Evaluating the effect of irrigation techniques, and strategies on the water footprint of crops using APEX and AquaCrop models

Author:
Derek Rodink (S1101455)
d.rodink@student.utwente.nl

Supervisor:
Abebe Chukalla
a.d.chukalla@utwente.nl

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Author:
Derek Rodink d.rodink@student.utwente.nl
s1101455

Supervisors:
Abebe Chukalla adchukalla@utwente.nl

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ABSTRACT

This research is focused on evaluating the effect of irrigation strategies on the water footprint for two different crop types; wheat and maize, using two models; AquaCrop and APEX. The research is done for a case study for the region of Badajoz, Spain. Climatic data for the years 1993-2012 were provided by my supervisor A.D.Chukalla. The models were set up with input data such as climatic data, soil data and irrigation options.

There are different types of irrigation strategies and techniques possible. In general there are four major irrigation strategies and techniques; rain-fed irrigation, full irrigation, deficit irrigation and supplementary irrigation. The most common irrigation techniques are furrow irrigation, sprinkler irrigation, drip irrigation and sub surface drip irrigation. The scope of the irrigation strategies and techniques was on rain fed irrigation and full irrigation, using furrow and sprinkler irrigation techniques. To enable comparison between the two models the research focusses on the blue and green components of the water footprint. Their sum is called the consumptive water footprint.

The water footprint method usually focusses on all three components; green water footprint, blue water footprint and grey water footprint. Since the AquaCrop model is unable to determine the grey water footprint as results of pollution by used fertilizers and pesticides the research focusses on the remaining green and blue water footprint. Instead of speaking about the total water footprint we use the term consumptive water footprint.

The yield and evapotranspiration of the crops are simulated for different irrigation techniques and strategies. The evapotranspiration is the sum of crop evaporation and transpiration and is expressed in mm and the yield produces is simulated in ton/ha. To determine the blue and green components of the water footprint the evapotranspiration has to be separated into a green and blue component. To do so, the assumption is made that with rain-fed strategy all the evapotranspiration is green (due to the absence of irrigation water), and that the same amount of green evapotranspiration can be applied when using irrigation techniques and strategies that do apply irrigation water.

The AquaCrop model shows consistent results for both maize and wheat production in the study area with sprinkler irrigation being the most efficient strategy and technique and rain fed having the highest water footprint. The APEX model does not show consistent results. The irrigation strategy has no impact on the water footprints for wheat production, and the water footprints for rain fed cropping are too high.

The results of the study show a major difference in terms of green, blue and consumptive water footprint when comparing the models. The AquaCrop model results show a consistent ranking in irrigation techniques and strategies in terms of efficiency, both for wheat and maize production. The consumptive water footprint of wheat is the lowest for the sprinkler technique with full irrigation strategy (892 m^3ton^{-1}), followed by the furrow technique with full irrigation strategy (962 m^3ton^{-1}) and rain fed strategy (2006 m^3ton^{-1}). For maize production a same pattern is observed; sprinkler technique with full irrigation strategy (455 m^3ton^{-1}), furrow technique with full irrigation strategy (514 m^3ton^{-1}) and rain fed strategy (715 m^3ton^{-1}) as least efficient.

Compared to rain-fed crop production of wheat, applying sprinkler and furrow irrigation techniques with full irrigation strategy reduces the consumptive water footprint by 55% and 52% respectively. Compared to rain-fed crop production of maize, applying sprinkler and furrow irrigation techniques with full irrigation strategy reduces the consumptive water footprint by 36% and 28% respectively. This indicates that using sprinkler or furrow irrigation techniques with full irrigation strategy for the studied crops in the

study area is more efficient than rain-fed cropping. The results from the AquaCrop model are compatible with benchmark studies.

For further research the output of the APEX has to be carefully checked. It seems like the model gives the exact same output in terms of yield and evapotranspiration or both sprinkler and furrow irrigation strategies. The consumptive water footprint for rain-fed strategy for wheat (8688 m^3ton^{-1}) and maize (4566 m^3ton^{-1}) are four to five times higher compared to the AquaCrop model. To make the results more comparable, the daily output of the AquaCrop model can be used instead of the output on the interface of the model (growth period) to determine the yearly average yield and evapotranspiration.

Preface

This concept report is the second stage in completing the bachelor thesis for the study of Civil Engineering, following the preliminary report with the research proposal. I would like to thank Abebe Chukalla for being my supervisor and doing everything within his powers to help me with this assignment, Jord Warmink for his ideas on possible subject matters and the department of Water Engineering and Management (WEM) for the opportunity to work on this research in their domain and Robin de Graaf for being my second supervisor.

Furthermore I would like to thank the study adviser Judith Roos-Krabbenbos for helping me through a rough last year. I also would like to thank my surroundings and in particular my brother and girlfriend for their help and support throughout the process of the bachelor thesis.

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1 INTRODUCTION

1.1 BACKGROUND

Water use has been growing globally at more than twice the rate of the population increase in the 20th century. Demographic growth and economic development are putting pressure on renewable but finite freshwater resources, especially in arid regions (Food and Agriculture Organization (FAO), 2009).

Agriculture is the largest freshwater user, accounting for 99% of the global consumptive (green and blue) water footprint (Hoekstra & Mekonnen, 2012). As a result of the increase in population and food preferences the consumptive water use from precipitation and irrigation for producing food and crops is expected to increase at 0.7% per year from its estimated level of 6400 billion m^3/year in 2000 to 9060 m^3/year in order to feeds the world population of 9.2 billion people in 2050. Global freshwater demand will increase to meet the growing demand of food. To reduce the pressure on the global freshwater resources, the water productivity has to be increase or the water footprint has to be reduced.

