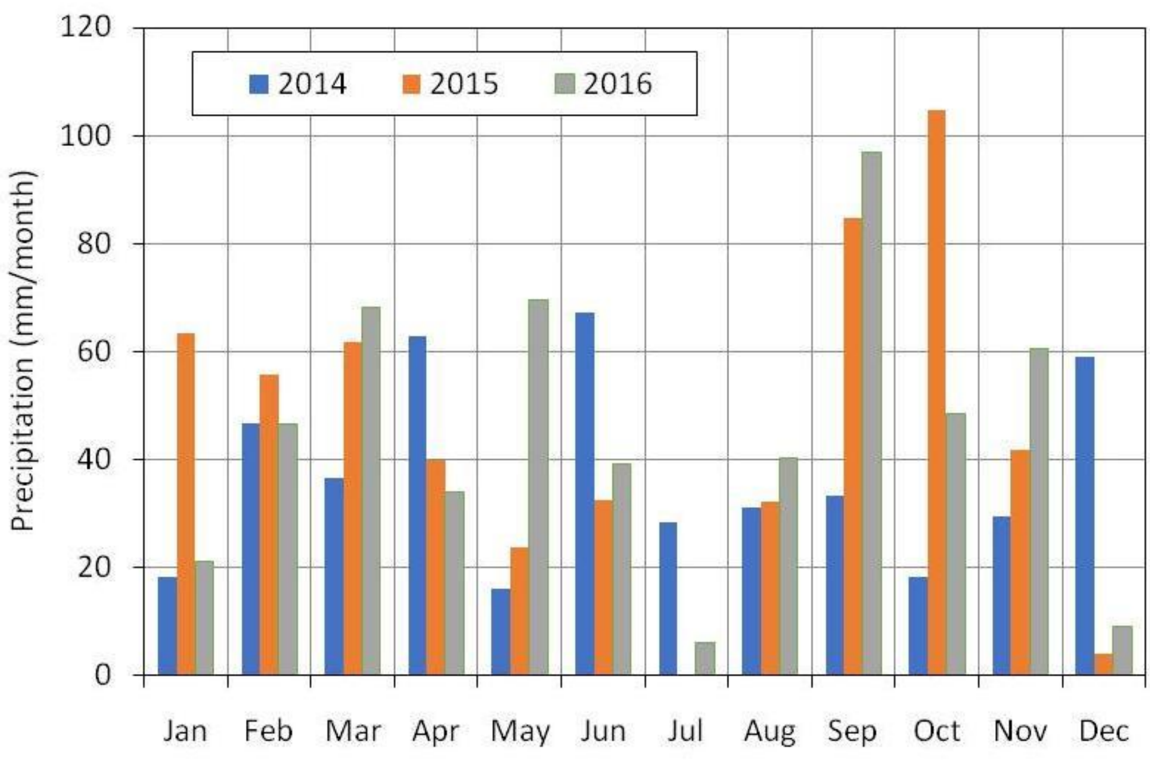

Fig. 4. Monthly rainfalls at Trinitapoli agro-meteorological station for the period 2014-2016.

2.1.2 Soil input parameters

Typical soils of the region are Eutric Fluvisols. Soil is very thick, deeper than 100 cm. It contains 140 mm of water per 1 m depth of soil. It has a loamy texture according to USDA classification. It contains 39% sand, 40% silt, and 21% clay, in the 0-30 cm depth, whereas the particle size distribution does not change a lot in the subsoil. Soil bulk density along the soil profile has values around 1.40 gcm^{-3}. Gravel content in the topsoil and subsoil is 4 and 7%, respectively. Soil is slightly calcaric, 0.5 to 2.5% of $CaCO_3$ in the topsoil and subsoil, and rich in exchangeable bases. It has a neutral to slightly alkaline reaction with topsoil pH in the water of 7.2, and 7.5 in the subsoil, respectively. Cation exchange capacity in the topsoil and subsoil is moderate to low, 16, and 14 $cmolkg^{-1}$, respectively. Soil is poor with total organic carbon in topsoil and subsoil, 0.86 and 0.38%, respectively. The electrical conductivity of soil saturation extract is 3 dS/m throughout the entire thickness of the profile for the tomato crop, and 2 dS/m for peach, respectively. Soil water-holding characteristics are presented in Table 3..

Table 3. Soil water characteristics.

Soil Layers (top-down)	Depth [cm]	Soil texture	Field capacity [vol%]	Wilting point [vol%]	Soil water content [mm/m]
1st	0–50	loam	40	26	140
2nd	50–100	loam	37	23	140
3rd	100–120	loam	37	23	140

2.1.3 Crop input parameters

Simulations were conducted on two chosen crops: tomato and peach. The input parameters for the two crops are given in **Error! Reference source not found.** – Table 7. Tomato is known as a **moderately sensitive crop** to soil salinity whereas peach is a **sensitive crop** to salinity.

2.1.4 Scenarios Management

The model was set up to start an irrigation event when the irrigation threshold is reached. The irrigation threshold is a crop-specific management parameter. In this simulation, for the full irrigation scenario, the irrigation threshold was set to be the same as the depletion fraction threshold for both crops, whereas, for the deficit irrigation scenario, the irrigation threshold was set up to be lower than the depletion fraction threshold for both crops. Additionally, the following five different irrigation water quality scenarios are tested: EC_w = 1 dS/m, EC_w = 2 dS/m, EC_w = 3 dS/m, EC_w = 4 dS/m and EC_w = 5 dS/m.
The different management input parameters are presented in **Error! Reference source not found.** and

Table **6** for tomato and peach, respectively. Additional crop input is presented in
Table **5** and Table 7.

Table 4. Tomato crop and management input.

	Crop stage	Initial	Crop development	Mid-season	Late season	Harvesting	Total length
Growing days	Length	30	40	45	30	145	145
	Starting day	April-1	May-1	June-10	July-25	August-24	
Crop coefficients	K_c values	0.60	1.15	1.15	0.80	0.80	
	K_y values					1.10[3]	
	K_c basal	0.15	1.10	1.10	0.70		
Rainfall	Rainfall coefficient[1]	0.90	0.90	0.90	0.90	0.90	
	Rainfall minimum (mm)[2]	1.00					
Depletion fraction threshold		0.40	0.40	0.40	0.40		
Irrigation	Irrigation threshold[4]	0.40	0.40	0.40	0.40		
	Irr_supply_1	1.00	1.00	1.00	1.00		
	Irr_supply_2	0.00	0.00	0.00	0.00		
	Irr_efficiency	0.85	0.85	0.85	0.85		
	Irr_wet_coef	1.00	1.00	1.00	1.00		

[1]To be multiplied with rainfall to obtain effective rainfall

[2]minimum amount of rainfall to be included in the calculation; lower than 1 mm is considered no rainfall

[3]whole season value

[4]under deficit irrigation scenarios, irrigation threshold during the entire season was set to be 0.6 and irrigation amount should be fulfilled field capacity water content

Table 5. Additional tomato crop input.

Additional input parameters	
Number of days to stop irrigation before harvesting	10
$EC_{e,\ threshold}$ [dS m^{-1}] – mean electrical conductivity of the saturation extract for the root zone when crop yield first reduces below maximum	2.5
b [%/(dS m-1)] – reduction in yield per increase in EC_e	9.0
ECw [dS m^{-1}] – electrical conductivity of irrigation water above which the yield starts to reduce below maximum	1.7
Crop height [cm]	60
Initial root depth [cm]	20
Maximum root depth [cm]	60
Base temperature [°C]	10
Cutoff temperature [°C]	35

Table 6. Peach crop and management input.

	Crop stage	Initial	Crop development	Mid-season	Late season	Harvesting	Total length
Growing days	Length	30	60	100	30	145	220
	Starting day	Mar-1	Mar-31	May-30	Sept-7	Oct-7	
Crop coefficients	K_c values	0.50	0.90	0.90	0.70	0.70	
	K_y values					1.10[3]	
	K_c basal	0.15	0.85	0.85	0.50		
Rainfall	Rainfall coefficient[1]	0.90	0.90	0.90	0.90	0.90	
	Rainfall minimum (mm)[2]	1.00					
Depletion fraction threshold		0.40	0.50	0.50	0.50	0.50	
Irrigation	Irrigation threshold[4]	0.50	0.50	0.50	0.50		
	Irr_supply_1	1.00	1.00	1.00	1.00		
	Irr_supply_2	0.00	0.00	0.00	0.00		
	Irr_efficiency	0.85	0.85	0.85	0.85		
	Irr_wet_coef	1.00	1.00	1.00	1.00		

[1]To be multiplied with rainfall to obtain effective rainfall

[2]minimum amount of rainfall to be included in the calculation; lower than 1 mm is considered no rainfall

[3]whole season value

[4]under deficit irrigation scenarios irrigation threshold during the entire season was set to be 0.7 and irrigation amount should fulfill field capacity water content

Table 7. Additional peach crop input.

Additional input parameters	
Number of days to stop irrigation before harvesting	15
$EC_{e, threshold}$ [dS m^{-1}] – mean electrical conductivity of the saturation extract for the root zone when crop yield first reduces below maximum	1.7
b [%/(dS m-1)] – reduction in yield per increase in EC_e	21.0
ECw [dS m^{-1}] – electrical conductivity of irrigation water above which the yield starts to reduce below maximum	1.1
Crop height [cm]	180
Initial root depth [cm]	100
Maximum root depth [cm]	100
Base temperature [°C]	10
Cutoff temperature [°C]	35

2.2 Simulation results

2.2.1 Scenario 1 (The year 2014) – Tomato

The results of Scenario 1 demonstrate the ability of the model to run with different irrigation water salinity scenarios. Input parameters are given in box 1 below.

Box 1. Scenario 1 input.

Input parameters	Full	Deficit
ECw [dS m^{-1}] – electrical conductivity of irrigation water	1, 2, 3, 4, 5	1, 2, 3, 4, 5
ECw [dS m^{-1}] – electrical conductivity of the saturation extract	1.5, 3, 4.5, 6, 7.5	1.5, 3, 4.5, 6, 7.5
Irrigation threshold = depletion threshold	0.4	0.6

The results of simulations for tomato crops are presented in Table 8.

- **Full irrigation:** For full irrigation, the obtained results indicate the maximum obtained yield in the scenario with the electrical conductivity of irrigation water below the threshold value of EC_w for tomato crop. The increase in ECw resulted in a relative yield decrease, reaching almost 50% reduction at ECw = 5 dS/m. After every irrigation event, the model is set to apply water up to field capacity water content. Consequently, the net irrigation requirement is the lowest at no salinity stress treatment, whereas in the stress treatments net irrigation requirement is 423.2 mm for all treatments. Anyway, due to salinity stress, one portion of this water is part of the leaching fraction (15%, or 65.1 mm), whereas the other part is drainage water. Leaching fraction remains the same in salinity stress treatments, whereas the drainage water increases with irrigation water salinity increase.
- **Deficit irrigation:** For deficit irrigation, the obtained results indicate the maximum obtained yield in the scenario with the electrical conductivity of irrigation water below the threshold value of EC_w for tomato crop. Anyway, a reduction of more than 10% was obtained. The increase in ECw resulted in a relative yield decrease, reaching a 50% reduction at ECw = 5 dS/m. After every irrigation event, the model is set to apply water up to field capacity water content. Consequently, the net irrigation requirement is the lowest at no salinity stress treatment, whereas in the stress treatments net irrigation requirement is 364.5 mm for all the treatments. Anyway, due to salinity stress, one portion of this water is part of the leaching fraction (15%, or 56.1 mm), whereas the other part is drainage water. Leaching fraction remains the same in salinity stress treatments, whereas the drainage water increases with irrigation water salinity increase.

Table 8. Scenario 1 results for full and deficit irrigation for tomato crop, the year 2014.

Parameter	ECw = 1 dS/m	ECw = 2 dS/m	ECw = 3 dS/m	ECw = 4 dS/m	ECw = 5dS/m
Full irrigation					
Relative yield (%)	99.7	95.3	81.8	68.4	54.9
Number of days under stress	8	143	143	143	143
ET_c (mm)	564.3	541.6	472.3	403	333.7
ET_{max} (mm)	565.7	565.7	565.7	565.7	565.7
NIR (mm)	367.0	423.2	423.2	423.2	423.2
Rainfall (mm)	176.4	176.4	176.4	176.4	176.4
Drainage (mm)	28.7	86.3	148.7	212.9	279.4
Leaching fraction (-)	0.00	0.15	0.15	0.15	0.15
Leaching fraction (mm)	0.0	65.1	65.1	65.1	65.1
Depletion at harvest (mm)	51.6	30.2	23.1	17.7	14.7
WUE (kg/m^3)	10.6	10.6	10.4	10.2	9.9
IWUE(kg/m^3)	16.3	13.5	11.6	9.7	7.8
Deficit irrigation					
Relative yield (%)	89.8	86.5	74.2	61.8	49.5
Number of days under stress	66	143	143	143	143
ET_c (mm)	513.1	496.5	433	369.4	305.9
ET_{max} (mm)	565.7	565.7	565.7	565.7	565.7
NIR + LF (mm)	315.9	364.5	364.5	364.5	364.5
Rainfall (mm)	176.4	176.4	176.4	176.4	176.4
Drainage (mm)	56.1	112.8	164.3	215.9	267.5
Leaching fraction (-)	0.00	0.15	0.15	0.15	0.15
Leaching fraction (mm)	0.0	47.5	47.5	47.5	47.5
Depletion at harvest (mm)	78.9	70.3	58.1	45.9	33.6
WUE (kg/m^3)	10.5	10.5	10.3	10.0	9.7
IWUE (kg/m^3)	17.1	14.2	12.2	10.2	8.1

The comparison of water use efficiency and irrigation water use efficiency for full irrigation and deficit irrigation treatments is given in Figure 5 and Figure 6. Water use efficiency is always higher in a respectful full irrigation scenario compared with deficit irrigation scenarios. Water use efficiency decreases with an irrigation water EC increase, but the difference of less than 10% between the highest and the lowest values was observed.

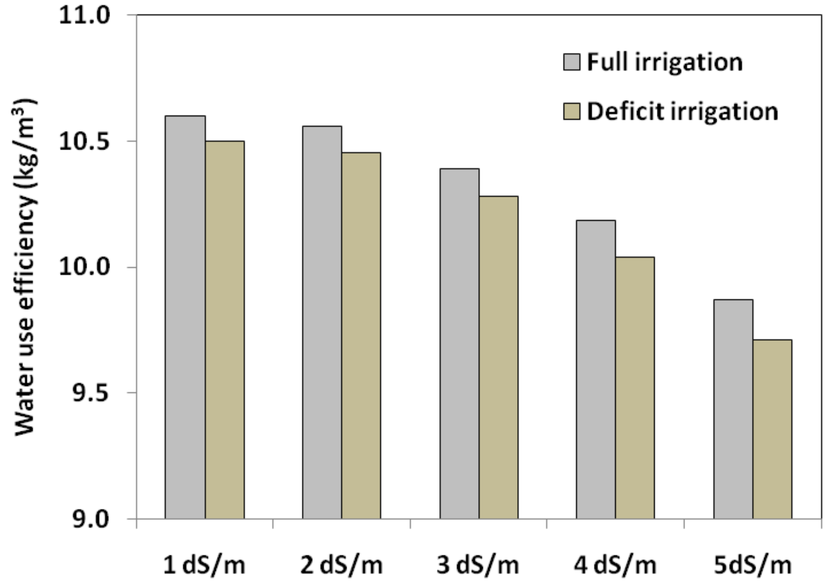

Fig. 5. Water use efficiency of tomato crop grown under full and deficit irrigation practices and different irrigation water quality.

The results of irrigation water use efficiency are much different. The values of IWUE decrease with an increase in ECw but too much compared with WUE. The lowest IWUE (8.1 kg/m^3) is more than twice lower compared with the highest IWUE (17.1 kg/m^3). On contrary to WUE, IWUE is always higher in deficit irrigation treatment compared with full irrigation treatment.

