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FACULTY OF ENGINEERING TECHNOLOGY

WATER ENGINEERING AND MANAGEMENT

MARGINAL ECONOMIC VALUE OF WATER IN CROP PRODUCTION

A thesis submitted in partial fulfillment of the requirements of the degree of Master of Science in Civil Engineering and Management

Author: Fitsum S. Hailu
S1647822

Supervisors: Prof. dr. ir. A.Y. Hoekstra
A.D. Chukalla

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree. All materials in this dissertation that are not the author's original work are cited through appropriate referencing and acknowledgement.

Signature: 

Name: Fitsum Samuel Hailu

Student No.: S1647822

Date: August 2017

Abstract

This study explores the effect of two types of management practices on the average and marginal water productivities. The management practices are three irrigation techniques (furrow, sprinkler, and drip irrigation) and two mulching practices (no mulching and organic mulching). A case for an arid environment around Tunis with sandy loam soil for two crop types (wheat and maize) was considered. The AquaCrop model was used to simulate the soil-water-balance and crop yield. A comparison was made on how changing the management practices affect the crop yield and irrigation requirement, which ultimately also affect the average and marginal water productivities. For all the management practices implemented, the maximum crop yield attained remained the same but they all achieved this maximum with different irrigation requirement. Drip irrigation required the least amount followed by furrow and sprinkler irrigation, respectively. Moreover, the maximum average water productivity is also the highest for drip irrigation and it is also reached with the least amount of water. However, for the marginal water productivity, switching between management practices did not affect the maximum value but the volume of water required to attain this maximum was also the least in the case of drip irrigation. The results obtained apply for both crops (wheat and maize). The only difference is the magnitudes of values but the shapes of the production and productivity curves are similar for both crops. In addition, by partially satisfying the crop's evaporative requirement we found out it is possible to save considerable amount of water with no reduction in the maximum crop yield. Furthermore, when there is scarcity of land or water, we can maximize the crop production using two different approaches. When land is scarce, we make sure we effectively use all the land we have and we irrigate at maximum yield in order to get the most out of the available land. Conversely, when water is scarce, we have to aim for maximum average water productivity as that will result in maximizing our crop production.

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All that I am, and ever hope to be, I owe it to you.

Fitsum Samuel Hailu
University of Twente
August 2017

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List of abbreviations and acronyms

AL	Available Land
AW	Available Water
AWP	Average Water Productivity
B	Biomass
CC	Green Canopy Cover
CWPF	Crop Water Production Function
CWU	Consumptive Water Use
DI	Deficit Irrigation
E	Evaporation
ET	Evapotranspiration
ET_o	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FI	Full Irrigation
f_m	Parameter for mulch material
HI	Harvest Index
IL	Irrigated Land
Irr	Irrigation Requirement
MWP	Marginal Water Productivity
MY	Maximum Yield
P	Production
RAW	Readily Available Water
RDI	Regulated Deficit Irrigation
RH	Relative Humidity
T	Transpiration
WP	Water Productivity
WP^*	Normalized Water Productivity
WUE	Water Use Efficiency
Y	Yield

1. Introduction

Agriculture plays a crucial role for the economy of most countries in the world. It is the main source of people's livelihood particularly in the developing and under-developed countries (Mendelsohn and Dinar, 1999). One of the main components of agriculture is crop production, and it encompasses a series of processes involved in the growing of crops – from land preparation through planting to the product reaching the consumer. Water is an integral part of this long and complicated process, and the main factor limiting crop production in parts of the world where the rainfall is insufficient to meet the crop demand. The competition for the finite water resources worldwide is continually increasing and the continuous rise in the demand for agricultural commodities causes it (Foley et al., 2011, Ali and Talukder, 2008). The fact that world population is expected to increase by 29% from 7.5 billion to 9.7 billion in 2050 will put an immense pressure on agriculture (Worldometers.info, 2017, DESA, 2015). By 2050, world annual demand for maize, rice and wheat is expected to reach 3.3 billion tons, or 800 million tons more than 2014's record combined harvest (Reeves et al., 2016). In order to meet the ever-increasing food demand, developed and developing countries have to increase their food production by about 60% and 100%, respectively (Alexandratos and Bruinsma, 2012). Much of the increase in production will need to come from existing farmland. However, one-third of that land is degraded, and farmers' share of water is under growing pressure from other sectors. This calls for an immediate response to improve the efficiency and productivity of water use in crop production to guarantee future food security and address the complications that will likely follow because of climate change (Steduto et al., 2012). Climate change is generally expected to worsen the situation. While some areas will receive higher rainfall, most of the currently water-scarce regions will become drier and warmer. These two changes will exacerbate scarcity: reduced rainfall means less flow in rivers; higher temperatures mean increased evaporation and water consumption by natural vegetation (compounding the reduction in runoff), and higher water demand for agricultural use. Hence, tensions between supply and demand are likely to be aggravated. There are different strategies that can be taken to ensure the future food demand is met. Such solutions include decreasing the yield gap, reducing wastage of food, adopting more sustainable diets, and increasing water productivity (Alexandratos and Bruinsma, 2012, Kiani and Abbasi, 2012, Foley et al., 2011, Kijne et al., 2009, Kijne et al., 2003).

Researchers have been trying to find different ways to increase the water productivity in crop production. They have applied different strategies to achieve that: changing the irrigation techniques (Xue and Ren, 2016, Oweis and Hachum, 2006), changing the mulching practices (Zamir et al., 2013, Ogban et al., 2008), and a combination of both the irrigation technique and mulching practice (Chukalla et al., 2015). Though increasing the physical water productivity is of paramount importance to ensure the future food demand, it should be done by also considering other influencing factors. Such factors include the amount of water available, environmental conditions, management practices and type of crop (Chukalla et al., 2015, Amarasinghe and Smakhtin, 2014, Bessembinder et al., 2005, Kijne et al., 2003, Molden, 1997). We have to consider those factors because in the process of increasing water productivity we should not compromise environmental sustainability (Hoekstra, 2013, Molden, 1997). In order to avoid the depletion of water and reduction of available water for other purposes, the scheme aimed at increasing water productivity should also take into account the water availability and environmental flow requirement (Qureshi et al., 2011).

Most of the previous studies available are about how we can increase water productivity and/or reduce water footprint (Chukalla et al., 2015, Amarasinghe and Smakhtin, 2014, Oweis and Hachum, 2006). Even though it is useful to determine ways to increase the water productivity, it will give more insight to know the additional value that can be obtained from an additional m³ of water, which depends on how much water is available already. Water productivity, as defined in most literatures is simply the ratio of yield to the amount of water consumed (Amarasinghe and Smakhtin, 2014, Molden, 1997). As such, it does not describe the incremental productivity of water. Hence, "water productivity cannot be an appropriate indicator of economic efficiency, which requires consideration of incremental gains and costs, including opportunity costs" (Wichelns, 2015). The number of researches done on marginal water productivity is very limited, and even those researches done are site specific (Elsheikh, 2015, Frija et al., 2014, Samarawickrema and Kulshreshtha, 2009).

Scientists used to approach the task of finding an ideal cropping system, and suitable soil and management strategies that can maximize the crop productivity by designing field experiments. However, given the complexity of factors involved and the number of possible combinations that need to be studied, the field experiments can prove to be very expensive and time-consuming (Sivakumar and Glinni, 2002). In addition, there are also some scenarios such as the effect of global warming which cannot be modelled experimentally on the field; hence making use of crop-growth models the best alternative. The scientific community has developed more than 70 different types of crop models with different levels of sophistication (Di Paola et al., 2016). The use of crop simulation models has an increasing role in scientific research, farm development, and policy decisions. All models have their own purpose and merit, and before a model is used, a critical evaluation of the most appropriate model for a study should be made, based on the model's scope and purpose (Bennett et al., 2013). It is followed by selection of the best compromise between accuracy and ease of use to explore the model qualifications and assumptions. For this study, the water driven dynamic model called AquaCrop, developed by the Food and Agriculture Organization (FAO) of the United Nations is used. It is able to simulate the attainable yield of herbaceous crops under various management and environmental conditions (Steduto et al., 2012, Hsiao et al., 2009).

AquaCrop employs a semi-quantitative approach that requires for users of the model to provide the soil fertility as an input instead of using nutrient-balance approach to model crop response to soil fertility (Van Gaelen et al., 2015). This semi-quantitative approach requires few input parameters (explicit and mostly intuitive), which are easily obtainable, then integrates the effects of various soil nutrients and mineralization processes, and attempts to balance simplicity, accuracy, and robustness (Steduto et al., 2009). Although other crop models have produced good crop yield simulation results, compared to them, the AquaCrop model is simpler, requires available field input data, and is highly reliable for the simulation of biomass, canopy cover, and yield under different climatic conditions.

This study was done for the area around Tunis for a sandy loam soil for two of world's highly harvested crops wheat and maize under different irrigation management practices. Bread and durum wheat (Triticum aestivum and Triticum durum, respectively) comprise the third largest crop produced in the world (first place held by Maize and second place by rice) (FAO, 2014). Wheat is the most important source of carbohydrate in a majority of countries. Wheat contains minerals, vitamins, and fats (lipids), and with a small amount of animal or leguminous protein added is highly nutritious. A predominately wheat-based diet is higher in fiber than a meat-based diet (Curtis et al., 2002). Wheat is also a popular source of animal feed, particularly in years where harvests are adversely affected by rain and significant quantities of the grain are made unsuitable for food use. Such low-grade grain is often used by industry to make adhesives, paper additives, several other products and even in the production of alcohol (Curtis et al., 2002). Maize ranks as the most important crop worldwide in terms of grain production; although wheat and rice are the most important for direct human consumption (Steduto et al., 2012). It provides nutrients for humans and animals and serves as a basic raw material for the production of starch, oil and protein, alcoholic beverages, food sweetener and more recently fuel (FAO, 1992).

In this study, by using AquaCrop model and knowledge of crop growth and developmental stages it was shown how irrigation scheduling affects the maximum crop yield obtained and the irrigation requirement to attain it. For the irrigation schedule selected, the relationship amongst the crop yield, average water productivity and marginal water productivity is explained. It was observed that changing the management practice (irrigation techniques and mulching practice) has no effect on the maximum crop yield obtained but the irrigation requirement varied and model experiments were done for both crops: wheat and maize. However, due to the change in the irrigation requirement when the management practices were altered, the average and marginal water productivities also changed and what these changes imply are also discussed. For each of the irrigation techniques and mulching practices used the maximum amount of irrigation water that can be saved with no decrease in the maximum crop yield attained was also calculated. Finally, decisions are made on how the crop production can be maximized when there is a scarcity of water or land.

Research Objectives

The main objective of this study was to estimate the average and marginal economic value of water in crop production as a function of the amount of water already applied for different management practices in an arid environment. This study covered the following specific objectives:

- To explore the effect of changing the management practice (irrigation scheduling, irrigation techniques, and mulching practices) on crop yield and irrigation requirement;
- To investigate the effect varying the management practices (irrigation techniques and mulching practices) on the average and marginal water productivities;
- To determine the effect of irrigation scheduling on irrigation water saving without reducing the maximum crop yield and determine how profit can be maximized when price of water is considered and;
- To determine the most suitable approach to maximize the crop production under land or water scarcity.

Case study for wheat and maize near Tunis in Tunisia for the year 1990.

Outline of dissertation

A brief explanation of the methods employed and data used is given in Chapter 2. FAO's AquaCrop model is used to simulate the soil-water-balance and crop yield for the different management practices. In addition, a short description of how the model works and how the experiment is set-up is also included.

The results and discussion of this research are summarized in Chapter 3. The final outputs of the model relevant to this study are crop yield and consumptive water use, and these are translated into average and marginal water productivities. Based on these results, the effect of management practices on the water productivities and how crop production can be maximized when there is a scarcity of land or water are discussed.

Finally, in Chapter 4 the conclusions drawn from the study and recommendations for improvement and further research are presented.

2. Method and Data

In this study, the different input variables are put in the crop water productivity model, AquaCrop which gives outputs of evapotranspiration (ET) and crop yield. These results are translated into average and marginal water productivity that were used to make further calculations and recommendations.

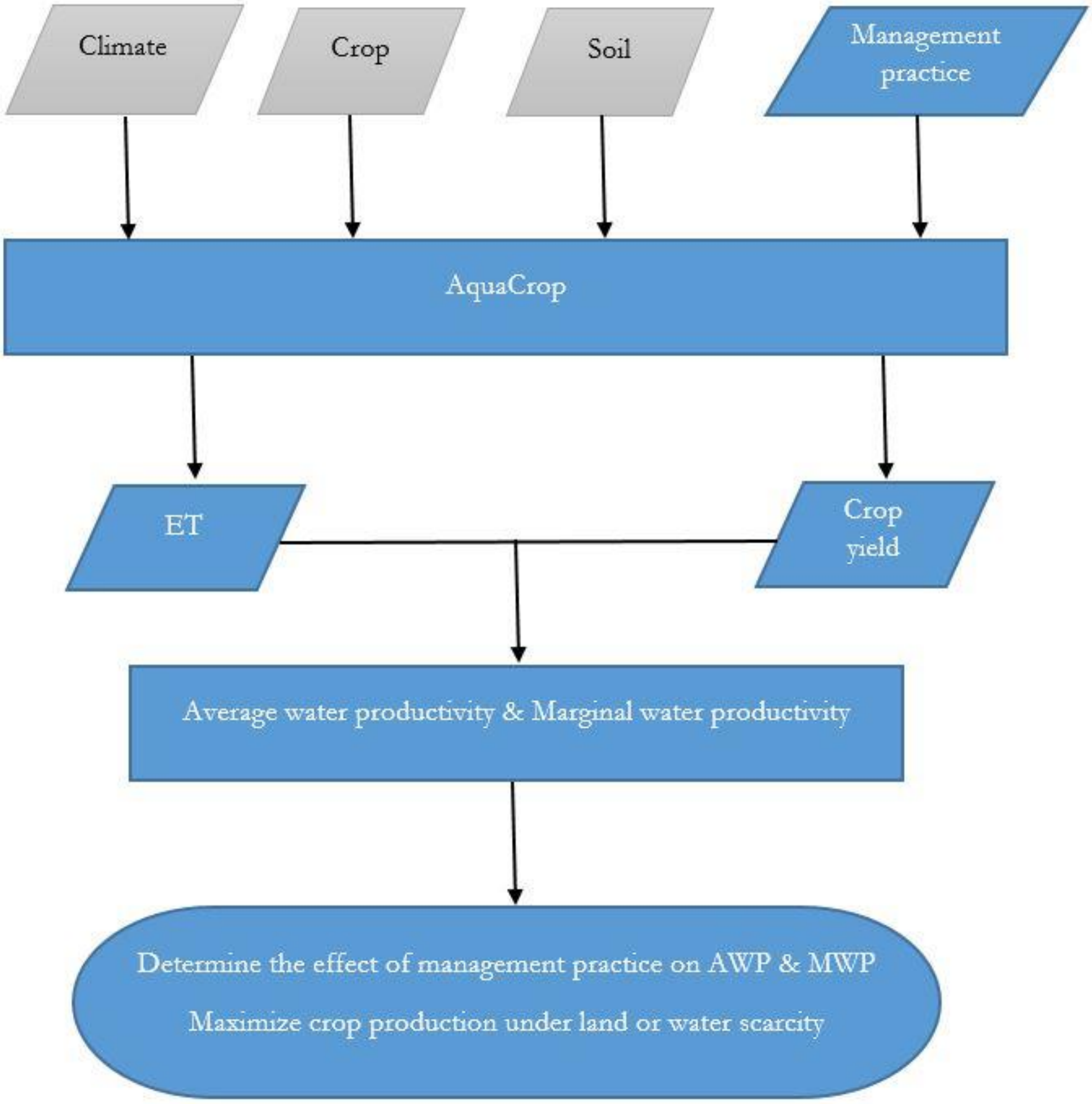


Figure 2.1 Flowchart for determining the average water productivity (AWP), marginal water productivity (MWP), and maximum crop production under land or water scarcity

In the above flowchart, the inputs in the gray parallelogram (climate, crop, and soil) are fixed. On the other hand, the input in the blue parallelogram, which is the management practice, is variable. It is by changing the management practice and keeping the others constant, we investigated the effect on the AWP and MWP.

Soil-water balance and crop growth model

In this study, FAO's AquaCrop model (version 5.0), which simulates the soil-water-balance and crop yield, is used to carry out a series of simulations with increasing water supply (rainfall and/or irrigation) over the growing period of a crop (keeping other things equal), monitoring the simulated ET and crop yield over the growing period. ET (m^3/ha, or mm) and crop yield (kg/ha) are used as input to calculate the Average Water Productivity (ton/m^3) and Marginal Water Productivity (ton/m^3), which is the additional crop yield obtained for the additional unit of water applied.