In 1993 professor Tony Allen introduced the concept of virtual water to understand how arid countries can feed its people. In 2002 professor Arjen Hoekstra created the water footprint as a tool to measure the amount of water used along the full supply chain of a product (Hoekstra & Mekonnen, 2008). The total water footprint is made up of three components, the green, blue and grey water footprints. In crop production, the green water footprint measures the volume of rainwater consumed during the growing period; the blue water footprint measures the volume of surface water and ground water consumed. The grey water footprint measures the volume of freshwater that is required to assimilate the nutrients of and pesticides leaching and running off from crop fields and reaching groundwater or surface water, based on natural background concentrations and existing ambient water quality standards (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011). The water footprint can be calculated as the ratio between evapotranspiration divided by yield (ET/Y).

Water has always been the main factor limiting crop production in much of the world where rainfall is insufficient to meet crop demand (Steduto, Hsiao, Fereres, & Raes, 2012). The general objective is to decrease the water footprint of crops with different irrigation techniques and strategies to reduce the pressure on the global freshwater resources in the future. Traditionally, agriculture has focused primarily on maximizing total production or yield. Nowadays, focus has shifted to the limiting factors in production systems, the availability of land or water. In arid regions, water is the limiting factor for crop growth.

This research is a case study to evaluate the effect of different irrigation management options on the water footprint of several crops. Good water quality is often the limiting factor for crop growth in arid and semi-arid environments. In many cases the water required for leaching of salts is not adequate. In such cases field management should aim at irrigation techniques adapted to saline soils and appropriate to the local conditions. Irrigation techniques and strategies have an impact on the yield and evapotranspiration of the crops, and therefore can decrease the water footprint of the crops produced.

The case study will be done for an area that is characterized by a semi-arid climate, namely the city of Badajoz in Spain. Badajoz (38.88 degrees N, -6.83 degrees E) is a city in the autonomous Extremadura region. However, measuring the evapotranspiration at field level is very costly and unusual (Hoekstra et al., 2011). Therefore models are used that are capable of simulating the crop growth and soil-water balance of the crop to determine the output yield and evapotranspiration. The output of the models has to be post processed to determine the water footprint for a crop, given the irrigation strategy.

1.2 Objective

The main objective of the research is to evaluate the effect of irrigation techniques and strategies on the water footprint of crop production in a semi-arid environment.

1.3 Scope

This research does not cover the whole spectrum of effects on irrigation techniques and strategies on the water footprint of crops. There are boundaries to this research that are being set due to time limitations of the research. These boundaries are explained in terms of irrigation techniques that are included in the research, irrigation strategies, the amount of crops that are studied, the components of the water footprint that are studied, the area and climate being studied.

Time

The aspect of time is relevant for this research. There is climatic data available from the period 1993-2012. The whole period of 20 years will be takin into account for the simulations in the models.

Crops

The crops that are included in this research are wheat and maize, which are both cereal grains. This makes them more comparable and compatible. These are the only two crop types that are being researched. The default options in the models for the crops are being used.

Area

The area and climate influence the effect of the irrigation techniques and strategies on the water footprint of the crops. This research is done for only one semi-arid location, Badajoz in Spain.

Soil type

There is only one soil type included in this research and that is loamy soil. The default options for this soil type in the models are being used.

Steps in water footprint assessment

There are four steps in the general water footprint assessment; 1. Goals and scope. 2. Accounting. Sustainability assessment. 4. Response formulation. This research will only focus on the first two steps of a water footprint assessment, with the primary focus on the water footprint accounting.

Irrigation strategies and techniques

There are different irrigation techniques and strategies that can be applied. In this research there are two irrigation strategies that are being examined; sprinkler irrigation and furrow irrigation. There are also different irrigation strategies that can be applied. This research will focus on only two of them; rain-fed cropping and full irrigation strategies.

Models

There are multiple software programs that are able to simulate crop growth and the soil water balance. For the purpose of simulating the yield and evapotranspiration of the crops there are two models being used; AquaCrop and APEX.

Components of water footprint

To make the results more comparable between the different models only the blue and green water footprint will be researched. Their sum is named the consumptive water footprint. The grey water footprint is thus not a part of this research and is excluded from the water footprint accounting.

1.4 RESEARCH QUESTIONS

There are different research questions that match the goal and scope set for this study. The main goal is evaluate on the effects of irrigation strategies on the water footprint of crops. Therefore the main research question can be phrased in a specific way. To answer the main research question, sub questions are phrased to eventually answer the main question.

What is the effect of *different irrigation strategies* on the *water footprint* (WF) of *crops* in a semi-arid environment? If this question could be answered, the objective of the assignment would be completed. We will make the main research question more specific for our case study: What is the effect of two different irrigation strategies (FI and rain-fed) and techniques (furrow and sprinkler irrigation) on the consumptive water footprint (WF_{green} and WF_{blue}) of two different type of crops (wheat and maize) for the region of Badajoz in the period 1993-2012?

Sub question 1: What are the most common irrigation strategies and irrigation techniques in the study area and what is the water footprint of the crops studied?
Sub question 1.1: What are the irrigation management strategies and techniques in general agricultural practices and in the study area?
Sub question 1.2: What are the benchmark values for the green and blue water footprint of the crops?

Sub question 2: What is the Water Footprint of these crops for different irrigation strategies according to APEX and AQUACROP models? This question is the outcome of the process of evaluating the water footprint for the different crops. In order to answer this question the output of the models (evapotranspiration and yield) have to be processed into a green and blue component, before the water footprints of the crops can be analyzed.

Sub question 2.1: What is the simulated evapotranspiration and yield of the crops in the APEX and AQUACROP model?
Sub question 2.2: What is the green and blue evapotranspiration of the crops given the irrigation management decision?
Sub question 2.3: What is the green and blue water footprint per crop type given the irrigation management decision?

2 Methods and Data

2.1 Experimental Setup

Figure 2 gives an overview of the setup of the experiment for determining the effect of irrigation techniques and irrigation strategies on the water footprint of the crops. It is consistent with the scope of the study that for the management options only two techniques (sprinkler and furrow) and two strategies (rain-fed cropping and full irrigation) are researched. The different management options are used in the two models to simulate the yield and evapotranspiration of the two crops (wheat and maize). This is done for a period of 20 years. The output of the models (yield and evapotranspiration) has to be processed into a green water footprint, blue water footprint and consumptive water footprint.