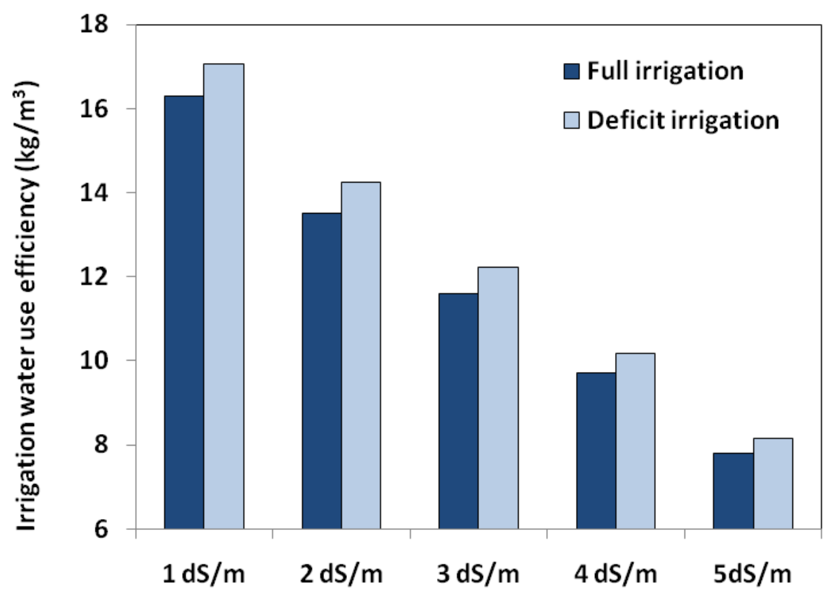

Fig. 6. Irrigation water use efficiency of tomato crop grown under full and deficit irrigation practices and different irrigation water quality.

2.2.2 Scenario 1 (The year 2014) – Peach

The results of Scenario 1 demonstrate the ability of the model to run with different irrigation water salinity scenarios. Input parameters are given in box 1 below.

Input parameters	Full	Deficit
ECw [dS m^{-1}] – electrical conductivity of irrigation water	1, 2, 3, 4, 5	1, 2, 3, 4, 5
ECw [dS m^{-1}] – electrical conductivity of the saturation extract	1.5, 3, 4.5, 6, 7.5	1.5, 3, 4.5, 6, 7.5
Irrigation threshold = depletion threshold	0.5	0.7

The results of simulations for peach are presented in Table 9.

- **Full irrigation:** The obtained results indicate the maximum obtained yield in the scenario with the electrical conductivity of irrigation water below the threshold value of EC_w for tomato crop. The increase in ECw resulted in a relative yield decrease, reaching more than 50% reduction at ECw = 3 dS/m. After every irrigation event, the model is set to apply water up to field capacity water content. Consequently, the net irrigation requirement is the lowest at no salinity stress treatment, whereas in the stress treatments net irrigation requirement is 497.3 mm for all treatments. One portion of this water is part of the leaching fraction (64.9 mm), whereas the other part is drainage water. Leaching fraction remains the same in salinity stress treatments, whereas the drainage water increases with irrigation water salinity increase.
- **Deficit irrigation:** The obtained results indicate the maximum obtained yield in the scenario with the electrical conductivity of irrigation water below the threshold value of EC_w for tomato crop. Anyway, a reduction of 6.1% was obtained. The increase in ECw resulted in a relative yield decrease, reaching a 50% reduction of yield at ECw 2.7 dS/m. After every irrigation event, the model is set to apply water up to field capacity water content. Consequently, the net irrigation requirement is the lowest at no salinity stress treatment, whereas in the stress treatments net irrigation requirement is 343.8 mm for all treatments. One portion of this water is part of the leaching fraction (44.8 mm), whereas the other part is drainage water. Leaching fraction remains the same in salinity stress treatments, whereas the drainage water increases with irrigation water salinity increase.

Table 9. Scenario 1 results for full and deficit irrigation for a peach crop, the year 2014.

Parameter	ECw = 1 dS/m	ECw = 2 dS/m	ECw = 3 dS/m	ECw = 4 dS/m	ECw = 5dS/m
Full irrigation					
Relative yield (%)	99.9	72.6	41.1	9.7	No yield
Number of days under stress	5	196	196	196	
ET_c (mm)	630.9	474.4	293.7	113	
ET_{max} (mm)	631.6	631.6	631.6	631.6	
NIR (mm)	430.7	497.3	497.3	497.3	
Rainfall (mm)	239.6	239.6	239.6	239.6	
Drainage (mm)	69	264	444.1	624.2	
Leaching fraction (-)	0	0.15	0.15	0.15	
Leaching fraction (mm)	0	64.9	64.9	64.9	
Depletion at harvest (mm)	30.2	1.9	1.2	0.5	
WUE (kg/m^3)	15.8	15.3	14.0	8.6	
IWUE (kg/m^3)	23.2	14.6	8.3	2.0	
Deficit irrigation					
Relative yield (%)	93.9	68.0	38.3	8.6	No yield
Number of days under stress	29	196	196	196	
ET_c (mm)	596.4	447.8	277.3	106.7	
ET_{max} (mm)	631.6	631.6	631.6	631.6	
NIR + LF (mm)	295.9	343.8	343.8	343.8	
Rainfall (mm)	239.6	239.6	239.6	239.6	
Drainage (mm)	32.3	197.9	332.9	481.4	
Leaching fraction (-)	0	0.15	0.15	0.15	
Leaching fraction (mm)	0	44.8	44.8	44.8	
Depletion at harvest (mm)	93.8	62.8	27	4.8	
WUE (kg/m^3)	15.7	15.2	13.8	8.1	
IWUE (kg/m^3)	31.7	19.8	11.1	2.5	

The comparison of water use efficiency and irrigation water use efficiency for full irrigation and deficit irrigation treatments is given in Error! Reference source not found. and **Error! Reference source not found.**. Water use efficiency is always higher in respectful full irrigation scenarios compared with deficit irrigation scenarios. Water use efficiency decreases with an irrigation water EC increase. The highest ECw treatment (4 dS/m) has very low water use efficiency compared with other treatments.

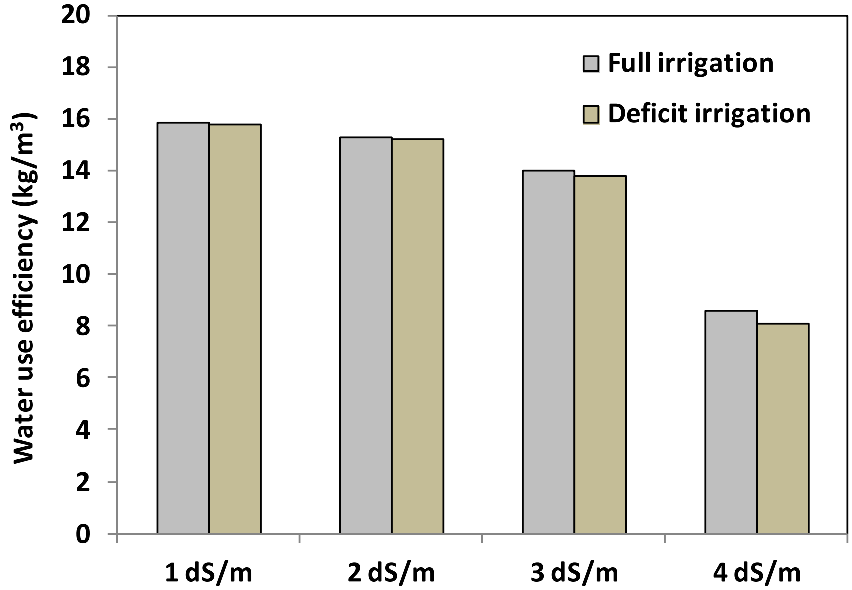

Fig. 7. Water use efficiency of peach grown under full and deficit irrigation practices and different irrigation water quality.

The values of IWUE decrease with an increase in ECw but to a higher extent compared with WUE. The difference between IWUE between the treatments is very high for both full and deficit irrigation. IWUE is always higher in deficit irrigation treatment compared with full irrigation treatment.

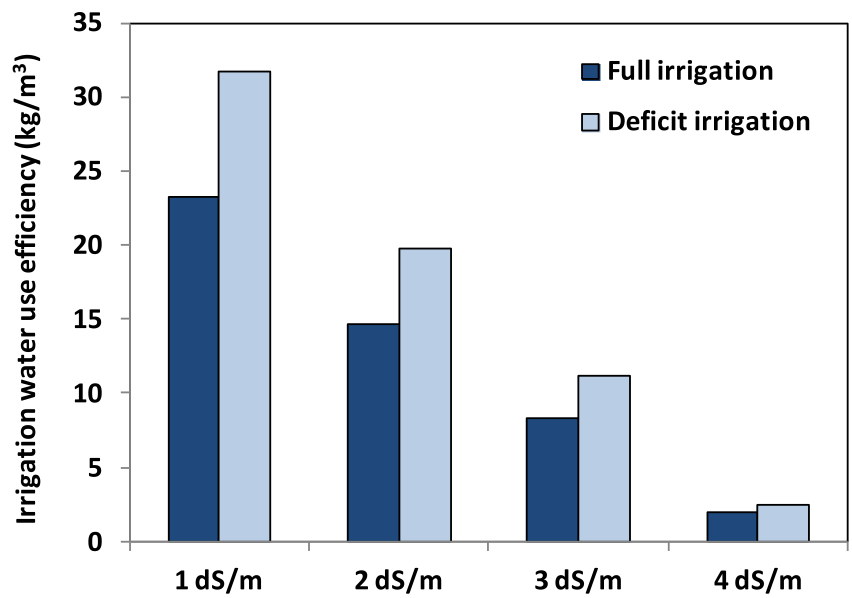

Fig. 8. Irrigation water use efficiency of peach grown under full and deficit irrigation practices and different irrigation water quality.

2.2.3 Scenario 1 (The year 2015) – Tomato

The results for scenario 1, tomato crop, fully irrigated, are presented in Table 10.

Table 10. Scenario 1 results for full and deficit irrigation for tomato crop, the year 2015.

Parameter	ECw = 1 dS/m	ECw = 2 dS/m	ECw = 3 dS/m	ECw = 4 dS/m	ECw = 5dS/m
Full irrigation					
Relative yield (%)	99.6	95.2	81.8	68.3	54.8
Number of days under stress	12	143	143	143	143
ET_c (mm)	615.3	590.8	515.2	439.6	364
ET_{max} (mm)	617.6	617.6	617.6	617.6	617.6
NIR (mm)	491.1	569.9	569.9	569.9	569.9
Rainfall (mm)	112.9	112.9	112.9	112.9	112.9
Drainage (mm)	20.7	96.3	171.3	246.4	321.4
Leaching fraction (-)	0.00	0.15	0.15	0.15	0.15
Leaching fraction (mm)	0.0	74.3	74.3	74.3	74.3
Depletion at harvest (mm)	34.3	6.4	5.6	4.8	4
WUE (kg/m^3)	9.7	9.7	9.5	9.3	9.0
IWUE (kg/m^3)	12.2	10.0	8.6	7.2	5.8
Deficit irrigation					
Relative yield (%)	89.8	86.5	74.2	61.8	49.5
Number of days under stress	66	143	143	143	143
ET_c (mm)	513.1	496.5	433	369.4	305.9
ET_{max} (mm)	565.7	565.7	565.7	565.7	565.7
NIR + LF (mm)	315.9	364.5	364.5	364.5	364.5
Rainfall (mm)	176.4	176.4	176.4	176.4	176.4
Drainage (mm)	56.1	112.8	164.3	215.9	267.5
Leaching fraction (-)	0.00	0.15	0.15	0.15	0.15
Leaching fraction (mm)	0.0	47.5	47.5	47.5	47.5
Depletion at harvest (mm)	78.9	70.3	58.1	45.9	33.6
WUE (kg/m^3)	10.5	10.5	10.3	10.0	9.7
IWUE (kg/m^3)	17.1	14.2	12.2	10.2	8.1

- Full irrigation: The obtained results indicate the maximum obtained yield in the scenario with the electrical conductivity of irrigation water below the threshold value of EC_w for tomato crop. The increase in ECw resulted in a relative yield decrease, reaching almost 50% reduction at ECw = 5 dS/m. The obtained results indicate the higher crop water requirements in the year 2015 compared with the year 2014. This was partially due to lower amounts of rainfall during the vegetative season, 63.5 mm less. Consequently, net irrigation applied was 146.1 mm higher in the more saline water treatments. Leaching amounts are also higher in the year 2015, as well as

drainage water. This has resulted in lower WUE and IWUE compared with the year 2014. The trend in WUE and IWUE decrease with irrigation water quality deterioration was present as in the year 2014.

- Deficit irrigation: The obtained results indicate the maximum obtained yield in the scenario with the electrical conductivity of irrigation water below the threshold value of EC_w for tomato crop. A reduction in yield of more than 10% was obtained. The increase in ECw resulted in a relative yield decrease, reaching a 50% reduction at ECw = 5 dS/m. Net irrigation requirement is the lowest at no salinity stress treatment, whereas in the stress treatments net irrigation requirement is 423.2 mm for all the treatments, and it is 58.7 mm higher compared with the same treatments in the year 2014. The leaching fraction is consequently lower compared with full irrigation treatment.

The trends in WUE and IWUE are the same. They both decrease with lower irrigation water quality. Both WUE and IWUE are always higher in deficit irrigation treatments compared with respectful full irrigation scenarios. Compared with the year 2014, IWUE and WUE are lower which can be contributed to a lower amount of rainfall, higher crop water requirements, and consequently higher net irrigation requirements.

2.2.4 Scenario 1 (The year 2015) – Peach

The results for scenario 1, peach, fully irrigated, are presented in Table 11. The increase in ECw resulted in a relative yield decrease, reaching almost 50% reduction at ECw = 2.7 dS/m. The obtained results indicate around 50 mm higher crop water requirements in the year 2015 compared with the year 2014. This was due to higher evaporative demand in the year 2015. Consequently, net irrigation applied was around 50 mm higher in the more saline water treatments. Leaching amounts are also higher in the year 2015, as well as drainage water. This has resulted in lower WUE compared with the year 2014, whereas the IWUE was very similar. The trend in WUE and IWUE decrease with irrigation water quality deterioration was present as in the year 2014. The reduction in yield for deficit irrigation treatment was almost 10% compared with the respectful fully irrigated treatment. The increase in ECw resulted in a relative yield decrease, reaching a 50% reduction at ECw = 5 dS/m. Net irrigation requirement is the lowest at no salinity stress treatment, whereas in the stress treatments net irrigation requirement is 459.6 mm for all the treatments, and it is 115.8 mm higher compared with the same treatments in the year 2014. The leaching fraction is consequently higher in the year 2015 compared with the year 2014.

The trends in WUE and IWUE are the same. They both decrease with lower irrigation water quality. Both WUE and IWUE have similarly valued in deficit and full irrigation treatments. Compared with the year 2014, IWUE and WUE are lower which can be contributed to higher net irrigation requirements, and a lower number of irrigation events in the year 2014.

Table 11. Scenario 1 results for full and deficit irrigation for a peach crop, the year 2015.

