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IR$_2$MA
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

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Guidebook for the performance of large scale participatory irrigation systems under a nexus perspective

Project co-funded by
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Guidebook for the performance of large scale participatory irrigation systems under a nexus perspective

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Abbreviation	**Explanation**
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
HDPE	High Density Polyethylene
GIR	Gross Irrigation Requirement
NIR	Net Irrigation Requirement
CWR	Crop Water Requirement
WUE	Water use efficiency
WP	Water productivity
IWUE	Irrigation water use efficiency
EEI	Eco-efficiency index
TVA	Total value added
GWP	Global warming potential
CED	Cumulative energy demand

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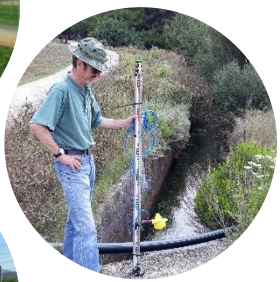
Summary

The global demand for water, energy, and food has been increasing steadily due to both population growth, economic development, and climate change. It is exerting pressure on irrigated agriculture systems involving complex trade-offs of water, energy, environment, and food, which may lead to a long-run worsening of sustainability. In this context, the performance evaluation of irrigation systems is being a widely studied subject to enhance resource efficiency and sustainability of agricultural production. During the last 20 years, several approaches, methodologies, and indicators have been developed for assessing irrigation performance from different perspectives. This guidebook presents a conceptual framework and specific basic indicators to support water managers, policymakers, researchers, and other professionals to evaluate the performance of irrigation systems using a nexus lens and eco-efficiency concept. This helps to better understand water–food–energy–environment synergies and tradeoffs. All these issues are illustrated by the use of calculation examples.

Keywords: water, energy, environment, food, climate change, sustainability, life cycle assessment (LCA)



1. Introduction

The modernization of irrigation is one of the main contemporary issues of irrigated agriculture. Irrigated agriculture is, on average, at least twice as productive per unit of land as rain-fed agriculture. Accordingly, irrigation plays a fundamentally important role assure global food security, stabilize agricultural production, and increase farm income. In many developing countries, it is a major driver of economic development and social security. Irrigation is by far the main user of freshwater in the world with irrigated land varying greatly among countries mainly because of specific climatic conditions and type of cultivation (Vignani et al., 2016). Irrigated agriculture accounts for 40% of total crop production (nearly 60% of cereal production) and 70% of freshwater withdrawals (Alexandratos and Bruinsma, 2012). Under current trends and future climate change projections, it will play an increasingly important role in agriculture with a share of about 47% of food production by 2030. This may lead to a 14% increase in water withdrawals for agriculture with the strongest (in absolute terms) effects in the more water-scarce regions.

Nowadays, irrigated agriculture is under considerable pressure to produce more with lower supplies of water. For many years, modernization has been focused on water-saving technologies, i.e., converting from traditional surface irrigation to localized methods, better monitoring of soil-plant-atmosphere continuum, improved estimate of crop water requirements and irrigation scheduling, conservative agricultural practices, optimization of water use at farm/district level, and use of remote sensing and smart IT solutions. On one side, it refers to more efficient water use; on the other, it means much higher energy consumption which is linked to environmental burdens and increased production costs (Perret and Payen, 2020).

Water use and agricultural practices in the Mediterranean region are becoming increasingly complex, contentious, and unsustainable (Saladini et al., 2018). Many irrigated agricultural systems suffer from low performance and management failures. On other hand, rainfed agriculture is associated with larger amounts of fertilizer and machinery operations, which if unmanaged can lead to significant social, economic, and environmental costs (FAO, 2017). A tool that can help to enhance sustainability is the periodical audit and performance assessment of relevant irrigation and agriculture systems. Performance assessment of irrigation schemes has gained momentum as proposed by several studies (Bos, 1997; Gorantiwar and Smout, 2005; Malano et al., 2004; Molden and Gates, 1990). Water use efficiency and water productivity were often the indicators utilized in evaluation and benchmarking procedures. Most recently, the performance of irrigation has focused on the application of life cycle thinking (LCT) to evaluate potential trade-offs between water savings, energy consumption, environmental impacts, and economic costs/benefits. The LCT indicators capture the complex and often "hidden" linkages between resources from a nexus perspective.

IRRIGATION FACTS

Irrigated agriculture represents 20% of cultivated land or 275 million hectares.

Irrigated agriculture produces two-time more yield than rainfed.

Irrigation accounts for 70 % of global freshwater withdrawals.

Global water withdrawal has increased three-times over 50 years (1960 – 2010).

Global agricultural water abstraction will increase by 14% in the period 2000-2030.

Globally, 56% of water withdrawn for irrigation is effectively used by crops.

The rise of energy consumption is becoming a major issue in the irrigation supply.

The nexus is becoming an increasingly common framework for sustainability research and nexus terminology is increasingly popular in irrigated agriculture. Nexus thinking is relevant for integrated water resources management (Hamidov and Helming, 2020) and to use and manage resource systems taking into account different sustainability goals (Reinhard et al. 2017). The nexus is increasingly recognized as a conceptual framework able to support the efficient implementation of the Sustainable Development Goals (Terrapon-Pfaff et al., 2018).

With increasing attention to sustainability issues has come a rising interest in metrics for measuring the nexus performance of irrigation and other farming practices. However, one of the major challenges is a lack of synthesis of nexus knowledge, especially for local and small-scale irrigators and non-technical audiences[1]. This guidebook is intended for water-related professionals and agriculture practitioners to enable them to design and carry out a simplified nexus life cycle thinking-based performance assessment and to evaluate the multi-dimensional implications of irrigation practices. Past this introduction, section 2 presents a brief overview of the crop production system, irrigation methods, and components. Section 3 highlights the necessary performance of irrigation systems. Sections 4, 5, and 6 present the water, energy, environmental part, respectively. Finally, conclusions and practical implications are drawn in section 7.

2. Crop production system

An agricultural system is an assemblage of components that are united by some form of interaction and interdependence and operate within a prescribed boundary and time interval to achieve a specified agricultural objective on behalf of the beneficiaries of the system (Fig. 1). It encompasses all cropping sequences practiced over space and time based on the available technologies of crop production. The system encompasses crop field operations (e.g. soil preparation, tillage operations, or irrigation), inputs applied in the fields (i.e., seeds, water, fertilizers, pesticides, etc.), infrastructures (buildings, equipment, and machinery), and the agricultural production of plant goods. Furthermore, in a larger sense – not considered in this guidebook, the agricultural system can comprehend also product conservation, transformation, and consumption. Through these interactions, crop production has a wide range of direct and indirect effects on the environment. The crop yield is a measurement of the amount of agricultural production harvested per unit of land area. It is an indicator of agricultural intensity (per 1 ha of land used) productivity (per 1 ton of yield produced) and economic value (per 1 Euro earned). There are two main ways that farmers use agricultural water to cultivate crops: rain-fed farming and irrigation. Rain-fed farming is the natural application of water to the soil through direct rainfall. In irrigated agriculture, water taken up by crops is partly or provided through human intervention to avoid yield reduction and economic losses.

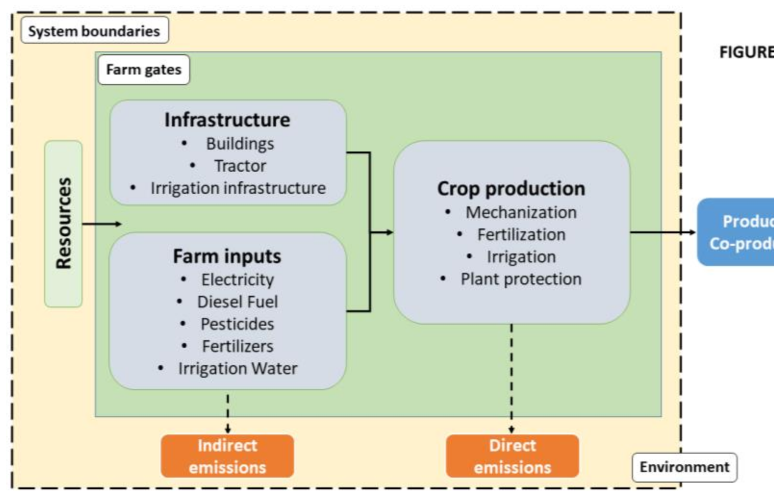


Fig. 1. Typical system delimitation, farm practices and inputs for crop production agriculture.

[1] Audience that has no real knowledge or distinct skills in irrigated agriculture.

3. Irrigation

Irrigation is one component of agricultural water management intended as the artificial application of water through an irrigation system to sustain plant growth and crop yield. It is the practice of applying water to crops when rainfall is not enough to, reliably, produce desired crop yields and quality. Besides meeting the crop water requirement, irrigation is also needed for field preparation, climate control (crop cooling and frost control), and leaching of excessive salts. The major advantages and disadvantages of irrigation as a practice are given in Fig. 2.

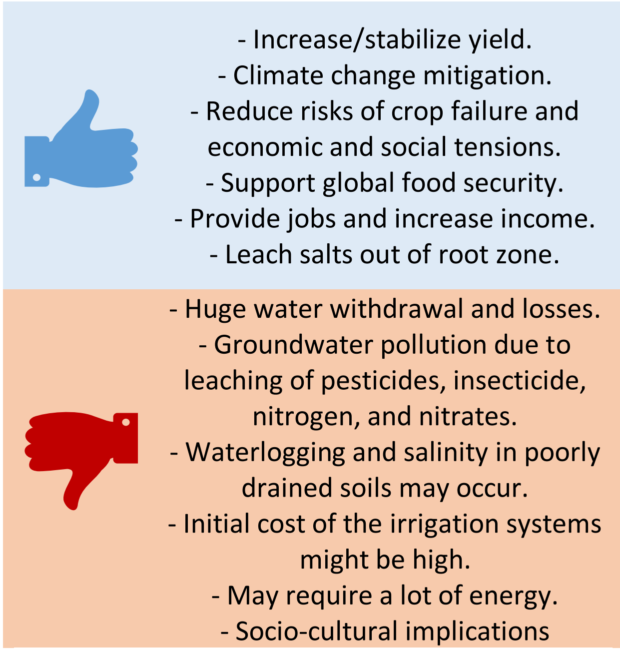


Fig. 2. Advantages and limitations of irrigation.

A typical agriculture water supply chain (Fig. 3) – delivering water to the crops – begins with a source, the mobilization (abstraction and conveyance), and treatment, storage, distribution, and final water delivery to farm gates for irrigation and production of goods and/or services. The sources of irrigation water include conventional (surface water and groundwater) and non-conventional resources (saline/drainage water, treated wastewater). In humid climates, irrigation relies mainly on surface water while under sub-humid and arid conditions underground water is the major water resource. About 7,700 m^3 of water per hectare is withdrawn on average annually for irrigation on a global level. However, irrigation efficiency—the amount of water required for irrigated crops over the volume withdrawn for irrigation—is around 56%. Treated wastewater use in agriculture represents only less than 0.5% of annual EU freshwater withdrawal – nevertheless, in some water-scarce countries, like Cyprus, reusing goes up to 90% of wastewater.

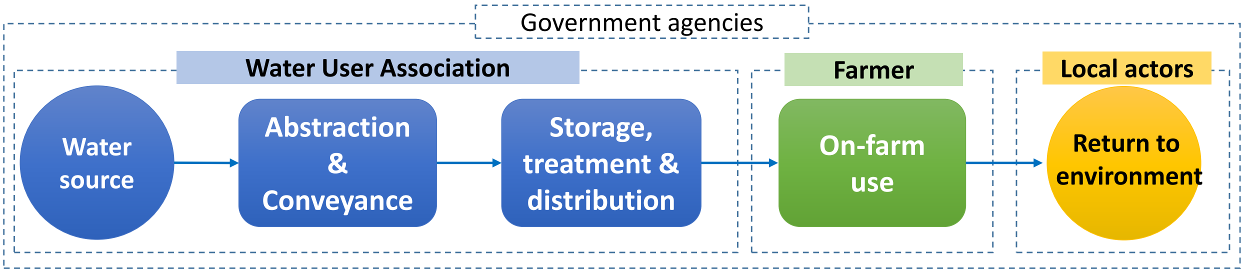


Fig. 3. Agricultural water supply chain.

To deliver the water to the irrigators, it is normally transported through conveyance infrastructures such as lined or unlined canals (gravity-fed conveyance) or pipelines (using a pumping system). From the main conveyance infrastructure, there are branch canals or delivery systems to either a group of irrigators or single irrigators. Water is not always suitable for irrigation and needs some level of water treatment before supply for the water supply system. There are various processes of treatment based on the source and quality of water in a specific region. In many irrigation schemes, the irrigation is managed by the local Water User Association (WUA) who is responsible for the operation and maintenance of the hydraulic structure and the operation of the pumps and water distribution. Once the water is delivered at the farm gate, the responsibility for distributing the water to the fields and on-farm application of the water to the crops becomes the responsibility of the individual farmer/irrigator. The WUA provides the service to the user, who in return remunerates the WUA. When the water is applied to the field, there is excess water that is drained from the field, or farms back into the groundwater or watersheds. This water is not used consumptively for irrigation.

Crops can be irrigated with water distributed by gravity-powered and pressure-driven systems and conveyed in either open channel or pipe. Examples of gravity-powered systems include furrow irrigation systems, basin irrigation systems, and hand irrigation systems. Gravity flow systems convey and distribute water at the field level by a free surface, overland flow regime.

Table 1. Comparing irrigation system characteristics.

Attribute	Drip	Sprinkler	Surface
Pressure (bar)	0.3 - 4	2-6	Low
Filtration (mesh)	120-200	20-80	None
Water quality	Free from sediment		No issue
Efficiency (%)	75-90%	70-90%	40-70%
Wetting pattern (m)	0.15-1.2	1.5-30	Broadcast
Irrigation rates	Excellent	Moderate	Poor
Application rates	Small	Medium	High
Frequency	Daily	Weekly	Monthly
Labor Cost	Low	Low	High
Initial cost	High	High	Low
Sophistication	High	Hight	Low
Fertigation	Preferable	Possible	Not used
Wastewater	Possible	Not permitted	Possible

Surface irrigation can be divided into three categories: basin, furrow, and border, all of which function very similarly (Rai et al., 2017). When irrigation water is applied to flat soil and it is called basin irrigation. Otherwise, where its slope is under 5% and it is called furrow irrigation and border irrigation. Surface irrigation systems can be used indefinitely as long as the irrigation system is well-maintained, but difficulties arise to adapt them to the specific needs of plants. The basins and furrows used for surface irrigation are made from natural materials – no infrastructure is assumed. However, land preparation using machines and/or human labor is needed to guarantee good irrigation efficiency. A pressure piped irrigation system is a network installation consisting of pumps, pipes, fittings, and other devices properly designed and installed to supply water under pressure from the source of the water to the irrigable area (Fig. 4). There are three commonly used methods: surface irrigation, sprinkler irrigation, and micro-irrigation (Table 1). The water delivery method and the kind of water emitters in the field are the main characteristics of a piped irrigation system. There are many variations of pressurized irrigation systems such as sprinkler, drip, bubbler, trickle, mist or spray, and sub-surface irrigation. The crops cultivated with pressurized irrigation systems achieve high water use efficiency, optimum growth, and high yields (Table 2). However, they have high initial capital costs and require good maintenance. Irrigation systems can be manual or automatic and classed solid installations (laid or installed at fixed permanent or seasonal positions), semi-permanent (mains and sub mains are permanent while the laterals are portable, hand move, or mechanically), or portable installations, where all the parts are portable.

Fig. 4. Examples of irrigation systems.

Table 2. Irrigation application efficiency and indicative bill of materials for different irrigation methods for 1 ha.

Parameter	Level border/ Furrow	Drip	Center Pivot	Hose move	Pipe irrigation	Solid set sprinkler	Travel spray	Traveling gun
Efficiency (%)	60-80	70-95	75-90	70-95	70-95	60-85	70-90	55-75
Pressure (bar)	-	0.7-2	0.7-2.5	1.5-3.7	1-2	3-4.5	3-4.5	4-8
Polyethylene (kg)	-	260.20	5.00	14.30	0.00	10.43	13.60	0.11
Polyvinyl chloride (kg)	-	7.61	3.33	38	456.67	0.54	-	0.03
Polypropylene (kg)	-	3.9	0	0.1	0.0076	0.03	-	0.0075
Steel (kg)	-	0.025	50.008	9.804	0.002	0.010	134.55	0.005
Aluminum (kg)	-	-	-	-	-	29.28	-	36.60
Rubber (kg)	-	-	23.1	-	-	-	-	-

Note: The list of materials for irrigation systems is retrieved from AusLCI datasets [http://auslci.com.au/index.php/Datasets]

3.1 Performance assessment of irrigation systems

In recent years, the performance of irrigation systems has become a growing concern of researchers, water policymakers, and donor agencies.