The structural components of AquaCrop, including the stress responses and the functional linkage among them, are shown schematically in the following figure. The continuous lines indicate direct links between variables and processes, whereas the dotted lines indicate feedbacks (Steduto et al., 2012).

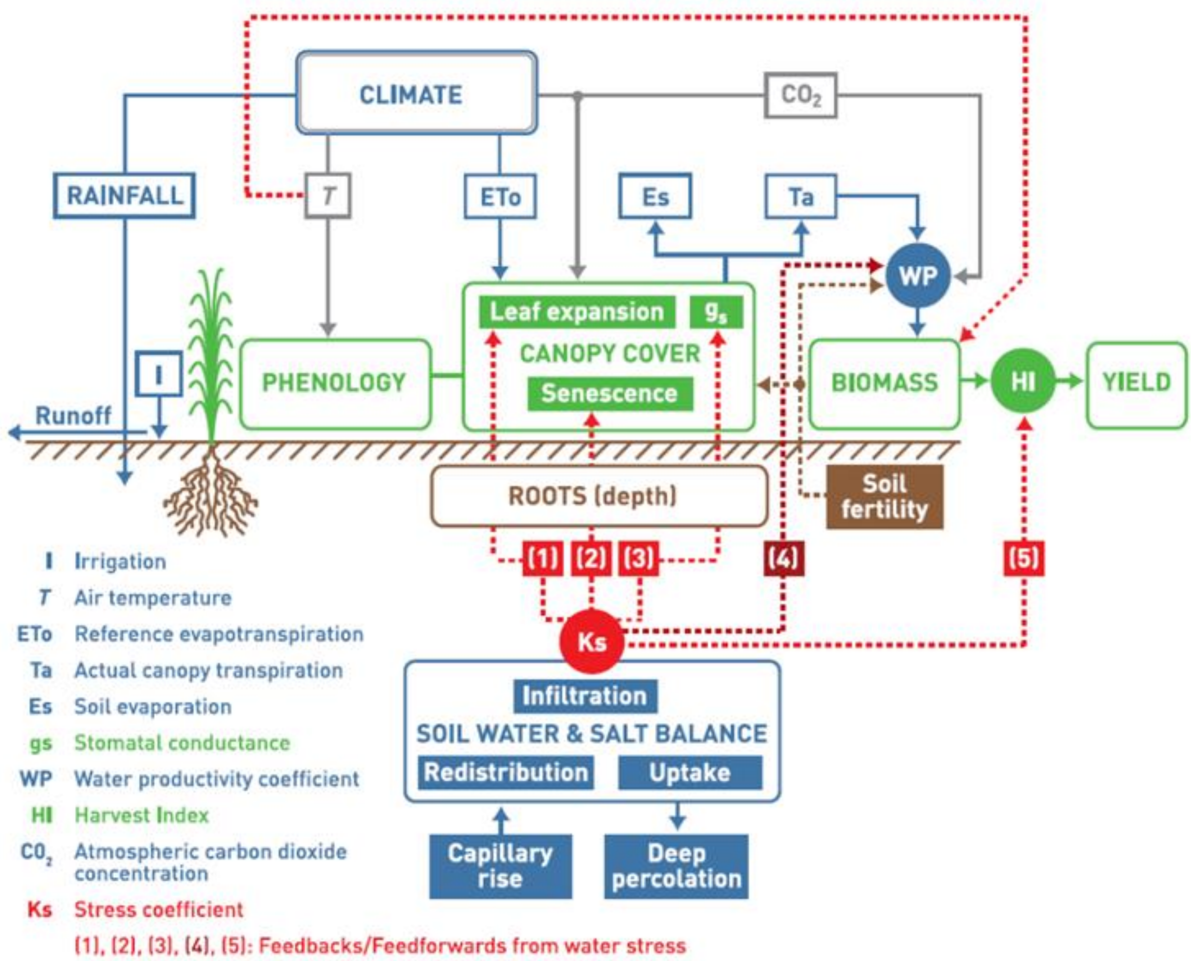


Figure 2.2 Chart of AquaCrop for the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. Source: Steduto et al. (2012).

AquaCrop simulates final crop yield in four easy to understand steps (which run in series in each daily time increment and ensure transparency in the modelling approach), as described below (FAO, 2016).

a) **Development of green canopy cover:** in AquaCrop, foliage development is expressed through green canopy cover (CC) rather than leaf area index. CC is the fraction of the soil surface covered by the canopy; it ranges from zero at sowing (i.e. 0 percent of the soil surface covered by the canopy) to a maximum value at mid-season as high as 1 if full canopy cover is reached (i.e. 100 percent of the soil surface is covered by the canopy). By adjusting the water content in the soil profile each day, AquaCrop keeps track of stresses that might develop in the root zone. Soil-water stress can affect the leaf and therefore canopy expansion; if severe, it can trigger early canopy senescence.

b) **Crop transpiration:** in well-watered conditions, crop transpiration (Tr) is calculated by multiplying the reference evapotranspiration (ET_o) with a crop coefficient (KcTr). The crop coefficient is proportional to CC and hence varies throughout the life cycle of a crop in accordance with the simulated canopy cover. Not only can water stress affect canopy development, it can also induce stomata closure and thereby directly affect crop transpiration.

The soil evaporation is adjusted for the withered canopy, mulches and partial wetting by irrigation. The AquaCrop model simulates the effect of mulching on evaporation and represents effects of soil organic matter through soil hydraulic properties influencing the soil water balance. Soil evaporation under mulching practice is simulated by correcting evaporation (E) with a factor that is described by two variables (Raes et al., 2012): soil surface covered by mulch (from 0 to 100 %); and mulch material (f_m). According to Allen et al. (1998), the values of the parameters for mulch material (f_m) are suggested to vary between 0.5 for mulches of plant material and close to 1.0 for plastic mulches (Raes et al., 2012).The correction factor for mulching is calculated as:

$$\text{Correction factor for mulching} = \left[1 - f_m \frac{\text{Percent covered by mulch}}{1}\right] \quad (1)$$

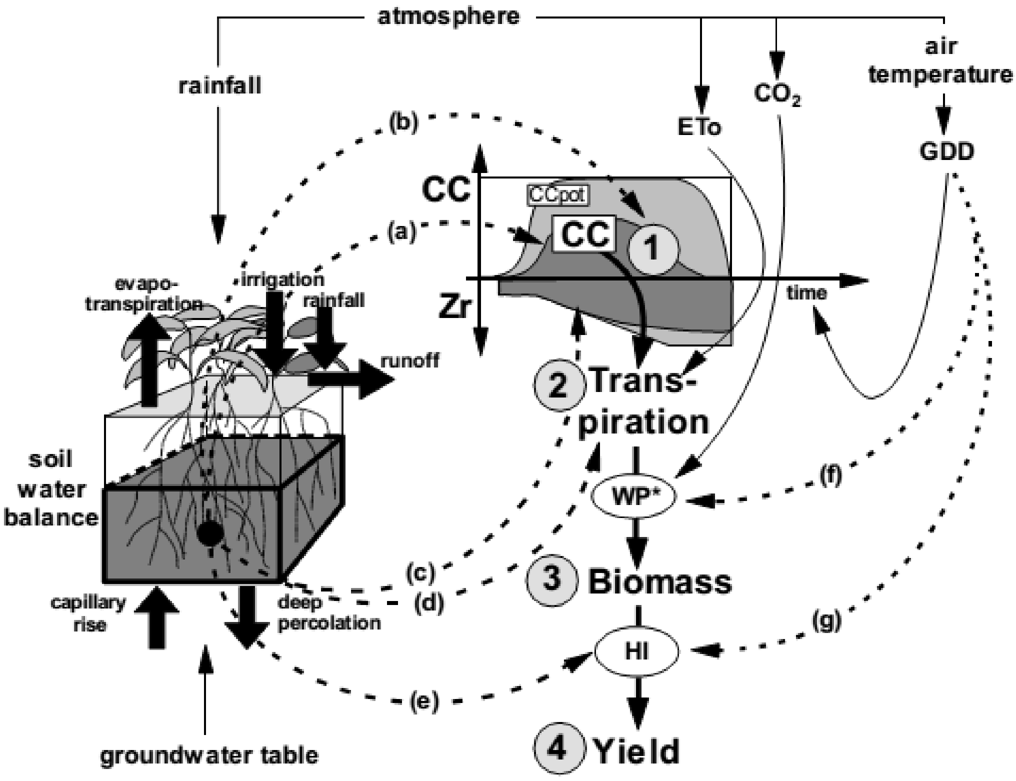


Figure 2.3 Calculation scheme of AquaCrop with indication of the four steps, and the processes (dotted arrows) affected by water stress (a to e) and temperature stress (f to g). Source: FAO (2016).

c) **Above-ground biomass:** the quantity of above-ground biomass (B) produced is proportional to the cumulative amount of crop transpiration (ΣTr); the proportional factor is known as biomass water productivity (WP). In AquaCrop, WP is normalized for the effect of climatic conditions, making normalized biomass water productivity (WP*) valid for diverse locations, seasons and concentrations of carbon dioxide.

d) **Crop yield:** the simulated above-ground biomass integrates all photosynthetic products assimilated by a crop during the season. Crop yield (Y) is obtained from B by using a harvest index (HI) – which is the fraction of B that is a harvestable product. The actual HI is obtained during simulation by adjusting the reference harvest index (HI_o) with an adjustment factor for stress effects.

Temperature and water stresses directly affect one or more of the aforementioned processes (Figure 2.3). AquaCrop considers also the effect of soil fertility and soil salinity stress on canopy development, crop transpiration and biomass production (FAO, 2016).

Water Productivity indices

Molden (2007) defined water productivity as the ratio of the net benefits from crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water required to produce those benefits. In its broadest sense, it reflects the objectives of producing more food, income, livelihoods, and ecological benefits at less social and environmental cost per unit of water used, where water use means either water delivered to a user or depleted by a user. Put simply, it means growing more food or gaining more benefits with less water. Water productivity has two representations: physical water productivity – the ratio of the mass of agricultural output to the amount of water used, and economic water productivity – the value derived per unit of water used.

The outputs files of AquaCrop simulation are the summary of the crop development and production, soil water balance, soil water content, salt balance, salt water content, soil salinity, and net irrigation requirement for the entire simulation. However, for this study, we only need the evapotranspiration, crop yield, and net irrigation requirement. Using these results, the water productivity indices (average water productivity and marginal water productivity) are calculated.

Average water productivity

The simple definition of average water productivity is the ratio of crop yield to water use:

$$\mathrm{AWP} = \frac{\mathrm{Y}}{\mathrm{WU}} \tag{2}$$

Water use in the denominator can be total consumptive water use or total water applied (rainfall and/or irrigation supply); the latter is used in this study when defining water productivity indices.

Marginal water productivity

Technically, the marginal productivity of a particular resource is defined as the addition to the gross output caused by an addition of one unit of that resource while other inputs are held constant. Hence, marginal water productivity is the ratio of change in crop yield to change in water use:

$$\mathrm{MWP} = \frac{\Delta\mathrm{Y}}{\Delta\mathrm{WU}} \tag{3}$$

Optimization of water and land under scarcity

In crop production, different resources are required but the most important and limiting ones are water and land. Depending on which resource is scarce, different approaches have to be taken to ensure maximum production. In order to determine which approach results in the highest production when one of the resources was scarce, an optimization was performed.

$$\text{if}\begin{cases}\dfrac{\text{AW}}{\text{Irr}} < \text{AL}, & \text{IL} = \dfrac{\text{AW}}{\text{Irr}} \quad (4)\\ \dfrac{\text{AW}}{\text{Irr}} \geq \text{AL}, & \text{IL} = \text{AL} \quad (5)\end{cases}$$

$$\text{if}\begin{cases}\text{IL} < \text{AL}, & \text{P} = \dfrac{\text{AW} * \text{Y}}{\text{Irr}} \quad (6)\\ \text{IL} \geq \text{AL}, & \text{P} = \text{Y} * \text{AL} \quad (7)\end{cases}$$

where:

$\text{AW} = \text{Available water } (\text{m}^3)$

$\text{Irr} = \text{Irrigation requirement } (\text{m}^3/ha)$

$\text{AL} = \text{Available land} = 1\text{ha}$

$\text{IL} = \text{Irrigated land (ha)}$

$\text{Y} = \text{Yield (ton/ha)}$

Experimental set-up

A comprehensive set of simulations were carried out, applying different management practices in an extensive number of cases (Table 2.1).

Table 2.1 Research model: management practices considered in a number of cases to simulate the effect on Average Water Productivity (AWP) and Marginal Water Productivity (MWP).

Management practices	Modeling	Effects
Three irrigation techniques: furrow, sprinkler and drip irrigation Two mulching practices: no mulching and organic mulching	Soil water balance and crop growth model (AquaCrop)	AWP MWP

Management Practices

The management practices implemented in this study were varying the irrigation scheduling (when and how much irrigation water is applied), irrigation techniques (the methods used to apply the irrigation water) and mulching practices.

Irrigation Scheduling

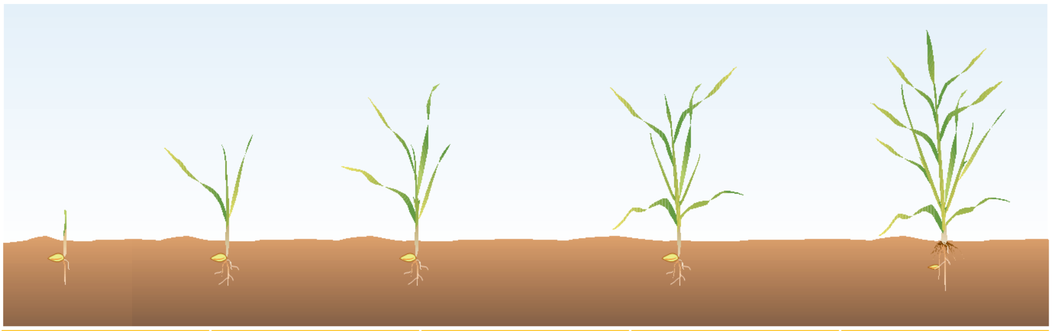
Irrigation scheduling is the water management strategy of determining when and how much water to apply to an irrigated crop in order to maximize the total crop yields. Commonly irrigation scheduling is defined as determining the time of irrigation and the amount of water to be applied. The maximization of crop yield requires a high level of water productivity, and this in turn requires the accurate measurement of the volume of water applied or of the depth of application. This is imperative because when crops are under water stresses there are reductions in crop yield and decrease in crop yield returns. To gain benefit from irrigation scheduling, there must be an efficient irrigation system.

Irrigation scheduling is one of the important management activities that are vital to the effective and efficient utilization of water. Water management strategies based on irrigation scheduling are intended to reduce the amount of water applied and minimize crop yield reduction due to water stress. It will ensure that water is applied to the crop when needed and in the amount required.

When we meet the full evaporative demand of the crop for the whole crop development stage it is referred to as full irrigation (FI). The main aim of FI is to maximize the crop yield obtained. AquaCrop can automatically generate the irrigation schedule with no stress condition. On the other hand, when we apply irrigation water below the evaporative requirement of the crop it is called deficit irrigation (DI) (Fereres and Soriano, 2007). The reduction can be for the whole crop development stage or only for some part of the crop development stage where the crop is more resistant to drought, known as sustained deficit irrigation and regulated deficit irrigation (RDI), respectively (Chukalla et al., 2015). However, in order to determine which irrigation schedule results in the highest crop yield and identify in which crop development stage or stages to apply deficit irrigation, a thorough knowledge of growth and development of crops is required.