Parameter	ECw = 1 dS/m	ECw = 2 dS/m	ECw = 3 dS/m	ECw = 4 dS/m	ECw = 5dS/m
Full irrigation					
Relative yield (%)	99.9	72.6	41.1	9.7	No yield
Number of days under stress	6	196	196	196	
ET_c (mm)	680.5	511.5	316.7	121.8	
ET_{max} (mm)	681.3	681.3	681.3	681.3	
NIR (mm)	432.9	501.8	501.8	501.8	
Rainfall (mm)	242.8	242.8	242.8	242.8	
Drainage (mm)	49.3	243.4	433.4	624.6	
Leaching fraction (-)	0.00	0.15	0.15	0.15	
Leaching fraction (mm)	0.0	65.5	65.5	65.5	
Depletion at harvest (mm)	54.8	10.9	5.8	2.0	
WUE (kg/m^3)	14.7	14.2	13.0	8.0	
IWUE (kg/m^3)	23.1	14.5	8.2	1.9	
Deficit irrigation					
Relative yield (%)	91.5	65.8	36.9	8.0	No yield
Number of days under stress	52	196	196	196	
ET_c (mm)	628.8	469.2	290.5	111.8	
ET_{max} (mm)	681.3	681.3	681.3	681.3	
NIR + LF (mm)	395.6	459.6	459.6	459.6	
Rainfall (mm)	242.8	242.8	242.8	242.8	
Drainage (mm)	55.6	243.5	417.5	592.6	
Leaching fraction (-)	0.00	0.15	0.15	0.15	
Leaching fraction (mm)	0.0	59.9	59.9	59.9	
Depletion at harvest (mm)	46.8	10.9	5.8	2.0	
WUE (kg/m^3)	14.6	14.0	12.7	7.2	
IWUE (kg/m^3)	23.1	14.3	8.0	1.7	

2.2.5 Relative yield vs. irrigation water quality

The model computes the relative yield of crops. **Error! Reference source not found.** is presented the variety of tomato and peach relative yields for full and deficit irrigation treatments concerning irrigation water quality. On one side, the results of simulations indicate that tomato crop can be grown with electrical conductivity of irrigation water near 5 dS/m, with the double reduction in yield compared to fully irrigated treatment. On the other side, peach yield reduced by 50% is obtained already at the electrical conductivity of irrigation water at 2.7 dS/m. To mention again, tomato is a moderately sensitive crop to irrigation water salinity, whereas peach is a sensitive crop.

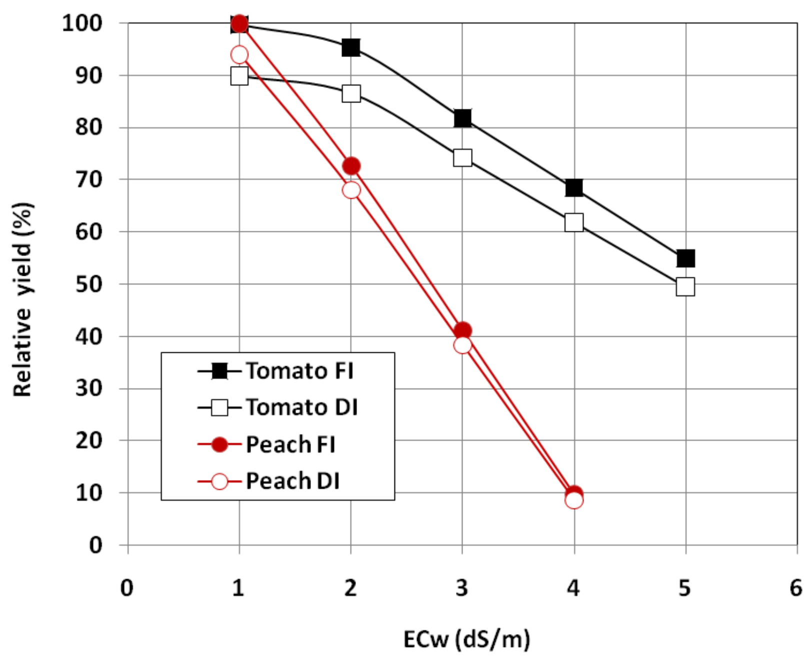

Fig. 9. Relative yields of tomato and peach under different management regimes and different irrigation water quality.

3.Facts to know about irrigation with saline water

3.1 Quality parameters of importance in agricultural use of saline water

Arid zones are characterized by high rates of evaporation and consequent deposition of salts which tend to accumulate within the soil profile. Soil physical properties, such as dispersion of particles, aggregate stability, and permeability, are very sensitive to the type of exchangeable ions present in irrigation water. Moreover, total dissolved solids (TDS) in the irrigation water affect the growth of plants by increasing the osmotic potential of soil solution which increases the amount of energy which plants must expend to absorb water from the soil. This increases the respiration rate and the growth and yield of most plants decline progressively as osmotic pressure increases. Another important concern is that some plants are also susceptible to specific ion toxicity. Many of the ions which are harmless or even beneficial at relatively low concentrations may become toxic to plants at high concentration, either through direct interference with metabolic processes or through indirect effects on other nutrients, which become inaccessible.
Taking into consideration agricultural water quality, a set of parameters that are relevant about the yield and quality of crops, maintenance of soil productivity, and protection of the environment, are included. Some important physical and chemical characteristics that are used in the evaluation of agricultural water quality are:

i. Total Salt Concentration – Total salt concentration or total dissolved solids (TDS) is expressed in milligrams per liter (mg/l) or parts per million (ppm). It is one of the most important agricultural water quality parameters. Soil salinity or soil water salinity is directly related to, and often determined by, the salinity of the irrigation water.

ii. Electrical Conductivity - Electrical conductivity indicates the total ionized constituents of water. The unit of electrical conductivity is deciSiemens per meter (dS/m). It is directly related to the sum of the cations (or anions) and is closely correlated with the total salt concentration. The symbol EC_w, is often used to represent the electrical conductivity of irrigation water and the symbol EC_e is used to designate the electrical conductivity of the soil saturation extract.

iii. Sodium Adsorption Ratio - Sodium is a cation having the most detrimental effect on soil. In excess amounts, it creates adverse physicochemical changes in the soil, particularly to soil structure. It disperses soil, which results in reduced infiltration rates of water and air into the soil. It is also a driver of soil crusting. Irrigation water could be a source of excess sodium in the soil solution. The most reliable index of the sodium hazard of irrigation water is the sodium adsorption ratio (SAR), defined by the formula:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad \text{Eq. 17}$$

Where:

Na, Ca and Mg are expressed in me/l from the water analysis.

iv. Exchangeable sodium percentage (ESP) - ESP is another measure related to salt-affected soils, and it presents the amount of adsorbed sodium on the soil exchange complex expressed in percent of the cation exchange capacity in milliequivalents per 100 g of soil or cmol per kg:

v. Toxic Ions - Irrigation water that contains certain ions (sodium, chloride, or boron) at concentrations above threshold values can cause plant toxicity problems.

vi. Trace Elements and Heavy Metals - Trace elements and heavy metals are normally present in relatively low concentrations, usually less than a few mg/l, in conventional irrigation waters, but attention should be paid to them when using sewage effluents of industrial origin.

vii. pH – pH is an indicator of the acidity or basicity of water. It is a routine measurement in irrigation water quality assessment. The normal pH range for irrigation water is from 6.5 to 8.4. If the analysis shows pH values outside this range, this is a good warning that the water is abnormal in quality.

3.2 Water quality guidelines for maximum crop production

Irrigation water is grouped into different **quality classes** to guide users to the potential advantages and problems associated with its use. The water quality classifications are only indicative guidelines and their application will have to be adjusted to conditions that prevail in the field. Annex 7 is presented with general water quality classification guidelines. The suitability of water for irrigation depends on soil physical and chemical characteristics, climatic conditions, crop salt tolerance, and management practices. Ayers and Westcot (FAO 1985) classified irrigation water into three groups referring to the restriction of water use to (a) no restriction, (b) slightly to moderate, and (c) severe restriction. Additionally, they mentioned four potential irrigation problems, namely, salinity, sodicity, toxicity, and miscellaneous hazards. Table 12 present the main laboratory determinations required to evaluate common irrigation water quality.

Table 12. Laboratory determinations needed to evaluate common irrigation water quality problems (Source: FAO, 1985).

Water parameter	Symbol	Unit[1]	Usual range in irrigation water
Salt Content			
Electrical Conductivity	EC_w	dS/m	0 – 3
Total Dissolved Solids	TDS	mg/l	0 – 2000
Cations and Anions			
Calcium	Ca^{++}	me/l	0 – 20
Magnesium	Mg^{++}	me/l	0 – 5
Sodium	Na^{+}	me/l	0 – 40
Carbonate	CO^{--}_3	me/l	0 – .1
Bicarbonate	HCO_3^{-}	me/l	0 – 10
Chloride	Cl^{-}	me/l	0 – 30
Sulfate	SO_4^{--}	me/l	0 – 20
NUTRIENTS[2]			
Nitrate-Nitrogen	NO_3-N	mg/l	0 – 10
Ammonium-Nitrogen	NH_4-N	mg/l	0 – 5
Phosphate-Phosphorus	PO_4-P	mg/l	0 – 2
Potassium	K^{+}	mg/l	0 – 2
MISCELLANEOUS			
Boron	B	mg/l	0 – 2
Acid/Basicity	pH	1–14	6.0 – 8.5
Sodium Adsorption Ratio	SAR	(me/l)[1]	0 – 15

[1] dS/m = deciSiemen/metre in S.I. units mg/l = milligram per litre ≃ parts per million (ppm). me/l = milliequivalent per litre (mg/l ÷ equivalent weight = me/l); in SI units, 1 me/l= 1 millimol/litre adjusted for electron charge.

[2] NO_3 - N means the laboratory will analyze for NO_3 but will report the NO_3 in terms of chemically equivalent nitrogen. Similarly, for NH_4-N, the laboratory will analyze for NH_4 but report in terms of chemically equivalent elemental nitrogen. The total nitrogen available to the plant will be the sum of the equivalent elemental nitrogen. The same reporting method is used for phosphorus.

3.3 Conditions for successful irrigation with saline water

Irrigation management should be fulfilled following basic conditions: irrigation amounts should be optimized; irrigation water quality should be acceptable; irrigation scheduling should be optimized; appropriate irrigation methods should be used; salt accumulation should be prevented by leaching; the rise of water table should be controlled by drainage; plant nutrients management should be optimized.
Excel–IRR model accounts for the above-mentioned conditions in a different manner:

1. Excel–IRR model computes **irrigation amounts** from daily soil water balance equations according to management allowable soil water depletion.
2. Excel–IRR model takes into consideration i**rrigation water quality.** It offers the possibility to irrigate with saline water taking into consideration the electrical conductivity of irrigation water as the only parameter. The ratio of ECw = 1.5 ECe is used as proposed in **Error! Reference source not found.** - **Error! Reference source not found.**.
3. **Irrigation scheduling** is accounted for in Excel–IRR model and the user can specify whether to run full irrigation or deficit irrigation.
4. Excel–IRR model accounts for **irrigation methods** by defining irrigation efficiency for irrigation module.
5. Excel–IRR model computes l**eaching requirements** in the conditions where saline water is used for irrigation. After many successive irrigation events, the salt accumulation in the soil will approach some equilibrium concentration based on the salinity of the applied water and the leaching fraction.
6. Excel–IRR model computes **drainage** water daily.

3.4 Crop selection

3.4.1 Crop selection to overcome salinity hazards

Crops respond to salinity differently. Some crops can produce high yields at much higher soil salinity than others. There is a high magnitude range in the salt tolerance of crops. This tolerance range greatly expands the acceptable range of water salinity (EC_w) considered suitable for irrigation. In Annex 8 are presented crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (EC_w) or soil salinity (EC_e) yield potential. **Error! Reference source not found.** is presented the relationship between relative crop yield and irrigation water salinity using four crop salinity classes. Some general conclusions related to irrigation water salinity (EC_w) are:

i. $EC_w < 0.7$ dS/m

- Full yield potential should be achievable with nearly all crops when using irrigation water with salinity less than

ii. EC_w = 0.7-3.0 dS/m (slight to moderate salinity)

- Full yield potential is possible but care must be taken to achieve the required leaching fraction to maintain soil salinity within the tolerance of the crops. Treated sewage effluent falls within this group.

iii. EC_w > 3.0 dS/m and sensitive crops

- It is not advisable to increase leaching to greater than 0.25 to 0.30 due to an excessive amount of water required, but rather to consider a more tolerant crop that will require less leaching, to control salts within crop tolerance levels.

iv. EC_w > 3.0 dS/m

- The water might still be usable but its use may need to be restricted to more permeable soils and more salt-tolerant crops, where high leaching fractions are more easily achieved.

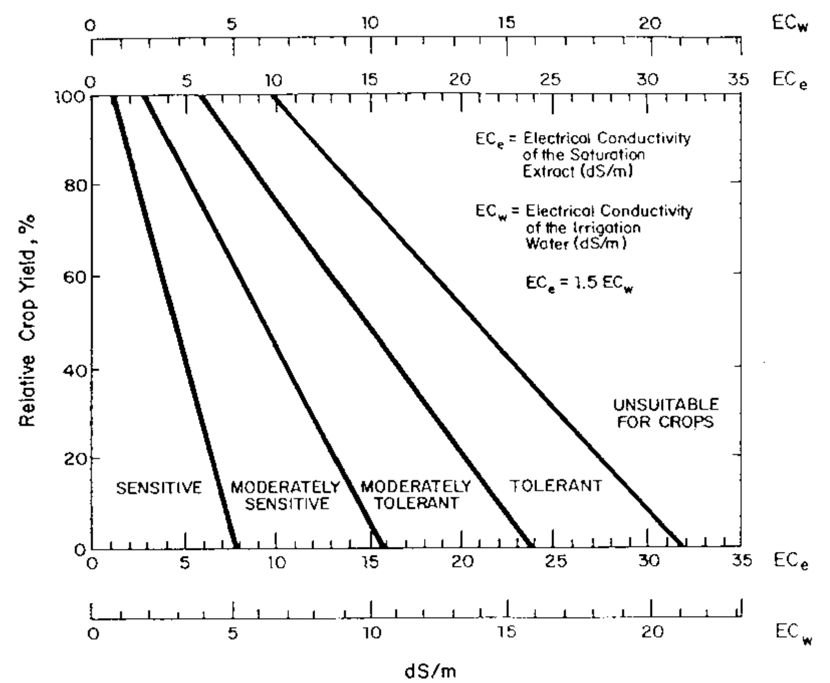

Fig. 10. Divisions for relative salt tolerance ratings of crops (Maas, 1984).

3.5 Field management practices in irrigation with saline water

3.5.1 Water management

Most treated wastewaters have salinity levels ranging between 500 and 2000 mg/l (ECw = 0.7 to 3.0 dS/m), although higher salinity concentration occurs. In any case, appropriate water management practices will have to be conducted to prevent salinization. Even if salt content in irrigation water is not very large (200 to 500 mg/l), with high irrigation amounts (20000 m^3/ha) irrespective it will add between 2 and 5 tons of salt annually to the soil, and this multiplies from year to year. If salts are not flushed out of the root zone by leaching and removed from the soil by effective drainage, salinity problems can build

up rapidly. Leaching and drainage are thus two important water management practices to avoid salinization of soils.

3.5.1.1 Leaching

Leaching is the key factor in controlling soluble salts brought into the soil by the irrigation water. Salt removal by leaching must exceed the salt additions by irrigation water or salts will accumulate and reach high concentrations. How much water should be used for leaching, i.e. what is the leaching requirement and when should leachings be applied? Leaching requirement can be computed from the following equation:

$$LR = \frac{EC_W}{5 \cdot EC_{e-} EC_W} \qquad \text{Eq. 18}$$

Where:

LR = minimum leaching requirement needed to control salts within the tolerance (EC_e) of the crop with ordinary surface methods of irrigation

EC_w = salinity of the applied irrigation water in dS/m

EC_e = average soil salinity tolerated by the crop as measured on a soil saturation extract. The appropriate EC_e value for the given crop and acceptable yield can be adopted from Table 4 of Ayers and Westcot (FAO, 1985) (Annex 8). It is recommended that the EC_e value that can be expected to result in at least a 90% or greater yield be used in the calculation. The less accurate necessary leaching requirement (LR) can be estimated from **Error! Reference source not found.** for general crop rotations reported. **Error! Reference source not found.** was developed using EC_e values for the 100% yield potential. For water in the moderate to high salinity range (>1.5 dS/m), it might be better to use the EC_e value for maximum yield potential (100%) since salinity control is critical to obtaining good yields.