> *Performance assessment of irrigation and drainage is the systematic observation, documentation, and interpretation of the management of an irrigation and drainage system, to ensure that the input of resources, operational schedules, intended outputs and required actions proceed as planned* ***(Bos et al., 2005)***

Performance assessment of irrigation and drainage is a methodology for investigating, using a limited number of indicators, the level of service of installed systems (Vincent et al., 2007). The performance is the result of several processes occurring at different space and time scales. At small scales (plant, plot) biophysical processes are predominant. At intermediate scales (fields, farm) technical aspects are predominant. At larger scales socio-economic and political aspects are predominant.

The main methods used to evaluate irrigation system performance are direct measurements for indicators, analysis hierarchy process, the Fuzzy set theory, and remote sensing (Elshaikh et al., 2018). For measuring performance indicators, operation data are collected and analyzed to determine the performance. By defining numeric indicators of performance, specific targets for improvement can be set and subsequently monitored. Several studies (Bos, 1997; Gorantiwar and Smout, 2005; Malano et al., 2004; Molden and Gates, 1990) have defined the sets of indicators that describe irrigation water performance. Performance indicators are broadly categorized into internal and external indicators. Internal indicators (water system-oriented) include classical irrigation efficiency, conveyance efficiency, storage efficiency, distribution efficiency, and application efficiency, while external indicators (system in the basin) include crop water productivity, food security, economic impact, social impact, environmental impact, etc. The number of indicators needed for an assessment depends on boundary conditions and the purpose of the assessment (Bos et al. 2005). Since performance is assessed from different perspectives, different indicators should be combined in the assessment process considering the significance of the multifaceted relationships between water, energy, environment, economic costs/benefits, and food (Fig. 5).

Fig. 5. Key performance categories and indicators for nexus-performance oriented irrigation systems.

3.2 Estimating irrigation water demand and supply

In each irrigation area, there is a demand for water to achieve potential yields and a supply of water. The precise estimation of water demand at large-scale irrigation perimeters is a key requirement for irrigation system design and water management. The water balance provides a tool at a crop, farm, or scheme level to analyze crop water needs and to optimize the operation of an irrigation system and its performance.

3.2.1 Soil-Water balance and irrigation scheduling

The water balance (accounting) method of irrigation scheduling is one method of estimating the required amount and timing of irrigation for a crop. Another method is monitoring soil water by using soil moisture sensors. The concept of a soil-water balance (SWB) can be defined as an estimation of the total amount of water that enters and leaves a volume of soil in a specific period. It is a dynamic parameter linked to the weather factors and root growth and it is used to predict the depletion of water in the effective root depth and, therefore, the amount of irrigation water to apply. The SWB method for irrigation scheduling requires knowledge about weather, soil, crop, and on-field irrigation system data. The components of the SWB are depicted in Fig. 6.

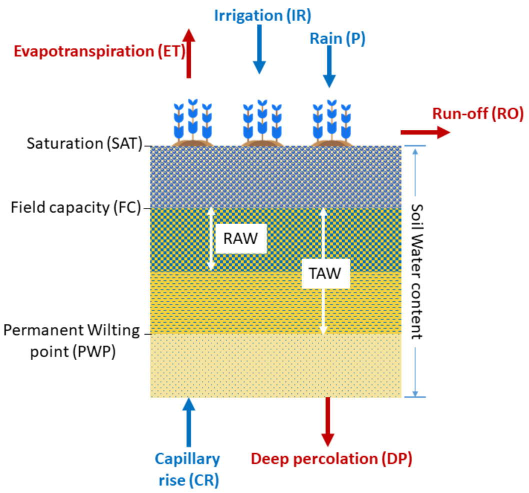


Fig. 6. The components of soil-water balance and main management terms (TAW – Total Available Water, RAW – Readily Available Water).

SWB is estimated daily, and it is expressed for a day *I* in terms of water depletion in the effective root zone $D_{r,i}$ (mm) through equation 1:

$$\boldsymbol{D_{r,i} = D_{r,i-1} - P_i - IR_i + ET_{c,i} + RO_i + DP_i} \quad (1)$$

Major inputs include precipitation (P) or rainfall and irrigation (IR). Outputs include crop evapotranspiration (ET_c), surface runoff (R), and deep percolation (DP). Crop evapotranspiration refers to soil evaporation and crop transpiration and it is the biggest subtraction from the water balance equation. RO occurs when precipitation and irrigation inputs are greater than the soil infiltration rate and refers to the water amount that does not enter the soil and runs off the irrigated land. From the hydrological (engineering) point of view, the runoff from a drainage basin can be considered as a product (gain) in a hydrological cycle. From the agronomic point of view, the runoff can be considered as precipitation losses in a rainfall-runoff analysis. Some components may not be relevant and be removed to simplify evaluation (e.g., no irrigation in rain-fed farming, no run-on (incoming overland flows), or no capillary rise from deep water table). RO can be neglected in arid and semiarid regions and the case of application of localized irrigation techniques (e.g. drip irrigation). Capillary rise (CR) is usually a very small component that should be taken into consideration only in the case of shallow groundwater level (i.e.when it is up to 2–3 m below the crop rooting system and for medium- and fine-textured soils).

Soil is the plant's water reservoir (Fig. 7). This reservoir has upper and lower limits of water that can be used by crops. This amount of water depends on soil texture and root depth and represents the difference between the field capacity (FC) and the permanent wilting point (PWP). The FC is defined as the water content at which drainage becomes negligible on free-draining soil. The minimum SWC is defined when plants permanently wilt and are called the PWP.

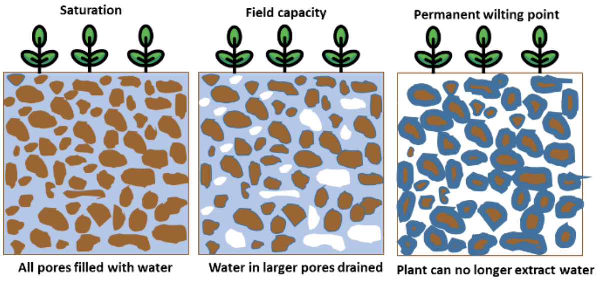


Fig. 7. Illustration of soil saturation, field capacity, and permanent wilting point.

The soil water stored between FC and the PWP is called the soil water holding capacity (SWHC) and it is expressed in mm of water per 1 m of soil depth. total available water or available water capacity (AWC). The SWHC should be multiplied by the root depth (Rd) of a specific crop to determine the Total Available Water (TAW).

$$TAW = \left(\frac{FC - PWP}{100} \times R_d\right) \quad (2)$$

Where: TAW is the total available soil water in the root zone [mm], FC is the volumetric water content at field capacity [$m^3\ m^{-3}$ in %], PWP is the volumetric water content at wilting point [$m^3\ m^{-3}$ in %], R_d is the rooting depth [mm].

Proper irrigation scheduling should never allow a complete depletion of plant-available water. The greater the depletion, the greater the water stress until the PWP threshold is reached and a plant's vital processes cease. Readily available water (RAW) represents the amount of water that can be depleted from the root zone without compromising crop growth (Eq. 3). RAW is estimated as a fraction (p) of TAW.

$$RAW = p \times TAW \quad (3)$$

Where RAW is the readily available soil water in the root zone [mm]; p average fraction of TAW that can be depleted from the root zone before crop water stress (reduction in ET) occurs [0-1]. This fraction (p) represents a threshold for maximum crop production (the optimum yield threshold, OYT). The factor p differs from one crop to another and varies from 0.3 to 0.7. A value of 0.50 for p is commonly used for many crops. When depletion > RAW soil water in the root zone drops below OYT. Root's capacity to extract water from the soil is reduced and stomata are going to close, thus, ET_c will be reduced. Management allowable depletion (MAD) specifies the maximum amount of soil water the irrigation manager chooses to allow the crop to extract from the active rooting zone between irrigations. The soil's MAD is less than its total AWC. Values of RAW (as a percentage of TAW) are typical: i) 25-40% for shallow or sparsely rooted crops; ii) 50% for deep-rooted crops; iii) 60-65% for deep-rooted crops with the dense rooting system; iv) may be decreased by 5-10% when ETo>6 mm/day,

Different soil types have different SWHC - AWC. For example, coarse soils, such as sands and sandy loam, have relatively large pores when compared to finer textured soil such as clay. Sandy soils drain rapidly and do not hold water well. Fine soils, like clays or clay loams, have small mineral particles and very small pores holding water well.

When the soil water depletion in the root zone (D_r) is greater than RAW, a dimensionless coefficient K_s (0–1) is used to account for the level of water stress (Eq. 4):

$$K_s = \frac{TAW - D_r}{TAW - RAW} \quad (4)$$

Where D_r is the root zone's soil water depletion, TAW is the total available water, and RAW is readily available water. For soil water limiting conditions, K_s < 1. Where D_r is lower or equal to RAW there is no water stress, K_s = 1.

To generate an irrigation schedule for evaluating or planning a particular irrigation strategy, time, and depth criteria have to be established (Table 3). Since crop water requirements vary over the growing season, farmers will need to adjust irrigation during the season based on the crop, its root depth and growing stage, availability and quality of water, soil infiltration rate, characteristics of the irrigation system, etc.

Table 3. Types of time and depth criteria used for generating irrigation schedules.

Time criterion	
Fixed interval (days)	The time interval between irrigations is fixed (e.g., 7 days).
Allowable depletion (mm water)	Amount of water that depletes from the root zone before the irrigation is needed (e.g., 30 mm).
Allowable depletion (% of RAW)	Percentage of RAW that depletes before the irrigation is needed (e.g., 100%).
Depth criterion	
Back to FC (± mm water)	Irrigate to bring the SWC back to FC plus/minus some value.
Fixed application depth (mm water)	Irrigate with a fixed amount of water (e.g., 20 mm).
Water layer between bunds (mm water)	The threshold for the depth of the surface water layer that should be maintained between the soil bunds (e.g., 5 mm) for the generation of irrigation events for flooded rice.

Three possible irrigation options are illustrated in Fig. 8: (i) return soil moisture to a specified level below FC, (ii) irrigate until FC level is reached, and (iii) irrigate to a specified level above FC. Applying water to a level below FC is suitable when weather forecasting indicates precipitation in the days succeeding the irrigation event and, therefore, irrigation water can be saved.

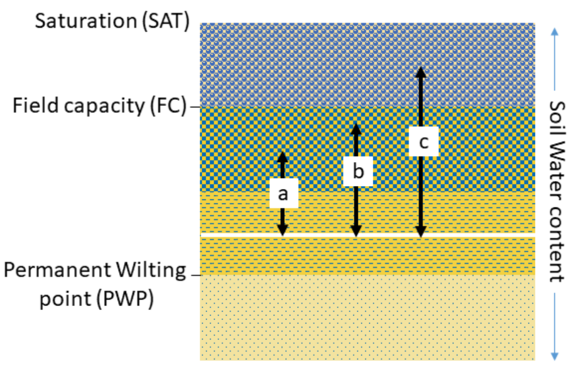


Fig. 8. Different irrigation application options: (a) to a specified level below FC, (b) to FC level, and (c) to a level above FC.

The irrigation above FC is suitable when low-quality water is applied and is necessary to leach salts out of the root zone. This irrigation option presupposes the presence of an adequate drainage system and should be applied possibly out of the crop-growing season to avoid the leaching of nutrients together with salts. The determination of irrigation amounts described here refers to Net Irrigation Requirements (NIR), which, for practical purposes, should be divided by the efficiency of the irrigation application method. In such a way, NIR is converted to Gross Irrigation Requirements (GIR) which represents the effective amount of water that should be applied in a field to guarantee that NIR is supplied to a specific crop. It is important to know that using too much irrigation water can reduce crop yield and quality, increase salinity levels, and leaching out of fertilizer from the field.

3.2.2 Crop evapotranspiration (ETc) and crop water requirement (CWR)

Accurate CWR assessment is a key component to optimize water use efficiency and develop efficient irrigation scheduling practices. CWR refers to the amount of water required to compensate for evapotranspiration losses from a cropped field during a specified period. The concept is intimately connected with crop evapotranspiration (ETc). The values of ETc and CWR are identical, so, the ETc is the CWR for a given crop/cropping pattern during a certain period. Nevertheless, there is some difference because ETc represents the water losses that occur (i.e., a hydrological term), whereas CWR indicates the amount of water that should be supplied to account for these losses (i.e., an irrigation management term). Therefore, the estimation of ETc precedes the estimation of CWRs where the latter usually represents the values of ETc aggregated over some time. Appropriate estimation of CWR facilitates:

(i) A day-to-day irrigation scheduling,
(ii) Determination of seasonal water needs of an existing irrigation scheme (i.e., seasonal irrigation planning), and
(iii) Estimation of water volumes to be supplied to newly irrigated areas (i.e., during the irrigation project design and definition of irrigation network hydraulic characteristics).

Crop evapotranspiration (ETc) is influenced by several weather parameters, crop characteristics, management, and environmental aspects. Commonly, ETc is calculated by multiplying the reference crop evapotranspiration (ETo) by the crop coefficient (Kc) as given in Eq. 5:

$$\mathrm{ET_c} = \mathrm{K_c} \times \mathrm{ET_o} \quad (5)$$

Where: ET_c = Crop evapotranspiration (mm/day); ET_o = Reference crop evapotranspiration (mm/day) K_c = a specific crop coefficient that changes during the growing season.

Reference evapotranspiration is defined by the FAO 56 (Allen et al., 1998) as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m-1 and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground.

The FAO 56 irrigation and drainage document (Allen et al. 1998) proposed a standard physically-sound method for the estimation reference evapotranspiration (ETo) based on the Penman-Monteith equation.

$$\mathrm{ET_o} = \frac{0.408 \cdot \Delta \cdot (\mathrm{R_n} - \mathrm{G}) \cdot \frac{900}{\mathrm{T}+273} \cdot \mathrm{u_2} \cdot (\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma \cdot (1 + 0.34 \cdot \mathrm{u_2})} \quad (6)$$

ETo = Reference evapotranspiration (mm/day); Rn = Net radiation at the crop surface (MJ/m^2 per day); G = Soil heat flux density (MJ/m^2 per day); T = Mean daily air temperature at 2 m height (°C); u2 = Wind speed at 2 m height (m/sec); es = Saturation vapour pressure (kPa); ea = Actual vapour pressure (kPa); es - ea = Saturation vapour pressure deficit (kPa).

The influence of the climate on crop water needs is given by the reference crop evapotranspiration (ETo). The only factors affecting ETo are climatic parameters, therefore ETo can be computed from meteorological data. If only a rough estimate of the ETo value is required Table 4 can be used. Crop coefficient (Kc) varies predominately with specific crop characteristics integrating the effect of characteristics that distinguish a typical field crop from the grass reference.

Table 4. Indicative values of ETo (mm/day) for climatic zones.

Climatic zone	Mean daily temperature		
	<15°C	15-25°C	>25°C
Desert/arid	4-6	7-8	9-10
Semi-arid	4-5	6-7	8-9
Sub-humid	3-4	5-6	7-8
Humid	1-2	3-4	5-6

Kc is the ratio of the crop ETc to the reference ETo and it represents the integration of four primary characteristics that distinguish the crop from reference grass: crop height (influences r_a); albedo (reflectance) of the crop soil surface (influences Rn); canopy resistance (affected by LAI, leaf age, and conditions, etc.) and evaporation from soil (especially from exposed soil).

A generalized crop coefficient curve is presented in Fig. 9.

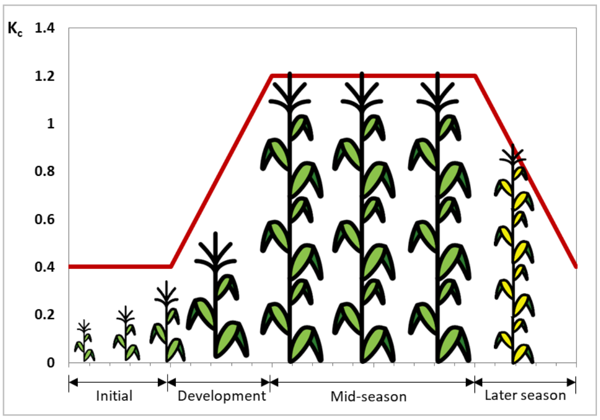


Fig. 9. Generalized crop coefficient curve for the main crop growing stages (adapted from FAO 56).

Table 5 indicates per crop the Kc values for different stages (initial, mid, and end). Crop coefficients are dimensionless numbers usually ranging from 0.3 to 1.2.

Table 5. Crop coefficients (Kc) for initial, mid-season, and late-season stages and maximum crop height.