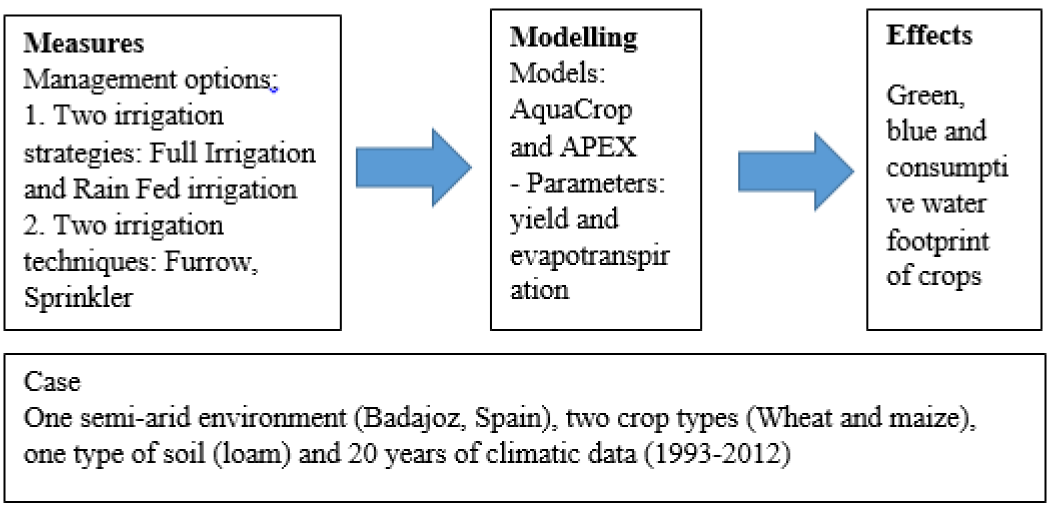

Figure 1: Overview experimental setup

2.2 Modelling Evapotranspiration and Yield in AquaCrop and APEX

First of all the models have to be run given the climatically data on the study area for the period 1993-2012. In order to make a fair comparison the settings in both models have to be similar in terms of climatic data, soil type, irrigation strategies, irrigation techniques and planting dates of the crops. The APEX model is run for a period of 20 years. The AquaCrop model is run yearly and the output from the interface of the model is used to determine the yearly yield and evapotranspiration.

Climatic data

Both the AquaCrop and APEX model were setup with the climatic data provided for this research. In AquaCrop the Badajoz file has to be selected and loaded into the model, for APEX there was also data available from different study cites, but the correct climatic data was already available.

Soil type

the soil in the area was classified as loam. Therefore the default options in both models for a loam soil were being used.

Crop type

The crop types in both models have different naimes. In the AquaCrop model the wheat and maize were selected for the simulations. The option with the GGD (Growth-degree-days) was selected for running the model. In APEX the crop ID's have to be selected for running the simulation. Maize was described as corn in the model (CORN) and wheat was described as summer wheat (SWHT) in the model.

Planting dates
The starting date of the simulation for both wheat and maize is set on the first of April. According to the FAO the planting date for Wheat in an area with Latitude (35-45 degrees) that Badajoz belongs to is March/April and for Maize in Spain this is April. In order to compare the results the assumption of the planting date of 1 April is made.

Irrigation techniques/strategies
The irrigation techniques of sprinkler and furrow irrigation are available in both AquaCrop and APEX. The default options in both models are used, no specific alterations have been made tot the default techniques and strategies in the models. In AquaCrop the default option is rain-fed cropping, by simply applying no irrigation water as a strategy. The full irrigation strategy is implemented by using the default setting in the model. In APEX in the subarea file it is possible to change the irrigation technique and strategy. For this, only values 0 (rain-fed), 1 (sprinkler) and 2 (furrow irrigation) have to be adjusted.

2.3 POST PROCESSING OUTPUT

The output of the models of AquaCrop and APEX are yield produced from the crop (in ton/ha), and the evapotranspiration of the crop (in mm). However, these are insufficient to determine the green and blue water footprint of the crops. The evapotranspiration has to be converted from mm into m^3/ha and has to be separated into a blue and green component. The process of converting the output of the models to the water footprint can be described in the three following steps.

Step 1: separate the evapotranspiration (in mm) in a green and blue component
The output of the software models only gives the total evapotranspiration (ET) in mm, which includes both the green- and blue evapotranspiration combined and the dry yield in ton/ha. We have to separate this into a green and a blue component. Therefore we use the following assumptions;
- For rain fed cropping no irrigation water is applied, thus $ET_{blue} = 0$ and thus $ET_{green} = ET_{consumptive}$.
- For full irrigation it is assumed that ET_{green} is constant, because the precipitation has not changed. To determine ET_{blue} , subtract ET_{green} from the consumptive evapotranspiration. By using this assumption for sprinkler and furrow irrigation, it is possible to separate the output into a green and blue component of evapotranspiration. This is a simplified method to determine Formula's 1.1-1.3 describe computations to determine the green and blue components of the total actual evapotranspiration.

$$ET_a[mm[= ET_{green}[mm] + ET_{blue}\ [mm]\ (1.1)$$

$$ET_{green}[mm] = ET_a[mm] - ET_{blue}[mm]\ (1.2)$$

$$ET_{blue}[mm] = ET_a[mm] - ET_{green}[mm]\ (1.3)$$

Step 2: convert ET_{green} and ET_{blue} from mm into m^3/ton to determine the crop water usage
The output of the software models AquaCrop and APEX is the evapotranspiration in mm. To convert the evapotranspiration from millimeters to cubic meters per ton the multiplication factor of 10 is used. The output is also named the Crop Water Use in the water footprint assessment manual. Formula's 2.1-2.2 describe this computations that can also be found in the water footprint assessment manual (Hoekstra et al., 2011).

$$CWU_{green}\left[\frac{m^3}{ton}\right] = ET_{green} in\ [mm] * 10\ (2.1)$$

$CWU_{blue}\left[\frac{m^3}{ton}\right] = ET_{blue} in\ [mm] * 10$ (2.2)

Step 3: determine the green, blue and consumptive water footprints
The water footprint consist of three different components, a green water footprint, a blue water footprint and a grey water footprint. The total water footprint is defined as the sum of the three individual components. Instead of using the term total water footprint we name the sum of green and blue water footprint the consumptive water footprint, because it does not include the effect of water pollution by the use of nutrients and pesticides.