When water is scarce, leaching practices should be designed to maximize crop water productivity and leaching requirements. Leaching can be carried out at each single irrigation event, as single separate irrigation practice, occasionally, from time to time or less frequently, such as seasonally or at even longer intervals. The objective is to keep the salinity in the soil below the threshold above which yield might be affected to an unacceptable level. Irrigation with high salinity water requires higher leaching requirements and large amounts of water. Therefore, rainfall must be considered in estimating the leaching requirement and in choosing the leaching method.

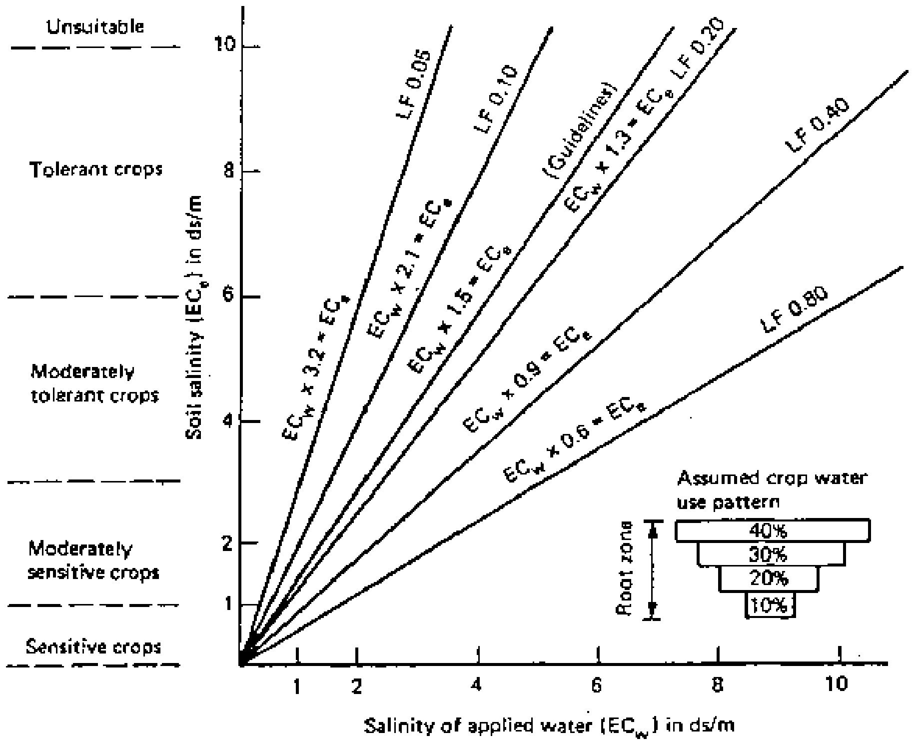

Fig. 11. Effect of applied water salinity (ECw) upon root zone soil salinity (ECe) at various leaching fractions (LF) (Source: FAO, 1985).

The total annual amount of water required to meet both the crop demand and leaching requirement can be estimated from Equation 19 $AW = \frac{ET}{1-LR}$ Eq. 19.

$$AW = \frac{ET}{1-LR} \quad \text{Eq. 19}$$

Where:
AW - Total amount of water (mm/year)
ET - total annual crop water demand (mm/year)
LR - leaching requirement expressed as a fraction (leaching fraction)

Drainage - Salinity problems in many irrigation projects in arid and semi-arid areas are associated with the presence of a shallow water table. In many soils, the capillary rise of water from groundwater into subsoil appears. This water balance factor is positive in the case that water is of good quality, whereas it has a negative connotation in conditions of saline groundwater. The role of drainage is to lower the water table to a level, at which it does not contribute to the root zone and the soil surface by capillarity.

Irrigation scheduling - The timing of irrigation, including irrigation frequency, pre-planting irrigation, and irrigation before a winter rainy season can reduce the salinity hazard and avoid water stress between irrigations. These practices are readily applicable to wastewater irrigation.

Blending of wastewater with other water supplies - If multiple sources are available, farmers can blend treated sewage with conventional sources of water, canal water, or groundwater, or if a farmer may have saline groundwater and non-saline treated wastewater, he could blend the two sources to obtain blended water of acceptable salinity level.

Alternating treated wastewater with other water sources - Another strategy is to use the treated wastewater alternately with the canal water or groundwater, instead of blending. The alternate applications of the two sources are superior compared with blending.

Land and soil management - Several other land and soil management practices can be adopted at the field level to overcome salinity, sodicity, toxicity, and health hazards that might be associated with the use of treated wastewater. Land development activities include land leveling to a given grade, establishment of adequate drainage; deep plowing, leaching to reduce soil salinity,

Annexes

ANNEX 1. Length of growth stages

FAO Irrigation and Drainage Paper No. 24 and 56 provide general information about lengths of the four distinct growth stages from the irrigation aspect, and the total growing period for various types of climates and locations. The table below is adopted from FAO Irrigation and Drainage Paper No. 56. The users of the EXCEL-IRR model are encouraged to search for the crop growth stages length in their local climatic and regional conditions.

The initial and development periods for some crops may be relatively short as they develop new leaves in spring fastly (deciduous trees and shrubs). The first period of development is affected by weather conditions in general and by mean daily air temperature in particular. Therefore, the length of time between planting and effective full cover varies depending on climate, latitude, elevation and planting date, and cultivar. The ending point of the mid-season and beginning of the late season is usually determined by leaves senescence. The length of the late-season period may be relatively short depending on weather conditions or crop type (some are harvested fresh). High temperatures accelerate the ripening and senescence of crops and cause some crops to go into dormancy. Moisture stress or other environmental stresses usually accelerate the rate of crop maturation and can shorten the mid and late season growing periods.

The values in Table A1 can be used only as a general guide and for comparison purposes. The listed lengths of growth stages are average lengths for the regions and periods specified. The users should adopt local observations of the specific plant stage development.

TABLE A1. Lengths of crop development stages* for various planting periods and climatic regions (days) – Adopted from FAO IDP 56 (Allen et al., 1998).

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

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

TABLE A1. Continued

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
b. Vegetables - Solanum Family *(Solanaceae)*							
Egg plant	30	40	40	20	130/140	October	Arid Region
	30	45	40	25	130/140	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
Sweet melons	25	35	40	20	120	May	Mediterranean
	30	30	50	30	140	March	Calif., USA
	15	40	65	15	135	Aug	Calif. Desert, USA
	30	45	65	20	160	Dec/Jan	Arid Region
Water melons	20	30	30	30	110	April	Italy
	10	20	20	30	80	May/Aug	Near East (desert)

TABLE A1. Continued

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
d. Roots and Tubers							
Beets, table	15	25	20	10	70	Apr/May	Mediterranean
	25	30	25	10	90	Feb/Mar	Mediterranean & Arid
Cassava: year 1	20	40	90	60	210	Rainy season	Tropical regions
year 2	150	40	110	60	360		
Potato	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid Climate
	25	30	45	30	130	May	Continental Climate
	30	35	50	30	145	April	Europe
	45	30	70	20	165	Apr/May	Idaho, USA
	30	35	50	25	140	Dec	Calif. Desert, USA
Sweet potato	20	30	60	40	150	April	Mediterranean
	15	30	50	30	125	Rainy seas.	Tropical regions
Sugarbeet	30	45	90	15	180	March	Calif., USA
	25	30	90	10	155	June	Calif., USA
	25	65	100	65	255	Sept	Calif. Desert, USA
	50	40	50	40	180	April	Idaho, USA
	25	35	50	50	160	May	Mediterranean
	45	75	80	30	230	November	Mediterranean
	35	60	70	40	205	November	Arid Regions
e. Legumes *(Leguminosae)*							
Beans (green)	20	30	30	10	90	Feb/Mar	Calif., Mediterranean
	15	25	25	10	75	Aug/Sep	Calif., Egypt, Lebanon
Beans (dry)	20	30	40	20	110	May/June	Continental Climates
	15	25	35	20	95	June	Pakistan, Calif.
	25	25	30	20	100	June	Idaho, USA

TABLE A1. Continued.

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
Faba bean, broad	15	25	35	15	90	May	Europe
bean	20	30	35	15	100	Mar/Apr	Mediterranean
- dry	90	45	40	60	235	Nov	Europe
- green	90	45	40	0	175	Nov	Europe
Green gram, cowpeas	20	30	30	20	110	March	Mediterranean
Groundnut	25	35	45	25	130	Dry	West Africa
	35	35	35	35	140	season	High Latitudes
	35	45	35	25	140	May	Mediterranean
						May/June	
Lentil	20	30	60	40	150	April	Europe
	25	35	70	40	170	Oct/Nov	Arid Region
Peas	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
	35	25	30	20	110	April	Idaho, USA
Soybeans	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	140	May	Central USA
	20	25	75	30	150	June	Japan
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)							
Artichoke	40	40	250	30	360	Apr (1st yr)	California
	20	25	250	30	325	May (2nd yr)	(cut in May)
Asparagus	50	30	100	50	230	Feb	Warm Winter
	90	30	200	45	365	Feb	Mediterranean
g. Fibre Crops							
Cotton	30	50	60	55	195	Mar-May	Egypt; Pakistan; Calif.
	45	90	45	45	225	Mar	Calif. Desert, USA
	30	50	60	55	195	Sept	Yemen
	30	50	55	45	180	April	Texas
Flax	25	35	50	40	150	April	Europe
	30	40	100	50	220	October	Arizona
h. Oil Crops							
Castor beans	25	40	65	50	180	March	(Semi) Arid Climates
	20	40	50	25	135	Nov.	Indonesia
Safflower	20	35	45	25	125	April	California, USA
	25	35	55	30	145	Mar	High Latitudes
	35	55	60	40	190	Oct/Nov	Arid Region
Sesame	20	30	40	20	100	June	China

Sunflower	25	35	45	25	130	April/May	Medit.; Calif.

TABLE A1. Continued.

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
i. Cereals							
Barley/Oats/ Wheat	15	25	50	30	120	November	Central India
	20	25	60	30	135	March/Apr	35-45 °L
	15	30	65	40	150	July	East Africa
	40	30	40	20	130	Apr	
	40	60	60	40	200	Nov	
	20	50	60	30	160	Dec	Calif. Desert, USA
Winter Wheat[2]	20	60	70	30	180	December	Calif., USA
	30	140	40	30	240	November	Mediterranean
	160	75	75	25	335	October	Idaho, USA
Grains (small)	20	30	60	40	150	April	Mediterranean
	25	35	65	40	165	Oct/Nov	Pakistan; Arid Reg.
Maize (grain)	30	50	60	40	180	April	East Africa (alt.)
	25	40	45	30	140	Dec/Jan	Arid Climate
	20	35	40	30	125	June	Nigeria (humid)
	20	35	40	30	125	October	India (dry, cool)
	30	40	50	30	150	April	Spain (spr, sum.); Calif.
	30	40	50	50	170	April	Idaho, USA
Maize (sweet)	20	20	30	10	80	March	Philippines
	20	25	25	10	80	May/June	Mediterranean
	20	30	50/30	10	90	Oct/Dec	Arid Climate
	30	30	30	10[3]	110	April	Idaho, USA
	20	40	70	10	140	Jan	Calif. Desert, USA
Millet	15	25	40	25	105	June	Pakistan
	20	30	55	35	140	April	Central USA
Sorghum	20	35	40	30	130	May/June	USA, Pakis., Med.
	20	35	45	30	140	Mar/April	Arid Region
Rice	30	30	60	30	150	Dec; May	Tropics; Mediter.
	30	30	80	40	180	May	Tropics

[2] These periods for winter wheat will lengthen in frozen climates according to days having zero growth potential and wheat dormancy. Under general conditions and in the absence of local data, fall planting of winter wheat can be presumed to occur in northern temperate climates when the 10-day running average of mean daily air temperature decreases to 17° C or December 1, whichever comes first. Planting of spring wheat can be presumed to occur when the 10-day running average of mean daily air temperature increases to 5° C. Spring planting of maize-grain can be presumed to occur when the 10-day running average of mean daily air temperature increases to 13° C.

[3] The late season for sweet maize will be about 35 days if the grain is allowed to mature and dry.

TABLE 1. Continued.

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
j. Forages							
Alfalfa[4], total season	10	30	var.	var.	var.		last -4°C in spring until first -4°C in fall
Alfalfa[4] 1st cutting cycle	10	20	20	10	60	Jan Apr (last - 4°C)	Calif., USA.
	10	30	25	10	75		Idaho, USA.
Alfalfa[4], other cutting cycles	5	10	10	5	30	Mar	Calif., USA.
	5	20	10	10	45	Jun	Idaho, USA.
Bermuda for seed	10	25	35	35	105	March	Calif. Desert, USA
Bermuda for hay (several cuttings)	10	15	75	35	135	---	Calif. Desert, USA
Grass Pasture[4]	10	20	--	--	--		
Sudan, 1st cutting cycle	25	25	15	10	75	Apr	Calif. Desert, USA
Sudan, other cutting cycles	3	15	12	7	37	June	Calif. Desert, USA
k. Sugar Cane							
Sugarcane, virgin	35	60	190	120	405		Low Latitudes
	50	70	220	140	480		Tropics
	75	105	330	210	720		Hawaii, USA
Sugarcane, ratoon	25	70	135	50	280		Low Latitudes
	30	50	180	60	320		Tropics
	35	105	210	70	420		Hawaii, USA
l. Tropical Fruits and Trees							
Banana, 1st yr	120	90	120	60	390	Mar	Mediterranean
Banana, 2nd yr	120	60	180	5	365	Feb	Mediterranean
Pineapple	60	120	600	10	790		Hawaii, USA
m. Grapes and Berries							
Grapes	20	40	120	60	240	April	Low Latitudes
	20	50	75	60	205	Mar	Calif., USA
	20	50	90	20	180	May	High Latitudes
	30	60	40	80	210	April	Mid Latitudes (wine)

[4] In climates having killing frosts, growing seasons can be estimated for alfalfa and grass as:
alfalfa: last -4° C in spring until first -4° C in fall (Everson, D. O., M. Faubion and D. E. Amos 1978. "Freezing temperatures and growing seasons in Idaho." Univ. Idaho Agric. Exp. station bulletin 494. 18 p.)
grass: 7 days before last -4° C in spring and 7 days after last -4° C in fall (Kruse E. G. and Haise, H. R. 1974. "Water use by native grasses in high altitude Colorado meadows." USDA Agric. Res. Service, Western Region report ARS-W-6-1974. 60 pages)

Hops	25	40	80	10	155	April	Idaho, USA

TABLE 1. Continued.

Crop	**Init. (L_{ini})**	**Dev. (L_{dev})**	**Mid (L_{mid})**	**Late (L_{late})**	**Total**	**Plant Date**	**Region**
n. Fruit Trees							
Citrus	60	90	120	95	365	Jan	Mediterranean
Deciduous Orchard	20	70	90	30	210	March	High Latitudes
	20	70	120	60	270	March	Low Latitudes
	30	50	130	30	240	March	Calif., USA
Olives	30	90	*60*	90	270[5]	March	Mediterranean
Pistachios	20	60	30	40	150	Feb	Mediterranean
Walnuts	20	10	130	30	190	April	Utah, USA
o. Wetlands - Temperate Climate							
Wetlands (Cattails, Bulrush)	10	30	80	20	140	May	Utah, USA; killing frost
	180	60	90	35	365	November	Florida, USA
Wetlands (short veg.)	180	60	90	35	365	November	frost-free climate

[5] Olive trees gain new leaves in March. See footnote 24 of Table 12 for additional information, where the Kc continues outside of the "growing period"

ANNEX 2. Crop coefficients

Crop coefficient (K_c) varies during the growing period with changes in vegetation and ground cover. The trends in K_c during the growing period are represented in the crop coefficient curve. To construct the crop coefficient curve, only three values for K_c are required:

- initial stage ($K_{c\ ini}$),
- mid-season stage ($K_{c\ mid}$) and
- end of the late-season stage ($K_{c\ end}$).