Crop	$K_{c,ini}$	$K_{c\ mid}$	$K_{c\ end}$	Max crop height (m)
Artichoke	0.5	1	0.95	0.7
Asparagus	0.5	0.95	0.3	0.2-0.8
Barley	0.3	1.15	0.25	1
Broccoli	0.7	1.05	0.95	0.3
Carrot	0.7	1	0.95	0.3
Lettuce	0.7	1	0.95	0.3
Maize, field	0.3	1.2	0.35	2
Maize, sweet	0.3	1.15	1.05	1.5
Olives	0.65	0.7	0.7	6-9
Potato	0.5	1.15	0.75	0.6
Spring Wheat	0.3	1.15	0.4	1
Strawberries	0.4	0.85	0.75	0.2
Sugar beet	0.35	1.2	0.7	0.5
Tablegrape	0.3	0.85	0.45	2
Tomato	0.6	1.05	0.9	0.6
Watermelon	0.4	1	0.75	0.4
Winegrape	0.3	0.7	0.45	1.5-2
Winter Wheat	0.7	1.15	0.4	1
Zucchini	0.95	0.75	0.3	0.95

In the case of water stress crop ET is reduced due to stomatal closure. Hence, crop ET is adjusted for water stress and estimated by multiplying the crop coefficient by the water stress coefficient K_s defined previously by equation 4. Accordingly, $ET_{c,adj}$ is determined as:

$$ET_{c,adj} = K_s \times K_c \times ET_o \qquad (7)$$

The reduction of ETc causes the decline of crop growth, i.e. biomass and yield. The simplest equation to estimate yield reduction due to water stress is proposed is given in Eq. 8:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \times \left(1 - \frac{ET_{c,adj}}{ET_c}\right) \qquad (8)$$

Where Y_a is the actual yield under water stress corresponding to adjusted ET ($ET_{c,adj}=K_s*K_c*ET_o$), Y_m is the maximum yield corresponding to the optimal water supply, and K_y is a crop-specific yield response factor that can vary during the growing season. Indicatively, Ky goes from 0.80 to 0.85, for the most water stress-tolerant crops, to 1.25–1.30 for the most sensible water stress crops.

3.2.3 Irrigation requirement (IR)

The irrigation requirement (IR) is one of the principal parameters for the planning, design, and operation of irrigation and water resources systems. IR is different from CWR. Irrigation requirement refers to the amount of irrigation that should be supplied to a crop whereas crop water requirement refers to the water used by crops for growth.

Irrigation requirements are crop specific and depend on the weather data (past, actual, and forecasted), soil, crop, irrigation system (method) characteristics, and depth of water table. Total irrigation requirements include net irrigation requirement (NIR) plus any losses in distributing and applying and operating the system.

The NIR is the depth of water needed to fulfill the CWR over any effective precipitation for a disease-free crop growing in large fields under non-restricting soil and soil water conditions and under adequate fertility (Allen et al. 2011). It is the amount of water that is not effectively provided by rainfall. The NIR is calculated by subtracting the effective rainfall from the crop water need (Eq. 9).

$$NIR = ET_c - P_{eff} \qquad (9)$$

In the cases where all water needed for optimal growth of a crop is provided by rainfall, irrigation is not required and NIR equals 0. In the cases where rainfall is zero during the growing season, all water has to be supplied by irrigation. Consequently, the irrigation water need (NIR) equals the crop water need (ET_{crop}). In most cases, however, part of the crop water need is supplied by rainfall and the remaining part by irrigation. In such cases, the NIR is the difference between the crop water need (ET_{crop}) and that part of the rainfall which is effectively used by the plants (P_{eff}).

Effective precipitation (P_{eff}) represents the amount of water effectively used by a crop (i.e. stored in the root zone) after a precipitation event. In other words, is that part of the total precipitation that replaces, or potentially reduces, a corresponding net quantity of required irrigation water. Factors that influence P_{eff} are precipitation type (rainfall or snow), precipitation quantity and intensity, soil texture, structure and depth, precedent soil moisture content, landscape, slope and cover, vegetation height, density, growing stage, and root depth. Besides, geographical location and other factors will also affect the calculation of effective rainfall.

Some empirically determined equations can be used for estimating P_{eff}. They have been developed under a given set of conditions that may be very different from those under which they have to be applied. The parameter P_{eff} can be calculated for each month from the FAO approach as:

(i) If P > 75 mm/month

$$P_{eff} = 0.8 \times P_{total} - 25 \quad (10)$$

(ii) If P < 75 mm/month

$$P_{eff} = 0.6 \times P_{total} - 10 \quad (11)$$

Another commonly used method is the USDA Soil Conservation Service Method. The USDA SCS equations to estimate effective rainfall is:

(i) For $P_{total} \leq 250$ mm

$$P_{eff} = P_{total} / 125 \times (125 - 0.2 \times P_{total}) \quad (12)$$

(ii) For $P_{total} \geq 250$ mm

$$P_{eff} = (125 + 0.1 \times P_{total}) \quad (13)$$

Where P_{eff} is the effective rainfall and P_{total} the total rainfall in the concerned period.

FAO approach is more suitable for the crops with shallow rooting systems and coarse soil texture, whereas the USDA SCS formulas are more suited for the deep-rooted and perennial crops and fine soil texture. As an alternative solution, it could be determined as a fixed percentage (usually 70% or 80%) of total precipitation. This option produces values of P_{eff} in between those proposed by the previous two approaches.

Net irrigation water requirements for specific plants are modeled as the amount of water that plants need according to atmospheric demand, taking into account the relative soil moisture and the water holding capacity of the irrigated layer. Estimates of irrigation requirements can be made from 1) historical observations or 2) numerical models.

Irrigation water withdrawal normally far exceeds the NIR or the consumptive use because of water loss in its distribution from its source to the crops. The total amount of water, inclusive of losses, applied through irrigation is termed as gross irrigation requirements (GIR) which account for the scheme irrigation efficiency a product of field application efficiency, and the conveyance efficiency of the distribution system (Eq. 14). The GIR is the amount that must be pumped/released from the source.

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\mathrm{E_c} \times \mathrm{E_d} \times \mathrm{E_a}} \quad (14)$$

Where: GIR = Gross irrigation requirements (mm); NIR = Net irrigation requirements (mm), E_c = conveyance efficiency (%), E_d = distribution efficiency (%), E_a = field application efficiency (%). GIR estimated in mm should be converted in m^3 ha^{-1} knowing that 1 mm of water corresponds to 10 m^3 ha^{-1}. Then, it should be multiplied by irrigated area (in ha) to determine the volume of water to be withdrawn for irrigation.

Water withdrawal indicates the aggregate sum of water withdrawn from rivers, lakes, and aquifers either permanently or temporarily and conveyed to a place of use. The conveyance and distribution efficiency mainly depends on the length and type of infrastructures used (lined/unlined canals, high/low-pressure conduits), the complexity of the interconnections (diversions, retention reservoirs, etc.), and the capacity of the management staff. Moreover, the losses of water stored in the accumulation lakes/reservoirs should be taken into considerations. The GIR can be determined for a field, for a farm, for an outlet command area, or an irrigation project, depending on the need, by considering the appropriate losses at various stages of growth of the crop. Typical ranges of irrigation application efficiency (Ea) for different irrigation methods are given in Table 1. A flow chart showing the calculation of irrigation water requirements is given in Fig. 10. Table 6 summarizes the information that WUA and single irrigators can compile for the planning and management of irrigation and assessment of performance.

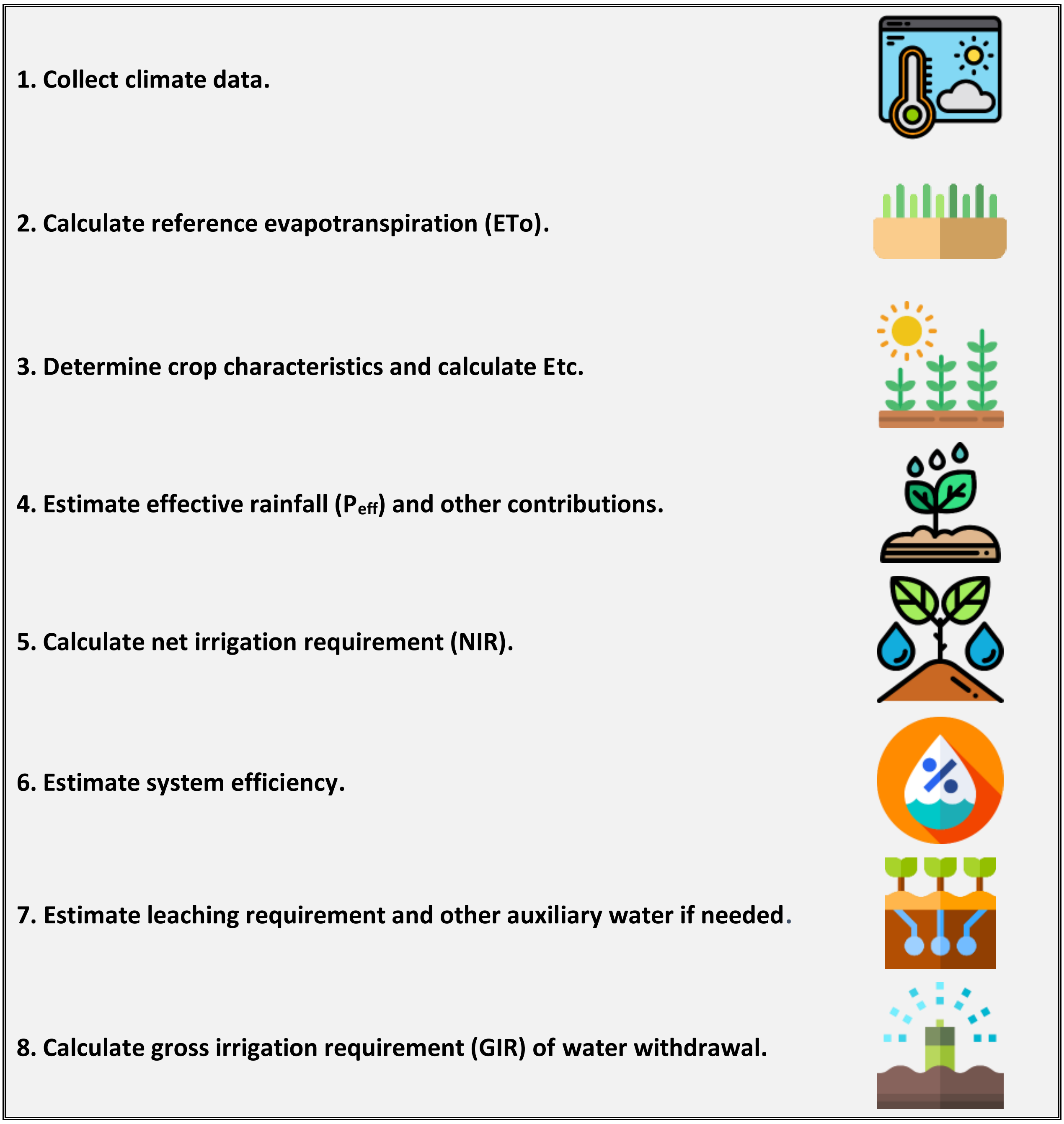


Fig. 10. Steps to compute gross irrigation water (GIR) requirements.

Table 6. Information to be gathered for data planning and management of irrigation water supply.

<table>
<tr><th>Category</th><th>Input</th><th>Output</th></tr>
<tr><td>Water withdrawal and delivery (wells, rivers, etc.)</td><td>– Type of water source (surface/groundwater)
– Volume and quality of water available for irrigation during a season
– Conveyance Diversions, Distribution Diversion, Conveyance efficiency, Distribution efficiency, Storage efficiency.
– In the case of single irrigators who are not in an irrigation scheme or abstract water from the wells, the volume of water delivered to the field</td><td>1. The volume of water at conveyance distribution and within a scheme
2. Water losses through conveyance and distribution.
3. The volume of water delivered/available to specific areas (farms/fields/crops) within an irrigation scheme.</td></tr>
<tr><td>Water demand</td><td>Climate characteristics
– Precipitation (mm/period)
– Minimum and maximum air temperatures (°C)
– Minimum and maximum (or average) humidity (%)
– Solar radiation or sunshine hours
– Average wind speed (m/s)
– Latitude and elevation of location</td><td rowspan="4">4. Reference evapotranspiration (mm/period);
5. Crop evapotranspiration (mm/period)
6. Effective rainfall (mm/period);
7. Net irrigation requirements (NIR) (mm/period);
8. Gross irrigation requirements (GIR) (mm/period)
9. Specific continuous discharge (l/s/ha)
10. Total available water –TAW (mm);
11. Readily available water – RAW (mm);
12. Daily soil moisture depletion (mm);
13. Irrigation time (date) or interval (days)
14. Irrigation amount (mm) applied or volume (m^3);
15. Lost irrigation water (mm or m3); -
16. Actual crop evapotranspiration – ETc (mm);
17. Yield reduction due to water stress (%)
18. Crop Yield (t/ha)</td></tr>
<tr><td>Water demand</td><td>Crops/Cropping Pattern
– Start of the growing season
– Duration of growing stages (initial, development, mid-season, and end)
– Crop coefficient (Kc)
– Rooting depth (m)
– Critical depletion (fraction)
– Yield response (Ky)
– Crop height (m)*
– Expected yield under optimal water supply (t/ha)</td></tr>
<tr><td>Water demand</td><td>Soil characteristics
– Soil texture
– Soil Water Holding Capacity (SWHC) - (mm/m)*
– Infiltration rate (mm/day)
– Initial soil moisture depletion (as % of TAW)*</td></tr>
<tr><td>Water application at a field (irrigation system))</td><td>– Irrigated land (ha)
– Irrigation method (sprinkler, drip, surface)
– Application efficiency
– System application rate
– Wetted area
–</td></tr>
</table>

Example 1: Predicting water demand using simulation tools

This example uses the main steps depicted in Fig. 10 and shows the estimation of SWB components of tomato crop cultivated in Trinitapoli (N 41° 19' 16.22'''; E 16° 07' 45.25''; elevation: 16 m a.s.l.), South Italy (Puglia region). Excel-IRR model (Todorovic, 2006) was applied for the calculation of ETo, ETc, NIR, and GIR using local weather variables (not shown here), main crop growth data (Table 7), and soil characteristics (Table 8). The crop evapotranspiration in the Excel-IRR model is estimated from reference evapotranspiration (ETo) and the single crop coefficient approach (Eq. 5). Reference evapotranspiration (ET_o) is calculated using the Penman-Monteith (PM) equation (Eq. 6).

Table 7. Tomato crop and management inputs.

Parameter	Crop stage	Init.	Dev.	Mid	Late	Harvesting	Total
Growing days	Length	30	40	45	30	145	145
	Starting day	Apr-1	May-1	June-10	July-25	Aug-24	
Crop coefficients	Kc values	0.60	1.15	1.15	0.80	0.80	
	Ky values					1.103	
	Kc basal	0.15	1.10	1.10	0.70		
Rainfall	Rainfall coef.[1]	0.90	0.90	0.90	0.90	0.90	
	Rainfall min (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 (to FC)	1.00	1.00	1.00	1.00		
	Irr_supply_2 (+-)	0.00	0.00	0.00	0.00		
	Appl_ 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 8. Soil water characteristics.

Layer	Depth [cm]	FC [vol%]	PWP [vol%]	SWC [mm/m]
1	0–50	340	20	140
2	50–100	31	19	140
3	100–120	31	19	140

Table 9 summarizes the results obtained by the model. In April, the tomato crop needs 46 mm of water, in March 97 mm of water, etc. The water needs of tomatoes over the total growing season (April-August: 145 days) is 565 mm. Within it, 176 mm is supplied by the rainfall. The remaining 423.2 mm has to be supplied by irrigation. Total GIR is 497.8 mm and the greatest needs are in July (159 mm). In the case the tomato is the only crop grown in the irrigation scheme, the irrigation system has to be designed in such a way to allow a flow large enough to supply 159 mm (in the peak month) or 0.59 l/s/ha[2]. In other words, for designing an irrigation scheme, the month of peak water supply is the critical month. If the irrigated area is 5 ha the total water need is 24,980 m^3. However, this volume, corresponding to water demand, should be lower or equal to the volume of water available at the gate (hydrant) of the irrigation scheme. Otherwise, some alternative management options should be examined.

Table 9. Computed ETc, P_{eff}, NIR, and GIR for tomato.

Month	ETo	ETc	P_{eff}	NIR	GIR
April [mm]	77	46	55	14	16
May [mm]	117	97	12	77	90
June [mm]	139	158	60	133	156
July [mm]	145	165	24	135	159
August [mm]	111	99	25	65	76
Seasonal [mm]	590	565	176	423.2	497.8

[2] In the design of irrigation systems, it is necessary to use water requirement of the peak period in dry year.

3.2.4 Water delivery performance indicators

Based on computed water balance components a key set of indicators can be related to the adequacy, equity, reliability, and consistency of the delivery system. Equity, as related to the water delivery system can be defined as the delivery of fair shares of water to the users throughout the system. Adequacy is an indicator for a water delivery system whether it attained a target or required water delivery over a certain period. The Relative Water Supply (RWS), Relative Irrigation Supply (RIS), and water use efficiency (WUE) are primary indicators used to assess the adequacy, equity, and efficiency of water utilization. RWS and RIS are used as the basic water supply indicators relating the water supply to the water demand.