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} \ (3.1)$$

Although the grey component is not included in this research, the computations for the green and blue component remain the same. The water footprint is the amount of evapotranspirated water from rainfall (green) or irrigation (blue) in [m^3/ha] used to produce the yield of a crop in [ton/ha]. Therefore the green and blue components are both expressed in terms of the amount of cubic meters of water used per hectare of land used. The yield is in the output of the software models [in ton/ha].

$$WF_{green} = \frac{CWU_{green}}{Y} = \frac{ET_{green}\ [\frac{m^3}{ton}]}{Y\ [\frac{ton}{ha}]} = \frac{ET_{green}}{Y} in \left[\frac{m^3}{ha}\right] (3.2)$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} = \frac{ET_{blue}\ [\frac{m^3}{ton}]}{Y\ [\frac{ton}{ha}]} = \frac{ET_{blue}}{Y} in \left[\frac{m^3}{ha}\right] (3.3)$$

$$WF_{consumptive} = WF_{green} + WF_{blue}\ in\ \left[\frac{m^3}{ha}\right] (3.4)$$

2.4 DATA

The climatic data for this case study was provided by A.Chukalla and included daily minimum and maximum temperatures, precipitation, the reference evapotranspiration of the atmosphere for the period 1993-2012. Using the AquaCrop model to 'read the data' it is possible to show the numerical or graphical output. Table 1 shows the monthly average climatic data over the study period. For the graphs of the data provided, see appendix E. Based on the data we can classify the climate accordingly.

Month	Rain (mm/month)	ET_0 (mm/month)	T_{min} (degrees)	T_{max} (degrees)
January	48,9	39,1	3,6	14,1
February	40,5	54,7	4,2	16,5
March	31,8	91,1	6,7	20,4
April	42,2	111	9	22,1
May	42,8	146,9	12,2	26,1
June	11,1	181,1	15,8	31,9
July	2,4	203,3	17,3	34,9
August	4,4	183,1	17,6	34,7
September	25,5	127,5	15,2	30
October	65,5	83,7	11,9	24,4
November	66,3	48,2	7,3	18
December	65,3	36,1	4,9	14,3

Table 1: Monthly average data study area

Based on the numerical output of the data and the graphs from AquaCrop we can determine the climate of the study area. The most frequently used climate classification map is that of Vladimir Koppen, presented in its latest version 1961 by Rudolf Geiger (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). By having a first look on the data, our hypothesis is that the study area has a BSk (Cold semi-arid) climate or Csa (Hot dry summer) climate. There is not a BSk climate, because the precipitation threshold is lower than the average precipitation. This leaves the Csa climate, which has the following conditions:

- 'C zones' or temperate climates have an average temperature above -3 °C, but below 18 °C in their coolest months.
- The second letter indicates the precipitation pattern ('S' represents dry summers). Koppen has defined a dry summer month as a month with less than 30 mm of precipitation and with less than one-third of the wettest winter month.
- The third letter indicates the degree of summer heat: "*a*" represents an average temperature in the warmest month above 22 °C.

For the study area the months: November, December, January, February, March and April fit the first criterion, so there is a temperate climate. The wettest winter month is December with 66,3 mm. There are 3 months that meet both criteria of the second mark: June, July and August are all dry summer months. The average temperature in the warmest month is August with 26.2 °C. According to the Koppen-climate classification and based on the data provided for the study area over the period 1993-2012 we can speak of a hot dry-summer climate (Csa) for the region of Badajoz, Spain.

3 RESULTS MODEL SIMULATIONS AND COMPUTATIONS

This chapter shows the outcomes of the model simulations. The following simulations have been done for the climatic data provided for a period of 20 years (1993-2012) for the location studied of Badajoz.

Type	Specified
Crops (2)	Wheat and maize
Models (2)	AquaCrop and APEX
Irrigation strategies (2)	Full Irrigation and Rain Fed cropping
Irrigation techniques (2)	Furrow irrigation and sprinkler irrigation

Table 2: Overview simulations

This chapter shows the graphs that are being made based on the post processed output of the AquaCrop model for the growth of wheat in the study area in the period 1993-2012. The assumptions being made during the process off running the models can be found in appendix A and B.

The output of the different simulations and the results of post processing the output can be found in Appendix C. For each method, the output is post processed according to the method explained in section 2.1. One numerical example of how to separate the evapotranspiration into a green and blue component and how to calculate the water footprint has been added for the year 1993 for wheat with the AquaCrop model for Rain Fed and Furrow irrigation. Due to the excessive amount of graphs only the average 20 yearly results are displayed in the results.

3.1 RESULTS AQUACROP MODEL

The average output over the period 1993-2012 is used to graph the yield production, evapotranspiration and water footprint graphs of the AquaCrop model. Figure 7 shows that the average yield production of the crops is higher for maize than for wheat. There is a significant difference between the output of rain fed and full irrigation. Within full irrigation, the furrow technique results in the highest yield production.