In Table 2 are given typical values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ for various crops. The values of crop coefficients are presented taking into consideration specific crop group types (i.e., small vegetables, berries, cereals, etc.). There is usually close similarity in the coefficients among the members of the same crop group. K_c values in Table 2 take into account both transpiration and evaporation over time. The values for K_c during the initial and crop development stages vary a lot depending on local conditions and refinements to the value used for $K_{c\ ini}$ should always be made. More accurate estimates of $K_{c\ ini}$ can be obtained considering the time interval between wetting events, evaporation power of the surface, the magnitude of wetting events, and the time interval between wetting events. The values for $K_{c\ mid}$ and $K_{c\ end}$ represent values for a sub-humid climate with an average daytime minimum relative humidity (RH_{min}) of about 45% and with calm to moderate wind speeds averaging 2 m/s. The given K_c values in Table 2 are values for non-stressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield.

TABLE A2. Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates (RH_{min} » 45%, u_2 » 2 m/s) for use with the FAO Penman-Monteith ETo. Adopted from FAO IDP 56 (Allen et al., 1998)

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (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	0.6
Garlic		1	0.7	0.3
Lettuce		1	0.95	0.3
Onions				
- dry		1.05	0.75	0.4
- green		1	1	0.3
- seed		1.05	0.8	0.5
Spinach		1	0.95	0.3
Radish		0.9	0.85	0.3
b. Vegetables - Solanum Family *(Solanaceae)*	**0.6**	**1.15**	**0.8**	
Egg Plant		1.05	0.9	0.8
Sweet Peppers (bell)		1.05[7]	0.9	0.7
Tomato		1.05[7]	0.70-0.90	0.6
c. Vegetables - Cucumber Family *(Cucurbitaceae)*	**0.5**	**1**	**0.8**	
Cantaloupe	0.5	0.85	0.6	0.3
Cucumber				
- Fresh Market	0.6	1.00[7]	0.75	0.3
- Machine harvest	0.5	1	0.9	0.3
Pumpkin, Winter Squash		1	0.8	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1	0.75	0.4

[6] 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 the dual $K_{cb\ ini} + K_e$.

[7] Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased Kc 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.

TABLE A2. Continued

Crop	$K_{c,initial}$[8]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
d. Roots and Tubers	**0.5**	**1.1**	**0.95**	
Beets, table		1.05	0.95	0.4
Cassava				
- year 1	0.3	0.80[9]	0.3	1
- year 2	0.3	1.1	0.5	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[10]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.1	0.95	0.6
Sugar Beet	0.35	1.2	0.70[11]	0.5
e. Legumes *(Leguminosae)*	**0.4**	**1.15**	**0.55**	
Beans, green	0.5	1.05[7]	0.9	0.4
Beans, dry and Pulses	0.4	1.05[7]	0.35	0.4
Chick pea		1	0.35	0.4
Faba bean (broad bean)				
- Fresh	0.5	1.15[7]	1.1	0.8
- Dry/Seed	0.5	1.15[7]	0.3	0.8
Grabanzo	0.4	1.15	0.35	0.8
Green Gram and Cowpeas		1.05	0.60-0.35[12]	0.4
Groundnut (Peanut)		1.15	0.6	0.4
Lentil		1.1	0.3	0.5
Peas				
- Fresh	0.5	1.15[7]	1.1	0.5
- Dry/Seed		1.15	0.3	0.5
Soybeans		1.15	0.5	0.5-1.0
f. Perennial Vegetables	**0.5**	**1**	**0.8**	
Artichokes	0.5	1	0.95	0.7
Asparagus	0.5	0.95[13]	0.3	0.2-0.8
Mint	0.6	1.15	1.1	0.6-0.8
Strawberries	0.4	0.85	0.75	0.2

[8] 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 the dual $K_{cb\ ini} + K_e$.

[9] 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.

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

[11] 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.

[12] The first $K_{c\ end}$ is for harvested fresh. The second value is for harvested dry.

[13] The K_c for asparagus usually remains at $K_{c\ ini}$ during harvest of the spears, due to sparse ground cover. The $K_{c\ mid}$ value is for following regrowth of plant vegetation following termination of harvest of spears.

TABLE A2. Continued.

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
g. Fibre Crops	**0.35**			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
Flax		1.1	0.25	1.2
Sisal[14]		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	**0.35**	**1.15**	**0.35**	
Castorbean (*Ricinus*)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15[15]	0.35	0.6
Safflower		1.0-1.15[14]	0.25	0.8
Sesame		1.1	0.25	1
Sunflower		1.0-1.15[14]	0.35	2
i. Cereals	**0.3**	**1.15**	**0.4**	
Barley		1.15	0.25	1
Oats		1.15	0.25	1
Spring Wheat		1.15	0.25-0.4[16]	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4[15]	1
- with non-frozen soils	0.7	1.15	0.25-0.4[15]	
Maize, Field (grain) *(field corn)*		1.2	0.60-0.35[17]	2
Maize, Sweet *(sweet corn)*		1.15	1.05[18]	1.5
Millet		1	0.3	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.2	1.05	2-4
Rice	1.05	1.2	0.90-0.60	1

[14] K_c for sisal depends on the planting density and water management
[15] The lower values are for rainfed crops having less dense plant populations.
[16] The higher value is for hand-harvested crops.
[17] The first $K_{c\ end}$ value is for harvest at high grain moisture. The second $K_{c\ end}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis).
[18] If harvested fresh for human consumption. Use $K_{c\ end}$ for field maize if the sweet maize is allowed to mature and dry in the field.

TABLE A2. Continued.

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
j. Forages				
Alfalfa Hay				
- averaged cutting effects	0.4	0.95[19]	0.9	0.7
- individual cutting periods	0.40[20]	1.20[19]	1.15[19]	0.7
- for seed	0.4	0.5	0.5	0.7
Bermuda hay				
- averaged cutting effects	0.55	1.00[18]	0.85	0.35
- Spring crop for seed	0.35	0.9	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.4	0.90[18]	0.85	0.6
- individual cutting periods	0.40[19]	1.15[19]	1.10[19]	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.5	0.90[19]	0.85	1.2
- individual cutting periods	0.50[19]	1.15[19]	1.10[19]	1.2
Grazing Pasture				
- Rotated Grazing	0.4	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.3	0.75	0.75	0.1
Turf grass				
- cool season[21]	0.90	0.95	0.95	0.1
- warm season[20]	0.80	0.85	0.85	0.1

[19] This $K_{c\ mid}$ coefficient for hay crops is an overall average $K_{c\ mid}$ coefficient that averages K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

[20] These K_c coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods.

[21] Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermuda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced and rapid growth is not required, K_c's for turf can be reduced by 0.10.

TABLE A2. Continued.

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
k. Sugar Cane	**0.4**	**1.25**	**0.75**	**3**
l. Tropical Fruits and Trees				
Banana				
- 1st year	0.5	1.1	1	3
- 2nd year	1	1.2	1.1	4
Cacao	1	1.05	1.05	3
Coffee				
- bare ground cover	0.9	0.95	0.95	2-3
- with weeds	1.05	1.1	1.1	2-3
Date Palms	0.9	0.95	0.95	8
Palm Trees	0.95	1	1	8
Pineapple[22]				
- bare soil	0.5	0.3	0.3	0.6-1.2
- with grass cover	0.5	0.5	0.5	0.6-1.2
Rubber Trees	0.95	1	1	10
Tea				
- non-shaded	0.95	1	1	1.5
- shaded[23]	1.10	1.15	1.15	2
m. Grapes and Berries				
Berries (bushes)	0.3	1.05	0.5	1.5
Grapes				
- Table or Raisin	0.3	0.85	0.45	2
- Wine	0.3	0.7	0.45	1.5-2
Hops	0.3	1.05	0.85	5

[22] The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil. The $K_{c\ mid} < K_{c\ ini}$ since $K_{c\ mid}$ occurs during full ground cover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, $K_{c's}$ given can be reduced by 0.10.

[23] Includes the water requirements of the shaded trees.

TABLE A2. Continued

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
n. Fruit Trees				
Almonds, no ground cover	0.4	0.9	0.65[24]	5
Apples, Cherries, Pears[25]				
- no ground cover, killing frost	0.45	0.95	0.70[23]	4
- no ground cover, no frosts	0.6	0.95	0.75[23]	4
- active ground cover, killing frost	0.5	1.2	0.95[23]	4
- active ground cover, no frosts	0.8	1.2	0.85[23]	4
Apricots, Peaches, Stone Fruit[24, 26]				
- no ground cover, killing frost	0.45	0.9	0.65[23]	3
- no ground cover, no frosts	0.55	0.9	0.65[23]	3
- active ground cover, killing frost	0.5	1.15	0.90[23]	3
- active ground cover, no frosts	0.8	1.15	0.85[23]	3
Avocado, no ground cover	0.6	0.85	0.75	3
Citrus, no ground cover[27]				
- 70% canopy	0.70	0.65	0.7	4
- 50% canopy	0.65	0.6	0.65	3
- 20% canopy	0.50	0.45	0.55	2
Citrus, with active ground cover or weeds[28]				
- 70% canopy	0.75	0.7	0.75	4
- 50% canopy	0.80	0.8	0.8	3
- 20% canopy	0.85	0.85	0.85	2

[24] These K_c end values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$ to 0.80 for actively growing ground cover.

[25] Refer to Eq. 94, 97 or 98 and footnotes 21 and 22 for estimating K_c for immature stands.

[26] Stone fruit category applies to peaches, apricots, pears, plums and pecans.

[27] The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. The midseason value is lower than initial and ending values due to the effects of stomatal closure during periods of peak ET. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2.

[28] The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2.

TABLE A2. Continued.

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
Conifer Trees[29]	1	1	1	10
Kiwi	0.4	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy)[30]	0.65	0.7	0.7	3-5
Pistachios, no ground cover	0.4	1.1	0.45	3-5
Walnut Orchard[24]	0.5	1.1	0.65[23]	3-5
o. Wetlands - temperate climate				
Cattails, Bulrushes, killing frost	0.3	1.2	0.3	2
Cattails, Bulrushes, no frost	0.6	1.2	0.6	2
Short Veg., no frost	1.05	1.1	1.1	0.3
Reed Swamp, standing water	1	1.2	1	1-3
Reed Swamp, moist soil	0.9	1.2	0.7	1-3
p. Special				
Open Water, < 2 m depth or in subhumid climates or tropics		1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate		0.65[31]	1.25[30]	

[29] Confers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c can easily reduce below the values presented, which represent well-watered conditions for large forests.
[30] These coefficients represent about 40 to 60% ground cover.
[31] These Kc's are for deep water in temperate latitudes where large temperature changes in the water body occur during the year, and initial and peak period evaporation is low as radiation energy is absorbed into the deep water body. During fall and winter periods (Kc end), heat is released from the water body that increases the evaporation above that for grass. Therefore, Kc_{mid} corresponds to the period when the water body is gaining thermal energy and $K_{c\ end}$ when releasing thermal energy. These $K_{c's}$ should be used with caution.

ANNEX 3 – Maximum root depth and depletion fraction

Total available water in the root zone is the difference between the water content at field capacity and wilting point, but no matter of previous soil water characteristics, the amount of available water depends on rooting depth or maximum soil depth which allows crops to normally develop their rooting system. The higher the rooting depth, the higher is total available water. Ranges of the maximum effective rooting depth for various crops are given in Table A3.

The fraction of total available water that a crop can extract from the root zone without suffering water stress is readily available soil water. Readily available is a crop-specific characteristic, as various crops have different possibilities to extract water from the soil. This crop specific parameter is called depletion fraction and is marked as p. Values for p are listed in Table A3 and they differ from one crop to another. Depletion fraction is a function of the evaporation power of the atmosphere. At low rates of ET_c, the p values listed in Table 3 are higher than at high rates of ET_c. Often, a constant value is used for p for a specific growing period, rather than varying the value each day.

TABLE 3. Ranges of maximum effective rooting depth (Zr), and soil water depletion fraction for no stress (p), for common crops. Adopted from FAO IDP 56 (Allen et al., 1998)

Crop	Maximum Root Depth[32] (m)	Depletion Fraction[33] (for ET ≈ 5 mm/day) (p)
a. Small Vegetables		
Broccoli	0.4-0.6	0.45
Brussel Sprouts	0.4-0.6	0.45
Cabbage	0.5-0.8	0.45
Carrots	0.5-1.0	0.35
Cauliflower	0.4-0.7	0.45
Celery	0.3-0.5	0.2
Garlic	0.3-0.5	0.3
Lettuce	0.3-0.5	0.3
Onions		
- dry	0.3-0.6	0.3
- green	0.3-0.6	0.3
- seed	0.3-0.6	0.35
Spinach	0.3-0.5	0.2
Radishes	0.3-0.5	0.3
b. Vegetables - Solarium Family *(Solanaceae)*		
Egg Plant	0.7-1.2	0.45
Sweet Peppers (bell)	0.5-1.0	0.3
Tomato	0.7-1.5	0.4

[32] The larger values for Z_r are for soils having no significant layering or other characteristics that can restrict rooting depth. The smaller values for Z_r may be used for irrigation scheduling and the larger values for modeling soil water stress or for rainfed conditions.

[33] The values for p apply for ETc » 5 mm/day. The value for p can be adjusted for different ETc according to p = p table 22 + 0.04 (5 - ETc), where p is expressed as a fraction and ETc as mm/day.

TABLE A3. Continued.

Crop	Maximum Root Depth[31](m)	Depletion Fraction[32] (for ET ≈ 5 mm/day) (p)
c. Vegetables - Cucumber Family (*Cucurbitaceae*)		
Cantaloupe	0.9-1.5	0.45
Cucumber		
- Fresh Market	0.7-1.2	0.5
- Machine harvest	0.7-1.2	0.5
Pumpkin, Winter Squash	1.0-1.5	0.35
Squash, Zucchini	0.6-1.0	0.5
Sweet Melons	0.8-1.5	0.4
Watermelon	0.8-1.5	0.4
d. Roots and Tubers		
Beets, table	0.6-1.0	0.5
Cassava		
- year 1	0.5-0.8	0.35
- year 2	0.7-1.0	0.4
Parsnip	0.5-1.0	0.4
Potato	0.4-0.6	0.35
Sweet Potato	1.0-1.5	0.65
Turnip (and Rutabaga)	0.5-1.0	0.5
Sugar Beet	0.7-1.2	0.55[34]
e. Legumes *(Leguminosae)*		
Beans, green	0.5-0.7	0.45
Beans, dry and Pulses	0.6-0.9	0.45
Beans, lima, large vines	0.8-1.2	0.45
Chick pea	0.6-1.0	0.5

[34] Sugar beets often experience late afternoon wilting in arid climates even at $p < 0.55$, with usually only minor impact on sugar yield.

TABLE A3. Continued.