Water supply can be either by rainfall, irrigation, or other inflows. The analysis of the scheme delivery performance, which determines how efficient the scheme is in delivering water to the farm boundary. The simplest, and yet probably the most important, operational performance indicator is the water delivery performance ratio (DPR).

$$\boldsymbol{DPR} = \frac{\boldsymbol{Actual\ volume\ of\ water}}{\boldsymbol{Intended\ volume\ of\ water}} \tag{15}$$

Another index for assessing the sufficiency of water supply is the Water Availability Index (WAI).

$$\mathrm{WAI} = \frac{\text{Total water supply}}{\text{Total water need}} \tag{16}$$

The index includes surface water as well as groundwater resources and compares the total water supply to total water needs.

Water use efficiency (WUE) is also often used to express the effectiveness of irrigation water delivery and use (entire distribution system). In irrigation, WUE represents the ratio between effective water use and actual water withdrawal. It characterizes, in a specific process, how effective is the use of water.

$$\mathrm{WUE} = \frac{\text{Crop water demand}}{\text{Total water supply}} = \frac{\mathrm{ET_c}}{\mathrm{IR} + \mathrm{P_{eff}}} \tag{17}$$

WUE assesses the adequacy, equity, and efficiency of water utilization. It can be calculated for conveyance, distribution, and application of the water to the irrigated field. The first two are determined at the scheme level while the latter at the field level.

The relative water supply (RWS) irrigation performance indicator focuses on the relation between the water that enters the system (total rainfall plus diverted irrigation supply) and the water required (evapotranspiration and leaching). It presents the natural view of the relationship between the amounts of water utilized for crop production and the amount of water delivered to meet crop demand.

$$\mathrm{RWS} = \frac{\text{Total water supply}}{\text{Crop water demand}} = \frac{\mathrm{IR} + \mathrm{P_{eff}}}{\mathbf{ET_c} + \mathbf{LR}} \tag{18}$$

RWS greater than one indicates that the total water application, i.e., irrigation plus total rainfall is meeting crop demand at a temporal timescale of consideration (usually a year). Otherwise, if the RWS is lower implies that the majority of rainfall was not effective and that irrigation demand was not being matched by irrigation supply.

The relative irrigation supply (RIS) indicator relates the volume of irrigation water supplied to users during the irrigation season to the volume of irrigation water required for the crop throughout its life cycle. When irrigation and rainfall meet the water requirements RIS is near unity. If the RIS is less than one, a situation of under irrigation is occurring, with the irrigation demand not being met by the irrigation supply.

$$\mathrm{RIS} = \frac{\text{Irrigation water supply}}{\text{Irrigation water demand}} \tag{19}$$

Crop Water Productivity (CWP) or Water Productivity (WP) is a more agronomic term that is commonly used to describe biophysical or economic gain from the use of a unit of water in crop production. Therefore, it could be defined as the relationship between agricultural output (in terms of biomass, yield, or economic value) and water consumed (crop evapotranspiration). Alternatively, in the denominator instead of crop ET can be used water supply (i.e., irrigation and precipitation). In the latter case, it can be named Irrigation Water Productivity (IWP).

3.2.5 Irrigation water quality

Irrigated agriculture is dependent on an adequate supply of water of usable quality. The quality of the irrigation water may affect both crop yields and soil physical properties, even if all other conditions and cultural practices are favorable/optimal. Besides, different crops require different irrigation water qualities. The quality of water in irrigation is also an important issue for the environment, resource management, and the health of the local population. The main issues of water quality in an irrigation system are related to salinity, environmental pollution, and water-related diseases. For irrigation water, the usual criteria include salinity, sodicity, and ion toxicities because they are major problems in irrigation waters. The parameters which determine the irrigation water quality are divided into three categories: physical, chemical, and biological (Fig. 11).

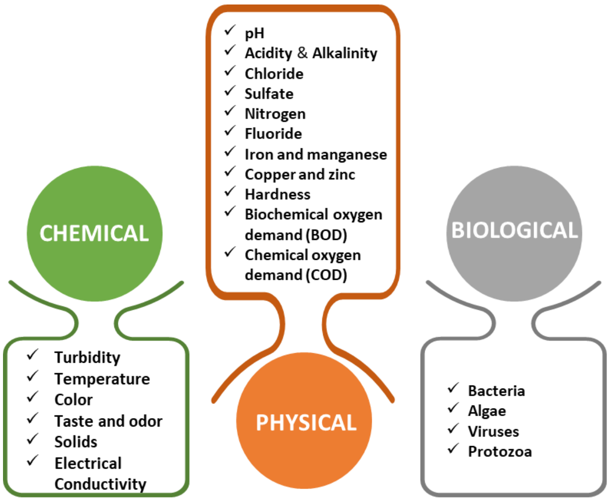


Fig. 11. Type of water quality parameters.

A summary of water quality parameters important for irrigation water sources is given in Table 10. Salinity is a common problem facing farmers who irrigate in arid climates whereas, in areas with intensive agriculture, fertilization is a major cause of aquifer salinization. A high salt concentration present in the water and soil will negatively affect crop yields, degrade the land and pollute groundwater. 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 affect plant metabolism and growth.

Table 10. Water quality parameters and level of concerns.

Parameter	Level of Concern
pH	<5.0 or >7.0
Total Alkalinity	< 30 or > 100 mg/L
Hardness (Ca and Mg)	< 50 or >150 mg/L
Calcium (Ca)	< 40 mg/L
Magnesium (Mg)	< 25 mg/L
Electrical Conductivity	> 0.75 mmhos/cm
Total Dissolved Solids (TDS)	> 640 mg/L
Boron (B)	> 2.0 mg/L
Chloride (Cl)	> 100 mg/L
Sodium (Na)	> 50 mg/L
Sodium Adsorption Ratio (SAR)	> 2.0
Nitrate-Nitrogen (NO_3-N)	>5.0 mg/L
Phosphorus (P)	> 5.0 mg/L (deficiency) >1.0 mg/L
Potassium (K)	No concern for plant growth.
Sulfur (S)	<10 mg/L
Iron (Fe)	> 0.30 mg/L micro-irrigation > 1.0 mg/L foliar spotting > 5.0 mg/L, toxicity
Manganese (Mn)	> 0.05 mg/L cloggin, > 2.0 mg/L toxic to some sensitive plants.
Copper (Cu)	>0.20 mg/L
Molybdenum (Mo)	> 0.05 mg/L
Zinc (Zn)	> 0.30 mg/L

Table 11 prescribes the guidelines for water use relative to its salt content. The Electrical Conductivity of a saturated extract method is the standard measure of salinity. The standard international unit of measure is decisiemens per meter (dS/m) corrected to a temperature of 25°C. Milimhos per centimeter (mmhos/cm) equals to dS/m and maybe still in use. In general, water for irrigation purposes must have a low to medium salinity level (i.e., the electrical conductivity of 0.6 to 1.7 dS/m).

Table 11. Salinity hazard of irrigation water.

Hazard	Remarks	EC (ds/m)
None	Used safely	0.75
Minor	With moderate leaching	0.75-1.5
Moderate	With management practices	1.5-3
Severe	Unsuitable for irrigation	3-7.5

Water with high electrical conductivity of irrigation water (ECi>1.5) and sodium adsorption ratio (SAR>6) should not be used for irrigation. Nevertheless, in some places with water shortages, water with high salinity concentration is used as a supplement for other sources, and therefore good management and control are essential, and the salt tolerance of the plants must be considered.

If the irrigation water salinity exceeds the threshold for a crop, then yield reduction occurs. For soil salinities exceeding the threshold of any given crop, relative yield (Yr) can be estimated with the following equation:

$$Y_r = 100 - b\,(ECe - a) \quad (20)$$

Where (b) is the percent loss in relative yield per unit increase in salinity, (a) is the EC threshold that a crop can tolerate and ECe is the electrical conductivity of the saturated soil paste, which is measured in the laboratory.

When salinity stress occurs without water stress, for conditions when $EC_e > EC_{e\ threshold}$ and soil water depletion is less than the readily available soil water depth (D_r < RAW) as given in Eq. 21:

$$K_s = 1 - \frac{b}{K_y \times 100} \times (EC_e - EC_{e,threshold}) \quad (21)$$

When soil water stress occurs in addition to salinity stress, for conditions when $EC_e > EC_{e\ threshold}$ and D_r > RAW the K_s is computed:

$$K_s = \left(1 - \frac{b}{K_y \times 100} \times (EC_e - EC_{e,threshold})\right) \times \frac{TAW - D_r}{TAW - RAW} \quad (22)$$

Stress coefficient Ks should be used in Eq. 7 for the estimation of crop ET adjusted for salinity stress (when Ks is estimated by Eq. 21) and for both salinity and water stress (when Ks is estimated by Eq. 22).

Typical management practices for efficient use of high salinity water include more frequent irrigation, use of extra water for leaching, conjunctive use of fresh and saline waters, and growth of salt-tolerant crops and varieties.

To estimate the leaching requirement (LR), both the irrigation water salinity (EC_w) and the crop tolerance to salinity, which is normally expressed as the electrical conductivity of the soil saturation extract (EC_e), have to be known.

The LR can be calculated for surface and sprinkler irrigation method (Eq. 23) and localized irrigation and high frequency (near-daily) sprinkler (Eq. 24):

$$LR_{fraction} = \frac{EC_w}{5\ EC_e - EC_w} \times \frac{1}{L_e} \quad (23)$$

$$LR_{fraction} = \frac{EC_w}{2\ Max\ EC_e} \times \frac{1}{L_e} \quad (24)$$

Where: LR (fraction) = The fraction of the water to be applied that passes through the entire root zone depth and percolates below; ECw = Electrical conductivity of irrigation water (dS/m); ECe = Electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction (dS/m); Max ECe = Maximum tolerable electrical conductivity of the soil saturation extract for a given crop (dS/m); Le = Leaching efficiency (in decimals).

The tolerance of various crops to the salinity of irrigation water is given in Table 12.

Table 12. Yield reduction in % at various ECw for some crops.

Field Crops	0%		10%		25%		50%		[3]100% "maximum"	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Barley	8.0	5.3	10	6.7	13	8.7	18	12	28	19
Cotton	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Sugarbeet	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16
Sorghum	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7	13	8.7
Wheat	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Wheat, durum	5.7	3.8	7.6	5.0	10	6.9	15	10	24	16
Soybean	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0	10	6.7
Peanut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Sugarcane	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12
Corn (maize)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Squash, zucchini	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Broccoli	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14	9.1
Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13	8.4
Cucumber	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10	6.8
Spinach	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15	10
Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Corn, sweet (maize)	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Sweet potato	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11	7.1
Pepper	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Lettuce	1.3	0.9	2.1	1.4	3.2	2.1	5.1	3.4	9.0	6.0
Onion	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.4	5.0
Carrot	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.0	8.1	5.4
Bean	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Grapefruit	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0	5.4
Orange	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0	5.3
Peach	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Almond	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.8	6.8	4.5
Plum, prune	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Strawberry	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4	2.7

Example 2. Predicting salinity effects using simulation tools.

One of the outputs of IR_2MA includes the development and testing of the DSS tool **"EXCEL–IRR"** for irrigation under different cropping patterns and water quantity/quality scenarios. Five different irrigation water quality scenarios 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 were tested for tomato crop. The different management input parameters are presented in Table 13. The Excel-IRR model utilizes 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) to predict the yield reduction of the crop. Excel–IRR model (Todorovic, 2006) computes irrigation amounts from daily soil water balance equations according to management allowable soil water depletion and computes leaching requirements in the conditions where saline water is used for irrigation.

Table 13. Results for tomato crop under different electrical conductivity (ECw) of irrigation water.

Parameter	EC_w =1	EC_w = 2	EC_w = 3	EC_w =4	EC_w = 5
ETc (mm)	564.3	541.6	472.3	403	333.7
NIR (mm)	367.0	367.0	367.0	367.0	367.0
Rainfall (mm)	176.4	176.4	176.4	176.4	176.4
Drainage (mm)	28.7	58.2	127.5	196.8.9	266.1
Leaching fraction (-)	0.00	0.15	0.15	0.15	0.15
Leaching fraction (mm)	0.0	56.4	56.4	56.4	56.4
Relative yield (%)	99.7	95.3	81.8	68.4	54.9

For full irrigation, the results indicate the maximum yield in the scenario with the EC of irrigation water below the threshold value of EC_w for tomato crop ($EC_{e,threshold}$=1.7 dS/m). The increase in EC_w above the threshold resulted in the decrease of ETc and a relative yield decrease, going down to 54.9% at ECw = 5 dS/m. After every irrigation event, the model is set to apply water up to field capacity water content. Consequently, the NIR remains constant at 367 mm for all treatments. However, due to salinity stress, an additional portion of water (15%, or 56.4 mm), is added as a leaching fraction. Leaching fraction remains the same in salinity stress treatments, whereas the drainage water increases with irrigation water salinity increase. The values of irrigation water productivity (IWP) decrease with an increase in EC_w from 16.3 kg/m^3) to 7.8 kg/m^3 due to reduction of yield (Fig. 12). Nevertheless, the reduction of water productivity (Fig. 12) was much lower – less than 10% between the highest value at EC_w = 1 dS/m and the lowest value observed at EC_w = 5 dS/m. This is because both yield and crop ET decrease with the increase of irrigation water salinity above a predefined threshold.

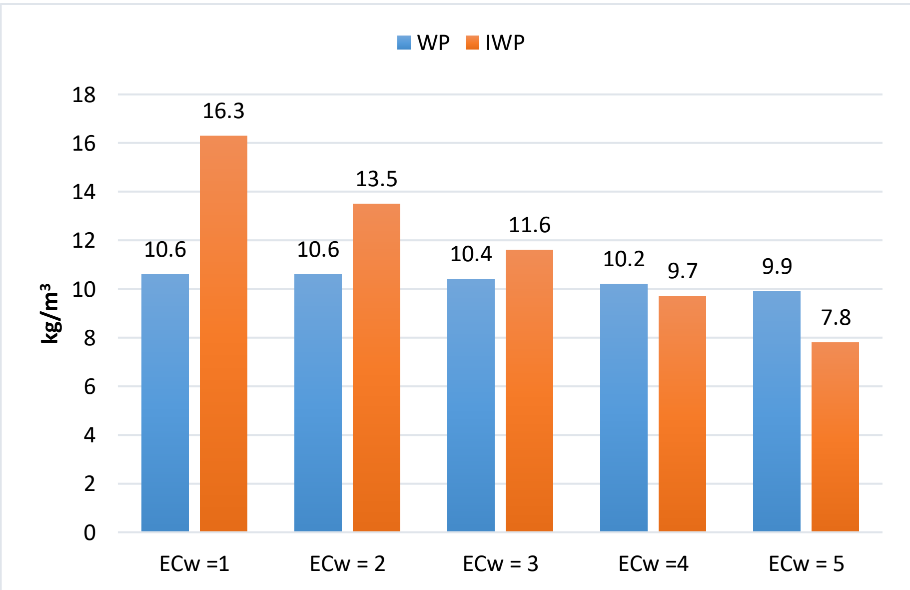


Fig. 12. Water productivity (WP) and Irrigation Water Productivity (IWP) of tomatoes grown under full irrigation and different water quality.

4. Energy in irrigation and crop cultivation

Energy is embodied in all of the equipment, inputs, and products of agriculture. Consequently, is one of the most examined agricultural sustainability indicators of field operation (Lampridi et al., 2020).

Irrigation accounts for a substantial portion of agricultural energy consumption and is the major energy-using process in arid regions of the world. All irrigation systems require energy that can direct or indirect (Fig. 13), as well as renewable and non-renewable.

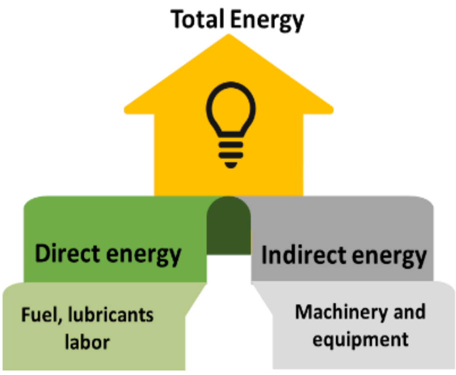


Fig. 13. Type of energy costs of agricultural operations.

Direct energy for irrigation is related to direct inputs (mostly electricity, diesel fuel, and labor) to run the irrigation system. It is consumed for various activities such as water extraction, conveyance, distribution, treatment, and desalination.

The direct energy of water extraction and pumping from ground and surface sources is a function of the level of pumping required, crop water requirement, total head, flow rate, and system efficiency (Eq. 25).

$$\text{Energy (kWh)} = \frac{\text{GIR} \times \text{TDH}}{367 \times \eta_{p,m}} \qquad (25)$$

Where:

GIR = Gross Irrigation requirement [m^3]

TDH = Total Dynamic head [m]

$\eta_{p,m}$= efficiency of the complete unit (pump + motor)

Irrigation energy consumption may be affected by climatic conditions, cultural, and management practices. Energy for water pumping alone may be several times greater than that for all the other agricultural field operations combined, especially when the origin of the water is from deep wells. Table 14 summarizes the range of efficiencies for diesel and electrical pumps. About 0.0027 kWh of energy is used to lift 1 m^3 of water (with a density of 1000 kg/m^3) 1 m at 100% efficiency. The efficiency of pumps varies with pump type and size.