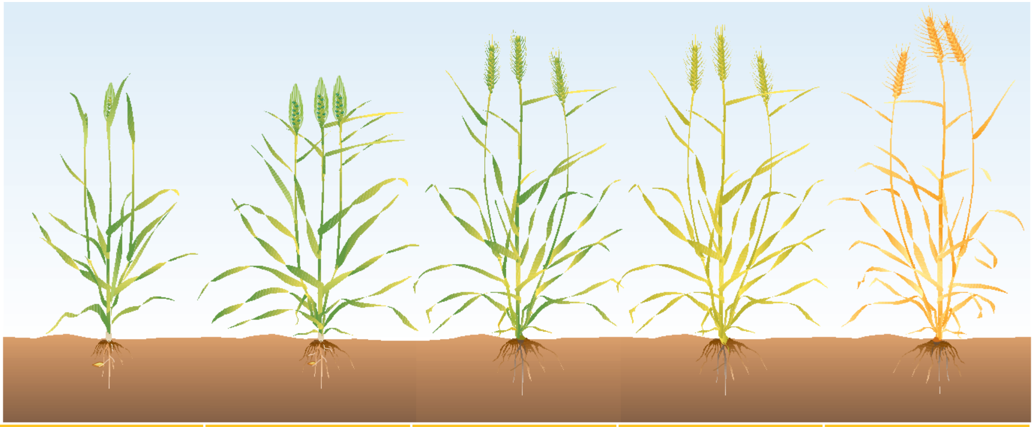
Growth and development in cereal plants do not proceed at a constant or fixed rate through time. They are modified by environmental factors like temperature, light intensity and duration, nutrition, and husbandry techniques (Landes and Porter, 1989). Therefore, calendar date is not suitable for the quantitative description of the developmental stage of plants. There have been many attempts to define precise and easily applicable methods for describing all the important periods and stages during cereal development. This need arises since cereal plants undergo, during their life cycles, periods and stages of differential sensitivity to environmental factors, notably temperature and photoperiod (Porter and Delecolle, 1987).

Different scales are used to describe the growth stage in cereals. For example, Feekes Scale developed by Feekes (1941) under North-west European conditions, uses four principal positions (Feekes' codes 2 to 5). The four-digit Feekes' scale is inefficient for data processing, and for computer storage and retrieval (Loegering, 1968). Haun Scale developed by Haun (1973) allows a continuous numerical expression of plant development until the complete emergence of the flag leaf. A major limitation of Haun's scale is its restriction to the period of leaf emergence (Cabeza et al., 1996). Zadoks Scale, most commonly used type of scale and also the scale used in this study was developed by Zadoks (1985). It uses decimal code system that divides into 10 distinct developmental phases covering 100 individual growth stages. These 10 development stages along with their respective scales are given in the following figures. The individual growth stages are denoted by the prefix GS (growth stage) or Z (Zadoks) (Poole, 2005)



Zadoks Growth Stage	GS 00 - 09	GS10 - 19	GS20 - 29	GS30 - 39	GS40 - 49
Development phase	Germination	Seedling growth	Tillering	Stem elongation	Booting

Figure 2.4 First half of Zadoks cereal growth stages. Source: (Poole, 2005)



Zadoks Growth Stage	GS 50 - 59	GS60 - 69	GS70 - 79	GS80 - 89	GS90 - 99
Development phase	Ear emergence	Flowering	Milk Development (grain fill period)	Dough Development (grain fill period)	Ripening

Figure 2.5 Second half of Zadoks cereal growth stages. Source: (Poole, 2005)

Not all stages of crop growth are uniformly susceptible to water scarcity. On the other hand, some stages can cope-up with water shortage very well, while others are more susceptible and water shortages at such stages may result in distinct crop yield losses. Moisture stress is known to reduce biomass, tillering ability, grains per spike and grain size at any stage when it occurs. Therefore, the overall effect of moisture stress depends on intensity and length of stress (Akram, 2011).

Based on this knowledge of the growth stages, different schedules such as irrigating at a constant irrigation interval, varying the initial date of irrigation, irrigating for only some part of the crop development stage, irrigating when the soil moisture content reaches a certain threshold and so on have been implemented. All these different types of irrigation schedules are applied using AquaCrop until the most suitable schedule is found. The irrigation application dose is generally selected as the depth criterion. The dose is obtained by considering the irrigation method, crop and soil characteristics, and common local practices. The time criterion consists in selecting an allowable depletion level of the root zone at which irrigation should be triggered. Once the most suitable irrigation schedule (the irrigation schedule that results in the highest crop yield for the least amount of irrigation water) is determined then we used that schedule for the rest of the study.

Irrigation Technique

According to Ali (2011), different criteria can be considered when classifying irrigation techniques such as the energy or pressure required, how or where the irrigation water is applied, and wetted area by irrigation. Based on the wetted surface area, irrigation techniques can be listed as flood irrigation, trickle or localized irrigation and sprinkler irrigation. The first of these, flood irrigation, comprises furrow, border and basin irrigation. The second, trickle irrigation comprises drip and subsurface drip. Given the existing irrigation practices in the environment that we consider, we analyze three irrigation techniques: furrow (with 80% surface wetting), sprinkler (100% surface wetting), and drip (30% wetting). Generic assumptions have been made about the specific details of the different irrigation techniques, following default settings in the model. For furrow irrigation, an 80% wetting percentage is assumed representative of every furrow (narrow bed) from the indicative range of 60 to 100% in the AquaCrop manual (Raes et al., 2012).

Mulching Practice

Mulching involves the use of organic or inorganic materials to cover the cropped soil surface. Mulching has the potential of reducing evaporation, conserving soil moisture, modifying soil temperature, and improving aeration (Ogban et al., 2008, McCraw and Motes, 1991). Crop residues and grasses are typical organic materials commonly used for mulching, while synthetic materials (e.g. polyethylene sheet of different thickness and colors) are typical inorganic materials use for mulching.

The mulching practice in AquaCrop considers mainly evaporation reduction from the soil surface. Two mulching practices were considered: no mulching and organic mulching with f_m=0.5 and a mulch cover of 100% were considered. It is assumed the mulches have no effect on the surface runoff.

Data

The operation of AquaCrop model requires input data consisting of climatic parameters, crop, soil and field and irrigation management data. However, the model contains a complete set of input parameters that can be selected and adjusted for different irrigation management and crop types.

Climate – Arid environment

The weather data required by AquaCrop model are daily values of minimum and maximum air temperature, reference crop evapotranspiration (ET_o), rainfall and mean annual carbon dioxide concentration (CO_2). ET_o was estimated using ET_o calculator using the daily maximum and minimum temperature, wind speed at 2 meters above ground surface, solar radiation and mean relative humidity (RH). For this study, an arid climate was chosen.

An arid environment can be defined as one in which the amount of precipitation an area receives, divided by the amount which is lost to evapotranspiration, yields a fraction which is less than 0.50 (Salem, 1989). For this study, we selected an area located near the Gulf of Tunis, Northern Africa (36.81°N, 10.81°E) that has an aridity of 0.333 as a typical representative. It is assumed that there is no rainfall and only irrigation takes place.

Crop – Wheat and Maize

Depending on the photosynthetic pathway which ultimately determines the water productivity, crops can be broadly classified into two classes: C_3 and C_4 (Lara and Andreo, 2011). The C_3 crops have an average productivity between 0.15 and 0.20 ton/ha, whereas C_4 crops have a higher average productivity between 0.30 and 0.35 ton/ha (Raes et al., 2012). C_4 plants owe their greater resource use efficiency and potential productivity to their evolved photosynthetic pathway that is adapted to high light intensity, high temperature, and dryness (Liu et al., 2017). The C_4 photosynthesis is an adaptation of the C_3 pathway that overcomes the limitation of the photorespiration, improving photosynthetic efficiency and minimizing the water loss in hot, dry environments (Edwards and Walker, 1983).

In this study, one representative crop was selected from each class: Wheat from C_3 and Maize from C_4. These crops were selected because they are two of the most harvested crops in the world and AquaCrop accurately models them (Raes et al., 2012).

Although grounded on basic and complex biophysical processes, AquaCrop uses a relative small number of crop parameters to characterize the crop. FAO has calibrated these crop parameters for several crops and provides them as default values in the crop files stored in AquaCrop database. For this study, these default values are used and extensive descriptions of these crop parameters are given in the appendix.

Soil type – Sandy loam soil

Soils in the arid zones are formed when the significant diurnal temperature changes mechanically disintegrate rocks, wind-blown sand abrades rock surfaces, or the root systems of plants break up rock particles (Salem, 1989). Based on the granular composition, the soil type in Tunis can be classified as sandy loam soil (Kayouli et al., 2006).

Groundwater characteristics – Deep

The considered characteristics of the groundwater table are its depth below the soil surface and its salinity, which can vary throughout the year. If the groundwater is shallow, water and salts might move upward from the water table to the root zone by capillary rise. The depth of the groundwater table, and characteristics and soil water content of the soil profile determine the amount of water transported upward. For this study, the groundwater depth is assumed sufficiently deep and no upward transport of water and salt takes place.

3. Results and Discussion

Overview of results from model experiments

The outcomes of the different irrigation schedules are plotted in Figure 3.1. The figure shows that for the different type of irrigation scheduling employed the maximum crop yield varies. This difference in the maximum crop yield is observed even when the amount of irrigation water used is the same. By changing the management practice (irrigation technique and mulching practice), the amount of water required to reach a maximum crop yield is also altered, as shown in Figure 3.3, 3.4 and 3.5, respectively. The relationship between the marginal water productivity and the crop yield as well as between marginal water productivity and average water productivity is explained. Because of the change in the irrigation requirement when the management practices were altered, the average and marginal water productivities will also change and what these changes imply are also discussed. For each of the irrigation techniques and mulching practices used the maximum amount of irrigation water that can be saved is calculated. Finally, decisions are made on how the crop production can be maximized when there is a scarcity of water or land.

Though the results of wheat are shown in almost all cases, a similar trend is observed for the case of maize as well. The only differences are that the maximum crop yield obtained is greater for maize than wheat and the irrigation requirement to attain this maximum is less in the case of maize. As a result, the values of the maximum average and maximum marginal water productivity are greater in maize than in wheat but the shapes of the productivity curves are similar.

Effect of management practice on crop yield

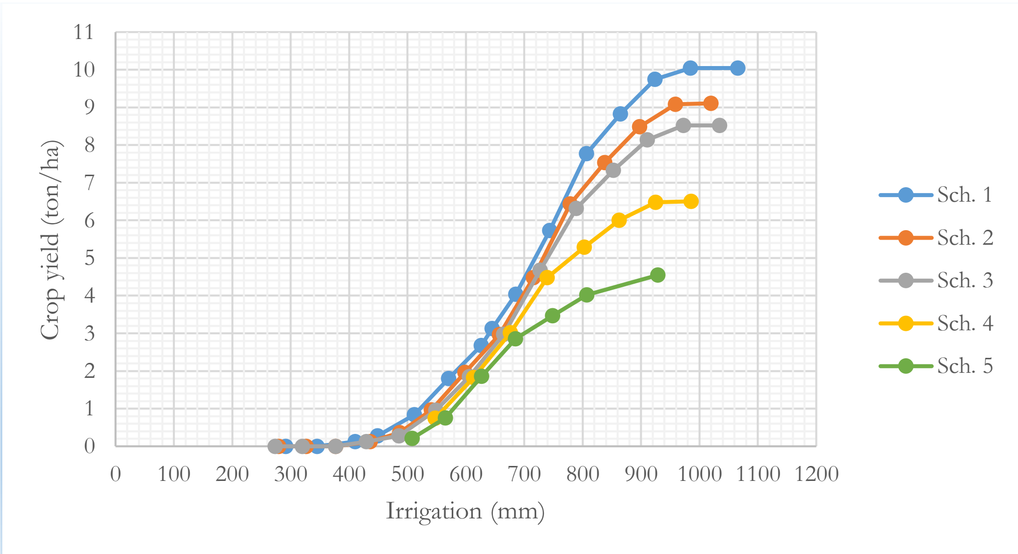


Figure 3.1 Crop yield versus irrigation supply for wheat obtained using furrow irrigation for different irrigation schedules. Sch. 1 is irrigating from crop sowing date until the end of crop development stage up to field capacity before crop starts to experience leaf expansion growth stress. Sch.2 is similar to Sch. 1 but irrigation is triggered before crop experiences canopy senescence stress. Sch. 3 and 4 are similar to Sch. 1 but irrigation started 7 and 10 days after sowing, respectively. Sch. 5 is when irrigation is every 10 days up to field capacity and irrigation is triggered if the crop has experienced stomatal closure stress.

The effect of different irrigation schedules (Sch. 1 to Sch. 5) on the crop yield and irrigation requirement are shown in Figure 3.1. Sch. 1 is an irrigation schedule in which irrigation is started from the crop sowing date and practiced throughout the whole crop development stages refilling up to field capacity when the moisture content in the root zone drops by 31% and 20% of the readily available water (RAW) for wheat and maize, respectively. Sch. 2 is similar to Sch. 1 except we allowed the soil moisture depletion to drop until the crop starts to experience canopy senescence stress. Sch. 3 and 4 are similar to Sch. 1 but irrigation started 7 and 10 days after sowing, respectively. Irrigating every 10 days up to field capacity if the moisture content in the root zone has dropped by 100% of RAW resulted in Sch. 5.

Among the different irrigation schedules implemented, Sch. 1 is selected as the most suitable one as it gives the highest possible crop yield for the smallest amount of irrigation water. Once the appropriate irrigation schedule is selected, it is possible to plot the average water productivity and marginal water productivity against the irrigation water applied on the same graph (Figure 3.2). The MWP curve has a shape that resembles a normal distribution because of the law of diminishing marginal return. The law states that the additional input (water in this case) will generally increase output (in this case crop yield), but there also is a point where adding more input will result in a smaller increase in the output, and there is another point where using even more input will lead to a decrease in the output.

The marginal water productivity curve has two parts: the increasing and decreasing part, but the decreasing part can be either positive or negative. The marginal water productivity and crop yield are related in a way that when the crop yield is increasing at an increasing rate then MWP is also increasing. This means the additional unit of water is producing more and more yield. Next, when the crop yield is increasing at a decreasing rate, then the MWP starts decreasing but remains positive. This means the additional unit of water is producing yield but this yield is not as much as it was before. Finally, when the crop yield starts to decline, then the MWP becomes negative. This is explained when we apply too much water, the crop yield declines due to waterlogging.

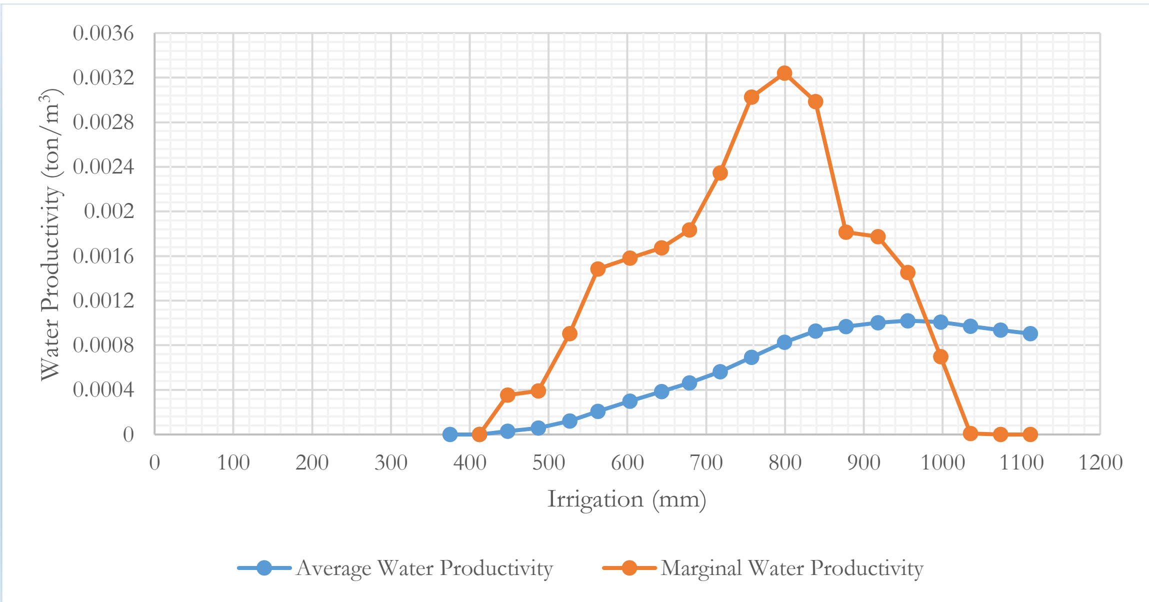


Figure 3.2 Average and marginal water productivity for wheat using furrow irrigation with no mulching practice

The average water productivity is increasing as long as the marginal water productivity is greater than the average water productivity. It is evident that when the MWP is increasing the AWP will also be increasing because in that part the crop yield is also increasing. However, when the MWP is decreasing but it is still greater than the AWP, then the AWP will increase because the additional yield obtained by the additional unit of water is not as large as the yield by the previous addition but is still more than the AWP at that point. This results in the increase of the AWP. When the MWP decreases to the point that the AWP is equal to the MWP, then that intersection point is the maximum AWP. After this point, the AWP is greater than the MWP and AWP is decreasing. Similarly, the additional crop yield obtained by the additional unit of water is smaller than it was before resulting in decreasing the AWP.