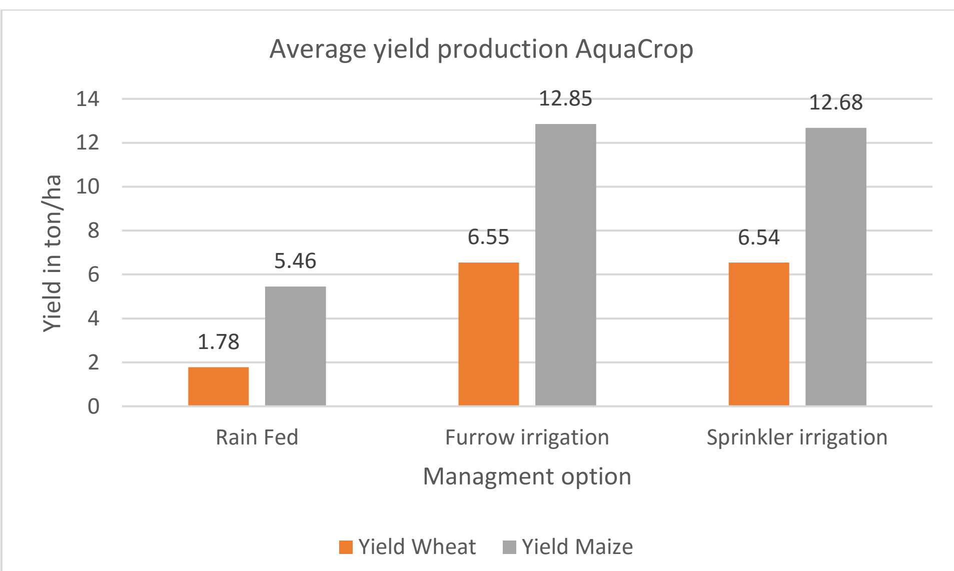

Figure 2: Average yield output AquaCrop

The other parameter that determines the water footprint is the evapotranspiration that is simulated. Figure 8 shows the average evapotranspiration for the different management options. This figure shows that by using irrigation water, this increases the evapotranspiration of the crops. The differences between the two crop types in terms of evapotranspiration are very small. The strategy with the highest evapotranspiration is furrow irrigation, which also produced the highest average yield.

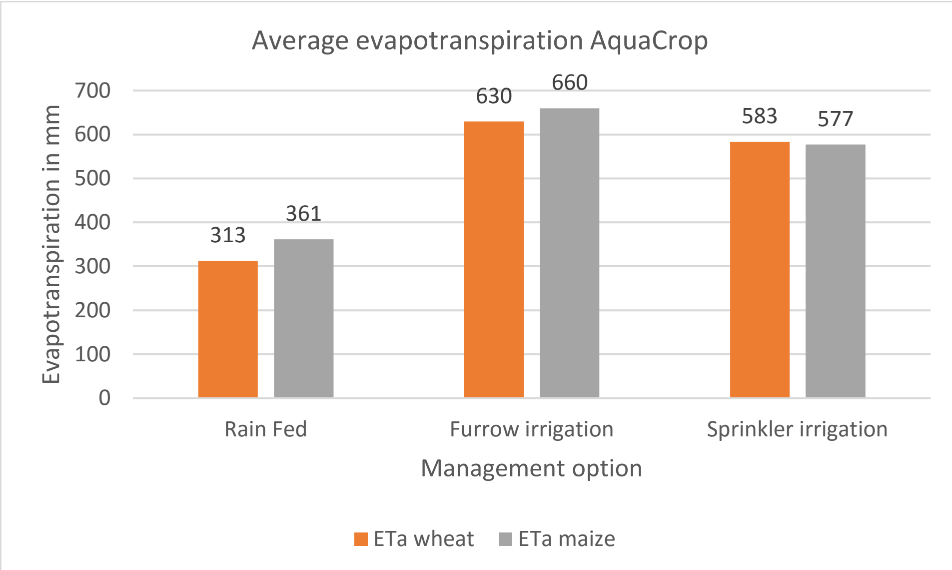

Figure 3: Average Evapotranspiration output AquaCrop

After the evapotranspiration is separated into a green and blue component and is being converted into m^3/ha it is possible to determine the blue, green and consumptive water footprints for the crops. Figure 9 shows the average consumptive water footprint for wheat and maize production under different management options. In terms of consumptive water footprint sprinkler irrigation is the most efficient (892 m^3/ton), closely followed by furrow irrigation (962 m^3/ton). The rain fed strategy seems the least efficient, with a water footprint twice as high as the full irrigation strategy (2006 m^3/ton).

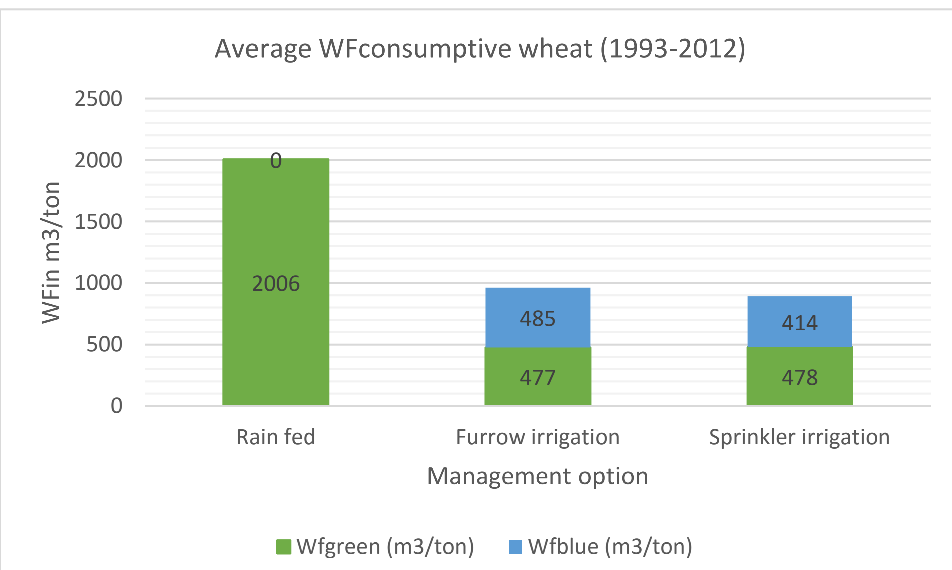

Figure 4: Average WFconsumptive wheat production for different management options.