Crop	Maximum Root Depth[31](m)	Depletion Fraction[32] (for ET ≈ 5 mm/day) (p)
Fababean (broad bean)		
- Fresh	0.5-0.7	0.45
- Dry/Seed	0.5-0.7	0.45
Grabanzo	0.6-1.0	0.45
Green Gram and Cowpeas	0.6-1.0	0.45
Groundnut (Peanut)	0.5-1.0	0.5
Lentil	0.6-0.8	0.5
Peas		
- Fresh	0.6-1.0	0.35
- Dry/Seed	0.6-1.0	0.4
Soybeans	0.6-1.3	0.5
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)		
Artichokes	0.6-0.9	0.45
Asparagus	1.2-1.8	0.45
Mint	0.4-0.8	0.4
Strawberries	0.2-0.3	0.2
g. Fibre Crops		
Cotton	1.0-1.7	0.65
Flax	1.0-1.5	0.5
Sisal	0.5-1.0	0.8
h. Oil Crops		
Castorbean *(Ricinus)*	1.0-2.0	0.5
Rapeseed, Canola	1.0-1.5	0.6
Safflower	1.0-2.0	0.6
Sesame	1.0-1.5	0.6
Sunflower	0.8-1.5	0.45

TABLE 3. Continued

Crop	Maximum Root Depth[31] (m)	Depletion Fraction[32] (for ET ≈ 5 mm/day) (p)
i. Cereals		
Barley	1.0-1.5	0.55
Oats	1.0-1.5	0.55
Spring Wheat	1.0-1.5	0.55
Winter Wheat	1.5-1.8	0.55
Maize, Field (grain) ***(field corn)***	1.0-1.7	0.55
Maize, Sweet ***(sweet corn)***	0.8-1.2	0.5
Millet	1.0-2.0	0.55
Sorghum		
- grain	1.0-2.0	0.55
- sweet	1.0-2.0	0.5
Rice	0.5-1.0	0.20[35]
j. Forages		
Alfalfa		
- for hay	1.0-2.0	0.55
- for seed	1.0-3.0	0.6
Bermuda		
- for hay	1.0-1.5	0.55
- Spring crop for seed	1.0-1.5	0.6
Clover hay, Berseem	0.6-0.9	0.5
Rye Grass hay	0.6-1.0	0.6
Sudan Grass hay (annual)	1.0-1.5	0.55

[35] The value for p for rice is 0.20 of saturation.

TABLE A3. Continued

Crop	Maximum Root Depth[31] (m)	Depletion Fraction[32] (for ET ≈ 5 mm/day) (p)
Grazing Pasture		
- Rotated Grazing	0.5-1.5	0.6
- Extensive Grazing	0.5-1.5	0.6
Turf grass		
- cool season[36]	0.5-1.0	0.4
- warm season[35]	0.5-1.0	0.5
k. Sugar Cane	1.2-2.0	0.65
l. Tropical Fruits and Trees		
Banana		
- 1st year	0.5-0.9	0.35
- 2nd year	0.5-0.9	0.35
Cacao	0.7-1.0	0.3
Coffee	0.9-1.5	0.4
Date Palms	1.5-2.5	0.5
Palm Trees	0.7-1.1	0.65
Pineapple	0.3-0.6	0.5
Rubber Trees	1.0-1.5	0.4
Tea		
- non-shaded	0.9-1.5	0.4
- shaded	0.9-1.5	0.45
m. Grapes and Berries		
Berries (bushes)	0.6-1.2	0.5
Grapes		
- Table or Raisin	1.0-2.0	0.35
- Wine	1.0-2.0	0.45
Hops	1.0-1.2	0.5

[36] Cool season grass varieties include bluegrass, ryegrass and fescue. Warm season varieties include bermuda grass, buffalo grass and St. Augustine grass. Grasses are variable in rooting depth. Some root below 1.2 m while others have shallow rooting depths. The deeper rooting depths for grasses represent conditions where careful water management is practiced with higher depletion between irrigations to encourage the deeper root exploration.

TABLE A3. Continued.

Crop	Maximum Root Depth[31] (m)	Depletion Fraction[32] (for ET ≈ 5 mm/day) (p)
n. Fruit Trees		
Almonds	1.0-2.0	0.4
Apples, Cherries, Pears	1.0-2.0	0.5
Apricots, Peaches, Stone Fruit	1.0-2.0	0.5
Avocado	0.5-1.0	0.7
Citrus		
- 70% canopy	1.2-1.5	0.5
- 50% canopy	1.1-1.5	0.5
- 20% canopy	0.8-1.1	0.5
Conifer Trees	1.0-1.5	0.7
Kiwi	0.7-1.3	0.35
Olives (40 to 60% ground coverage by canopy)	1.2-1.7	0.65
Pistachios	1.0-1.5	0.4
Walnut Orchard	1.7-2.4	0.5

ANNEX 4 – Salt tolerance of crops

Under optimum management, in saline conditions, crop yields remain at potential levels, until a specific, threshold electrical conductivity of the saturation soil water extract ($EC_{e\ threshold}$) is reached. If the average EC_e of the root zone increases above this critical threshold value, the yield is presumed to begin to decrease linearly in proportion to the increase in salinity. The rate of decrease in yield with an increase in salinity is usually expressed as a slope, b, having units of % reduction in yield per dS/m increase in EC_e. Salt tolerance for many crops is provided in the FAO Irrigation and Drainage Papers No. 33, 48, and 56. The $EC_{e,threshold,}$ and slope b from these sources are listed in Table A4.

TABLE A4. Salt tolerance of common crops expressed as the electrical conductivity of the soil saturation extract at the threshold when crop yield first reduces below the full yield potential ($EC_{e,\ threshold}$) and as the slope (b) of reduction in crop yield with increasing salinity beyond $EC_{e,threshold}$ - Adopted from FAO IDP 56 (Allen et al., 1998)

Crop[37]	**$EC_{e\ treshold}$**[38] **(dS m^{-1})**[39]	**b**[40] **(%/dS m^{-1})**	**Rating**[41]
a. Small vegetables			
Broccoli	2.8	9.2	MS
Brussels sprouts	1.8	9.7	MS
Cabbage	1.0-1.8	9.8-14.0	MS
Carrots	1	14	S
Cauliflower	1.8	6.2	MS
Celery	1.8-2.5	6.2-13.0	MS
Lettuce	1.3-1.7	12	MS
Onions	1.2	16	S
Spinach	2.0-3.2	7.7-16.0	MS
Radishes	1.2-2.0	7.6-13.0	MS
b. Vegetables - Solanum Family *(Solanaceae)*			
Egg Plant	-	-	MS
Peppers	1.5-1.7	12.0-14.0	MS
Tomato	0.9-2.5	9	MS

[37] The data serve only as a guideline - Tolerance varies depending upon climate, soil conditions and cultural practices. Crops are often less tolerant during germination and seedling stage.

[38] $EC_{e,\ threshold}$ means average root zone salinity at which yield starts to decline.

[39] Root zone salinity is measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS m-1) at 25 °C

[40] 4 b is the percentage reduction in crop yield per 1 dS/m increase in ECe beyond ECe threshold

[41] Ratings are: T = Tolerant, MT = Moderately Tolerant, MS = Moderately Sensitive and S = Sensitive

TABLE A4. Continued.

Crop[36]	**$EC_{e\ treshold}$**[37] **(dS m^{-1})**[38]	**B**[39] **(%/dS m^{-1})**	**Rating**[40]
c. Vegetables Cucumber Family *(Cucurbitaceae)*			
Cucumber	1.1-2.5	7.0-13.0	MS
Melons		-	MS
Pumpkin, winter squash	1:02	13	MS
Squash, Zucchini	4.7	10	MT
Squash (scallop)	3.2	16	MS
Watermelon	-	-	MS
d. Roots and Tubers			
Beets, red	4	9	MT
Parsnip	-	-	S
Potato	1.7	12	MS
Sweet potato	1.5-2.5	10	MS
Turnip	0.9	9	MS
Sugar beet	7	5.9	T
e. Legumes *(Leguminosae)*			
Beans	1	19	S
Broadbean (faba bean)	1.5-1.6	9.6	MS
Cowpea	4.9	12	MT
Groundnut (Peanut)	3.2	29	MS
Peas	1.5	14	S
Soybeans	5	20	MT
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)			
Artichokes	-	-	MT
Asparagus	4.1	2	T
Mint	-	-	-
Strawberries	1.0-1.5	11.0-33.0	S

TABLE A4. Continued.

Crop[36]	$EC_{e\ treshold}$[37] (dS m^{-1})[38]	B[39] (%/dS m^{-1})	Rating[40]
g. Fibre crops			
Cotton	7.7	5.2	T
Flax	1.7	12	MS
h. Oil crops			
Casterbean	-	-	MS
Safflower	-	-	MT
Sunflower	-	-	MS
i. Cereals			
Barley	8	5	T
Oats	-	-	MT
Maize	1.7	12	MS
Maize, sweet (sweet corn)	1.7	12	MS
Millet	-	-	MS
Sorghum	6.8	16	MT
Rice[42]	3	12	S
Wheat *(Triticum aestivum)*	6	7.1	MT
Wheat, semidwarf *(T. aestivum)*	8.6	3	T
Wheat, durum *(Triticum turgidum)*	5.7-5.9	3.8-5.5	T
j. Forages			
Alfalfa	2	7.3	MS
Barley (forage)	6	7.1	MT
Bermuda	6.9	6.4	T
Clover, Berseem	1.5	5.7	MS
Clover (alsike, ladino, red, strawberry)	1.5	12	MS
Cowpea (forage)	2.5	11	MS

[42] Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged

TABLE A4. Continued.

Crop[36]	**$EC_{e\ treshold}$**[37] **(dS m^{-1})**[38]	**B**[39] **(%/dS m^{-1})**	**Rating**[40]
Fescue	3.9	5.3-6.2	MT
Foxtail	1.5	9.6	MS
Hardinggrass	4.6	7.6	MT
Lovegrass	2	8.4	MS
Maize (forage)	1.8	7.4	MS
Orchardgrass	1.5	6.2	MS
Rye-grass (perennial)	5.6	7.6	MT
Sesbania	2.3	7	MS
Sphaerophysa	2.2	7	MS
Sudangrass	2.8	4.3	MT
Trefoil, narrowleaf birdsfoot	5	10	MT
Trefoil, big	2.3	19	MS
Vetch, common	3	11	MS
Wheatgrass, tall	7.5	4.2	T
Wheatgrass, fairway crested	7.5	6.9	T
Wheatgrass, standard crested	3.5	4	MT
Wildrye, beardless	2.7	6	MT
k. Sugar cane	1.7	5.9	MS
l. Tropical Fruits and Trees			
Banana	-	-	MS
Coffee	-	-	-
Date Palms	4	3.6	T
Palm trees	-	-	T
Pineapple (multi-year crop)	-	-	MT
Tea	-	-	-

TABLE A4. Continued.

Crop[36]	**$EC_{e\ treshold}$**[37] **(dS m^{-1})**[38]	**B**[39] **(%/dS m^{-1})**	**Rating**[40]
m. Grapes and berries			
Blackberry	1.5	22	S
Boysenberry	1.5	22	S
Grapes	1.5	9.6	MS
Hops	-	-	-
n. Fruit trees			
Almonds	1.5	19	S
Avocado	-	-	S
Citrus (Grapefruit)	1.8	16	S
Citrus (Orange)	1.7	16	S
Citrus (Lemon)	-	-	S
Citrus (Lime)	-	-	S
Citrus (Pummelo)	-	-	S
Citrus (Tangerine)	-	-	S
Conifer trees	-	-	MS/MT
Deciduous orchard			
- Apples	-	-	S
- Peaches	1.7	21	S
- Cherries	-	-	S
- Pear	-	. -	S
- Apricot	1.6	24	S
- Plum, prune	1.5	18	S
- Pomegranate	-	-	MT
Olives	-	-	MT

ANNEX 5 – Yield response factor (Ky)

K_y is a factor that describes the reduction in relative yield according to the reduction in ETc caused by soil water shortage. K_y values are crop-specific and may vary over the growing season. Values for K_y for individual growth periods and the complete growing season have been included in the FAO Irrigation and Drainage Paper N° 33. Seasonal values for Ky are adopted from FAO 56 IDP and summarized in Table A5.

TABLE A5. Seasonal yield response functions from. Adopted from FAO IDP 33 (Doorenbos and Kassam, 1979)

Crop	K_y
Alfalfa	1.1
Banana	1.2-1.35
Beans	1.15
Cabbage	0.95
Citrus	1.1-1.3
Cotton	0.85
Grape	0.85
Groundnut	0.7
Maize	1.25
Onion	1.1
Peas	1,15
Pepper	1.1
Potato	1.1
Safflower	0.8
Sorghum	0.9
Soybean	0.85
Spring Wheat	1.15
Sugarbeet	1
Sugarcane	1.2
Sunflower	0.95
Tomato	1.05
Watermelon	1.1
Winter wheat	1.05

ANNEX 6 – Saline waters

Classification of saline water is adopted from FAO IDP 24 (Doorenbos and Pruitt, 1977).

TABLE A6. Classification of saline waters. Adopted from FAO IDP 24 (Doorenbos and Pruitt, 1977)

Water class	EC (dS/m)	Salt concentration (mg/l)	Type of water
Non-saline	<0.7	<500	drinking and irrigation water
Slightly saline	0.7-2	500-1500	Irrigation water
Moderately saline	2-10	1500-7000	Primary drainage water and groundwater
Highly saline	10-25	7000-15000	Secondary drainage water and groundwater
Very highly saline	25-45	15000-35000	Very saline groundwater
Brine	>45	>35000	Seawater

ANNEX 7 – Water quality for irrigation

Guidelines for the evaluation of water quality for irrigation are given in Table A7. They emphasize the long-term influence of water quality on crop production, soil conditions, and farm management and are adopted from FAO IDP 29 Rev. 1. The guidelines are based on certain assumptions that must not be become rigid prerequisites. No soil or cropping problems are experienced when using water with values lower than those shown for 'no restriction on use'. If the restrictions are in the slight to moderate range, gradually increase care in the selection of crop and management alternatives for achieving full yield potential. If water with values shown severe restrictions are used, then the water user should experience soil and cropping problems or reduced yields, and also requires a high level of management skills for acceptable production.

TABLE A7. Guidelines for interpretations of water quality for irrigation[43] - FAO IDP 29 Rev. 1 (Ayers, R.S. and D.W. Westcot, 1985)

Potential irrigation problem	Units	Degree of restriction on use		
		None	Slight to moderate	Severe
Salinity (affects crop water availability)				
Ec_w[44]	dS/m	< 0.7	0.7 - 3.0	> 3.0
or				
TDS	mg/l	< 450	450 - 2000	> 2000
Infiltration (affects infiltration rate of water into the soil – Evaluate using EC_w and SAR together)				
SAR[45] = 0 - 3 and EC_w		> 0.7	0.7 - 0.2	< 0.2
SAR = 3 - 6 and EC_w		> 1.2	1.2 - 0.3	< 0.3
SAR = 6 - 12 and EC_w		> 1.9	1.9 - 0.5	< 0.5
SAR = 12 - 20 and EC_w		> 2.9	2.9 - 1.3	< 1.3
SAR = 20 - 40 and EC_w		> 5.0	5.0 - 2.9	< 2.9
Specific ion toxicity (affects sensitive crops)				
Sodium (Na)				
Surface irrigation	SAR	< 3	3 - 9	> 9
Sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)				
Surface irrigation	me/l	< 4	4 - 10	> 10
Sprinkler irrigation	me/l	< 3	> 3	
Boron (B)	mg/l	< 0.7	0.7 - 3.0	> 3.0
Trace Elements (see Table 21**)**				
Miscellaneous effects (affects susceptible crops)				
Nitrogen (NO_3-N)	mg/l	< 5	5 - 30	> 30
Bicarbonate (HCO_3)	me/l	< 1.5	1.5 - 8.5	> 8.5
pH			Normal range 6.5-8.4	

43 Adapted from University of California Committee of Consultants 1974.

44 EC_w means electrical conductivity of water

45 SAR means sodium adsorption ratio

ANNEX 8 – Crop salt tolerance and yield potential

Crops respond to salinity differently. Some crops can achieve higher or acceptable yields at much greater soil salinity than others. This is because they can extract more water from saline soil. There is a wide range of salt tolerance within different crops. The relative salt tolerance for many common fields, vegetable, forage, and tree crops are given in Table 8 and are adopted from FAO IDP 29. Table A8 gives changes in relative yields of selected crops depending on irrigation water salinity or soil salinity. The salt tolerance data of Table A8 are used in the calculation of the leaching requirement.