Irrigation techniques

The irrigation technique used determined how much percent of the surface is wetted and this determined the amount of evaporation that took place, which ultimately influenced the water productivity. By switching among the three types of irrigation techniques (sprinkler, furrow and drip irrigation), the maximum crop yield obtained remained the same, what varied was the irrigation water required to attain this maximum. With increasing efficiency of water application, the amount of water required to reach the maximum crop yield decreased. For instance, to produce a maximum of 10.048 tons of wheat in 1ha of land; we need 9513 m^3, 10355 m^3 and 10422 m^3 of water for drip, furrow and sprinkler irrigation, respectively (Figure 3.3).

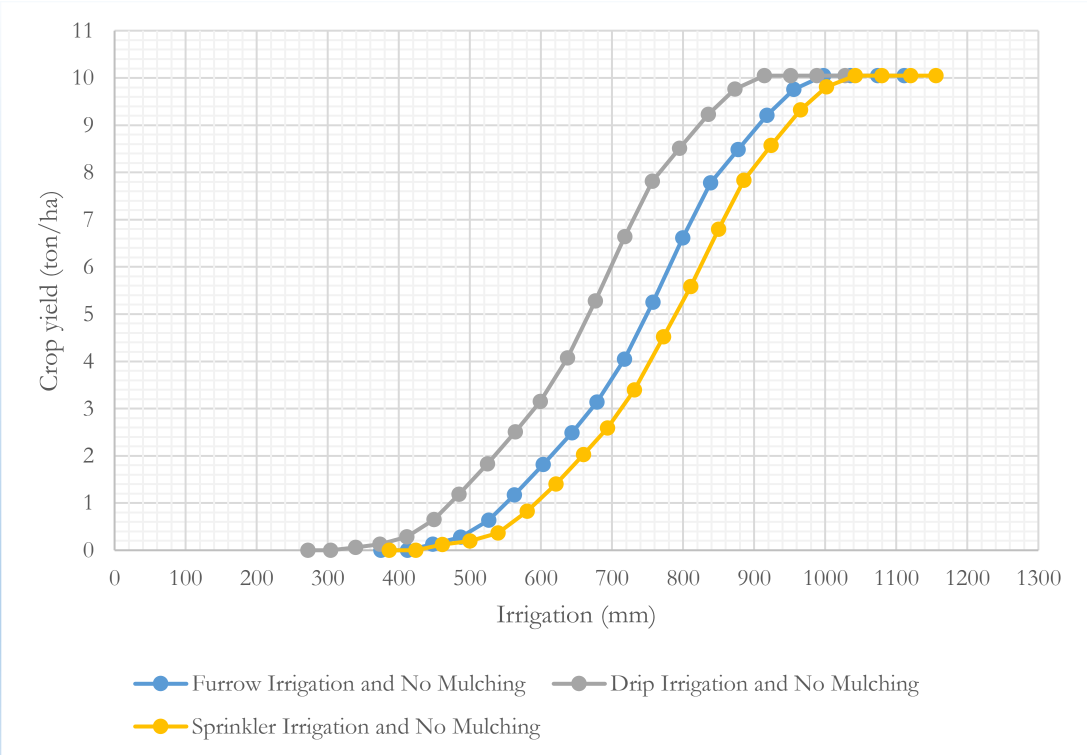


Figure 3.3 Crop yield of wheat for the three irrigation techniques with no mulching practice

Mulching practices

The mulching practice used controlled the percentage of surface that is covered. This also determined the amount of evaporation that also influenced the water productivity. Similar to changing the irrigation technique, changing the mulching practice does not affect the maximum crop yield obtained. However, it lowers the amount of water required to attain this maximum crop yield by reducing the evaporation that takes place. For example, to produce a maximum of 10.048 tons of wheat in 1ha of land; we need for furrow irrigation, 10355 m^3 and 9668 m^3 of water for no mulching, and organic mulching, respectively (Figure 3.4). For sprinkler irrigation, 10422 m^3 and 9733 m^3 of water for no mulching, and organic mulching, respectively (Figure 3.5). For drip irrigation, no reduction in the irrigation water requirement has been observed when organic mulches are used.

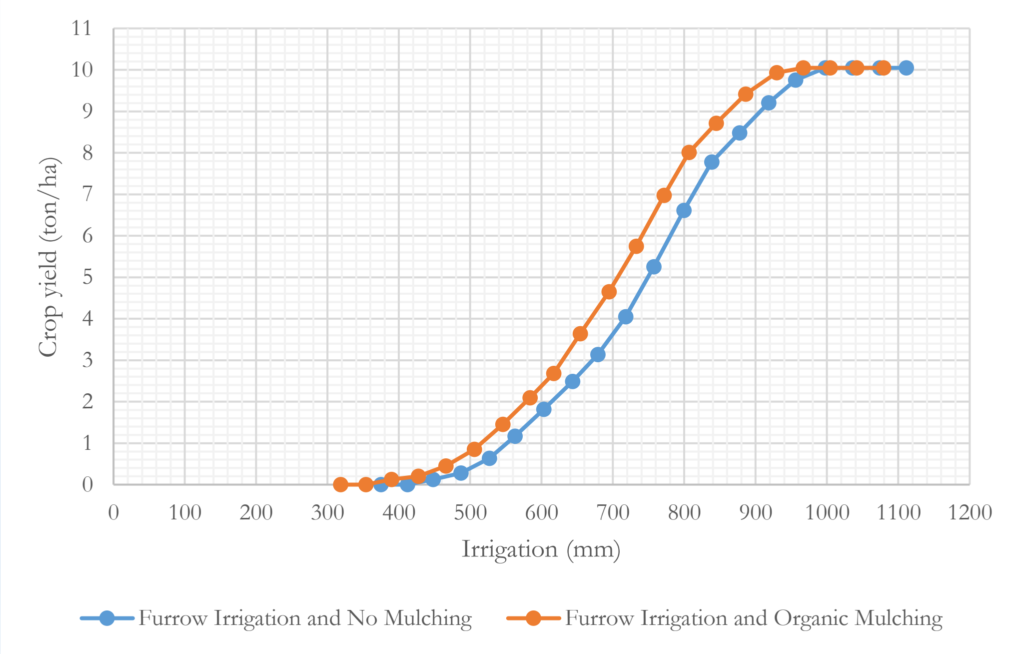


Figure 3.4 Crop yield of wheat for furrow irrigation with no mulching and organic mulching practices

Figure 3.5 Crop yield of wheat for sprinkler irrigation with no mulching and organic mulching practices

Effect of management practice on water productivity

The effect management practices (irrigation techniques and mulching practices) have on average and marginal water productivities is explained as follows.

Irrigation techniques

Average water productivity

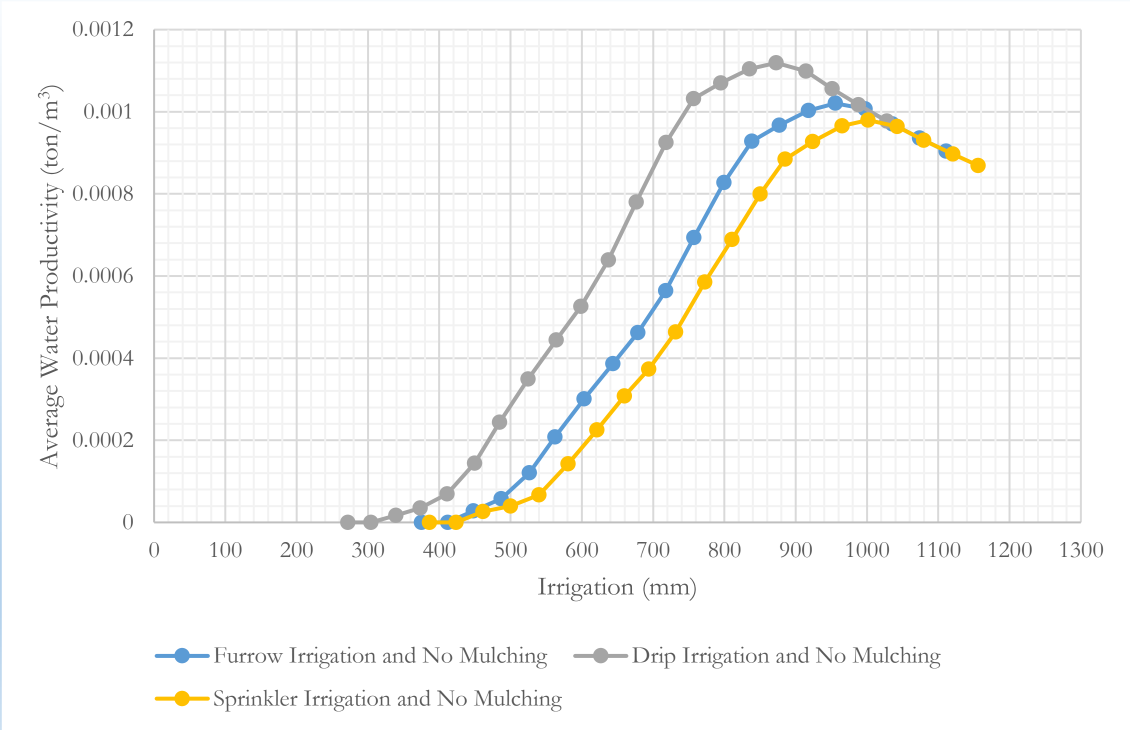


Figure 3.6 Average water productivity of wheat for the three irrigation techniques with no mulching practice

Switching the irrigation technique from sprinkler to furrow and to drip irrigation with no mulching practice resulted in the increase of the maximum average water productivity as shown in the above figure. Figure 3.6 also shows that with the change in the irrigation technique not only has the maximum AWP been increased but the volume of water required to reach this maximum has also been reduced. The main reason for sprinkler irrigation having a smaller maximum AWP has to do with the percentage of surface wetting. It wets 100% of the surface and that requires more amount of water and this also leads to more evaporation. On the other hand, drip irrigation wets only 30% of the surface that results in less evaporation and requiring less amount of water, which ultimately leads to attaining a higher maximum AWP. The AWP of furrow irrigation with 80% wetting lies in between the above two irrigation techniques (sprinkler and drip). Thus, by using more efficient irrigation techniques we can attain a higher maximum AWP with a lesser amount of water.

Marginal water productivity

The results show that when irrigation technique is changed the maximum MWP remains relatively the same but the volume at which this maximum is reached varies. The shape of the MWP is more or less the same because the MWP is simply the ratio of the change in crop yield to change in water use, and there is a similar change in the crop yield for the different irrigation techniques. This can be seen from the crop yield versus irrigation water use in Figure 3.3. As a more efficient irrigation techniques are applied the volume of water required becomes smaller and smaller. Drip irrigation requiring the least followed by furrow irrigation and sprinkler irrigation at the last place.

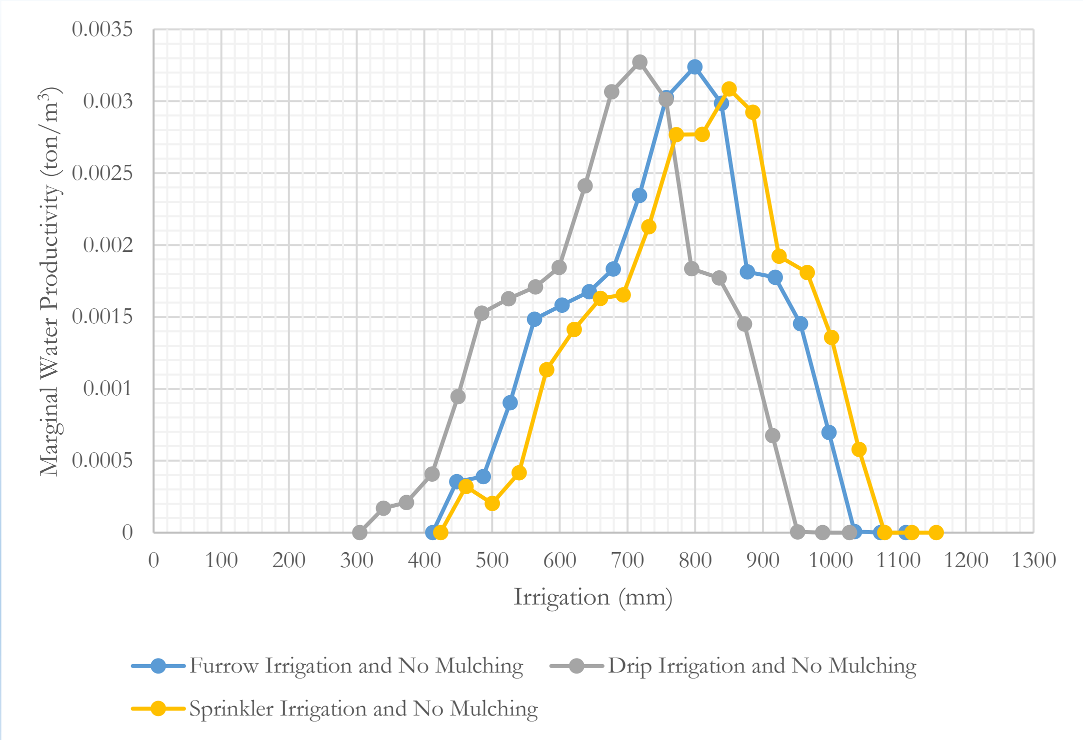


Figure 3.7 Marginal water productivity of wheat for the three irrigation techniques with no mulching practice

Mulching practices

Average water productivity

Figure 3.8 Average water productivity of wheat for furrow irrigation with two different mulching practices

Similar to switching the irrigation technique, changing the mulching practice also has an effect on the AWP. When organic mulches are used the amount of water that evaporates decreased and this resulted in increasing the maximum AWP; and this reduction in evaporation also decreased the amount of water required to reach this maximum value. As the percentage of surface wetted is highest in sprinkler irrigation, we observe a more pronounced change in this technique, followed by furrow irrigation. The use of organic mulches does not have any effect when drip irrigation is used, but due to the effectiveness of this technique, it results in attaining a highest maximum AWP with the least irrigation requirement as compared to both the other techniques even when organic mulches are used.

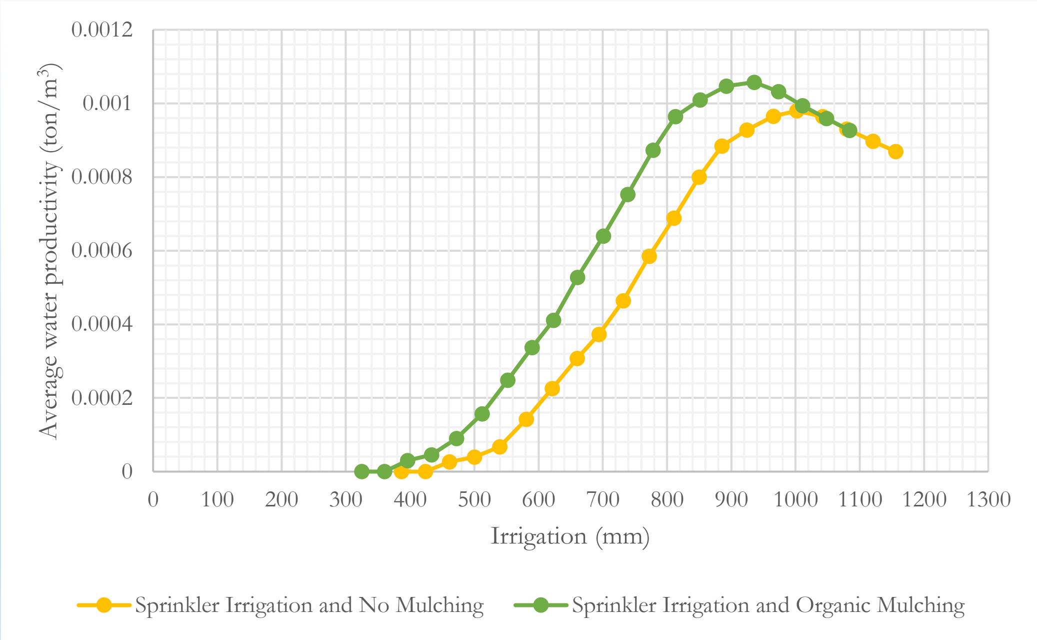


Figure 3.9 Average water productivity of wheat for sprinkler irrigation with two different mulching practices

Marginal water productivity

Figure 3.10 Effect of organic mulching on the marginal water productivity of wheat for furrow irrigation

Organic mulching has a similar effect as using a better and more efficient irrigation techniques, it does not increase the maximum MWP but rather shifts it a little to the left so it can be achieved with a smaller volume of water. In the case of furrow irrigation, there is a slight decrease in this maximum MWP when organic mulches are used (Figure 3.10) and a slight increase in sprinkler irrigation (Figure 3.11). On the other hand, for drip irrigation, no difference is observed when organic mulches are used but as observed in the case of AWP, the maximum MWP of drip irrigation is still slightly higher and is attained at a lower volume as compared with furrow and sprinkler irrigation (Figure 3.14).