Table 14. Indicative pump efficiencies for diesel and electric motors.

Pump type & efficiency	Low	High
Pump hydraulic efficiency	60%	90%
Overall diesel pump efficiency	18%	36%
Overall electric pump efficiency	48%	86%

Electricity is more cost-efficient for pumping than diesel but not all farms can connect to the grid. Pumps can be powered by diesel or electrical energy with the latter supplied from the grid or renewable energy sources. Non-renewable energy sources include diesel fuel, electricity made from coal or natural gas, and machinery while renewable energy sources such as wind and solar systems. Diesel pumps also have higher maintenance requirements than electrical pumps.

The following default assumption is made when no better data is available:

- Arable crops: diesel-powered
- Perennials crops: electricity powered in OECD, diesel-powered in other countries
- Horticultural crops: electricity powered in OECD, diesel powered in other countries.

The total intensity (kWh/m^3) depends upon the specific technologies applied at each stage of the water cycle. Energy use for irrigation water is a function of many variables, including water source, treatment, intended end-use, distribution, and amount of water loss in the system, and the level of wastewater treatment. Recycled water energy intensity is high by definition because the source water quality is low. The electrical energy consumption per m^3 of wastewater treated can vary, ranging from approximately 0.26–0.84

kWh/m^3 depending on several operational and environmental characteristics, such as pollutant loads, plant size and age, and type of WWTP. Membrane technologies tend to have a high energy consumption. The energy consumption for reverse osmosis plants (desalinated water) depends on the salinity of the feed water and the recovery rate.

The indirect energy is related to the operation performed but concern the acquisition and the ownership of the equipment the materials for dams, canals, pipes, pumps, and on-farm irrigation equipment. Indirect energy inputs can be determined from machine sizes, usage, and lifetimes. The energy embodied in the production of farm machinery is assumed to be depreciated over the economic life of the equipment (Eq. 26).

$$E_{ind}\left(\frac{\text{unit}}{\text{ha}}\right) = \text{Weight (unit)} \times \frac{\text{Operation (h/ha)}}{\text{Equipment life time (h)}} \quad (26)$$

Based on the quantified inputs and outputs, composite energy-related indicators can be calculated (Table 15). Indicators of specific energy and energy efficiency are integrative indicators of potential environmental impacts of crop production (Khan et al., 2009). Because irrigation networks are water and energy-hungry and that both resources are scarce, many strategies have been developed to reduce this consumption. On-site energy conservation in irrigation can be accomplished through the following steps (Fig. 14):

Table 15. Energy-based performance indicators for irrigation water supply and crop production.

Indicator name	Indicator formula	Unit	Domain
Specific energy	$\frac{\text{Energy consumed (kWh)}}{\text{Water supplied (m}^3\text{)}}$	kWh/m^3	Energy use
Specific energy	$\frac{\text{Energy consumed (kWh)}}{\text{Area irrigated (ha)}}$	kWh/ha	Energy use
Specific energy	$\frac{\text{Energy consumed (kWh)}}{\text{Yield (kg)}}$	kWh/kg	Energy use
Energy efficiency	$\frac{\text{Total energy output (kWh)}}{\text{Total energy input (kWh)}}$	-	Production efficiency
Energy productivity	$\frac{\text{Yield (kg/ha)}}{\text{Irrigation energy (kWh/ha)}}$	kg/kWh	Production efficiency
Water-energy productivity	$\frac{\text{Yield (kg)}}{\text{Water supplied (m}^3\text{)} \times \text{Irrigation energy (kWh)}}$	kg/kWh/m^3	Production efficiency
Water energy ratio	$\frac{\text{Energy input from water (kWh/ha)}}{\text{Total energy input (kWh/ha)}}$	%	Production efficiency
Water direct energy ratio	$\frac{\text{Irrigation direct energy (kWh/ha)}}{\text{Total energy input (kWh/ha)}}$	%	Production efficiency
Water indirect energy ratio	$\frac{\text{Indirect irrigation energy (kWh/ha)}}{\text{Total energy input (kWh/ha)}}$	%	Production efficiency

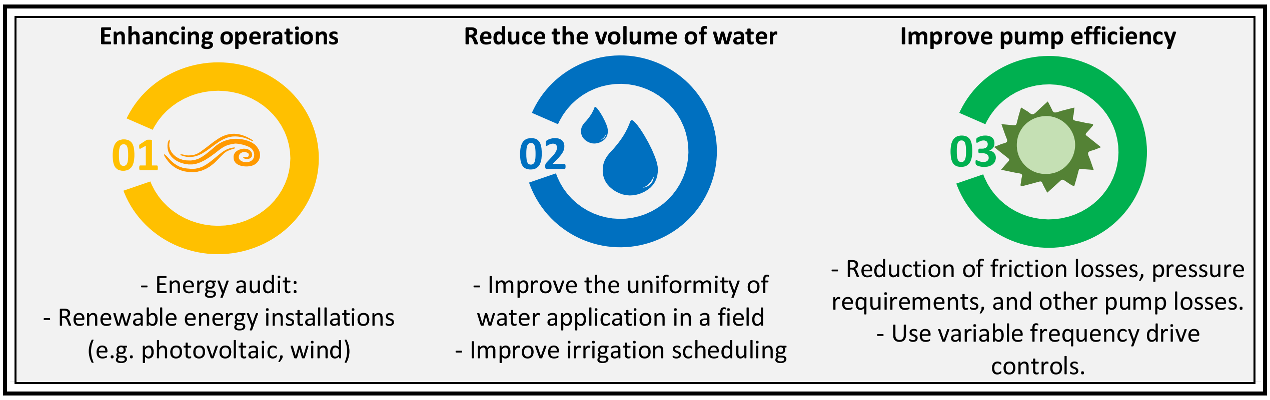


Fig. 14. Energy conservation steps in irrigation.

Along with water management, modern agriculture requires an energy input also at agricultural production such as direct use of energy in farm machinery, cultivation, and harvesting. One of the major energy inputs in arable farming is diesel fuel for field machinery associated with tillage operations where different methods and machinery are used. The life cycle inventory of fieldwork processes in crop production is closely linked to the crop and the production system. Specific volumetric fuel consumption for the given tractor power is 0.3 l/kW*h for gasoline and 0.223 l/kW*h for diesel tractors (Grisso et al., 2004). To be able to estimate diesel consumption for specific operations, it is necessary to know the duration of an operation, and the machines' effective power in kW, which usually has to be calibrated. In general, the specific fuel consumption of the tractor decreases as the load levels and the travel speeds increase (Farias et al., 2017). The indirect energy from the production of farm machinery and tractors can be expressed as the fractional weight of the equipment for a working unit of a specific process as given in Eq. 26.

Energy is also used for mineral fertilizers, chemical pesticides, fungicides, and herbicides in their production, distribution, and transport processes.

The energy demand of inputs in agricultural production is presented in Table 16. Energy consumption for different operations contributes towards the "total energy input" for agricultural production.

Table 16. Energy demand for inputs used in crop production.

Input	CED (MJ/unit)
Irrigation, (1 m^3 freshwater)	6.4
Electricity production, hard coal (kWh)	11
Electricity production, geothermal (kWh)	37
Electricity production, lignite (kWh)	13.2
Electricity production, oil (kWh)	12.6
Electricity production, peat (kWh)	14.7
Electricity production, hydro, run-of-river (kWh)	3.8
Electricity production, hydro, pumped storage (kWh)	16.2
Electricity production, nuclear (kWh)	12.6
Electricity production, natural gas (kWh)	8.63
Irrigation pump 40 Watt (unit)	119.2
High-Density Poly Ethylene (kg)	78.6
Polyvinyl chloride (kg)	82.5
Low-Density Poly Ethylene (kg)	81
Polypropylene (kg)	76.5
Reinforcing Steel (kg)	23.6
Aluminum (kg)	74
Concrete (m^3)	2476.2
Plastic film (kg)	11
Synthetic Rubber (kg)	94.2
N generic fertilizer (kg N)	80.4
N ammonium nitrate, 27.5% N (kg N)	64.6
N urea, 46% N (kg N)	64.2
N calcium nitrate, 11.86% N (kg N)	20.2
N urea-ammonium nitrate, 32% N (kg N)	70.7
N ammonium sulfate, 21% N (kg N)	30.7
N ammonia liquid, 82% N (kg N)	41.2
P generic fertilizer (kg P_2O_5)	39.1
P triple-superphosphate (kg P_2O_5)	38.3
P superphosphate (kg P_2O_5)	42.5
P di-ammonium phosphate (kg P_2O_5)	35.9
K potassium fertilizer (kg K_2O)	15.4
K potassium sulfate (kg K_2O)	25.8
K potassium nitrate (kg)	18.3
K potassium chloride (kg K_2O)	9.45
Diesel fuel (kg)	57.8
Lubricant oil (kg)	80.4
Petrol, unleaded (kg)	60.7
Tractor, 4-wheel (kg)	126.5
Harvester (kg)	88
Trailer (kg)	87
Agriculture machinery, unspecified (kg)	67.2
Agriculture machinery, tillage (kg)	75
Industrial machine, heavy, unspecified,	27.3
Pesticide, unspecified	205.7

5. Environmental impacts

Irrigation plays an essential role in crop cultivation and yield rates boost, and at the same time, it is one of the agricultural techniques with the highest environmental impact. Irrigation can affect the environment through:

- Direct impacts upon water sources – both their quality and quantity, affecting ground and surface waters.
- Direct impacts upon soils – both quality (e.g. through contamination) and quantity (through erosion).
- Direct impacts upon biodiversity and landscapes – by displacing former habitats and creating new ones, by degrading or maintaining existing habitats, and by affecting the diversity and composition of landscapes.
- Secondary impacts arising from the intensification of agricultural production permitted by irrigation, such as increased fertilizer use.

From a nexus perspective impacts from agricultural irrigation include water application (extraction, conveyance, distribution) and production and construction of irrigation facilities.

Recently, life cycle analysis (LCA) is used to provide a broad view of the environmental impacts of irrigation.

5.1 Basics of Life cycle assessment (LCA)

LCA is a comprehensive method for assessing all direct and indirect environmental impacts across the full life cycle of a product system using metrics like carbon footprint (CF), water footprint (WF), acidification potential (AP), eutrophication potential (EP), toxicity-related and other additional indicators. An LCA standardized by ISO 14040 and 14044 is divided into four phases: Goal and scope definition, inventory analysis, Life Cycle Impact Assessment (LCIA), and Interpretation (Fig. 15).

Fig. 15. The four steps of LCA methodology.

5.1.1 Goal and scope definition

In the goal definition, the intended application and purpose of an LCA study are defined. During the scope definition, the product or process system under study is characterized, all assumptions are detailed and the methodology used to set up the production system is defined. The LCA can be either stand-alone or comparative. A stand-alone example is to identify the environmental impacts of crop cultivation with drip irrigation in Italy. A comparative LCA is to compare the environmental impacts of crop cultivation with surface and drip irrigation.

System boundaries determine the limits of the studied system, always in concordance with the proposed goal and scope. If the goal of the study is only irrigation (for the example case of a water user association) the boundaries start with pumping water from wells and water bodies and end with delivering water to the plant. It includes the water pumping, energy use, infrastructure, but not the on-farm water consumption and water emissions of irrigation (Fig. 16). In this case, the functional unit can be 1 m^3 irrigation water distributed to the point-of-use or 1 year of operation of the irrigation scheme. When the water supplied to the plants ($1m^3$) and the water evaporated or infiltrated are include they shall be included in the crop production datasets (Fig. 17). Full-fledged crop-based LCA results are reported on mass (1 kg) to analyze the efficiency of a production system for a particular crop or area (1 ha) to analyze production intensity.

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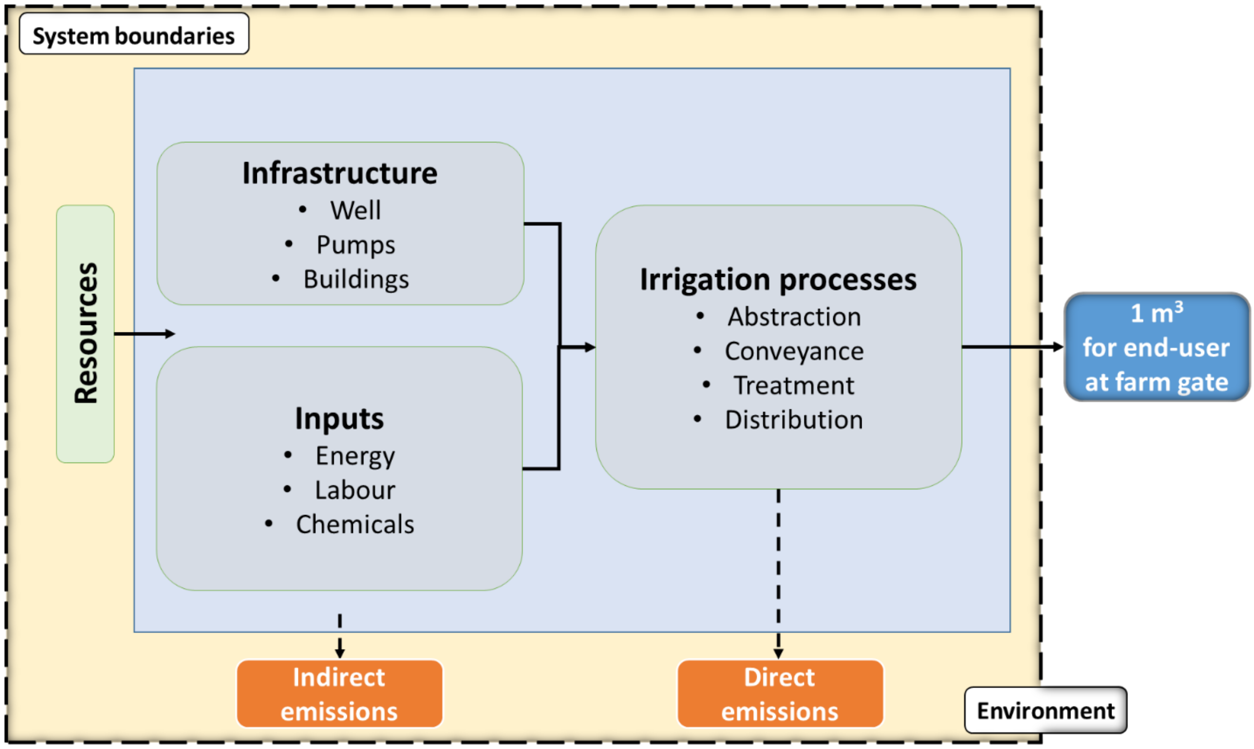

Fig. 16. Representation of the system boundaries for LCA of irrigation water supply.

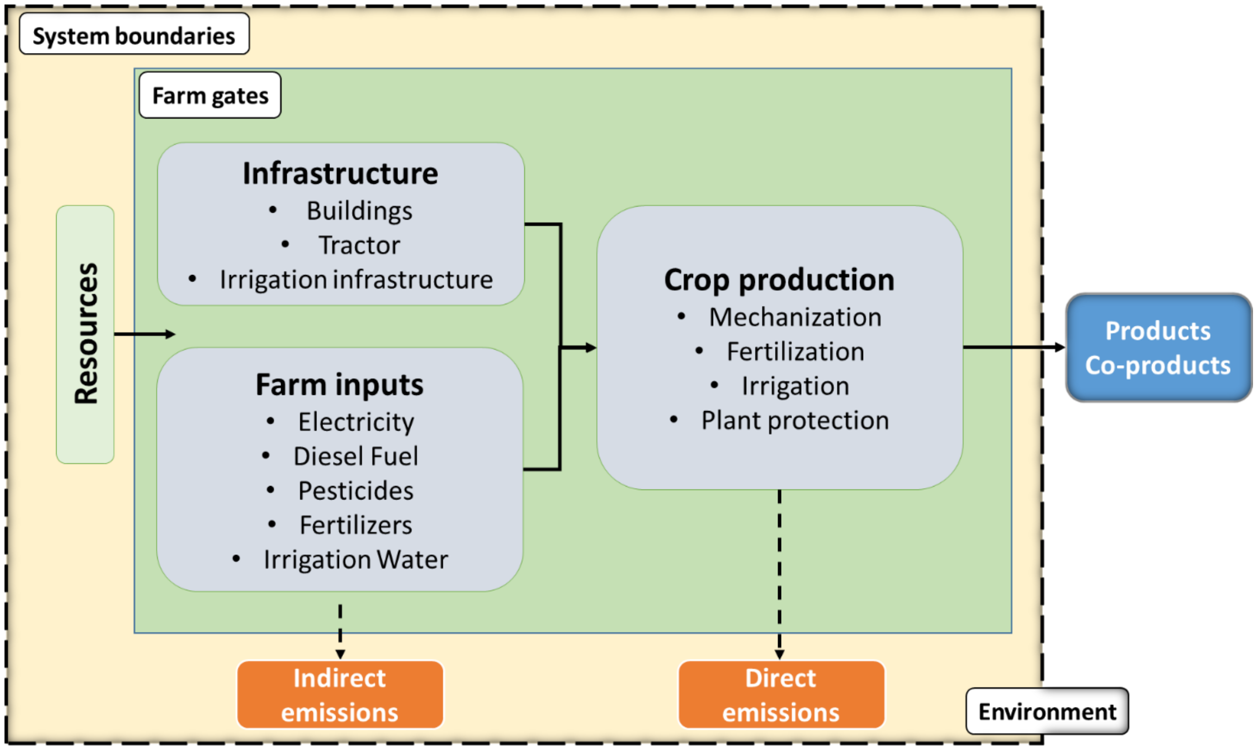

Fig. 17. Representation of the system boundaries for LCA of crop production.