Figure 10 shows the average consumptive water footprint for maize production under different management options. In terms of consumptive water footprint sprinkler irrigation is the most efficient (455 m^3/ton), closely followed by furrow irrigation (514 m^3/ton). The rain fed strategy seems the least efficient, with a water footprint twice as high as the full irrigation strategy (715 m^3/ton).

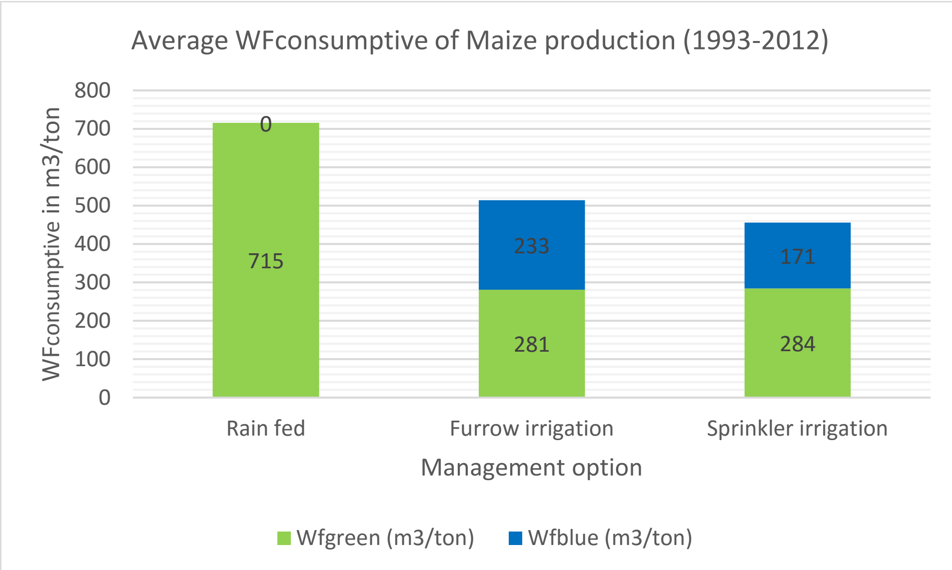

Figure 5: Average consumptive water footprint for different management options

AquaCrop	*Wheat*			*Maize*		
Strategy	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]
Rain Fed	2006	0	2006	715	0	715
Full Irrigation/Furrow	477	485	962	281	233	514
Full irrigation/Sprinkler	478	414	892	284	171	455

Table 3: summary output AquaCrop

3.2 RESULTS APEX MODEL

The average output over the period 1993-2012 is used to graph the yield production, evapotranspiration and water footprint graphs of the APEX model. Figure 11 shows that the average yield production of the crops based on the APEX model. It shows very strange results. Changing from rain fed cropping to full irrigation has a major impact on the yield for maize, but has no effect on the yield for wheat production. Another remarkable note is that the outputs for furrow and sprinkler techniques are exactly the same, even though the settings in the models have been altered.

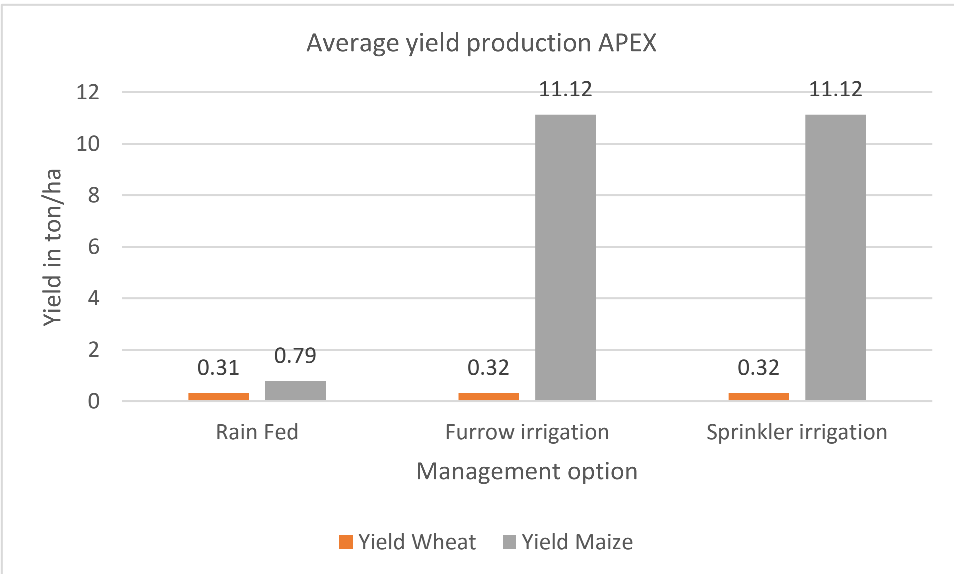

Figure 6: Average yield output AquaCrop

The other parameter that determines the water footprint is the evapotranspiration that is simulated. Figure 12 shows the average evapotranspiration for the different management options. Just as for the yield production the irrigation strategies have almost no impact on the evapotranspiration. By looking into this we found that the model only irrigation in the first year of simulating, and not in the other years.