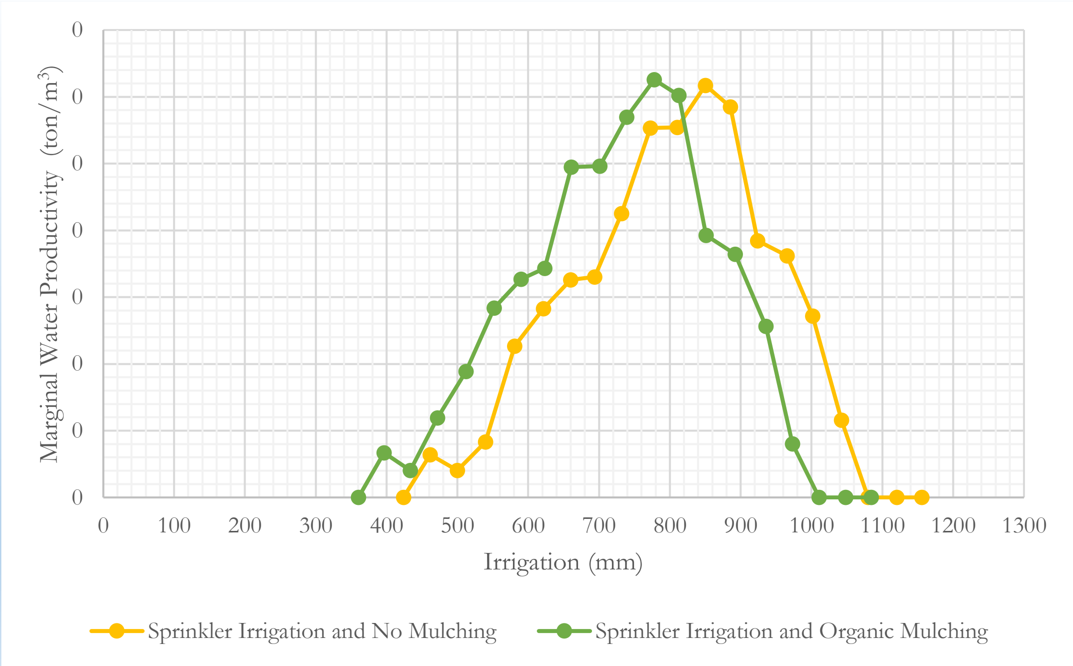


Figure 3.11 Effect of organic mulching on the marginal water productivity of wheat for sprinkler irrigation

When we put all the irrigation technique and mulching practice combinations in one single plot to show the difference in crop yield, AWP and MWP, the following figures are obtained.

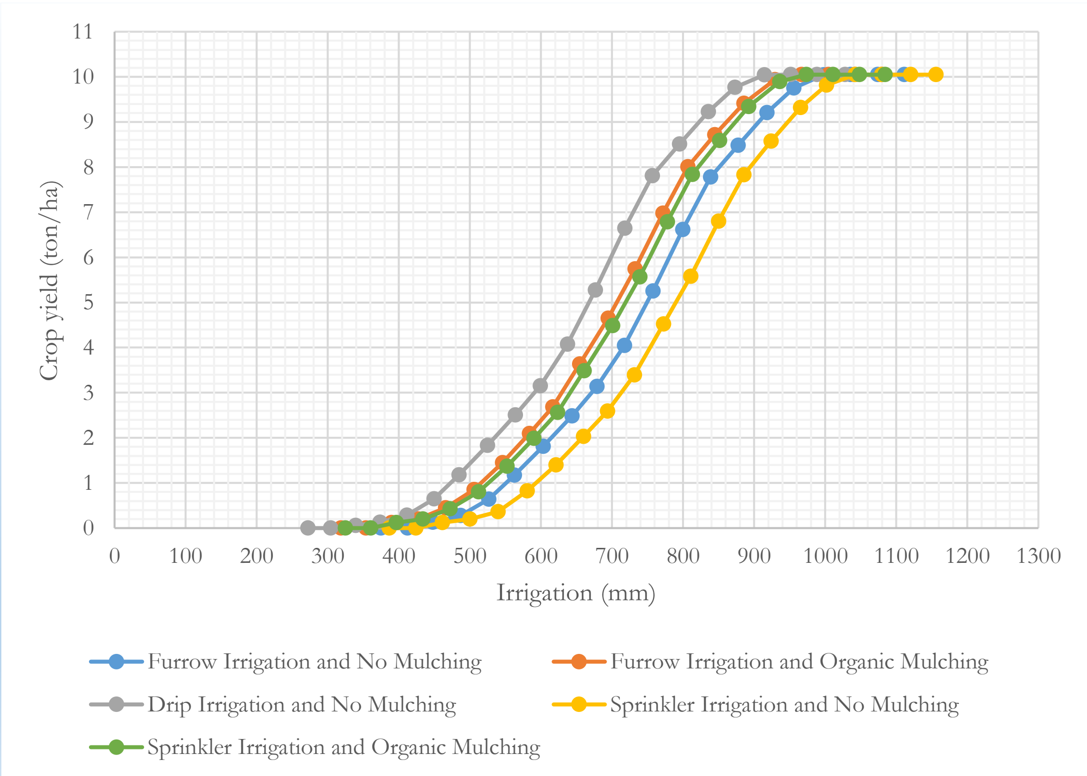


Figure 3.12 Crop yield of wheat for the different irrigation technique and mulching practice combinations

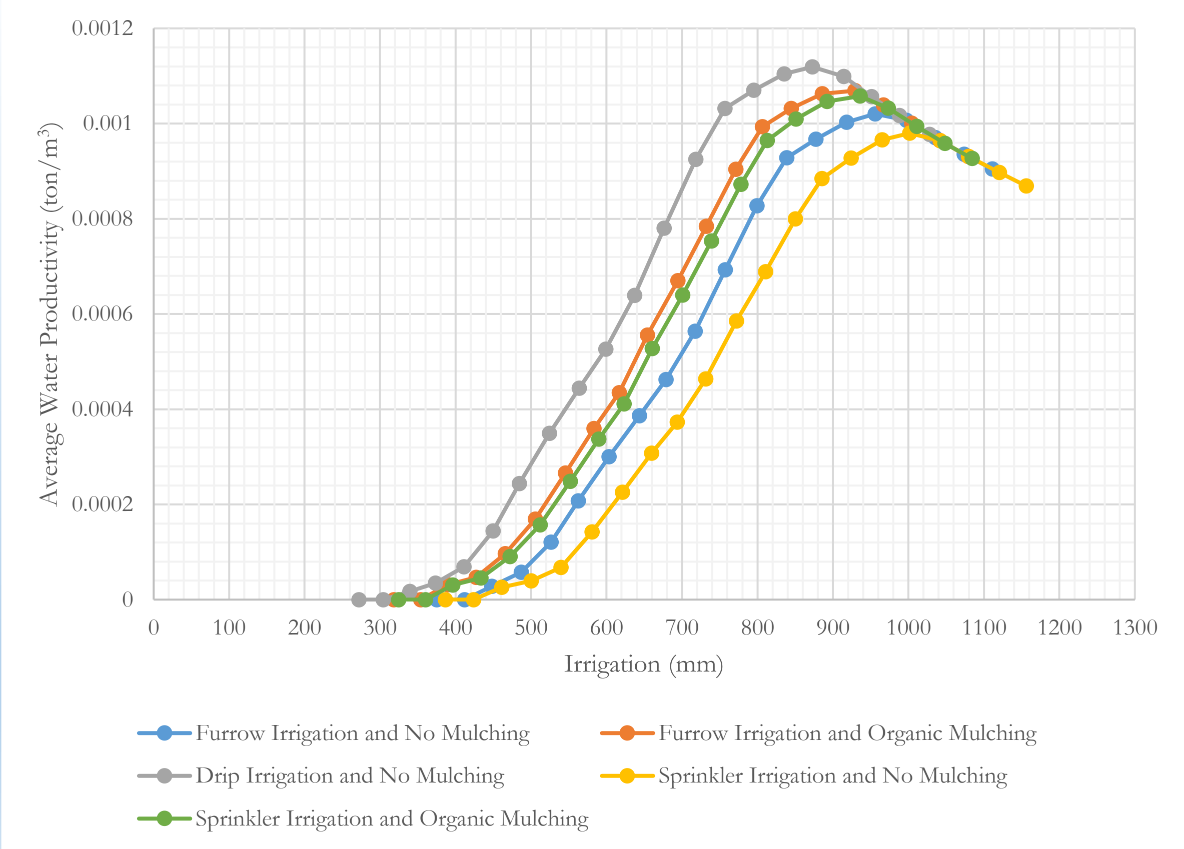


Figure 3.13 Average water productivity of wheat for the different irrigation technique and mulching practice combinations

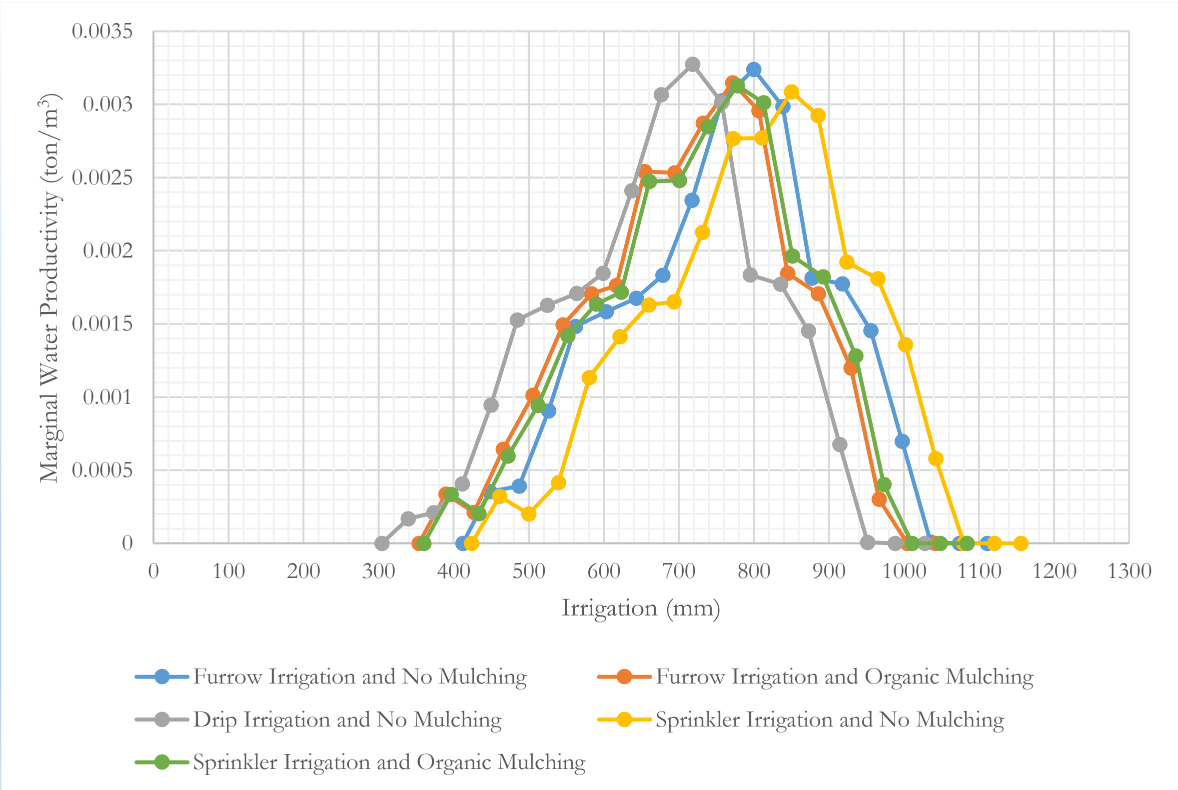


Figure 3.14 Marginal water productivity of wheat for the different irrigation technique and mulching practice combinations

Effect of irrigation scheduling on irrigation water saving and maximizing profit

Effect of irrigation scheduling on irrigation water saving while keeping the maximum crop yield

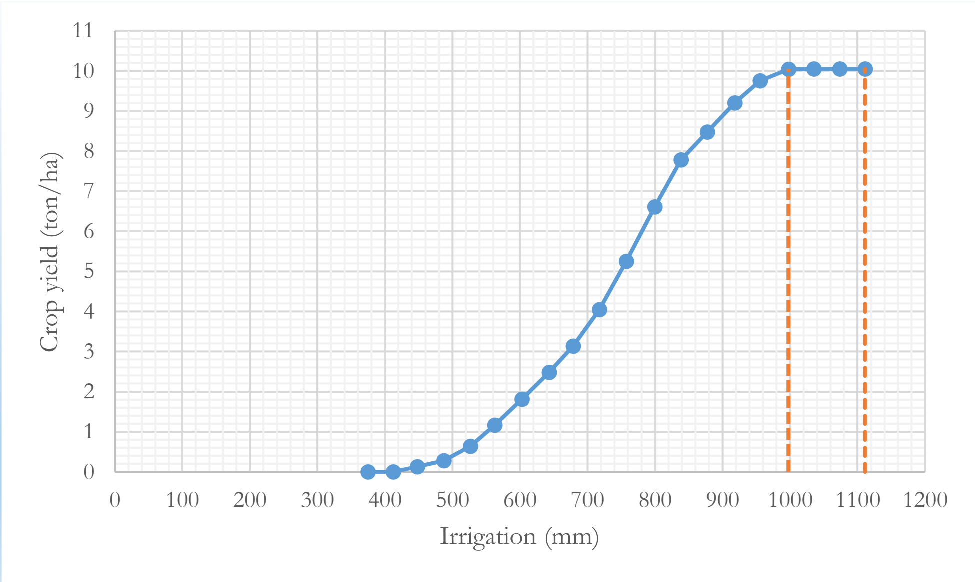


Figure 3.15 Volume of water saved by switching from fully meeting the crop's evaporative demand to partially meeting the demand for furrow irrigation in wheat

Appropriate irrigation scheduling plays an important role in irrigation water saving. By switching from the full irrigation in which we irrigate throughout the entire crop development (satisfying the crop's full evaporative demand) to irrigating up to a certain crop development stage (partially satisfying the crop's evaporative demand), a considerable amount of water is saved with no reduction in crop yield whatsoever. This was achieved with adequate knowledge of the drought sensitive stages of the crop development and applying this in the AquaCrop model. The volume of water that can be saved in a given area was calculated for a crop under a specific management practice.

Table 3.1 Amount of irrigation water saved using the different management practices for wheat and maize

Irrigation technique	Mulching practice	Irrigation water saved (m^3/ha)	
		Wheat	Maize
Furrow	No mulching	1135	1512
	Organic mulching	1123	1499
Sprinkler	No mulching	1137	1495
	Organic mulching	1109	1504
Drip	No mulching Organic mulching	1138	1587

Results show that about 1100 and 1500 m^3/ha of water can be saved for wheat and maize, respectively. The reason why more volume of water can be saved in maize than in wheat is due to the drought resistive nature of maize. Since maize is a C_4 plant, scarcity of water has a lesser impact on it.

Effect of irrigation scheduling in maximizing profit by considering price of water

When we ignore the price of water and unit price of the yield, then it is always profitable to aim for maximum crop yield. However, when we consider the prices of water and crop then how the profit can be maximized is not so straightforward. The following table shows for varying prices of water the profitability of producing at maximum crop yield, maximum AWP or maximum MWP.

$$\text{Difference} = \text{Revenue} - \text{Cost} \tag{8}$$

where:

$$\text{Revenue} = \text{Yield} * \text{Area} * \text{Unit price} \tag{9}$$

$$\text{Cost} = \text{Irrigation} * \text{Water Price} \tag{10}$$

In this study, an area of 1ha is assumed, the crop yield and irrigation requirement are determined using AquaCrop. For wheat the current unit price is 168 €/ton (FAO, 2017).