5.1.2 Life cycle inventory (LCI)

The 'life cycle inventory' is the result of the second step of an LCA. This phase is a data collecting activity to input-output analysis (Table 19) for all the processes and elements within the system boundary. It may include raw material input, electricity, fuel, and water embedded within the agricultural water use system.

Table 17. Input to be collected for LCA of irrigation and crop production.

Input category	Input
LCA of irrigation water supply	
Irrigation	• Country • Electricity mix • Total water (m^3) delivered for irrigation; • Total diesel or electricity used for pumping (MJ); • Total items used for irrigation infrastructure and their list of materials
LCA of crop production	
Irrigation	• Region or Watershed to which it belongs • Irrigation water consumption (m^3) and their type; • Total diesel or electricity used for pumping and application (MJ); • Electricity mix • Irrigation method applied
Fertilization	• Amount per nutrient N, P, and K, or N-fertilizer type, P-fertilizer type, K-fertilizer type
Mechanization	• Total hours per work Process, • Fuel consumption per work process
Plant protection	• Amount of input per pesticide group: herbicide, insecticide, fungicide. • Alternatively the total amount
Seeds	• Quantity of seeds

To develop the inventory, a model of the system is usually constructed using data on inputs and outputs of each process. The emissions are classified as direct and indirect. Direct field and farm emissions are substances emitted from an agricultural area or directly at the Farm (Fig. 17). Indirect emissions denote emissions that occur in the upstream processes, from the manufacturing of farm inputs used in agriculture or transports. The main direct field and farm emissions emitted from an agricultural area are listed in Table 20.

Table 18. Main direct emissions from crop production.

Input category	Input
Emission to air	• Water from irrigation (evapotranspired) • NH_3-based fertilizer • N_2O-based fertilizer • NO_x-based fertilizer • CO_2-urea based fertilizer • Fuel combustion emissions (CO_2, NH_3, N_2O, NO_x, CH_4, etc). • Pesticides (if any applied)
Emission to water	• Phosphorus, surface water (P from erosion) • Phosphate, surface water (PO_4^{3-} from run-off) • Heavy metals: Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni), and Zinc (Zn); • Water from irrigation
Mechanization	• Fuel combustion emissions (CO_2, NH_3, N_2O, NO_x, CH_4, etc).
Plant protection	• Field emissions

5.1.3 Life cycle impact assessment (LCIA)

Life cycle impact assessment (LCIA) quantifies the overall impact of resource consumption and environmental emissions at different stages of a product life cycle using impact assessment method/s. In practice, this step is usually carried out with LCA software, and the practitioner only chooses the method and some other details. The LCIA phase (Fig. 18) comprises two mandatory steps (classification and characterization) and two optional steps (normalization and weighting).

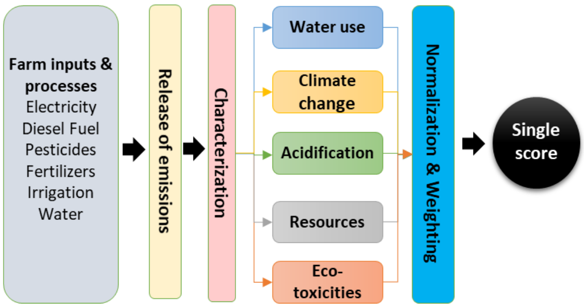

Fig. 18. LCIA Steps for environmental impact in one single score.

Classification is a qualitative step based on scientific analysis of relevant environmental mechanisms. For example, CO_2, CH_4, and N_2O are grouped into global warming, whereas NO_x and SO_x are grouped into acidification. Certain outputs (e.g. emissions) contribute to various impact categories. Characterizing impacts involves assessing the environmental impacts of impact categories due to the flows identified in the product system. A distinction must be made between the midpoint (problem-oriented) and endpoint end-point (damage-oriented). The former translates impacts on environmental themes such as water consumption, climate change, acidification, human toxicity, etc., while the latter translates environmental impacts into issues of concern such as human health, natural environment, and natural resources (Huijbregts et al., 2017). Thus, the potential impacts are estimated at the mid- or endpoint levels through characterization factors. The indicator result received at the midpoint level is calculated as follows:

$$I_m = \sum_i Q_{m,i} \times m_i \qquad (27)$$

Where: I_m - Indicator result for midpoint impact category m; $Q_{m,i}$ - Characterization factor between intervention i and the midpoint impact category m; m_i - Magnitude of intervention i unit of environmental pressure for intervention (i.e. the mass of substance emitted or resource consumed). The indicator result received at the endpoint level can be extracted in two ways. One is to calculate the indicator result at the endpoint level based on the indicator result at the midpoint level:

$$I_e = \sum_i Q_{e,i} \times m_i \qquad (28)$$

Where: I_e - Indicator result for endpoint impact category m; $Q_{e,i}$ - Characterization factor between intervention i and the endpoint impact category m; m_i - Magnitude of intervention i unit of environmental pressure for intervention (i.e. the mass of substance emitted or resource consumed). The other way is through bypassing the midpoints and calculate the indicator result based on the intervention:

$$I_e = \sum_i Q_{e,m} \times I_m \qquad (29)$$

Where: I_e - Indicator result for endpoint impact category m; $Q_{e,m}$ - Characterization factor between intervention i and the endpoint impact category m; I_m - Indicator result for midpoint impact category m;

Usually, the interpretation of the endpoint results does not require a thorough knowledge of the environmental effects (easy decisions can be made), however, the statistical uncertainties are higher. On the other hand, midpoint results may be more difficult to interpret because they consider a large number of impacts, but provide robust results (Caffrey and Veal, 2013). For communication purposes, the category indicators may be normalized concerning reference values. The normalization of the respective mid- and endpoint category adjusts the indicator result to the result of the region of interest (for example, the world), and it varies depending on ideological perspective.

Weighting is a procedure that can be quantitative or qualitative and applies weights (weighting factors) to each impact category following the relevance attributed by, for instance, decision-makers or specialists. The weighting of the endpoint impact categories also varies depending on the ideological perspective.

There are many impact assessment methods like TRACI, commonly used in the United States;

Ecoindicator, ReCiPe, and ILCD, employed in Europe; and the CML method. These LCIA methods operate with midpoint and endpoint indicators or both. These footprint calculation methods provide different levels of detail (Leach et al., 2016). The CML methodology, developed by the Institute of Environmental Sciences of the University of Leiden in the Netherlands, is the most used and is often considered the most complete.

LCAs are used by a variety of users for a range of purposes such as marketing, product development, product improvement, strategic planning. Carbon footprint (CF), water footprint (WF), and life cycle assessment (LCA) are popular formalized methods for calculating and communicating the sustainability criteria behind the product footprint (EC, 2010).

5.1.4 Water footprint (WF)

Water Footprint (WF) is an important metric to assess potential impacts associated with water all along the life cycle. It can be applied as a stand-alone assessment or as part of an LCA. The WF is recognized as an important sustainability indicator for the agri-food sector guiding policy towards sustainable use of freshwater (Aivazidou et al., 2015). The concept allows calculating the total volume of freshwater that is used directly (operational) or indirectly (supply chain =) to produce the product or service (Hoekstra et al., 2011). Direct water refers to the water (i.e. irrigation water) that is consumed on-farm to produce agricultural products/s. Indirect water consumption relates to water consumed by the supply chain (or background processes or water embedded in energy, pump, fertilizers, or other farm inputs). WF can be conducted for a single product (crop), several products (whole cropping pattern) within a geographically delineated region. The WF can be measured m^3/ton, m^3/ha, m^3/€, and in other functional units.

Concerning the use of water, WF includes quantity (consumption or consumptive use) and quality of the resource (degradative use) footprint.

"Consumptive use" describes all freshwater losses on the watershed level which are caused by evaporation, evapotranspiration from plants, freshwater integration into products, and release of freshwater from the technosphere into seawater (e.g. from wastewater treatment plants located on the coastline). "Degradative use", in contrast, denotes the use of water with associated quality alterations and describes the pollution of water (e.g. if tap water is transformed to wastewater during use). The WF assessment methods are proposed by two different communities (Fig. 19), the Water Footprint Network (WFN), and the Life Cycle Assessment (LCA) community (Pfister et al., 2017). The WFN approach is based on indicators at the inventory level; an LCA-based water footprint is based on indicators at the impact assessment level. The WFA methodology addresses freshwater resources appropriation in a four-step approach including setting goals and scope, water footprint accounting, sustainability assessment, and response formulation (Figure 6). Similar to life cycle assessment (LCA), the water footprint assessment consists of four phases namely: setting goals and scope (Phase 1); water footprint accounting (Phase 2); water footprint sustainability assessment (Phase 3); water footprint response formulation (Phase 4).

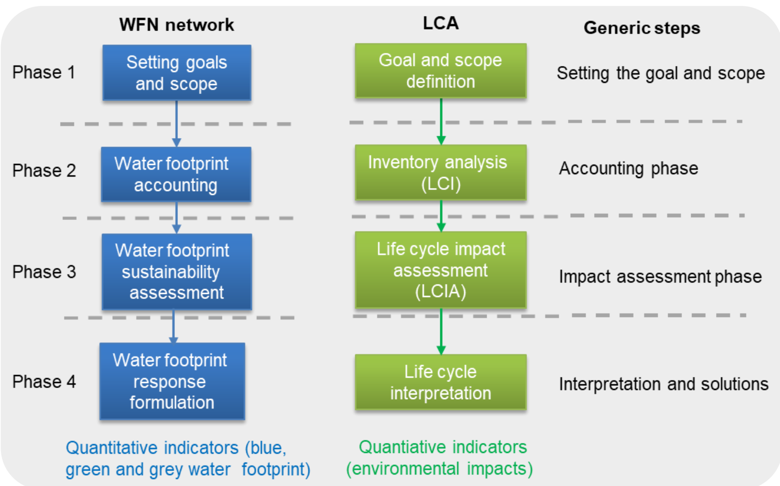

Fig. 19. Phases of LCA and WFA assessment.

Water footprint accounting (WF) – The Hoekstra et.al., 2011 approach

$\mathbf{WF_{crop}}$	=	$\mathbf{WF_{crop,blue}}$	+	$\mathbf{WF_{crop,green}}$	+	$\mathbf{WF_{crop,grey}}$
Definition		The blue WF is an indicator of the consumptive use of so-called blue water, in other words, fresh surface or groundwater.		The green WF is the volume of rainwater consumed during the production process.		The grey WF of a process step is an indicator of the degree of freshwater pollution.

The total water footprint of the process of growing crops (WF_{crop}) is the sum of the green, blue, and grey components. The green component in the process water footprint of growing a crop or tree (WF_{crop}, green, m^3/ton) is calculated as the green component in crop water use (CWU_{green}, m^3/ha) divided by the crop yield (Y, ton/ha). The blue component (WF_{crop}, blue, m^3/ton) is calculated similarly.

$$WF_{crop} = WF_{crop,green} + WF_{crop,blue} + WF_{crop,grey} \text{ [Volume/mass]} \quad (30)$$

The green and blue components in crop water use (CWU, m^3/ha) are calculated by the accumulation of daily evapotranspiration (ET, mm/day) over the complete growing period. Factor 10 is meant to convert water depths in millimeters into water volumes per land surface in m^3/ha.

$$\mathrm{WF_{crop,green}} = \frac{10 \times \sum_{d=1}^{lgp} \mathrm{ET_{green}}}{\mathrm{Y}} \quad (31)$$

$$\mathrm{WF_{crop,blue}} = \frac{10 \times \sum_{d=1}^{lgp} \mathrm{ET_{blue}}}{\mathrm{Y}} \quad (32)$$

Where: CWU_{green} - green component in crop water use (m^3/ha), CWU_{blue} - blue component in crop water use (m^3/ha), Y - Crop yield (Y, ton/ha).

Green and blue water evapotranspiration during crop growth can be estimated with the CROPWAT model (Smith, 1992). Green water evapotranspiration (ET_{green}), in other words, evapotranspiration of rainfall, can be equated with the minimum of total crop evapotranspiration (ET_c) and effective rainfall (P_{eff}). Bluewater evapotranspiration (ET_{blue}), in other words, field-evapotranspiration of irrigation water, is equal to the total crop evapotranspiration minus effective rainfall (P_{eff}), but zero when effective rainfall exceeds crop evapotranspiration:

$$\mathrm{ET_{green}} = \min\ (\mathrm{ET_c}, \mathrm{P_{eff}}) \qquad \text{[length/time]} \quad (33)$$

$$\mathrm{ET_{blue}} = \max\ (0, \mathrm{ET_c} - \mathrm{P_{eff}}) \qquad \text{[length/time]} \quad (34)$$

In the case of rain-fed crop production, blue CWU is zero and green CWU (m^3/ha) was calculated by aggregating the daily values of actual crop evapotranspiration over the length of the growing period. In the case of irrigated crop production, the green water use was assumed to be equal to the actual crop evapotranspiration for the case without irrigation. The grey component in the water footprint of growing a crop or tree (WF_{crop}, grey, m^3/ton) is calculated as the chemical application rate to the field per hectare (AR, kg/ha) times the leaching-run-off fraction (α) divided by the maximum acceptable concentration (c_{max}, kg/m^3) minus the natural concentration for the pollutant considered (c_{nat}, kg/m^3) and then divided by the crop yield (Y, ton/ha). The pollutants generally consist of fertilizers (nitrogen, phosphorus, and so on), pesticides, and insecticides.

$$\mathbf{WF_{crop,grey}} = \frac{\frac{(\alpha \times AR)}{(c_{max} - c_{net})}}{Y} \quad (35)$$

Example 3. Application of the EXCEL-IRR model for WF assessment.

This section provides an example of how to estimate the green, blue, and gray water footprint applied to the cultivation process of one hectare of irrigated Tomatoesin Capitanata, Southern Italy. Green-blue water evapotranspiration (Table 19) was estimated using the Excel-IRR model (Todorovic, 2006) using climatic and crop data. The total evapotranspiration of the green water is obtained by adding ET_{green} to the growth period. The evapotranspiration of blue water (ET_{blue}) is estimated as the difference between the total evapotranspiration of the crop (ET_c) and the actual total rainfall (P_{eff}). When the actual rainfall is greater than the total crop evapotranspiration, ET_{blue} is equal to zero.

Table 19. Calculation of the green and blue components of the process water footprint for tomato in Capitanata, Southern Italy.

Month	ETo	ETc	P_{eff}	NIR	GIR	CWU green	CWU blue
	mm/day	mm/dec	(mm/ha)	(mm/ha)	(mm/ha)	(mm/ha)	(mm/ha)
April [mm]	77	46	55	14	16	46	0
May [mm]	117	97	12	77	90	12	77
June [mm]	139	158	60	133	156	60	133
July[mm]	145	165	24	135	159	24	135
August [mm]	111	99	25	65	76	25	65
Seasonal [mm]	590	565	176	423.2	497.8	167	410

Table 20 and Fig. 16 detail the water footprint values of tomatoes for an average yield of 60 tons/ha. The total water footprint of the cultivation process (total WF) is the sum of the green, blue and gray components in the volume of water by mass The total WF was calculated 121 m^3/ton. Of this total, the green WF 23% or 27.8 m^3/ton is rainwater evaporated from the tomato field during the growing period. About 56% or 68.3 m^3/ton is irrigation water consumed (evaporated) by the tomato plant. The grey WF for a nitrogen application rate of 150 kg/ha and a leaching rate of 15% was calculated at 25 m^3/ton. This is 21 % of the total water footprint.

Table 20. Water footprint indicators of tomato production using the Hoekstra 2011 approach.

Components	Unit	WF_{total}
Crop Yield	ton/ha	60
WF_{green}	m^3/ton	27.8
WF_{blue}	m^3/ton	68.3
WF_{grey} (Eq. 34)	m^3/ton	25
WF_{green} + WF_{blue} + WF_{grey}	m^3/ton	121.4

The analysis of water scarcity in a monthly phase provides information on the scarcity that is not revealed in the annual studies, in particular the fact that the scarcity occurs in some periods of the year and not in others.