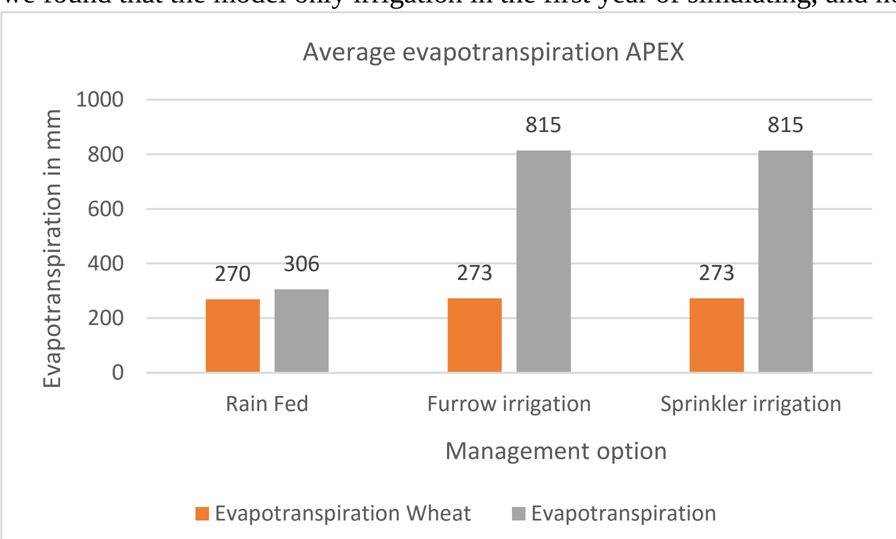

Figure 7: Average Evapotranspiration output APEX

After the evapotranspiration is separated into a green and blue component and is being converted into m^3/ha it is possible to determine the blue, green and consumptive water footprints for the crops. Because the output of the yield production and evapotranspiration is flawed, the results show unrealistic high water footprints for the crops. Figures 13 and 14 show the average consumptive water footprint for wheat and maize production under different management options. In chapter 5 we will elaborate on the differences between the outcomes of both models.

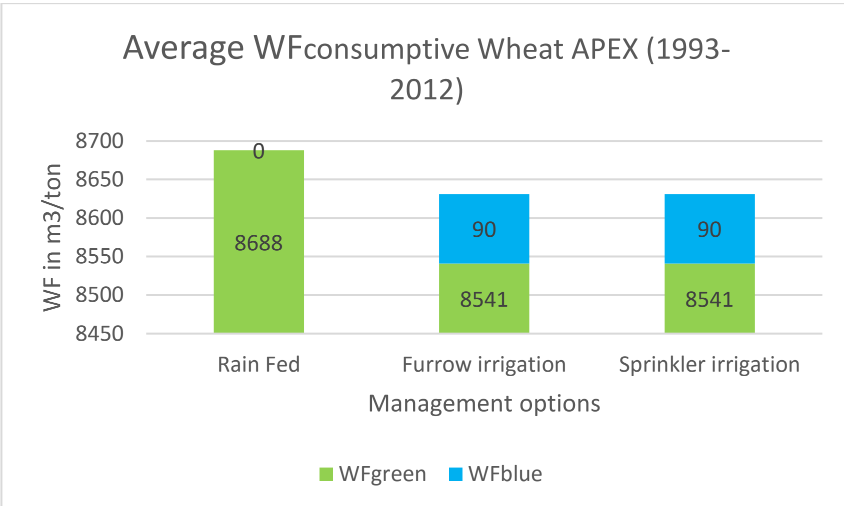

Figure 8: Average WFconsumptive wheat production APEX model

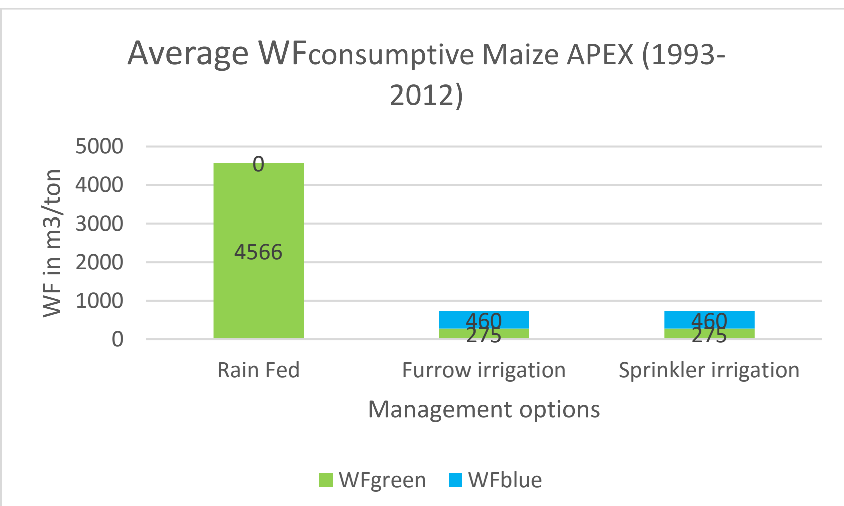

Figure 9: Average consumptive water footprint for different management options

APEX	*Wheat*			*Maize*		
Strategy	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]
Rain Fed	8688	0	8688	4566	0	4566
Full Irrigation/Furrow	8541	90	8631	275	460	735
Full irrigation/Sprinkler	8541	90	8631	275	460	735

Table 4: Summary output APEX

CHAPTER 5: DISCUSSION

Based on the results of the previous chapter we can discuss the outcomes of the research. The differences between the AquaCrop and APEX models in terms of 3 parameters will be discussed; the yield output, evapotranspiration and finally the water footprints.

Yield production
The models simulate the growth of the crops over a period of time. According to the climatic data and growth degree days, the growth period is determined. The models determine the biomass and yield that is produced. The biomass is converted into the dry yield by applying the harvest index. The output of yield production differs a lot between the two models. In AquaCrop there is a clear increase in yield production from Rain Fed to Full irrigation for both crops studied. In the APEX model the yield from rain fed cropping is lower than for APEX. One possible explanation for this is that the in the output of APEX is average throughout the whole year, whereas for AquaCrop the output over only the growth period is used. The growth period is approximately 1/3rd of a year (135-150 days).

Another explanation might be that the simulations in APEX are not done correctly. It is remarkable that for wheat the yield does not increase when switching from rain fed to full irrigation. The reason for this is that almost no irrigation water is applied. Only in the base year (1993) irrigation water is applied in the APEX model for wheat production. Also the results for Furrow Irrigation and Sprinkler irrigation are exactly the same. For AquaCrop the output in terms of yield are also quite similar for furrow and sprinkler irrigation, but not exactly the same.