Table 3.2 Revenue-cost calculation for varying prices of water for wheat using furrow irrigation and no mulching

Wheat - Furrow Irrigation & No Mulching				Water Price (€/m³)					
				0.001			0.002	0.118	0.171
Irr (m³)	Y (ton/ha)	AWP (ton/m³)	MWP (ton/m³)	Revenue (€)	Cost (€)	Difference (€)	Diff. (€)	Diff. (€)	Diff. (€)
3749	0	0		0.00	3.75	-3.75	-7.50	-442.38	-641.08
4121	0	0	0	0.00	4.12	-4.12	-8.24	-486.28	-704.69
4478	0.126	0.00028	0.00035	21.17	4.48	16.69	12.21	-507.24	-744.57
4870	0.279	0.00057	0.00039	46.87	4.87	42.00	37.13	-527.79	-785.90
5266	0.637	0.00121	0.00090	107.02	5.27	101.75	96.48	-514.37	-793.47
5624	1.168	0.00208	0.00148	196.22	5.62	190.60	184.98	-467.41	-765.48
6031	1.812	0.00300	0.00158	304.42	6.03	298.39	292.35	-407.24	-726.89
6434	2.487	0.00387	0.00167	417.82	6.43	411.38	404.95	-341.40	-682.40
6788	3.136	0.00462	0.00183	526.85	6.79	520.06	513.27	-274.14	-633.90
7176	4.046	0.00564	0.00235	679.73	7.18	672.55	665.38	-167.04	-547.37
7574	5.25	0.00693	0.00303	882.00	7.57	874.43	866.85	-11.73	-413.15
7995	6.614	0.00827	**0.00324**	1111.15	8.00	1103.16	1095.16	167.74	-255.99
8386	7.781	0.00928	0.00298	1307.21	8.39	1298.82	1290.44	317.66	-126.80
8772	8.481	0.00967	0.00181	1424.81	8.77	1416.04	1407.26	389.71	-75.20
9180	9.205	0.01003	0.00177	1546.44	9.18	1537.26	1528.08	463.20	-23.34
9557	9.753	**0.01021**	0.00145	1638.50	9.56	1628.95	1619.39	**510.78**	**4.26**
9976	10.045	0.01007	0.00070	1687.56	9.98	1677.58	**1667.61**	510.39	-18.34
10355	10.048	0.00970	0.00001	1688.06	10.36	**1677.71**	1667.35	466.17	-82.64

As it can be seen from Table 3.2 using maximum AWP becomes profitable only when the price of water is between 0.118 and 0.171 €/m³. When the price of water is more than 0.171 €/m³, then it is better not to irrigate at all as it will only result in loss. On the other hand, when the price of water is less than 0.002 €/m³ then it is actually more profitable to irrigate at maximum crop yield as the price of water compared to the price of wheat is very small, hence resulting in a higher profit.

Maximizing crop production under scarcity

Depending on how much area we irrigate, we can have different possible production values for the same amount of available water. The results for three different amounts of available water for wheat in furrow irrigation with no mulching practice are shown in the following table. The highlighted values indicate the highest possible amount that can be produced for the available water and land.

Table 3.3 Calculation to determine the maximum production

Furrow Irrigation and No Mulching - Wheat										
Irr (mm)	Irr (m^3/ha)	Y (ton/ha)	MWP (ton/m^3)	AWP (ton/m^3)	Available water (m^3)					
					6000		10000		12000	
					P (ton)	IL (ha)	P (ton)	IL (ha)	P (ton)	IL (ha)
374.9	3749	0		0	0.000	1.000	0.000	1.000	0.000	1.000
412.1	4121	0	0	0	0.000	1.000	0.000	1.000	0.000	1.000
447.8	4478	0.126	0.00035	0.00003	0.126	1.000	0.126	1.000	0.126	1.000
487	4870	0.279	0.00039	0.00006	0.279	1.000	0.279	1.000	0.279	1.000
526.6	5266	0.637	0.00090	0.00012	0.637	1.000	0.637	1.000	0.637	1.000
562.4	5624	1.168	0.00148	0.00021	1.168	1.000	1.168	1.000	1.168	1.000
603.1	6031	1.812	0.00158	0.00030	1.803	0.995	1.812	1.000	1.812	1.000
643.4	6434	2.487	0.00167	0.00039	2.319	0.933	2.487	1.000	2.487	1.000
678.8	6788	3.136	0.00183	0.00046	2.772	0.884	3.136	1.000	3.136	1.000
717.6	7176	4.046	0.00235	0.00056	3.383	0.836	4.046	1.000	4.046	1.000
757.4	7574	5.25	0.00303	0.00069	4.159	0.792	5.250	1.000	5.250	1.000
799.5	**7995**	**6.614**	**0.00324**	**0.00083**	4.964	0.750	6.614	1.000	6.614	1.000
838.6	8386	7.781	0.00298	0.00093	5.567	0.715	7.781	1.000	7.781	1.000
877.2	8772	8.481	0.00181	0.00097	5.801	0.684	8.481	1.000	8.481	1.000
918	9180	9.205	0.00177	0.00100	6.016	0.654	9.205	1.000	9.205	1.000
955.7	**9557**	**9.753**	**0.00145**	**0.00102**	**6.123**	0.628	9.753	1.000	9.753	1.000
997.6	9976	10.045	0.00070	0.00101	6.041	0.601	**10.045**	1.000	10.045	1.000
1035.5	**10355**	**10.048**	**0**	**0.00097**	5.822	0.579	9.704	0.966	**10.048**	1.000

From Table 3.3, it can be seen that maximum crop production is not a single point from the CWPF but rather numerous points depending on the amount of water available for irrigation. When the available water is less than the volume of water required to attain maximum water productivity (9557 m^3/ha in this case), then in order to maximize crop production irrigation should be done to attain maximum productivity but this can only be achieved by irrigating lesser area than what is available. For instance, when we have 6000 m^3 and an area of 1ha, instead of irrigating the whole 1ha which would require 9557 m^3 of water, we can irrigate only 0.628ha and produce 6.123 tons. On the other hand, when the amount of water available is more than the volume of water required to attain maximum crop yield (10355 m^3/ha in this case), then in order to maximize crop production we should irrigate all the available land. For example, when the available water is 12000 m^3, then we can irrigate at maximum yield to produce 11.644 tons but this requires an area of 1.159ha which is more than tha available land (1ha). Hence, we irrigate the available 1ha at maximum yield to produce 10.048 tons. In the case the available water is between the volumes required to attain maximum productivity and maximum crop yield, then we can refer to the CWPF so as to know where exactly we can produce the most. This is summarized in the following figure.

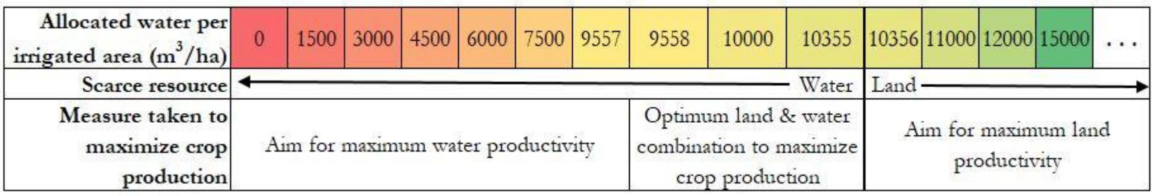


Figure 3.16 Heat map showing how crop production can be maximized under scarcity

The previous heat map shows the measure that should be taken for different values of available water in order to maximize crop production. Next we calculated the irrigated land and respective crop production for a range of available water and the results are summarized as follows:

Table 3.4 Irrigated land, crop production and respective crop yield for various amounts of available water

AW (m^3)	0	4000	6000	8000	9700	10356	11000	12000
IL (ha)	0	0.419	0.628	0.837	0.972	1	1	1
P (ton)	0	4.082	6.123	8.164	9.767	10.048	10.048	10.048
Y=P/IL (ton/ha)	-	9.753	9.753	9.753	10.045	10.048	10.048	10.048

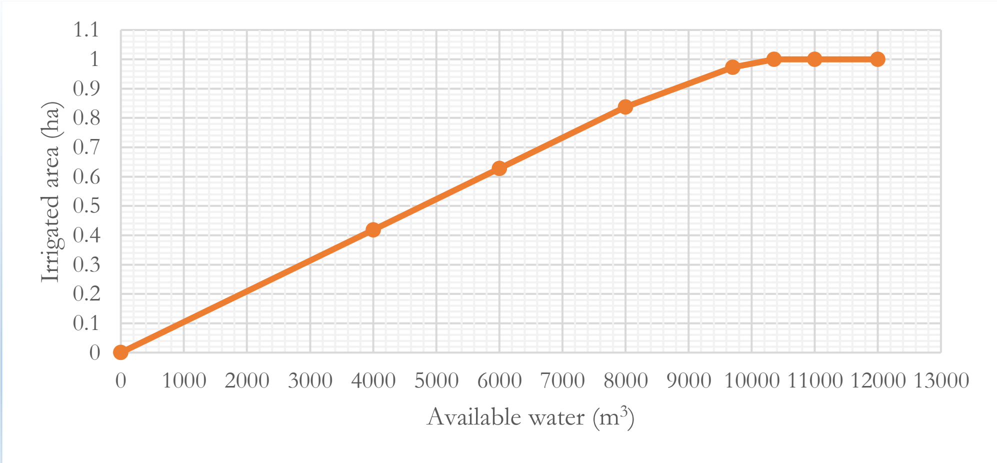


Figure 3.17 Irrigated land that results in the maximum production for the water and land available

From Figure 3.17, it can be seen that as the amount of available water increases the area that can be irrigated also increases linearly. This continues until all the available land is irrigated. Once all the available land is irrigated at maximum crop yield any further increase in the available water will not result in an increase the production as the land has reached its maximum producing potential and there is no more land available to be irrigated.

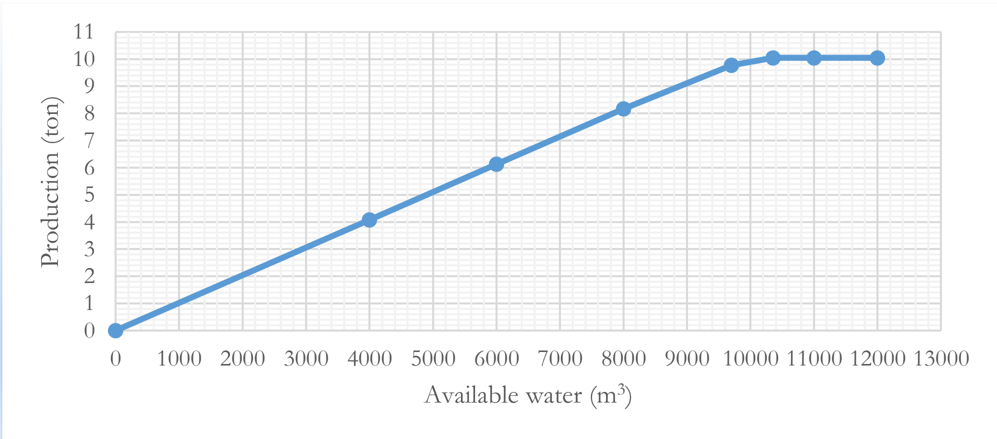


Figure 3.18 Maximum production based on the available land and water

Figure 3.18 shows that as the irrigated land increases linearly with the available water so does the production. However, once the maximum production is attained at maximum crop yield any further increase in the available water will not result in an increase in production unless the land that can be irrigated is also increased.

4. Conclusions

Water management strategies based on irrigation scheduling are intended to reduce the amount of water applied and to minimize yield reduction due to water stress. This will ensure that water is applied to the crop when needed and in the amount needed. Based on the knowledge of the growth stages and application in AquaCrop model we can conclude that, irrigation from first day of sowing throughout the crop development stage up to field capacity before the soil moisture drops to a threshold where the crop starts to experience canopy cover expansion stress results in the highest yield with the least irrigation requirement.

The water management practices implemented included other measures such as altering the irrigation technique and the mulching practice. From the study conducted, we can infer that the maximum crop yield obtained remains the same regardless of the management practices (irrigation techniques and mulching practices) employed; however, the amount of irrigation water required to reach the maximum crop yield is different. This applies for both wheat and maize, the only difference being that the maximum crop yield attained by maize is more than that of wheat. Using drip irrigation resulted in requiring the least amount of irrigation water followed by furrow and sprinkler irrigation, respectively. Using organic mulches reduced the evaporation that takes place reducing the crop's water requirement. However, using organic mulches in drip irrigation has no effect. Similarly, the maximum marginal productivity is unaffected by the different irrigation techniques and mulching practices employed but the irrigation requirement at which the crops reached this maximum varied.

With adequate knowledge of crop growth and drought sensitive stages, it is possible to reduce the irrigation volume in order to save about 1500 m^3/ha and 1100 m^3/ha of water for maize and wheat, respectively with no reduction in the maximum crop yield whatsoever. This implies that we can reduce the irrigation water by not meeting the full evaporative demand of the crop, but care should be taken to make sure we provide ample water in the drought sensitive stage so that the crop yield will not be compromised.

Competition for scarce water resources is already widely evident—from the Murray Darling basin in Australia to rivers of the Middle East, southern Africa and the Americas, and from the aquifers of northern India to the Maghreb and the Ogallala in the central US. In addition, with an increase in population arable land is also going to be scarcer. Therefore, in order to maximize our production under such scarcity, we need to consider which resource is scarce. When water is scarce, we should make sure we make every available drop count by producing at maximum water productivity even if we do not irrigate all the land we have available. On the other hand, when the scarce resource is land then we should irrigate at maximum land productivity so we can get the maximum yield and maximize our crop production.

We have noticed that AquaCrop has some inherent limitations, such as the neglecting of lateral water flows in the field, the inability to simulate the effects of nutrient limitation, fertilizer application, the effect of organic mulching on the organic content of the soil and decomposition of organic materials, and interception losses from sprinklers. In addition, the model is designed to predict at the single field scale (point simulations), which means the field is assumed uniform without spatial differences in crop development, transpiration, soil characteristics or management; and only green and blue water footprint are considered, gray water footprint is not taken into account. These limitations put a disclaimer on the results of our study, but we believe that the results of this study can provide a useful reference for similar future studies with other models. We see the need for further validation of our model results with field experiments, but this is costly and will generally need to focus on varying just a few management practices under a limited number of cases.