TABLE A8. Crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (EC_w) or soil salinity (EC_e) - FAO IDP 29 Rev. [46] (Ayers, R.S. and D.W. Westcot, 1985)

Crop	**100%**		**90%**		**75%**		**50%**		**0% "maximum"[47]**	
	EC_e	**EC_w**	**EC_e**	**EC_w**	**EC_e**	**EC_w**	**EC_e**	**EC_w**	**EC_e**	**EC_w**
FIELD CROPS										
Barley (Hordeum vulgare)[48]	8	5.3	10	6.7	13	8.7	18	12	28	19
Cotton *(Gossypium hirsutum)*	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Sugarbeet (Beta vulgaris)[49]	7	4.7	8.7	5.8	11	7.5	15	10	24	16
Sorghum *(Sorghum bicolor)*	6.8	4.5	7.4	5	8.4	5.6	9.9	6.7	13	8.7
Wheat *(Triticum aestivum)*[47],[50]	6	4	7.4	4.9	9.5	6.3	13	8.7	20	13
Wheat, durum *(Triticum turgidum)*	5.7	3.8	7.6	5	10	6.9	15	10	24	16
Soybean *(Glycine max)*	5	3.3	5.5	3.7	6.3	4.2	7.5	5	10	6.7
Cowpea *(Vigna unguiculata)*	4.9	3.3	5.7	3.8	7	4.7	9.1	6	13	8.8
Groundnut (Peanut) *(Arachis hypogaea)*	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice (paddy) *(Oriza sativa)*	3	2	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Sugarcane *(Saccharum officinarum)*	1.7	1.1	3.4	2.3	5.9	4	10	6.8	19	12
Corn (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Flax *(Linum usitatissimum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Broadbean *(Vicia faba)*	1.5	1.1	2.6	1.8	4.2	2	6.8	4.5	12	8
Bean *(Phaseolus vulgaris)*	1	0.7	1.5	1	2.3	1.5	3.6	2.4	6.3	4.2

[46] Adapted from Maas and Hoffman (1977) and Maas (1984). These data should only serve as a guide to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions and cultural practices. In gypsiferous soils, plants will tolerate about 2 dS/m higher soil salinity (EC_e) than indicated but the water salinity (EC_w) will remain the same as shown in this table.

[47] The zero yield potential or maximum EC_e indicates the theoretical soil salinity (EC_e) at which crop growth ceases.

[48] Barley and wheat are less tolerant during germination and seeding stage; EC_e should not exceed 4–5 dS/m in the upper soil during this period.

[49] Beets are more sensitive during germination; EC_e should not exceed 3 dS/m in the seeding area for garden beets and sugar beets.

[50] Semi-dwarf, short cultivars may be less tolerant.

TABLE A8. Continued.

Crop	100%		90%		75%		50%		0% "maximum"[46]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
VEGETABLE CROPS										
Squash, zucchini (courgette) (Cucurbita pepo melopepo)	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Beet, red (Beta vulgaris)[48]	4	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15	10
Squash, scallop (Cucurbita pepo melopepo)	3.2	2.1	3.8	2.6	4.8	3.2	6.3	4.2	9.4	6.3
Broccoli (Brassica oleracea botrytis)	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14	9.1
Tomato (Lycopersicon esculentum)	2.5	1.7	3.5	2.3	5	3.4	7.6	5	13	8.4
Cucumber (Cucumis sativus)	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10	6.8
Spinach (Spinacia oleracea)	2	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15	10
Celery (Apium graveolens)	1.8	1.2	3.4	2.3	5.8	3.9	9.9	6.6	18	12
Cabbage (Brassica oleracea capitata)	1.8	1.2	2.8	1.9	4.4	2.9	7	4.6	12	8.1
Potato (Solanum tuberosum)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Corn, sweet (maize) (Zea mays)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Sweet potato (Ipomoea batatas)	1.5	1	2.4	1.6	3.8	2.5	6	4	11	7.1
Pepper (Capsicum annuum)	1.5	1	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Lettuce (Lactuca sativa)	1.3	0.9	2.1	1.4	3.2	2.1	5.1	3.4	9	6
Radish (Raphanus sativus)	1.2	0.8	2	1.3	3.1	2.1	5	3.4	8.9	5.9
Onion (Allium cepa)	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.4	5
Carrot (Daucus carota)	1	0.7	1.7	1.1	2.8	1.9	4.6	3	8.1	5.4
Bean (Phaseolus vulgaris)	1	0.7	1.5	1	2.3	1.5	3.6	2.4	6.3	4.2
Turnip (Brassica rapa)	0.9	0.6	2	1.3	3.7	2.5	6.5	4.3	12	8
Wheatgrass, tall (Agropyron elongatum)	7.5	5	9.9	6.6	13	9	19	13	31	21
Wheatgrass, fairway crested (Agropyron cristatum)	7.5	5	9	6	11	7.4	15	9.8	22	15

TABLE A8. Continued.

Crop	100%		90%		75%		50%		0% "maximum"[3]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
VEGETABLE CROPS										
Bermuda grass (Cynodon dactylon)[51]	6.9	4.6	8.5	5.6	11	7.2	15	9.8	23	15
Barley (forage) (Hordeum vulgare)[47]	6	4	7.4	4.9	9.5	6.4	13	8.7	20	13
Ryegrass, perennial (Lolium perenne)	5.6	3.7	6.9	4.6	8.9	5.9	12	8.1	19	13
Harding grass (Phalaris tuberosa)	4.6	3.1	5.9	3.9	7.9	5.3	11	7.4	18	12
Fescue, tall (Festuca elatior)	3.9	2.6	5.5	3.6	7.8	5.2	12	7.8	20	13
Wheatgrass, standard crested (Agropyron sibiricum)	3.5	2.3	6	4	9.8	6.5	16	11	28	19
Vetch, common (Vicia angustifolia)	3	2	3.9	2.6	5.3	3.5	7.6	5	12	8.1
Sudan grass (Sorghum sudanense)	2.8	1.9	5.1	3.4	8.6	5.7	14	9.6	26	17
Cowpea (forage) (Vigna unguiculata)	2.5	1.7	3.4	2.3	4.8	3.2	7.1	4.8	12	7.8
Trefoil, big (Lotus uliginosus)	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.6	5
Sphaerophysa (Sphaerophysa salsula)	2.2	1.5	3.6	2.4	5.8	3.8	9.3	6.2	16	11
Alfalfa (Medicago sativa)	2	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16	10
Corn (forage) (maize) (Zea mays)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15	10
Clover, berseem (Trifolium alexandrinum)	1.5	1	3.2	2.2	5.9	3.9	10	6.8	19	13
Orchard grass (Dactylis glomerata)	1.5	1	3.1	2.1	5.5	3.7	9.6	6.4	18	12
Foxtail, meadow (Alopecurus pratensis)	1.5	1	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Clover, red (Trifolium pratense)	1.5	1	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, ladino (Trifolium repens)	1.5	1	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, strawberry (Trifolium fragiferum)	1.5	1	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6

[51] Tolerance given is an average of several varieties; Suwannee and Coastal Bermuda grass are about 20 percent more tolerant, while Common and Greenfield Bermuda grass are about 20percent less tolerant.

TABLE A8. Continued.

Crop	100%		90%		75%		50%		0% "maximum"[3]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
FRUIT CROPS[10]										
Date palm (phoenix dactylifera)	4	2.7	6.8	4.5	11	7.3	18	12	32	21
Grapefruit (Citrus paradisi)[52]	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8	5.4
Orange (Citrus sinensis)	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8	5.3
Peach (Prunus persica)	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot (Prunus armeniaca)[51]	1.6	1.1	2	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape (Vitus sp.)[51]	1.5	1	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Almond (Prunus dulcis)[51]	1.5	1	2	1.4	2.8	1.9	4.1	2.8	6.8	4.5
Plum, prune (Prunus domestica)[51]	1.5	1	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Blackberry (Rubus sp.)	1.5	1	2	1.3	2.6	1.8	3.8	2.5	6	4
Boysenberry (Rubus ursinus)	1.5	1	2	1.3	2.6	1.8	3.8	2.5	6	4
Strawberry (Fragaria sp.)	1	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4	2.7

[52] Tolerance evaluation is based on tree growth and not on yield.

ANNEX 9 – Relative salt tolerance of agricultural crops

Relative salt tolerance ratings are listed in Table A9 for a large number of crops, including many of those given in Table 8.

TABLE a9. Relative salt tolerance of agricultural crops[53,54] - FAO IDP 29 Rev. 1 (Ayers, R.S. and D.W. Westcot, 1985)

TOLERANT[55]	
Fibre, Seed and Sugar Crops	
Barley	*Hordeum vulgare*
Cotton	*Gossypium hirsutum*
Jojoba	*Simmondsia chinensis*
Sugarbeet	*Beta vulgaris*
Grasses and Forage Crops	
Alkali grass, Nuttall	*Puccinellia airoides*
Alkali sacaton	*Sporobolus airoides*
Bermuda grass	*Cynodon dactylon*
Kallar grass	*Diplachne fusca*
Saltgrass, desert	*Distichlis stricta*
Wheatgrass, fairway crested	*Agropyron cristatum*
Wheatgrass, tall	*Agropyron elongatum*
Wildrye, Altai	*Elymus angustus*
Wildrye, Russian	*Elymus junceus*
Vegetable Crops	
Asparagus	*Asparagus officinalis*
Fruit and Nut Crops	
Date palm	*Phoenix dactylifera*

[53] Data taken from Maas (1984).

[54] These data serve only as a guide to the relative tolerance among crops. Absolute tolerances vary with climate, soil conditions and cultural practices.

[55] Detailed tolerances can be found in Table 4 and Maas (1984).

TABLE 9A. Continued.

MODERATELY TOLERANT[54]	
Fibre, Seed and Sugar Crops	
Cowpea	*Vigna unguiculata*
Oats	*Avena sativa*
Rye	*Secale cereale*
Safflower	*Carthamus tinctorius*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Triticale	*X Triticosecale*
Wheat	*Triticum aestivum*
Wheat, Durum	*Triticum turgidum*
Grasses and Forage Crops	
Barley (forage)	*Hordeum vulgare*
Brome, mountain	*Bromus marginatus*
Canary grass, reed	*Phalaris arundinacea*
Clover, Hubam	*Melilotus alba*
Clover, sweet	*Melilotus*
Fescue, meadow	*Festuca pratensis*
Fescue, tall	*Festuca elatior*
Harding grass	*Phalaris tuberosa*
Panic grass, blue	*Panicum antidotale*
Rape	*Brassica napus*
Rescue grass	*Bromus unioloides*
Rhodes grass	*Chloris gayana*
Ryegrass, Italian	*Lolium italicum multiflorum*

TABLE A9. Continued.

MODERATELY TOLERANT[54]	
Grasses and Forage Crops	
Ryegrass, perennial	*Lolium perenne*
Sudan grass	*Sorghum sudanense*
Trefoil, narrowleaf	*Lotus corniculatus*
birdsfoot	*tenuifolium*
Trefoil, broadleaf	*Lotus corniculatus*
birdsfoot	*arvenis*
Wheat (forage)	*Triticum aestivum*
Wheatgrass, standard crested	*Agropyron sibiricum*
Wheatgrass, intermediate	*Agropyron intermedium*
Wheatgrass, slender	*Agropyron trachycaulum*
Wheatgrass, western	*Agropyron smithii*
Wildrye, beardless	*Elymus triticoides*
Wildrye, Canadian	*Elymus canadeneis*
Vegetable Crops	
Artichoke	*Helianthus tuberosus*
Beet, red	*Beta vulgaris*
Squash, zucchini	*Cucurbita pepo melopepo*
Fruit and Nut Crops	
Fig	*Ficus carica*
Jujube	*Ziziphus jujuba*
Olive	*Olea europaea*
Papaya	*Carica papaya*
Pineapple	*Ananas comosus*
Pomegranate	*Punica granatum*

TABLE A9. Continued

MODERATELY SENSITIVE[54]	
Fibre, Seed and Sugar Crops	
Broadbean	*Vicia faba*
Castorbean	*Ricinus communis*
Maize	*Zea mays*
Flax	*Linum usitatissimum*
Millet, foxtail	*Setaria italica*
Groundnut/Peanut	*Arachis hypogaea*
Rice, paddy	*Oryza sativa*
Sugarcane	*Saccharum officinarum*
Sunflower	*Helianthus annuus*
Grasses and Forage Crops	
Alfalfa	*Medicago sativa*
Bentgrass	*Agrostis stolonifera palustris*
Bluestem, Angleton	*Dichanthium aristatum*
Brome, smooth	*Bromus inermis*
Buffelgrass	*Cenchrus ciliaris*
Burnet	*Poterium sanguisorba*
Clover, alsike	*Trifolium hydridum*
Clover, Berseem	*Trifolium alexandrinum*
Clover, ladino	*Trifolium repens*
Clover, red	*Trifolium pratense*
Clover, strawberry	*Trifolium fragiferum*
Clover, white Dutch	*Trifolium repens*
Corn (forage) (maize)	*Zea mays*
Cowpea (forage)	*Vigna unguiculata*

TABLE A9. Continued.

MODERATELY SENSITIVE[54]	
Dallis grass	*Paspalum dilatatum*
Foxtail, meadow	*Alopecurus pratensis*
Grama, blue	*Bouteloua gracilis*
Lovegrass	*Eragrostis sp.*
Milkvetch, Cicer	*Astragalus cicer*
Oatgrass, tall	*Arrhenatherum Danthonia,*
Oats (forage)	*Avena sativa*
Orchard grass	*Dactylis glomerata*
Rye (forage)	*Secale cereale*
Sesbania	*Sesbania exaltata*
Siratro	*Macroptilium atropurpureum*
Sphaerophysa	*Sphaerophysa salsula*
Timothy	*Phleum pratense*
Trefoil, big	*Lotus uliginosus*
Vetch, common	*Vicia angustifolia*
Vegetable Crops	
Broccoli	*Brassica oleracea botrytis*
Brussels sprouts	*B. oleracea gemmifera*
Cabbage	*B. oleracea capitata*
Cauliflower	*B. oleracea botrytis*
Celery	*Apium graveolens*
Corn, sweet	*Zea mays*
Cucumber	*Cucumis sativus*
Eggplant	*Solanum melongena esculentum*
Kale	*Brassica oleracea acephala*

TABLE A9. Continued

MODERATELY SENSITIVE[54]	
Kohlrabi	*B. oleracea gongylode*
Lettuce	*Latuca sativa*
Muskmelon	*Cucumis melo*
Pepper	*Capsicum annuum*
Potato	*Solanum tuberosum*
Pumpkin	*Cucurbita peop pepo*
Radish	*Raphanus sativus*
Spinach	*Spinacia oleracea*
Squash, scallop	*Cucurbita pepo melopepo*
Sweet potato	*Ipomoea batatas*
Tomato	*Lycopersicon lycopersicum*
Turnip	*Brassica rapa*
Watermelon	*Citrullus lanatus*
Fruit and Nut Crops	
Grape	*Vitis sp.*

TABLE A9. Continued.