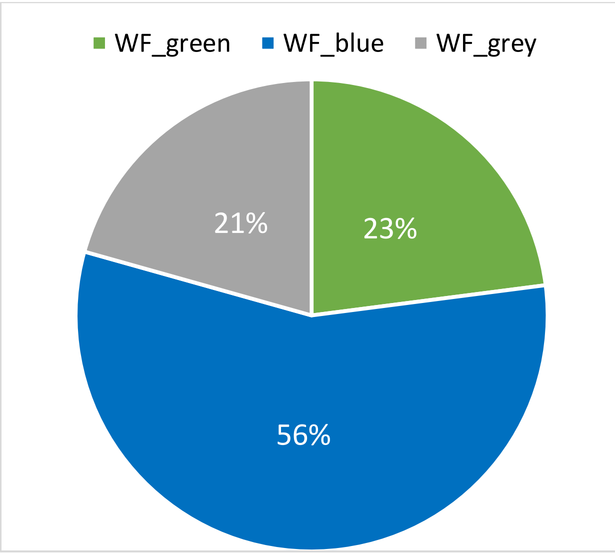

Fig. 20. Share of green, blue, and grey water footprint indicators of tomato production using the Hoekstra 2011 approach.

5.1.4.1 Water scarcity footprint (WSF) – The AWARE method

The AWARE method is to be used as a water use midpoint indicator for calculating water scarcity impact. It assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived (Boulay et al., 2018). The AWARE method is recommended by the UNEP-SETAC Life Cycle Initiative, the PEF/OEF Program of the European Commission, and the International EPD system to assess water consumption impact assessment in LCA. The method is based on the quantification of the relative Available WAter REmaining per area once the demand of humans and aquatic ecosystems has been met. It is first calculated as the water Availability Minus the Demand (AMD) of humans and aquatic ecosystems and is relative to the area (m^3 m^{-2} $month^{-1}$). The AMD (availability minus demand, Eq. 36) represents the relative available water remaining per area in a watershed (i.e., determining the water availability minus the demand of humans and environmental water requirements (EWR)). The sum of human water consumption (HWC) and environmental water requirement (EWR) is referred to as demand.

$$\mathrm{AMD}_{\mathrm{i,j}} = \frac{\mathrm{A}_{\mathrm{i,j}} - (\mathrm{HWC}_{\mathrm{i,j}} + \mathrm{EWR}_{\mathrm{i,j}})}{\mathrm{Area}_{\mathrm{j}}} \quad (36)$$

Where: $A_{i,j}$ is the water availability in the ith month in region j (m^3/month); $HWC_{i,j}$ is the human water consumption (m^3/month); $EWR_{i,j}$ is the environmental water requirement (m^3/month); $Area_j$ is the jth area (m^2). In a second step, the AWARE indicator is scaled by the world weighted-average result for the water AMDs (0.0136 m^3 $m^{-2}month^{-1}$), expressed in m region/m^3 word−equivalent and representing whether a region has more or less remaining water in comparison to the world average region where water is consumed.

$$\mathrm{CF}_{AWARE_{\mathrm{i,j}}} = \frac{1/\mathrm{AMD}_{\mathrm{i,j}}}{1/\mathrm{AMD}_{\mathrm{world.avg}}} = \frac{\mathrm{AMD}_{\mathrm{i,j}}}{\mathrm{AMD}_{\mathrm{world.avg}}} \quad (37)$$

The $CF_{i,j}$ is a dimensionless AWARE characterization factor, expressed as m^3 world-eq/$m^3_{i,j.}$ The Aware indicator is limited to a range from 0.1 to 100, with a value of 1 corresponding to the world average, and a value of 10, for example, representing a region where there is 10 times less available water remaining per area than the world average. The AWARE CFs close to 100 means that has no or very little remaining freshwater in an area and consequently this area is facing water scarcity (Kaewmai et al. 2019).

$$\mathrm{CF}_{AWARE_{\mathrm{i,j}}} = Max = 100, for\ AMD_i < 0.01 \times AMD_{world\ avg} \quad (38)$$

$$\mathbf{CF}_{\boldsymbol{AWARE}_{\mathbf{i,j}}} = Min = 0.1, for\ AMD_i > 10 \times AMD_{world\ average} \quad (39)$$

The local AWARE characterization factor is meant to be multiplied with the local water consumption inventory for Water scarcity characterization: WSF_{AWaRe} (Eq. 40). The water scarcity footprint (WSF) is the metric that quantifies the potential environmental impacts related to water scarcity (based on ISO 14046:2014).

$$\mathrm{WSF}_{\mathrm{AWARE}} = \mathrm{WC}_{\mathrm{i,j}} \times \mathrm{CF}_{\mathrm{AWARE}_{\mathrm{i,j}}} \quad (40)$$

The AWARE characterization factors for water scarcity footprint in m^3 world eq./m^3 consumed in country-level values (annual and monthly, excel format) and (Sub) Watershed level (annual and monthly, google earth) are available at http://www.wulca-waterlca.org/aware.html. The WSF_{AWARE} for inputs in agriculture is presented in Table 21.

Table 21. Water scarcity footprint for inputs used in crop production.

Input	WSF (m^3/unit)
Irrigation, (1 m^3 freshwater, avg Europe)	43.4
Electricity production, hard coal (kWh)	0.08
Electricity production, geothermal (kWh)	0.56
Electricity production, lignite (kWh)	0.12
Electricity production, oil (kWh)	0.10
Electricity production, peat (kWh)	0.15
Electricity production, hydro, run-of-river (kWh)	0.0023
Electricity production, hydro, pumped storage (kWh)	0.37
Electricity production, nuclear (kWh)	0.13
Electricity production, natural gas (kWh)	0.035
Irrigation pump 40 Watt (unit)	4.41
High-Density Poly Ethylene (kg)	0.52
Polyvinyl chloride (kg)	2.45
Low-Density Poly Ethylene (kg)	0.77
Polypropylene (kg)	0.68
Reinforcing Steel (kg)	0.00
Aluminum (kg)	2.47
Concrete (m^3)	157.60
Plastic film (kg)	0.90
Synthetic Rubber (kg)	1.80
N generic fertilizer (kg N)	5.50
N ammonium nitrate, 27.5% N (kg N)	3.40
N urea, 46% N (kg N)	7.96
N calcium nitrate, 11.86% N (kg N)	1.13
N urea-ammonium nitrate, 32% N (kg N)	3.42
N ammonium sulfate, 21% N (kg N)	0.23
N ammonia liquid, 82% N (kg N)	2.47
P generic fertilizer (kg P_2O_5)	2.76
P triple-superphosphate (kg P_2O_5)	4.51
P superphosphate (kg P_2O_5)	2.34
P di-ammonium phosphate (kg P_2O_5)	0.00
K potassium fertilizer (kg K_2O)	2.18
K potassium sulfate (kg K_2O)	1.56
K potassium nitrate (kg)	0.73
K potassium chloride (kg K_2O)	0.43
Diesel fuel (kg)	27.54
Lubricant oil (kg)	0.46
Petrol, unleaded (kg)	0.29
Tractor, 4-wheel (kg)	2.71
Harvester (kg)	2.40
Trailer (kg)	2.49
Agriculture machinery, unspecified (kg)	2.03
Agriculture machinery, tillage (kg)	2.21
Industrial machine, heavy, unspecified,	1.84
Pesticide, unspecified	3.59

5.1.5 Carbon footprint (CF)

The carbon footprint is the total amount of GHG emitted throughout it's the life cycle of a product or service, expressed in kilograms of CO_2-equivalents. A carbon footprint is often interchanged with global warming potential (GWP). However other different terms have been suggested and/or used, such as climate footprint, CO2 footprint, GHG footprint, and methane footprint (Čuček et al., 2012). The emissions from any purchased agricultural goods can be estimated as shown in Eq. 41.

$$\mathrm{GWP}\left[\mathrm{kgCO}_{2-\mathrm{eq}}\right] = \mathrm{AD} \times \mathrm{EF} \tag{41}$$

Where: AD = activity data on inputs consumed or produced by a process (unit); EF = Emission factor that converts activity data into greenhouse gas emissions data (e.g. kg CO_2-eq emitted per kWh of electricity used).

When direct emissions data has been collected, an emission factor is not needed and the basic equation to calculate inventory results for input, output, or process is:

$$\mathrm{GWP}\left[\mathrm{kgCO}_{2-\mathrm{eq}}\right] = \mathrm{AD}_{GHG} \times \mathrm{GWP}_{GHG} \tag{42}$$

Where: AD = activity data on greenhouse gas i such as carbon dioxide, methane, or nitrous oxide released by a process (unit); GWP = a factor describing the radiative forcing impact (degree of harm to the atmosphere) of one unit of a given GHG, relative to one unit of CO_2 over a 100-year time horizon.

The "carbon footprint" calculation is based on LCA principles with a 100 years time horizon. The main agricultural GHG is carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Fossil fuel use is the primary source of CO_2 while fertilizer use is the primary source of N_2O emissions. Enteric fermentation of feed in the stomachs of livestock (particularly cattle) is the largest single source of CH4. Nitrous Oxide (N_2O) has a GWP 265 - 298 times that of CO_2 for a 100-year timescale. Methane (CH_4) is estimated to have a GWP of 28 -

36 over 100 years. Precipitation and soil N fertilization are factors that drive emissions GHG emissions where nitrogen fertilization and water additions have been reported to increase N_2O emissions (Kostyanovsky et al., 2019). Soil N_2O are classified as direct (Eq. 43) and indirect emissions (Eq.44 and Eq. 45).

$$\mathrm{GWP}_{\mathrm{N2O-N,d}} = \mathrm{F}_{SN} \times \mathrm{EF}_1 \times \mathrm{GWP}_{N2O} \quad (43)$$

Where: $\mathrm{GWP}_{\mathrm{N2O-d}}$ - Global warming from direct N_2O emission as a result of nitrogen application within the project boundary; F_{SN} - Total amount of nitrogen applied from synthetic fertilizer; EF_1 - Emission Factor for emissions from N inputs,

Indirect N_2O emissions from atmospheric deposition (Eq. 44) and agricultural N leaching and runoff (Eq.45).

$$\mathrm{GWP}_{\mathrm{N2O-N,ATD}} = \mathrm{F}_{SN} \times \mathrm{F}_{\mathrm{GASF}} \times \mathrm{EF}_4 \times \mathrm{GWP}_{N2O} \quad (44)$$

$$\mathrm{GWP}_{\mathrm{N2O-N,L}} = \mathrm{F}_{SN} \times \mathrm{F}_{\mathrm{Leach}} \times \mathrm{EF}_5 \times \mathrm{GWP}_{N2O} \quad (45)$$

Where: GWP- Global warming from indirect N2O emission associated atmospheric deposition from NH_3 volatilization; FGASF - partitioning factor for the fraction of synthetic fertilizer N applied to soils that volatilize as NH_3 and NOx; EF4 - Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O–N/ kgNH_3-N/kg N. $\mathrm{GWP}_{\mathrm{N2O-L}}$ - Global warming from indirect N_2O emission associated with fertilizer leaching and run-off; Fleach - partitioning factor for the fraction of fertilizer and manure N applied to soils that are lost through leaching and runoff. EF5 - Fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N/kg N additions.

Conversion of N_2O–N emissions to N_2O emissions for reporting purposes is performed by multiplying by 1.571429 (44/28).

Emissions from soils and livestock are usually calculated using equations and default factors from

Table 22. The carbon footprint for inputs used in crop production.

Input	CF ($kgCO_2$-eq/unit)
Irrigation, (1 m^3 freshwater)	0.35
Electricity production, hard coal (kWh)	1.15
Electricity production, geothermal (kWh)	0.065
Electricity production, lignite (kWh)	1.32
Electricity production, oil (kWh)	0.93
Electricity production, peat (kWh)	1.49
Electricity production, hydro, run-of-river (kWh)	0.005
Electricity production, hydro, pumped storage (kWh)	1.14
Electricity production, nuclear (kWh)	0.015
Electricity production, natural gas (kWh)	0.489
Irrigation pump 40 Watt (unit)	8.7
High-Density Poly Ethylene (kg)	2.1
Polyvinyl chloride (kg)	5.14
Low-Density Poly Ethylene (kg)	2.26
Polypropylene (kg)	2.12
Reinforcing Steel (kg)	0.000
Aluminum (kg)	4.66
Concrete (m^3)	399.9
Plastic film (kg)	0.59
Synthetic Rubber (kg)	3.10
N generic fertilizer (kg N)	10.86
N ammonium nitrate, 27.5% N (kg N)	8.55
N urea, 46% N (kg N)	3.5
N calcium nitrate, 11.86% N (kg N)	3.2
N urea-ammonium nitrate, 32% N (kg N)	6.5
N ammonium sulfate, 21% N (kg N)	2.04
N ammonia liquid, 82% N (kg N)	2.09
P generic fertilizer (kg P_2O_5)	2.10
P triple-superphosphate (kg P_2O_5)	1.73
P superphosphate (kg P_2O_5)	1.85
P di-ammonium phosphate (kg P_2O_5)	-
K potassium fertilizer (kg K_2O)	0.75
K potassium sulfate (kg K_2O)	1.49
K potassium nitrate (kg)	2.45
K potassium chloride (kg K_2O)	0.55
Diesel fuel (kg)	0.60
Lubricant oil (kg)	1.20
Petrol, unleaded (kg)	0.83
Tractor, 4-wheel (kg)	8.59
Harvester (kg)	6.94
Trailer (kg)	7.39
Agriculture machinery, unspecified (kg)	5.92
Agriculture machinery, tillage (kg)	6.76
Industrial machine, heavy, unspecified,	2.45
Pesticide, unspecified	11.18

IPCC publications (Table 23). The direct N_2O emissions are estimated using a default factor of 1% from IPCC (2006). This means 1% of the N input is lost to the atmosphere as N_2O-N. The uncertainty range for this emission factor is 0.3%-3%. The results converted from kg N_2O-N to kg N_2O by multiplying by the ratio of N_2O/N_2O-N (44/28).

Table 23. Low, average, and high emission factors used for estimating N_2O emissions from N fertilizer and lime using IPCC guidelines.

Category	Symbol	Low	Avg.	High
Direct N_2O emission (kg N_2O-N/kg N added)	EF_1	0.03 %	1%	3%
%N fertilizer that volatilizes (kg NH_3-N + NO_x-N)/ kg N applied	F_{GASM}	3%	10%	30%
EF for volatilized N (kg N_2O-N/ (kg NH_3-N + NO_x-N volatized)	EF_4	0.2%	1%	5%
% of N fertilizer that leach	F_{LEACH}	10%	30%	80%
EF for leached N (kg N leaching or runoff / kg N applied)	EF_5	0.05 %	0.75 %	2.5%

EXAMPLE. Calculations footprint from synthetic fertilizers

To grow the potato crop in 1 ha the farmer uses 250 ammonium nitrate with 27.5% nitrogen content. The estimated total amount of nitrogen applied (F_{SN}) is therefore 68.75 kg N. The direct N_2O emission from Eq. 43 is calculated at 1.08 kg N_2O/ha. The indirect N_2O emission from atmospheric deposition (Eq. 44) becomes 0.11 kg N_2O/ha while from agricultural N leaching and runoff (Eq. 45) becomes 0.24 kg N_2O/ha. Considering the CF of N_2O = 265 kgCO_2-eq/kg N_2O the total carbon footprint from soil N_2O emission is 379 kgCO_2-eq/ha.

Example 4. Calculation of CF and WSF of a crop and all processes.

The objective of this example is to analyze the CFand WSF of tomato production in an Italian open field from a cradle to the farm-gate perspective (Fig. 17). The reference unit of analysis is 1 ha and 1 kg of fresh tomatoes. The inventory (Table 24) includes the processes of growing tomatoes on arable land. The NIR of Tomato is 4500 m^3/ha. Tomato is grown under drip irrigation systems (90% efficiency) supplied by an electricity-powered pump with a capacity at 3.5 bars pressure output (total pressure head) and overall pump efficiency of 63%. Field N_2O emissions were estimated using Eq. 43, 44, and 45.

Table 24. Input/output for tomato cultivation.

Tomato Crop	Input
Yield (ton/ha)	100
GIR (mm/ha)	500
Energy irrigation (kWh)	1046.83
N (kg/ha)	150
P_2O_5 (kg/ha)	100
K_2O (kg/ha)	150
Pesticides (kg/ha)	5
Fuel (kg)	50.00
Tractor (kg/ha)	5.00
Direct (N_2O), nitrification	2.36
N_2O, leaching	0.53
N_2O, volatilization	0.24

The GWP resulting from tomato cultivation is estimated to be 3511 kg CO_2-eq/ha or 35.11 kg CO_2-eq/ton. About 80% of total GWP is produced from fertilizers, 13% from irrigation, 5% from mechanization, and 2% from pesticides (Fig. 21).