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Appendices

Appendix A – Model simulation results

Wheat

Table A. 1 Summary of results for wheat using furrow irrigation with no mulching

Furrow Irrigation and No Mulching						
Irr (mm)	**E (mm)**	**T (mm)**	**ET (mm)**	**Y (ton/ha)**	**MWP (ton/m³)**	**AWP (ton/m³)**
374.9	111.5	263.8	375.3	0		0
412.1	114.1	298.2	412.3	0	0	0
447.8	115.9	332	447.9	0.126	0.00035	0.00003
487	117.2	368	485.2	0.279	0.00039	0.00006
526.6	118.4	405.1	523.5	0.637	0.00090	0.00012
562.4	119.2	439.6	558.8	1.168	0.00148	0.00021
603.1	119.9	478.8	598.7	1.812	0.00158	0.00030
643.4	120.4	517.1	637.5	2.487	0.00167	0.00039
678.8	120.7	551.2	671.9	3.136	0.00183	0.00046
717.6	120.9	588.9	709.8	4.046	0.00235	0.00056
757.4	121.1	627.3	748.4	5.25	0.00303	0.00069
799.5	121.1	668.4	789.5	6.614	**0.00324**	0.00083
838.6	121.1	705.7	826.8	7.781	0.00298	0.00093
877.2	121.5	740.3	861.8	8.481	0.00181	0.00097
918	122	772	894	9.205	0.00177	0.00100
955.7	122.6	795.7	918.3	9.753	0.00145	**0.00102**
997.6	123.3	808.5	931.8	10.045	0.00070	0.00101
1035.5	124.6	808.6	933.2	**10.048**	0.00001	0.00097
1073.7	126.8	808.6	935.4	10.048	0	0.00094
1111.1	131.2	808.6	939.8	10.048	0	0.00090

Table A. 2 Summary of results for wheat using furrow irrigation with organic mulching

Furrow Irrigation and Organic Mulching						
Irr (mm)	**E (mm)**	**T (mm)**	**ET (mm)**	**Y (ton/h**	**MWP (ton/m³)**	**AWP (ton/m³)**
318.3	72.7	244.6	317.3	0		0
353.7	74.5	278.3	352.8	0	0	0
389.7	75.8	313.1	388.9	0.121	0.00034	0.00003
427	76.7	348.7	425.4	0.2	0.00021	0.00005
465.7	77.4	384.9	462.3	0.449	0.00064	0.00010
505.7	77.9	423.8	501.7	0.854	0.00101	0.00017
545.7	78.3	462.7	541	1.451	0.00149	0.00027
583.5	78.5	500	578.5	2.096	0.00171	0.00036
616.8	78.6	531.9	610.5	2.683	0.00176	0.00043
654.3	78.8	569	647.8	3.636	0.00254	0.00056
694.4	78.7	608.5	687.2	4.652	0.00253	0.00067
732.4	78.8	645.8	724.6	5.743	0.00287	0.00078
771.5	78.7	684	762.7	6.974	**0.00315**	0.00090
806.5	78.7	717.5	796.2	8.009	0.00296	0.00099
844.7	79.1	750.5	829.6	8.714	0.00185	0.00103
885.7	79.4	781	860.4	9.413	0.00170	0.00106
929.3	79.8	803.6	883.4	9.935	0.00120	**0.00107**
966.8	80.5	808.6	889.1	**10.048**	0.00030	0.00104
1004.3	81.6	808.6	890.2	10.048	0	0.00100
1041.7	83.6	808.6	892.2	10.048	0	0.00096
1079.1	85.6	808.6	894.2	10.048	0	0.00093

Table A. 3 Summary of results for wheat using sprinkler irrigation with no mulching

Sprinkler Irrigation and No Mulching						
Irr (mm)	E (mm)	T (mm)	ET (mm)	Y (ton/ha)	MWP (ton/m³)	AWP (ton/m³)
386.3	145.4	240.7	386.1	0		0
423.8	149	274.1	423.1	0	0	0
461.3	151.7	308.8	460.5	0.12	0.00032	0.00003
500	154	344	498	0.198	0.00020	0.00004
539.7	155.8	379.8	535.6	0.363	0.00042	0.00007
580.6	157.2	418.2	575.4	0.826	0.00113	0.00014
621.3	158.6	456.9	615.5	1.401	0.00141	0.00023
659.8	159.7	494.2	653.9	2.028	0.00163	0.00031
693.7	160.4	526.2	686.6	2.588	0.00165	0.00037
731.6	161.3	563.4	724.7	3.394	0.00213	0.00046
772.3	161.9	602.9	764.8	4.52	0.00277	0.00059
810.6	162.4	640.3	802.7	5.581	0.00277	0.00069
850	162.8	678.6	841.4	6.797	**0.00309**	0.00080
885.3	163.2	712.4	875.6	7.829	0.00292	0.00088
923.9	163.9	746.1	910	8.571	0.00192	0.00093
965.3	164.7	777.4	942.1	9.32	0.00181	0.00097
1001.6	165.4	798.3	963.7	9.813	0.00136	**0.00098**
1042.2	166.2	808.6	974.8	**10.048**	0.00058	0.00096
1079.8	167.4	808.6	976	10.048	0	0.00093
1120.3	170.3	808.6	978.9	10.048	0	0.00090
1155.9	177.1	808.6	985.7	10.048	0	0.00087

Table A. 4 Summary of results for wheat using sprinkler irrigation with organic mulching

Sprinkler Irrigation and Organic Mulching						
Irr (mm)	E (mm)	T (mm)	ET (mm)	Y (ton/ha)	MWP (ton/m³)	AWP (ton/m³)
324.7	81.5	240.6	322.1	0		0
360.2	83.6	274.3	357.9	0	0	0
396.2	85	309.1	394.1	0.12	0.00033	0.00003
433.5	86.2	344.6	430.8	0.196	0.00020	0.00005
472.1	87.1	380.6	467.7	0.426	0.00060	0.00009
512.2	87.8	419.3	507.1	0.804	0.00094	0.00016
552.1	88.5	458.4	546.9	1.37	0.00142	0.00025
589.9	89	495.9	584.9	1.988	0.00163	0.00034
623.3	89.4	528	617.4	2.561	0.00172	0.00041
660.7	89.9	565.2	655.1	3.486	0.00247	0.00053
700.9	90.1	604.7	694.8	4.483	0.00248	0.00064
738.9	90.4	642.3	732.7	5.565	0.00285	0.00075
778	90.6	680.6	771.2	6.788	**0.00313**	0.00087
812.9	90.8	714.3	805.1	7.839	0.00301	0.00096
851.2	91.2	747.7	838.9	8.591	0.00196	0.00101
892.2	91.6	778.7	870.3	9.338	0.00182	0.00105
935.8	92	802	894	9.897	0.00128	**0.00106**
973.3	92.3	808.6	900.9	**10.048**	0.00040	0.00103
1010.8	93	808.6	901.6	10.048	0	0.00099
1048.2	94.5	808.6	903.1	10.048	0	0.00096
1084.2	96.3	808.6	904.9	10.048	0	0.00093

Table A. 5 Summary of results for wheat using drip irrigation with no mulching

Drip Irrigation and No/Organic Mulching						
Irr (mm)	**E (mm)**	**T (mm)**	**ET (mm)**	**Y (ton/ha)**	**MWP (ton/m³)**	**AWP (ton/m³)**
272	35.8	234.1	269.9	0		0
304.2	36.2	266	302.2	0	0	0
339.2	36.8	300.5	337.3	0.059	0.00017	0.00002
373.2	37.1	334.2	371.3	0.13	0.00021	0.00003
411.1	37.8	369.9	407.7	0.284	0.00041	0.00007
449.6	38	407.1	445.1	0.648	0.00095	0.00014
484.6	38.2	441.5	479.7	1.182	0.00153	0.00024
524.5	38.2	480.6	518.8	1.831	0.00163	0.00035
564	38.3	518.6	556.9	2.506	0.00171	0.00044
598.9	38.3	552.6	590.9	3.15	0.00185	0.00053
637.1	38.2	590.2	628.4	4.071	0.00241	0.00064
676.4	38.2	628.6	666.8	5.276	0.00307	0.00078
718.1	38	669.6	707.6	6.641	**0.00327**	0.00092
756.9	37.9	706.8	744.7	7.81	0.00301	0.00103
795	38	741.3	779.3	8.509	0.00183	0.00107
835.5	38.1	772.8	810.9	9.226	0.00177	0.00110
872.7	38.3	796.2	834.5	9.766	0.00145	**0.00112**
914.2	38.5	808.6	847.1	10.046	0.00067	0.00110
951.3	38.7	808.6	847.3	**10.048**	0.00001	0.00106
988	39.3	808.6	847.9	10.048	0	0.00102
1028	40.9	808.6	849.5	10.048	0	0.00098

Maize

Table B. 1 Summary of results for maize using furrow irrigation with no mulching

Furrow Irrigation and No Mulching						
Irr (mm)	E (mm)	T (mm)	ET (mm)	Y (ton/ha)	MWP (ton/m³)	AWP (ton/m³)
137.3	61.7	67.3	129	0		0
154.2	66.2	81.4	147.6	0	0	0
168.8	70.7	92.9	163.6	0.105	0.00072	0.00006
185.3	75.9	104.9	180.8	0.175	0.00042	0.00009
203.8	79.3	120.2	199.5	0.269	0.00051	0.00013
224.6	81.8	137.8	219.6	0.47	0.00097	0.00021
243.9	82.5	155.5	238	0.811	0.00177	0.00033
271	82.8	181.5	264.3	1.492	0.00251	0.00055
294	82.7	203.8	286.5	2.169	0.00294	0.00074
325.1	82.6	233.1	315.7	3.058	0.00286	0.00094
351.8	82.4	258.4	340.8	3.973	0.00343	0.00113
382.1	82.1	287.4	369.5	5.073	0.00363	0.00133
411.5	81.8	315.3	397.1	6.265	0.00405	0.00152
442.8	81.5	344.2	425.7	7.819	0.00496	0.00177
477.6	81.1	376.6	457.7	9.361	0.00443	0.00196
506.8	80.7	404.1	484.8	10.921	**0.00534**	0.00215
538.5	80.3	433.5	513.8	11.966	0.00330	**0.00222**
571.6	80.3	456.7	537	12.673	0.00214	0.00222
609.3	80.4	475.5	555.9	13.232	0.00148	0.00217
649	80.6	485.6	566.2	13.503	0.00068	0.00208
685.9	80.8	486.7	567.5	**13.528**	0.00007	0.00197
722.2	81.1	486.7	567.8	13.528	0	0.00187
758.7	81.7	486.7	568.4	13.528	0	0.00178
796.5	83.6	486.7	570.3	13.528	0	0.00170
837.1	90.3	486.7	577	13.528	0	0.00162

Table B. 2 Summary of results for maize using furrow irrigation with organic mulching

Furrow Irrigation and Organic Mulching						
Irr (mm)	E (mm)	T (mm)	ET (mm)	Y (ton/ha)	MWP (ton/m³)	AWP (ton/m³)
107	37.9	57.7	95.6	0		0
119.6	41.7	69	110.7	0	0	0
134.3	44.5	82.9	127.4	0	0	0
149.8	47.9	96.1	144	0.108	0.00070	0.00007
172	51.1	115.8	166.9	0.258	0.00068	0.00015
193.5	52.2	135.3	187.5	0.461	0.00094	0.00024
216	52.7	156.1	208.8	0.816	0.00158	0.00038
242.7	52.6	182	234.6	1.5	0.00256	0.00062
265.4	52.6	204.2	256.8	2.177	0.00298	0.00082
296.2	52.4	233.4	285.8	3.065	0.00288	0.00103
322.8	52.2	258.6	310.8	3.98	0.00344	0.00123
353.1	52	287.7	339.7	5.08	0.00363	0.00144
382.4	51.7	315.5	367.2	6.272	0.00407	0.00164
413.6	51.5	344.3	395.8	7.825	0.00498	0.00189
448.4	51.2	376.8	428	9.368	0.00443	0.00209
477.6	50.9	404.3	455.2	10.927	**0.00534**	0.00229
509.3	50.6	433.7	484.3	11.971	0.00329	**0.00235**
542.4	50.6	456.8	507.4	12.677	0.00213	0.00234
580	50.7	475.5	526.2	13.235	0.00148	0.00228
619.7	50.8	485.7	536.5	13.504	0.00068	0.00218
656.5	50.9	486.7	537.6	**13.528**	0.00007	0.00206
692.8	51.1	486.7	537.8	13.528	0	0.00195
729.2	51.6	486.7	538.3	13.528	0	0.00186
766.8	52.9	486.7	539.6	13.528	0	0.00176
806.4	57.8	486.7	544.5	13.528	0	0.00168

Table B. 3 Summary of results for maize using sprinkler irrigation with no mulching

Sprinkler Irrigation and No Mulching						
Irr (mm)	E (mm)	T (mm)	ET (mm)	Y (ton/ha)	MWP (ton/m³)	AWP (ton/m³)
150.4	76.9	64.7	141.6	0		0
164	81.4	76.1	157.5	0	0	0
184.1	88.7	90.6	179.3	0.102	0.00051	0.00006
202.9	96.3	103	199.3	0.114	0.00006	0.00006
221.8	100.1	118.4	218.5	0.262	0.00078	0.00012
240.1	102.6	132.7	235.3	0.374	0.00061	0.00016
263.1	104.4	152.6	257	0.694	0.00139	0.00026
290.5	105.3	179.1	284.4	1.434	0.00270	0.00049
313.5	105.7	201.4	307.1	2.089	0.00285	0.00067
344.6	106.1	230.8	336.9	2.966	0.00282	0.00086
371.4	106.2	256	362.2	3.888	0.00344	0.00105
401.7	106.2	285	391.2	4.966	0.00356	0.00124
431.2	106.2	312.9	419.1	6.149	0.00401	0.00143
462.4	106.1	341.8	447.9	7.697	0.00496	0.00166
497.2	106	374.3	480.3	9.254	0.00447	0.00186
526.5	105.9	401.8	507.7	10.795	**0.00526**	0.00205
558.2	105.8	431.4	537.2	11.864	0.00337	0.00213
591.4	105.9	454.9	560.8	12.604	0.00223	**0.00213**
629.1	106	473.9	579.9	13.187	0.00155	0.00210
668.8	106.1	484.8	590.9	13.484	0.00075	0.00202
705.7	106.3	486.7	593	**13.528**	0.00012	0.00192
742.1	106.4	486.7	593.1	13.528	0	0.00182
778.6	106.6	486.7	593.3	13.528	0	0.00174
816.6	107.5	486.7	594.2	13.528	0	0.00166
855.2	113	486.7	599.7	13.528	0	0.00158

Table B. 4 Summary of results for maize using sprinkler irrigation with organic mulching

Sprinkler Irrigation and Organic Mulching						
Irr (mm)	E (mm)	T (mm)	ET (mm)	Y (ton/ha)	MWP (ton/m³)	AWP (ton/m³)
119.7	43.6	67.1	110.7	0		0
134.4	46.4	80.9	127.3	0	0	0
149.8	49.3	94.8	144.1	0.107	0.00069	0.00007
172.4	53.3	113.3	166.6	0.19	0.00037	0.00011
194	55.2	133.1	188.3	0.438	0.00115	0.00023
216.5	56.3	154.3	210.6	0.778	0.00151	0.00036
243.1	56.8	180.5	237.3	1.44	0.00249	0.00059
265.8	57.1	202.7	259.8	2.102	0.00292	0.00079
296.7	57.3	231.9	289.2	2.983	0.00285	0.00101
323.3	57.3	257.1	314.4	3.889	0.00341	0.00120
353.5	57.3	286.1	343.4	4.987	0.00364	0.00141
382.9	57.3	314	371.3	6.171	0.00403	0.00161
414.1	57.3	342.9	400.2	7.727	0.00499	0.00187
448.9	57.2	375.5	432.7	9.293	0.00450	0.00207
478.1	57.2	403	460.2	10.836	**0.00528**	0.00227
509.7	57.1	432.5	489.6	11.908	0.00339	**0.00234**
542.8	57.2	455.8	513	12.636	0.00220	0.00233
580.5	57.2	474.6	531.8	13.209	0.00152	0.00228
620.1	57.3	485.2	542.5	13.492	0.00071	0.00218
657	57.4	486.7	544.1	**13.528**	0.00010	0.00206
693.3	57.5	486.7	544.2	13.528	0	0.00195
729.7	57.6	486.7	544.3	13.528	0	0.00185
767.3	57.9	486.7	544.6	13.528	0	0.00176
807.4	60.5	486.7	547.2	13.528	0	0.00168

Table B. 5 Summary of results for maize using drip irrigation with no mulching

Drip Irrigation and No/Organic Mulching						
Irr (mm)	**E (mm)**	**T (mm)**	**ET (mm)**	**Y (ton/ha)**	**MWP (ton/m³)**	**AWP (ton/m³)**
95.2	22.3	60.9	83.2	0		0
109.5	24	76.3	100.3	0	0	0
127.8	25.6	94.5	120.1	0.107	0.00058	0.00008
145.9	27.2	111.6	138.8	0.187	0.00044	0.00013
166.9	28.1	131.2	159.3	0.372	0.00088	0.00022
188.3	28.6	150.8	179.4	0.699	0.00153	0.00037
212.8	28.9	174.6	203.5	1.332	0.00258	0.00063
237	28.9	198.2	227.1	1.993	0.00273	0.00084
265.7	29	225.6	254.6	2.824	0.00290	0.00106
298.5	28.9	256.6	285.5	3.963	0.00347	0.00133
330.7	28.8	287.5	316.3	5.079	0.00347	0.00154
360.5	28.8	315.7	344.5	6.464	0.00465	0.00179
391.7	28.6	344.5	373.1	7.832	0.00438	0.00200
426.4	28.4	377	405.4	9.375	0.00445	0.00220
455.6	28.2	404.5	432.7	10.935	**0.00534**	0.00240
487.2	28	433.9	461.9	11.978	0.00330	**0.00246**
520.3	28	457	485	12.682	0.00213	0.00244
558	28.1	475.7	503.8	13.238	0.00147	0.00237
597.5	28.1	485.7	513.8	13.505	0.00068	0.00226
634.4	28.2	486.7	514.9	**13.528**	0.00006	0.00213
670.6	28.3	486.7	515	13.528	0	0.00202
714.4	28.4	486.7	515.1	13.528	0	0.00189
757.6	29.3	486.7	516	13.528	0	0.00179
793.1	30.8	486.7	517.5	13.528	0	0.00171