SENSITIVE[54]	
Fibre, Seed and Sugar Crops	
Bean	*Phaseolus vulgaris*
Guayule	*Parthenium argentatum*
Sesame	*Sesamum indicum*
Vegetable Crops	
Bean	*Phaseolus vulgaris*
Carrot	*Daucus carota*
Okra	*Abelmoschus esculentus*
Onion	*Allium cepa*
Parsnip	*Pastinaca sativa*
Fruit and Nut Crops	
Almond	*Prunus dulcis*
Apple	*Malus sylvestris*
Apricot	*Prunus armeniaca*
Avocado	*Persea americana*
Blackberry	*Rubus sp.*
Boysenberry	*Rubus ursinus*
Cherimoya	*Annona cherimola*
Cherry, sweet	*Prunus avium*
Cherry, sand	*Prunus besseyi*
Currant	*Ribes sp.*
Gooseberry	*Ribes sp.*
Grapefruit	*Citrus paradisi*

TABLE 9. Continued

SENSITIVE[54]	
<u>**Fruit and Nut Crops**</u>	
Lemon	*Citrus limon*
Lime	*Citrus aurantiifolia*
Loquat	*Eriobotrya japonica*
Mango	*Mangifera indica*
Orange	*Citrus sinensis*
Passion fruit	*Passiflora edulis*
Peach	*Prunus persica*
Pear	*Pyrus communis*
Persimmon	*Diospyros virginiana*
Plum: Prume	*Prunus domestica*
Pummelo	*Citrus maxima*
Raspberry	*Rubus idaeus*
Rose apple	*Syzygium jambos*
Sapote, white	*Casimiroa edulis*
Strawberry	*Fragaria sp.*
Tangerine	*Citrus reticulata*

ANNEX 10 – Sodium tolerance

Sodium toxicity is not as easily diagnosed as chloride toxicity, but clear cases are found as a result of relatively high sodium concentrations in the water (high Na or SAR). Typical toxicity symptoms are leaf burn, scorch, and dead tissue along the outside edges of leaves. An extended period (many days or weeks) is normally required before accumulation reaches toxic concentrations. Sensitive crops include deciduous fruits, nuts, citrus, avocados, and beans, but there are many others. For tree crops, sodium in the leaf tissue over 0.25 to 0.50 percent (dry weight basis) is often associated with sodium toxicity.

Many crops do show sodium toxicity. The toxicity guidelines of Table 7 use SAR as the indicator of the potential for a sodium toxicity problem. Table A10 gives the relative sodium tolerance of several representative crops. The data in the table are given not in terms of SAR but of soil exchangeable sodium (ESP). There are three categories of tolerance according to approximate levels of exchangeable sodium percentage (ESP): (a) sensitive – less than 15 ESP; (b) semi-tolerant 15–40 ESP; (c) tolerant more than 40 ESP. Tolerance decreases in each column from top to bottom. Tolerances in most instances were established by first stabilizing soil structure since the soil with an ESP above 30 will usually have a poor physical structure for good crop production. Particular care in the assessment of potential toxicity due to SAR or sodium is needed with high SAR water because apparent toxic effects of sodium may be due to or complicated by poor water infiltration. As shown in Table 15, only the more sensitive perennial crops have yield losses due to sodium if the physical condition of the soil remains good enough to allow adequate infiltration. Several of the crops listed as more tolerant do show fair growth when soil structure is maintained and, in general, these crops can withstand higher ESP levels if the soil structure and aeration can be maintained, as in coarse-textured soils.

TABLE A10. Relative tolerance of selected crops to exchangeable sodium[56]. Adopted from FAO IDP Rev. 1 (Ayers, R.S. and D.W. Westcot, 1985)

Sensitive[2]	Semi-tolerant[2]	Tolerant[2]
Avocado	**Carrot**	**Alfalfa**
(Persea americana)	*(Daucus carota)*	*(Medicago sativa)*
Deciduous Fruits	**Clover, Ladino**	**Barley**
Nuts	*(Trifolium repens)*	*(Hordeum vulgare)*
Bean, green	**Dallisgrass**	**Beet, garden**
(Phaseolus vulgaris)	*(Paspalum dilatatum)*	*(Beta vulgaris)*
Cotton (at germination)	**Fescue, tall**	**Beet, sugar**
(Gossypium hirsutum)	*(Festuca arundinacea)*	*(Beta vulgaris)*
Maize	**Lettuce**	**Bermuda grass**
(Zea mays)	*(Lactuca sativa)*	*(Cynodon dactylon)*
Peas	**Bajara**	**Cotton**
(Pisum sativum)	*(Pennisetum typhoides)*	*(Gossypium hirsutum)*
Grapefruit	**Sugarcane**	**Paragrass**
(Citrus paradisi)	*(Saccharum officinarum)*	*(Brachiaria mutica)*
Orange	**Berseem**	**Rhodes grass**
(Citrus sinensis)	*(Trifolium alexandrinum)*	*(Chloris gayana)*
Peach	**Raya**	**Wheatgrass, crested**
(Prunus persica)	*(Brassica juncea)*	*(Agropyron cristatum)*
Tangerine	**Oat**	**Wheatgrass, fairway**
(Citrus reticulata)	*(Avena sativa)*	*(Agropyron cristatum)*
Mung	**Onion**	**Wheatgrass, tall**
(Phaseolus aurus)	*(Allium cepa)*	*(Agropyron elongatum)*
Mash	**Radish**	**Karnal grass**
(Phaseolus mungo)	*(Raphanus sativus)*	*(Diplachna fusca)*
Lentil	**Rice**	
(Lens culinaris)	*(Oryza sativus)*	
Groundnut (peanut)	**Rye**	
(Arachis hypogaea)	*(Secale cereale)*	
Gram	**Ryegrass, Italian**	
(Cicer arietinum)	*(Lolium multiflorum)*	
Cowpeas	**Sorghum**	
(Vigna sinensis)	*(Sorghum vulgare)*	
	Spinach	
	(Spinacia oleracea)	
	Tomato	
	(Lycopersicon esculentum)	
	Wheat	
	(Triticum vulgare)	

[56] Adapted from data of FAO-Unesco (1973); Pearson (1960); and Abrol (1982).

ANNEX 11 – Boron tolerance

Boron is an essential element for plant growth. It is required in relatively small amounts, but present in amounts appreciably greater, it becomes toxic. For some crops, 0.2 mg/l boron in water is essential, but 1 to 2 mg/l may be toxic. Boron problems originating from the water are probably more frequent than those originating in the soil. Boron toxicity can affect nearly all crops but, like salinity, there is a wide range of tolerance among crops. Boron toxicity symptoms normally appear first on older leaves as a yellowing, spotting, or drying of leaf tissue at the tips and edges. Drying and chlorosis often progress toward the center between the veins (interveinal) as more and more boron accumulate with time. Table A11 is not based on plant symptoms, but upon a significant loss in yield to be expected if the indicated boron value is exceeded.

TABLE A11. Relative boron tolerance of agricultural crops[57,58]. Adopted from FAO IDP 29 Rev. 1 (Ayers, R.S. and D.W. Westcot, 1985)

Very Sensitive (<0.5 mg/l)	
Lemon	*Citrus limon*
Blackberry	*Rubus spp.*
Sensitive (0.5 – 0.75 mg/l)	
Avocado	*Persea americana*
Grapefruit	*Citrus X paradisi*
Orange	*Citrus sinensis*
Apricot	*Prunus armeniaca*
Peach	*Prunus persica*
Cherry	*Prunus avium*
Plum	*Prunus domestica*
Persimmon	*Diospyros kaki*
Fig, kadota	*Ficus carica*
Grape	*Vitis vinifera*
Walnut	*Juglans regia*
Pecan	*Carya illinoiensis*
Cowpea	*Vigna unguiculata*
Onion	*Allium cepa*
Sensitive (0.75 – 1.0 mg/l)	
Garlic	*Allium sativum*
Sweet potato	*Ipomoea batatas*
Wheat	*Triticum eastivum*
Barley	*Hordeum vulgare*
Sunflower	*Helianthus annuus*
Bean, mung	*Vigna radiata*
Sesame	*Sesamum indicum*
Lupine	*Lupinus hartwegii*
Strawberry	*Fragaria spp.*
Artichoke, Jerusalem	*Helianthus tuberosus*
Bean, kidney	*Phaseolus vulgaris*
Bean, lima	*Phaseolus lunatus*
Groundnut/Peanut	*Arachis hypogaea*

[57] Data taken from Maas (1984).

[58] Maximum concentrations tolerated in soil-water or saturation extract without yield or vegetative growth reductions. Boron tolerances vary depending upon climate, soil conditions and crop varieties. Maximum concentrations in the irrigation water are approximately equal to these values or slightly less.

TABLE A11. Continued.

Moderately Sensitive (1.0 – 2.0 mg/l)	
Pepper, red	*Capsicum annuum*
Pea	*Pisum sativa*
Carrot	*Daucus carota*
Radish	*Raphanus sativus*
Potato	*Solanum tuberosum*
Cucumber	*Cucumis sativus*
Moderately Tolerant (2.0 – 4.0 mg/l)	
Lettuce	*Lactuca sativa*
Cabbage	*Brassica oleracea capitata*
Celery	*Apium graveolens*
Turnip	*Brassica rapa*
Bluegrass, Kentucky	*Poa pratensis*
Oats	*Avena sativa*
Maize	*Zea mays*
Artichoke	*Cynara scolymus*
Tobacco	*Nicotiana tabacum*
Mustard	*Brassica juncea*
Clover, sweet	*Melilotus indica*
Squash	*Cucurbita pepo*
Muskmelon	*Cucumis melo*
Tolerant (4.0 – 6.0 mg/l)	
Sorghum	*Sorghum bicolor*
Tomato	*Lycopersicon lycopersicum*
Alfalfa	*Medicago sativa*
Vetch, purple	*Vicia benghalensis*
Parsley	*Petroselinum crispum*
Beet, red	*Beta vulgaris*
Sugarbeet	*Beta vulgaris*
Very Tolerant (6.0 – 15.0 mg/l)	
Cotton	*Gossypium hirsutum*
Asparagus	*Asparagus officinalis*

ANNEX 12 – Trace metals in irrigation water

Trace elements and heavy metals are some elements that are normally present in relatively low concentrations, usually less than a few mg/l, in conventional irrigation waters, but attention should be paid to them when using sewage effluents of industrial origin. These elements include Aluminum (Al), Beryllium (Be), Cobalt (Co), Fluoride (F), Iron (Fe), Lithium (Li), Manganese (Mn), Molybdenum (Mo), Selenium (Se), Tin (Sn), Titanium (Ti), Tungsten (W) and Vanadium (V). Heavy metals are capable of creating definite health hazards when taken up by plants. They include Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg), and Zinc (Zn). Table A12 presents the recommended maximum concentrations of trace elements in irrigation water.

TABLE A12. Recommended maximum concentrations of trace elements in irrigation water[59]. Adopted from FAO IDP 29 Rev. 1 (Ayers, R.S. and D.W. Westcot, 1985).

Element	Recommended Maximum Concentration[60] (mg/l)	Remarks
Al (aluminium)	5	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
As (arsenic)	0.1	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice.
Be (beryllium)	0.1	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.
Cd (cadmium)	0.01	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits are recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co (cobalt)	0.05	Toxic to tomato plants at 0.1 mg/l in the nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr (chromium)	0.1	Not generally recognized as an essential growth element. Conservative limits are recommended due to a lack of knowledge of its toxicity to plants.
Cu (copper)	0.2	Toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions.
F (fluoride)	1	Inactivated by neutral and alkaline soils.
Fe (iron)	5	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment, and buildings.
Li (lithium)	2.5	Tolerated by most crops up to 5 mg/l; mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/l). Acts similarly to boron.
Mn (manganese)	0.2	Toxic to some crops at a few-tenths to a few mg/l, but usually only in acid soils.

[59] Adapted from National Academy of Sciences (1972) and Pratt (1972).

[60] The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10 000 m3 per hectare per year). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10 000 m3 per hectare per year. The values given are for water used on a continuous basis at one site.

TABLE 12. Continued

Element	Recommended Maximum Concentration[59] (mg/l)	Remarks
Mn (manganese)	0.2	Toxic to several crops at a few-tenths to a few mg/l, but usually only in acid soils.
Mo (molybdenum)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni (nickel)	0.2	Toxic to several plants at 0.5 mg/l to 1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Pd (lead)	5	Can inhibit plant cell growth at very high concentrations.
Se (selenium)	0.02	Toxic to plants at concentrations as low as 0.025 mg/l and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element to animals but in very low concentrations.
Sn (tin)		
Ti (titanium)	----	Effectively excluded by plants; specific tolerance unknown.
W (tungsten)		
V (vanadium)	0.1	Toxic to many plants at relatively low concentrations.
Zn (zinc)	2	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine-textured or organic soils.

ANNEX 13 – Water quality for drip irrigation systems

Table 13 presents an interpretation of potential problems that drip irrigation systems could face due to clogging. This information should not be used to provide firm criteria.

The main cause of clogging is solid particles in suspension, but this is also the easiest problem to solve. Filtration is a more reliable way to solve a problem and consists of screening or passage through a suitable medium, normally graded sand.

Another cause of clogging is chemical precipitation of materials such as lime ($CaCO_3$) and phosphates ($Ca_3(PO_4)_2$). High temperatures or high pH are usually part of the precipitation problem. Precipitation can result from an excess of calcium or magnesium carbonates and sulfates, or from iron which is in the ferrous form but when in contact with oxygen is oxidized to the insoluble ferric form. The most effective method of preventing problems caused by precipitation of calcium carbonate is to control the pH or to clean the system periodically with an acid to prevent deposits from building up to levels where clogging might occur. A common practice among those with problems is to inject hydrochloric (muriatic) or sulphuric acid into the system periodically. The system may need to be flushed as often as once a week.

Iron is more difficult to evaluate for its clogging potential as it is frequently a contributor to other problems, especially those of iron bacterial slime. The limitation given in Table 13 of 5 mg/l should be considered a maximum for drip irrigation systems but, in practical terms, a value above 2.0 may be near maximum since filtration costs become excessive above this limit. A concentration of 0.5 mg/l should be considered a potential problem if tannin-like compounds (often in acid waters) or total sulfides exceed 2 mg/l. The combination of the two normally produces undesirable slime growths. To prevent iron precipitation, it must first be oxidized to the insoluble form, usually by chlorination to a residual of 1 mg/l chlorine. An alternative method is an aeration in an open pond or by injection of air into the water supply by mechanical means. This causes oxidized iron to precipitate. Then it can be filtered and removed before the water enters the irrigation line. Both are expensive and difficult processes and the practicality of treatment plus filtering should be evaluated.

Many cases of clogging have occurred from biological growths inside the irrigation lines and openings. These are caused by small quantities of micro-organisms such as algae, slimes, fungi, bacteria, snails, and miscellaneous larvae. These problems are difficult to evaluate and prevent since they are affected by several factors. Such problems occur when the water contains organics and iron or hydrogen sulfide. One of the most severe forms of clogging is caused by a white, gelatinous sulfur slime associated with sulfur bacteria. Another one is the brown slime mass caused by filamentous iron bacteria. Algae and other growths can cause problems especially if their growth rates are enhanced by excess nutrient levels (nitrogen or phosphorous). The use of wastewater in localized (drip) irrigation systems would be especially troublesome since effluents normally contain nutrients, dissolved organics, and micro-organisms, all of which may increase the potential for clogging problems.

Chemical treatment (chlorine) is one of the most effective methods for controlling biological growths but is costly and requires close and careful management to use safely.

TABLE A13. Influence of water quality on the potential for clogging problems in localized (drip) irrigation systems[61]

Potential Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
		Physical		
Suspended Solids	mg/l	< 50	50 – 100	> 100
		Chemical		
pH		< 7.0	7.0 – 8.0	> 8.0
Dissolved Solids	mg/l	< 500	500 – 2000	> 2000
Manganese[62]	mg/l	< 0.1	0.1 – 1.5	> 1.5
Iron[63]	mg/l	< 0.1	0.1 – 1.5	> 1.5
Hydrogen Sulphide	mg/l	< 0.5	0.5 – 2.0	> 2.0
		Biological		
Bacterial populations	maximum number/ml	<10 000	10 000 – 50 000	>50 000

[61] Adapted from Nakayama (1982).
[62] While restrictions in use of localized (drip) irrigation systems may not occur at these manganese concentrations, plant toxicities may occur at lower concentrations.
[63] Iron concentrations > 5.0 mg/l may cause nutritional imbalances in certain crops.

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