Table 25. GWP and WSF for 1 ha of tomato cultivation.

Process	Global warming (GWP100a)	WSF (AWARE)
Irrigation	469.65	18,792
Fertilization	2815.53	1256,95
Mechanization	170.3	25,51
Pesticides	55.89	17,96

Production of nitrogen fertilizer produced 46% of impacts while the N_2O emissions due to nitrogen fertilization produced 24% of total GWP. About 74% correspond to the background sub-system and the rest to the foreground (Fig. 21).

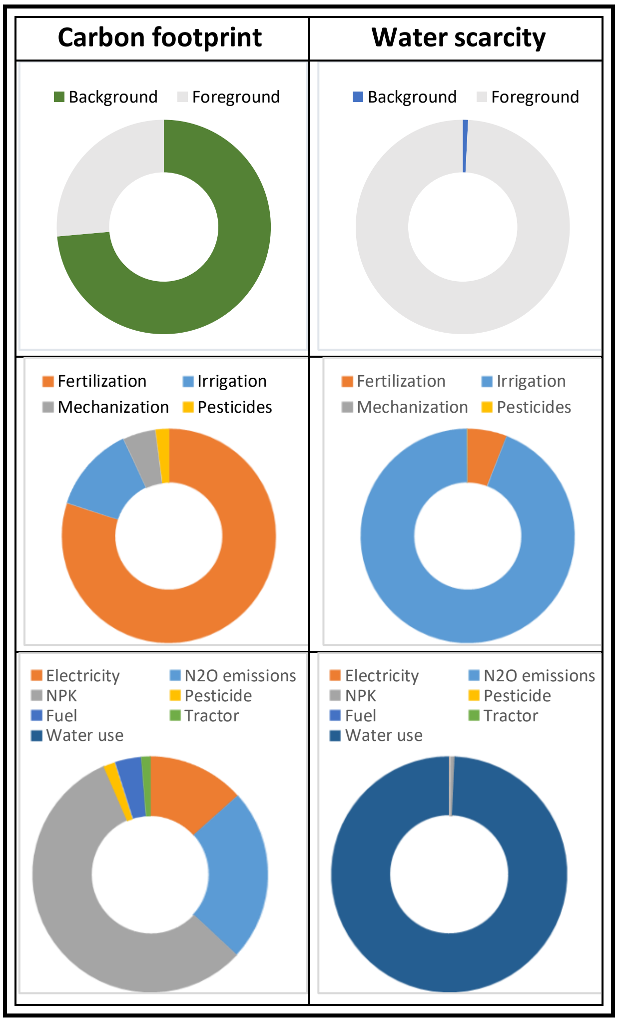

Fig. 21. GWP and WSF analysis of tomato cultivation at subsystem and process levels.

The total calculated WSF was 20,091 m^3 world-eq/ha or 200 m^3 world-eq/ ton. About 93.5% was related to irrigation WSF and the rest to the production of fertilizers, pesticides, fuel, and tractors. About 92.8% correspond to the foreground system due to irrigation water use while the rest to the background (Fig. 21). It should be noted that the scarcity has wide regional disparities. The *annual AWARE Agri* factor (Boulay and Lenoir 2020) for Italian Northern regions is significantly lower (e.g. 2.89 m^3 world eq./m^3 for Lombardy or 2.91 m^3 world eq./m^3 for Piemonte) while for south like Sicily and Apulia is the highest (92.1 and 90.89 m^3 world eq/ m^3 consumed, respectively).

6. Eco-efficiency of irrigated cropping systems

Eco-efficiency is a management strategy of doing more with less (Glavič et al., 2012). The benefits of eco-efficiency research are significant and show that its application will lead to efficient resource utilization while minimizing environmental impact (John et al., 2020).

Eco-efficiency is recognized as a sustainability measure combining environmental and economic performances (Saling, 2016). Therefore, an eco-efficiency indicator is a ratio between an environmental and a financial variable. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are appropriate methodologies to investigate the eco-efficiency of production systems. The ISO has published in 2012 an International Standard (ISO 14045:2012) of eco-efficiency. The assessment framework is presented in Fig. 22. The environmental assessment in eco-efficiency shall be conducted based on life cycle assessment standards ISO 14040/14044.

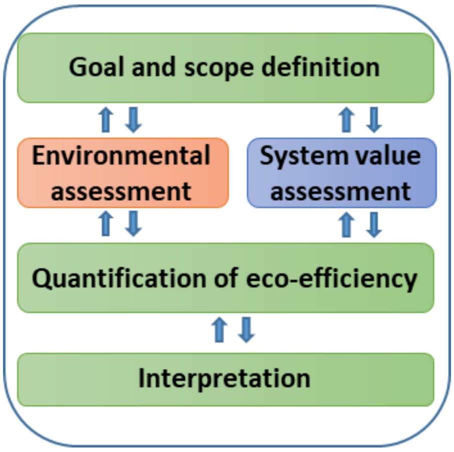

Fig. 22. Eco-efficiency assessment framework (ISO 14045:2012).

Usually, eco-efficiency indicators are ratios of value-added and environmental indicators (use of nature).

$$\mathrm{EEI} = \frac{\text{Total value added}}{\text{Environmental impact}} \tag{46}$$

Five generic environmental issues include the following: (a) water use; (b) Energy use; (c) Global warming contribution; (d) Ozone-depleting substances; (e) Waste.

The TVA due to water and fertilizer use and adopted management practices is calculated as follows.

$$\mathrm{TVA} = \left(\left(C_y \times \mathrm{MP_P}\right) - \mathrm{EXP_{NW}}\right) - \mathrm{TFC_{WS}} - \mathrm{TIC} \quad (47)$$

Where: C_Y – Crop yield (kg/ha); MP – The market price of the product (€/kg); EXP_{NW} – representing the expenses for all the non-water inputs; TFC_{WS} – Total financial cost related to water supply provision; TIC – Annual equivalent future cash flow generated from the introduction of new technologies in the system.

Differently based on the determined environmental impact indicators (LCA) and the LCC indicator representing the discounted stream of life cycle costs and depicting the cost of producing a product unit equivalent to the functional unit adopted in the LCA analysis, the eco-efficiency indicator can be determined as follows

$$\mathrm{EEI} = \frac{1}{\mathrm{LCA} \times \mathrm{LCC}} \quad (48)$$

The LCC is the total cost incurred in the life cycle including initial investment cost; installation and commissioning costs, energy cost, operating cost, maintenance and repairs costs, downtime, loss of production, environmental costs, disposal costs.

The eco-efficiency method includes a weighting of environmental impacts and costs, resulting in a two-dimensional diagram and four quadrants (Fig. 23). This graph enables the reader an easier understanding and simultaneous assessment of efficiency and eco-efficiency of product/services studied. By considering all attributes and aspects within one Eco-efficiency Assessment, potential trade-offs can be identified and assessed. Improved quality or increased value and reduced environmental impact lead to better eco-efficiency of a product or production system.

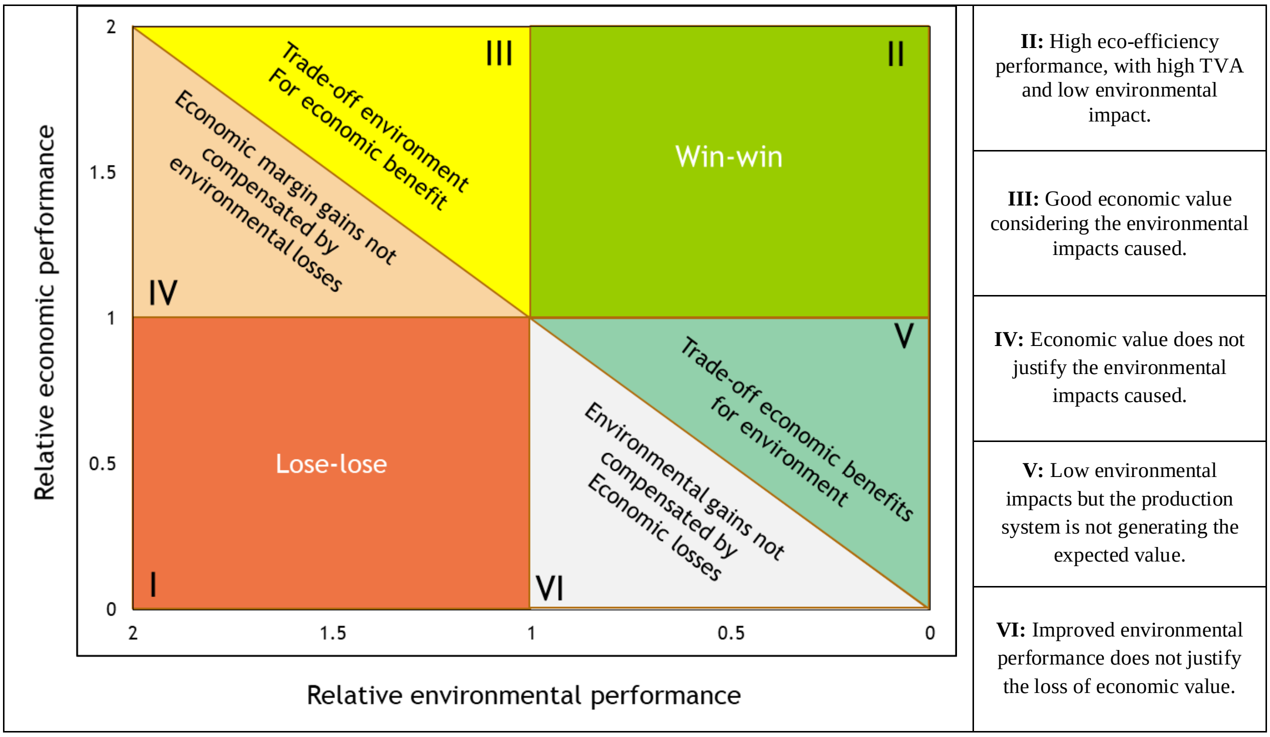

Fig. 23. The weighting of environmental impacts and costs, resulting in a two-dimensional diagram.

6.1 Example - Eco-efficiency of tomato production

Using data in Table 26 eco-efficiency of the tomato cropping system is computed. The total value added was 6631 €/ha and 66.3 €/ton. The gross production value was 8000 €/ha The computed eco-efficiency indicator as a ratio total valued added to environmental impact (global warming) was 1.74 €/kgCO_2-eq. The assessment LCA and LCC results were aggregated and presented in the form of the eco-efficiency portfolio (Fig. 24) including a sensitivity analysis of price, yield, and resource efficiency.

Table 26. Crop market price and cost incurred per unit input in tomato cultivation.

Tomato Crop	Input	Price/Cost
Yield	100 ton/ha	80 €/ton
GIR	500 mm/ha	0.1 €/m^3
Energy irrigation	1046.83 kWh	0.12 €/kWh
N	150 kg N/ha	1.35 €/kg
P_2O_5	100 kg P_2O_5/ha	0.75 €/kg
K_2O	150 kg K_2O /ha	1.5 €/kg
Pesticides	5 kg/ha	35 €/kg
Fuel	50 kg/ha	1 €/kg
Tractor	10 **h**/ha	25 €/h

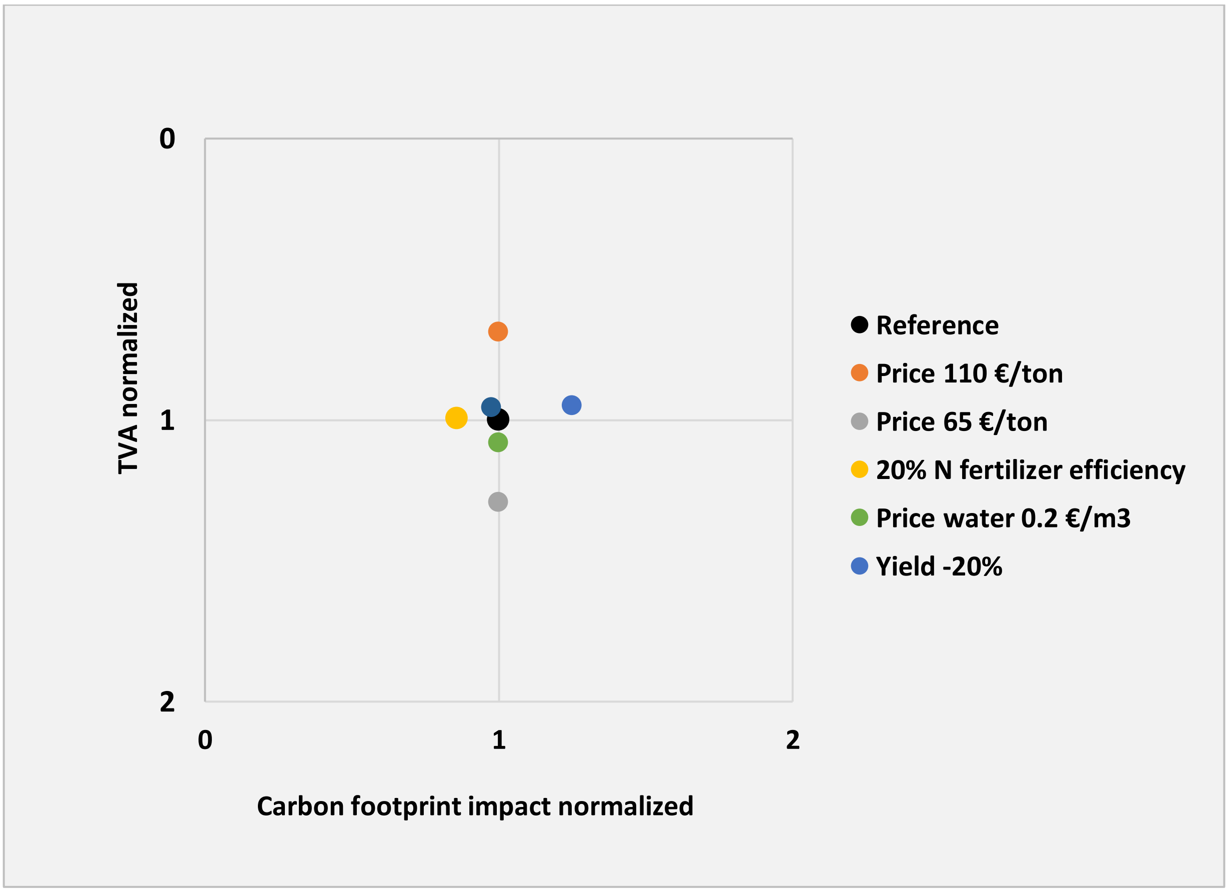

Fig. 24. Eco-efficiency portfolio combining economic (TVA) and ecological data (carbon footprint) for tomato production under different crop input and management strategies.

7. Conclusions

This guidebook presents a framework and a specific set of data and basic indicators to help researchers, agricultural water districts, and irrigation organizations for the evaluation of irrigation system performance using a nexus lens and eco-efficiency performance. This helps to better understand the complex and dynamic interrelationships between resource use and generated impacts. By using this guidebook all the target stakeholders can:

- Enhance global knowledge of water-supply balance at farm-level;
- Learn more about the fundamentals of energy use in water pumping;
- Assess water-related energy use and energy-related water use for irrigation and other field operations at farm level;
- Calculate water-energy-environment nexus of irrigation and other field operations at farm level;
- Monitoring of crop and irrigation system performance from one year to another with a special focus on eco-efficiency as a proxy of sustainability;

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Annexes

ANNEX 1. Length of growth stages

FAO Irrigation and Drainage Paper No. 24 and 56 provide general information about the 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
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
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
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
	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)

[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
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	Tropical regions
year 2	150	40	110	60	360	season	
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
Faba bean, broad bean	15	25	35	15	90	May	Europe
	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 May/June	Mediterranean
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

TABLE A1. Continued.

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
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.
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 A1. 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)
Hops	25	40	80	10	155	April	Idaho, USA
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

[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)

[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 A2 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
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

[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.

[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.

TABLE A2. Continued.

Crop	$K_{c,initial}$[6]	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
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
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
k. Sugar Cane	**0.4**	**1.25**	**0.75**	**3**

[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.

[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)
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
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]	

[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.

[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, $K_{c\ mid}$ 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 A3 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 A3. 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
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

[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)
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
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

[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)
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
n. Fruits 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
Citrus 50% canopy	1.1-1.5	0.5
Citrus 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

[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.

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
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

[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]
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
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	-	-	-
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 is 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	

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.

[43] Adapted from University of California Committee of Consultants 1974.

[44] EC_w means electrical conductivity of water

[45] SAR means sodium adsorption ratio

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
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

[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"[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
TABLE A8. RUIT 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

[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.
[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*
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*

[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 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*
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*
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*
SENSITIVE[54]	
Fruit and Nut Crops	
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 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. 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)** **W (tungsten)**	----	Effectively excluded by plants; specific tolerance unknown.
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 A13 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 the chemical precipitation of materials such as lime (CaCO3) and phosphates (Ca3(PO4)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 the 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 A13 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 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.