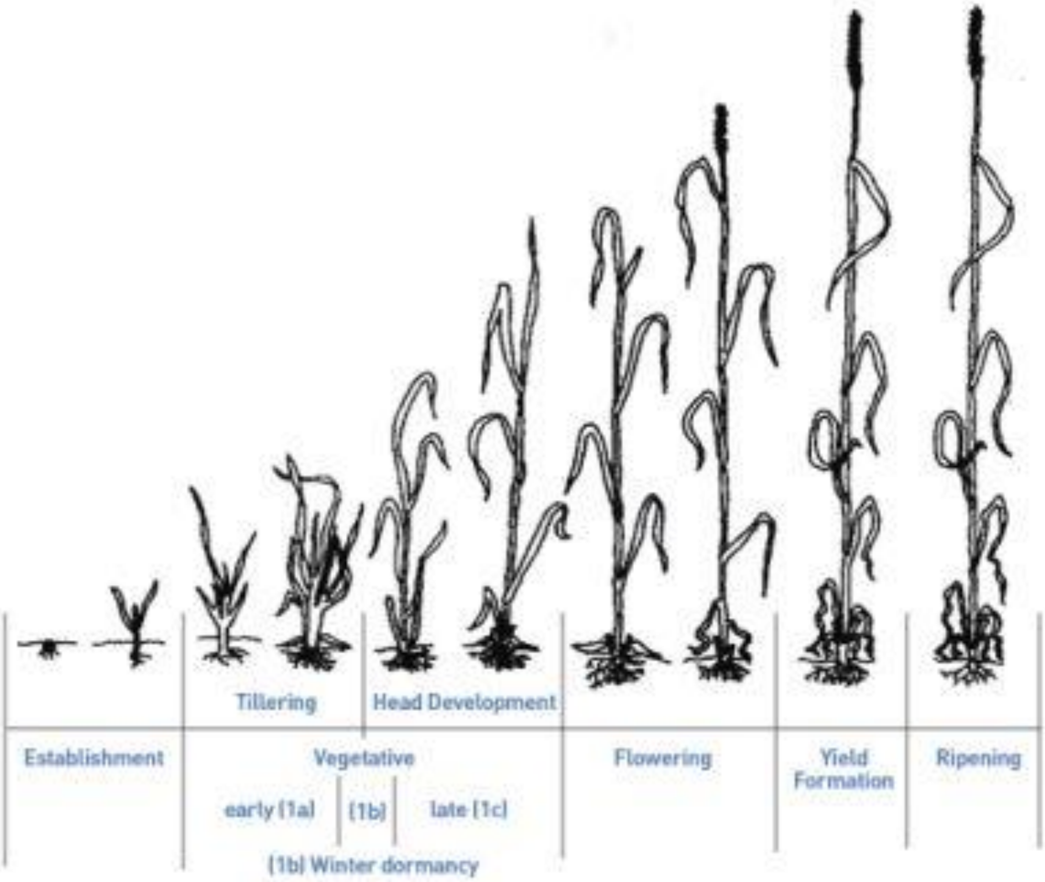
Appendix B – Crop parameters

According to Raes et al. (2009), the recommended values provided for the crop parameters in the tables below represent estimates obtained in calibration-validation exercises of AquaCrop with experimental data. How good these estimates are depends on how extensive and thorough were the calibration and validation, and varies with the crop species listed. The experimental data used for a crop might have been taken in one to many locations, with or without water and temperature as limiting factors, and representing a few to many years of experiments. The notes and symbols before each table provides an indication of the thoroughness of the calibration-validation process with respect to optimal and water stress conditions, as well as with respect to the coverage of major production areas of that crop around the world. Note that if a crop is important in many geographical areas, even if testing with data from four or five diverse locations would not be considered thorough, whereas testing with data from three locations for a crop limited to one geographical area may be considered as adequate.

The experiments used for calibration and validation were generally conducted under high levels of management, with the control treatments aimed at production levels close to the maximum potential achievable in that location. All the data used were obtained under conditions of good soil mineral nutrient status. The soil fertility feature of AquaCrop is just beginning to be tested now with data.

AquaCrop is a relatively simple model by design, yet suitable for the simulation of most herbaceous species. The decision was made to keep the model simple and more general. The model can be modified to account for some unusual characteristic specific for a particular crop, but to do that for a number of crops each with its own special characteristics would make the model too complex. The user should be aware of this limitation of the model. Examples of such special characteristics are: (1) The cutout phenomenon exhibited by cotton under some conditions, when additional flowers (squares) and young fruits (bolls) no longer form when the fruit load is already large; but once the existing fruits mature and conditions are favorable, new flowers and fruits are produced again. Cutout can be induced by mild to moderate water stress but is simulated only indirectly in a limited way by the model. (2) Low land (flooded) rice can experience substantial variations in the water level of the field. This would determine how much of the canopy is submerged and not transpiring or photosynthesizing, and hence not producing biomass. The model does not consider submergence and assumes only a very small part of the canopy is submerged and this has no effect on transpiration or biomass production.

Wheat



Goodness of the calibration

- Non-limiting conditions ☺ ☺
- Water stress conditions ☺
- Geographical coverage (with respect to the world cropped areas) ☺ ☺
- Overall ☺ ☺

◘	No calibration
☺	Minimum degree of calibration
☺ ☺	Medium degree of calibration
☺ ☺ ☺	Good degree of calibration
☺ ☺ ☺ ☺	Optimum degree of calibration

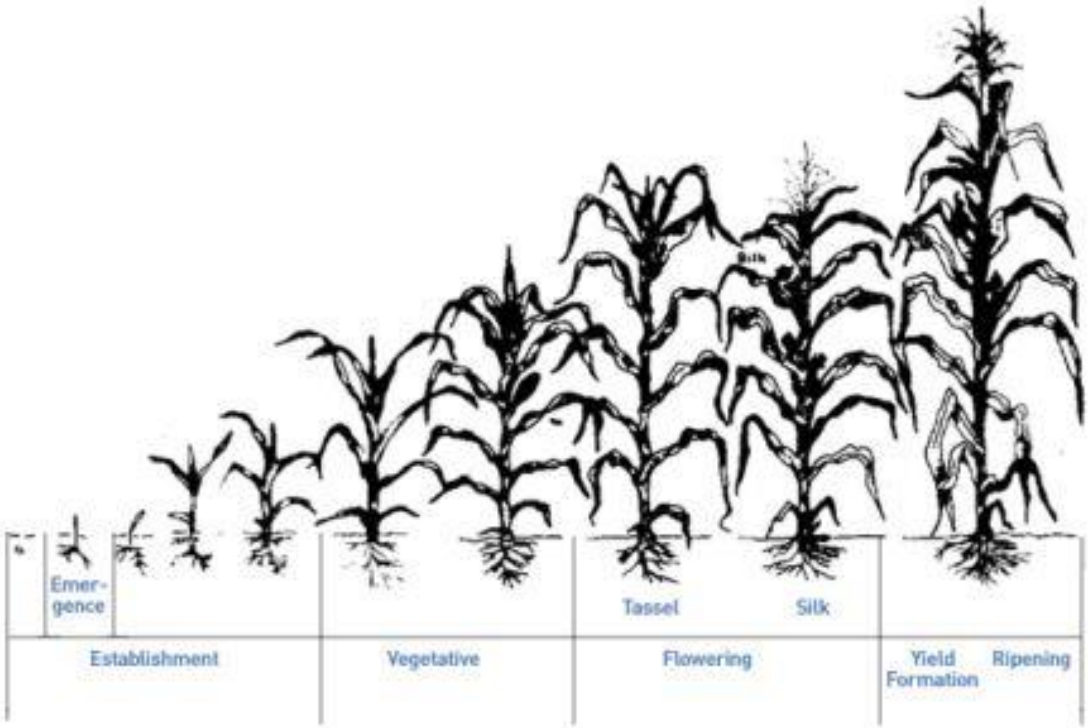
1. Crop Phenology			
Symbol	Description	Type (1), (2), (3), (4)	Values / ranges
1.1 Threshold air temperatures			
T_{base}	Base temperature (°C)	Conservative (1)	0.0
T_{upper}	Upper temperature (°C)	Conservative (1)	26.0
1.2 Development of green canopy cover			
cc_0	Soil surface covered by an individual seedling at 90% emergence (cm2/plant)	Conservative (2)	1.50
	Number of plants per hectare	Management (3)	2,000,000 – 7,000,000
	Time from sowing to emergence (growing degree day)	Management (3)	100 - 250
CGC	Canopy growth coefficient (fraction per growing degree day)	Conservative (1)	0.005 - 0.007
CC_x	Maximum canopy cover (%)	Management (3)	80 – 99 %
	Time from sowing to start senescence (growing degree day)	Cultivar (4)	Time to emergence + 1000 - 2000
CDC	Canopy decline coefficient (fraction per growing degree day)	Conservative (1)	0.004
	Time from sowing to maturity, i.e. length of crop cycle (growing degree day)	Cultivar (4)	Time to emergence + 1500 - 2900
1.3 Flowering			
	Time from sowing to flowering (growing degree day)	Cultivar (4)	Time to emergence + 1000 - 1300
	Length of the flowering stage (growing degree day)	Cultivar (4)	150 - 280
	Crop determinacy linked with flowering	Conservative (1)	Yes
1.4 Development of root zone			
Z_n	Minimum effective rooting depth (m)	Management (3)	0.30
Z_x	Maximum effective rooting depth (m)	Management (3)	Up to 2.40
	Shape factor describing root zone expansion	Conservative (1)	1.5

2. Crop transpiration			
Symbol		Type (1), (2), (3), (4)	Values / ranges
$Kc_{Tr,x}$	Crop coefficient when canopy is complete but prior to senescence	Conservative (1)	1.10
	Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc.	Conservative (1)	0.15
	Effect of canopy cover on reducing soil evaporation in late season stage	Conservative (1)	50
3. Biomass production and yield formation			
3.1 Crop water productivity			
WP*	Water productivity normalized for ETo and CO_2 (gram/m^2)	Conservative (1)	15.0
	Water productivity normalized for ETo and CO_2 during yield formation (as percent WP* before yield formation)	Conservative (1)	100
3.2 Harvest Index			
HI_o	Reference harvest index (%)	Cultivar (4)	45 - 50
	Possible increase (%) of HI due to water stress before flowering	Conservative (1)	Small
	Excess of potential fruits (%)	Conservative (2)	Medium
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Conservative (1)	Small
	Coefficient describing negative impact of stomatal closure during yield formation on HI	Conservative (1)	Moderate
	Allowable maximum increase (%) of specified HI	Conservative (1)	15

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

4. Stresses			
Symbol		Type (1), (2), (3), (4)	Values / ranges
4.1 Soil water stresses			
$p_{exp,lower}$	Soil water depletion threshold for canopy expansion - Upper threshold	Conservative (1)	0.20
$p_{exp,upper}$	Soil water depletion threshold for canopy expansion - Lower threshold	Conservative (1)	0.65
	Shape factor for Water stress coefficient for canopy expansion	Conservative (1)	5.0
p_{sto}	Soil water depletion threshold for stomatal control - Upper threshold	Conservative (1)	0.65
	Shape factor for Water stress coefficient for stomatal control	Conservative (1)	2.5
p_{sen}	Soil water depletion threshold for canopy senescence - Upper threshold	Conservative (1)	0.70
	Shape factor for Water stress coefficient for canopy senescence	Conservative (1)	2.5
p_{pol}	Soil water depletion threshold for failure of pollination - Upper threshold	Conservative (1)	0.85 (Estimate)
	Vol% at anaerobiotic point (with reference to saturation)	Cultivar (4) Environment (3)	Moderately tolerant to water logging
4.2 Air temperature stress			
	Minimum air temperature below which pollination starts to fail (cold stress) (°C)	Conservative (1)	5.0 (Estimate)
	Maximum air temperature above which pollination starts to fail (heat stress) (°C)	Conservative (1)	35.0 (Estimate)
	Minimum growing degrees required for full biomass production (°C - day)	Conservative (1)	13.0 - 15.0 (Estimated)
4.3 Salinity stress			
ECe_n	Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur)	Conservative (1)	6.0
ECe_x	Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect)	Conservative (1)	20.1

Maize



Goodness of the calibration

- Non-limiting conditions ☺ ☺ ☺
- Water stress conditions ☺ ☺
- Geographical coverage (with respect to the world cropped areas) ☺ ☺ ☺
- Overall ☺ ☺ ☺

◘	No calibration
☺	Minimum degree of calibration
☺ ☺	Medium degree of calibration
☺ ☺ ☺	Good degree of calibration
☺ ☺ ☺ ☺	Optimum degree of calibration

1. Crop Phenology			
Symbol	Description	Type (1), (2), (3), (4)	Values / ranges
1.1 Threshold air temperatures			
T_{base}	Base temperature (°C)	Conservative (1)	8.0
T_{upper}	Upper temperature (°C)	Conservative (1)	30.0
1.2 Development of green canopy cover			
cc_0	Soil surface covered by an individual seedling at 90% emergence (cm2/plant)	Conservative (2)	6.50
	Number of plants per hectare	Management (3)	50,000 – 100,000
	Time from sowing to emergence (growing degree day)	Management (3)	60 - 100
CGC	Canopy growth coefficient (fraction per growing degree day)	Conservative (1)	0.012 - 0.013
CC_x	Maximum canopy cover (%)	Management (3)	65 – 99 %
	Time from sowing to start senescence (growing degree day)	Cultivar (4)	Time to emergence + 1150 - 1500
CDC	Canopy decline coefficient (fraction per growing degree day)	Conservative (1)	0.010
	Time from sowing to maturity, i.e. length of crop cycle (growing degree day)	Cultivar (4)	Time to emergence + 1450 - 1850
1.3 Flowering			
	Time from sowing to flowering (growing degree day)	Cultivar (4)	Time to emergence + 600 - 900
	Length of the flowering stage (growing degree day)	Cultivar (4)	150 - 200
	Crop determinacy linked with flowering	Conservative (1)	Yes
1.4 Development of root zone			
Z_n	Minimum effective rooting depth (m)	Management (3)	0.30
Z_x	Maximum effective rooting depth (m)	Management (3)	Up to 2.80
	Shape factor describing root zone expansion	Conservative (1)	1.3

2. Crop transpiration			
Symbol		Type (1), (2), (3), (4)	Values / ranges
$Kc_{Tr,x}$	Crop coefficient when canopy is complete but prior to senescence	Conservative (1)	1.05
	Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc.	Conservative (1)	0.30
	Effect of canopy cover on reducing soil evaporation in late season stage	Management (3)	50
3. Biomass production and yield formation			
3.1 Crop water productivity			
WP*	Water productivity normalized for ETo and CO_2 (gram/m^2)	Conservative (1)	33.7
	Water productivity normalized for ETo and CO_2 during yield formation (as percent WP* before yield formation)	Conservative (1)	100
3.2 Harvest Index			
HI_o	Reference harvest index (%)	Cultivar (4)	48 - 52
	Possible increase (%) of HI due to water stress before flowering	Conservative (1)	None
	Excess of potential fruits (%)	Conservative (2)	Small
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Conservative (1)	Small
	Coefficient describing negative impact of stomatal closure during yield formation on HI	Conservative (1)	Strong
	Allowable maximum increase (%) of specified HI	Conservative (1)	15

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

4. Stresses			
Symbol		Type (1), (2), (3), (4)	Values / ranges
4.1 Soil water stresses			
$p_{exp,lower}$	Soil water depletion threshold for canopy expansion - Upper threshold	Conservative (1)	0.14
$p_{exp,upper}$	Soil water depletion threshold for canopy expansion - Lower threshold	Conservative (1)	0.72
	Shape factor for Water stress coefficient for canopy expansion	Conservative (1)	2.9
p_{sto}	Soil water depletion threshold for stomatal control - Upper threshold	Conservative (1)	0.69
	Shape factor for Water stress coefficient for stomatal control	Conservative (1)	6.0
p_{sen}	Soil water depletion threshold for canopy senescence - Upper threshold	Conservative (1)	0.69
	Shape factor for Water stress coefficient for canopy senescence	Conservative (1)	2.7
p_{pol}	Soil water depletion threshold for failure of pollination - Upper threshold	Conservative (1)	0.80 (Estimate)
	Vol% at anaerobiotic point (with reference to saturation)	Cultivar (4) Environment (3)	Moderately tolerant to water logging
4.2 Air temperature stress			
	Minimum air temperature below which pollination starts to fail (cold stress) (°C)	Conservative (1)	10.0 (Estimate)
	Maximum air temperature above which pollination starts to fail (heat stress) (°C)	Conservative (1)	40.0 (Estimate)
	Minimum growing degrees required for full biomass production (°C - day)	Conservative (1)	12.0 (Estimated)
4.3 Salinity stress			
ECe_n	Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur)	Conservative (1)	1.7
ECe_x	Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect)	Conservative (1)	10.0