Evapotranspiration
The simulated average evapotranspiration is also different between the models. For rain fed cropping the simulated evapotranspiration is higher in the AquaCrop model then APEX for both wheat and maize. For the full irrigation strategies the simulated evapotranspiration for maize is higher in APEX and for wheat is higher in AquaCrop. The differences in evapotranspiration for wheat can be explained by the minimalistic amount of irrigation water applied in the APEX simulations. Also here, the APEX model simulates the whole year, where in AquaCrop only the growth period of the crop is taken into the calculations.

Water footprint
Looking at the results of the water footprints in tables 8 and 9 we can conclude that the results are difficult to compare. In the AquaCrop model only the growth period of the crops has been taken into account, whereas for APEX the whole has been simulated. The APEX output calculations are more likely to be off, whereas the AquaCrop calculations seem to be reasonable.

For further research, the output of the APEX model has to be analyzed. It seems like there are some mistakes in the computations, causing the results off the model to be different than expected. There has to be looked into two things; first of all into the relationship between biomass and yield produced. The AquaCrop models has a higher harvest index than the APEX model, causing the obtained yield to be higher. Secondly, to make the results more compatible the daily output of AquaCrop can be used to determine the yearly output instead of the output from only the growth period. This influences both the yield and evapotranspiration and thus also the water footprint of the crops.

CHAPTER 6: CONCLUSIONS

Looking at the results of the water footprints in tables 8 and 9 we can conclude that the results are difficult to compare. In the AquaCrop model only the growth period of the crops has been taken into account, whereas for APEX the whole year has been simulated. The APEX output calculations are more likely to be off, whereas the AquaCrop calculations seem to be reasonable. The following conclusion is therefore based on the results of the AquaCrop model;

AquaCrop	*Wheat*			*Maize*		
Strategy/technique	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]
Rain Fed	2006	0	2006	715	0	715
Full Irrigation/Furrow	477	485	962	281	233	514
Full irrigation/Sprinkler	478	414	892	284	171	455

APEX	*Wheat*			*Maize*		
Strategy/technique	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]	WF_{green} [m^3/ton]	WF_{blue} [m^3/ton]	$WF_{consumptive}$ [m^3/ton]
Rain Fed	8688	0	8688	4566	0	4566
Full Irrigation/Furrow	8541	90	8631	275	460	735
Full irrigation/Sprinkler	8541	90	8631	275	460	735

The strategy with the lowest consumptive water footprint, and thus the highest efficiency overall is the full irrigation strategy with sprinkler technique. Although the furrow technique on average gives a higher yield, it does not generate the lowest consumptive water footprint. The reason for this is that there is a lot of more irrigation water used in the process of irrigating the surface. The differences between the sprinkler technique and furrow irrigation however are very small in terms of yield production and consumptive difference.

Because in rain fed irrigation only rain water is available for crop growth it yields the lowest yield off all the strategies. The abundance of extra irrigation water used cannot compensate this loss in yield, which causes it to be the least efficient strategy (highest consumptive water footprint) based on the results of the rain fed strategy. It is worth notifying that there are major differences between the two crop types.

The consumptive water footprint of wheat is the lowest for the sprinkler technique with full irrigation strategy (892 $m^3 ton^{-1}$), followed by the furrow technique with full irrigation strategy (962 $m^3 ton^{-1}$) and rain fed strategy (2006 $m^3 ton^{-1}$). For maize production a same pattern is observed; sprinkler technique with full irrigation strategy (455 $m^3 ton^{-1}$), furrow technique with full irrigation strategy (514 $m^3 ton^{-1}$) and rain fed strategy (715 $m^3 ton^{-1}$) as least efficient.

Compared to rain-fed crop production of wheat, applying sprinkler and furrow irrigation techniques with full irrigation strategy reduces the consumptive water footprint by 55% and 52% respectively. Compared to rain-fed crop production of maize, applying sprinkler and furrow irrigation techniques with full irrigation strategy reduces the consumptive water footprint by 36% and 28% respectively. This indicates that using sprinkler or furrow irrigation techniques with full irrigation strategy for the studied crops in the study area is more efficient than rain-fed cropping. The results from the AquaCrop model are compatible with benchmark studies.

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Appendix A: Assumptions AquaCrop model

This section explains the assumptions being made for simulating the output for the AquaCrop model. Just as for the model itself, the assumptions are being categorized in climate, crop, management, soil and simulation assumptions.

Climate
The climatic data are from my supervisor A.Chukalla. In the description of the file. The source of the rainfall and temperature data is from the European Climate Assessment and Dataset (ECA&D). The data provides information on the rainfall, minimum and maximum temperatures, and evaporative demand from the atmosphere for the study area between 1993 and 2012 per day. The whole period of 20 years is being simulated.

Crop
The scope of this study contains two types of crops: wheat and maize. They both belong to the group of cereals. There are two options in the model for using the default crops; the calendar mode and the Growth Degree Days (GDD) one. For all the simulations the GDD option was used. The starting date of the simulation for both wheat and maize is set on the first of April. According to the FAO the planting date for Wheat in an area with Latitude (35-45 degrees) that Badajoz belongs to is March/April and for Maize in Spain this is April. In order to compare the results the assumption of the planting date of 1 April is made.

Management
There are multiple management options being investigated. For the Rain Fed strategy no irrigation option is selected. The results from Rain Fed cropping have no irrigation water, thus the output of evaporation and transpiration is all green. For Full Irrigation strategy there are two methods being simulated, furrow irrigation and sprinkler irrigation. With the furrow irrigation technique it is assumed that 80% of the surface is wetted. The allowable depletion is 20% of RAW. With sprinkler irrigation it is assumed that 100% of the surface is wetted. The allowable depletion is 80% of RAW. These are the default management options for Furrow and Sprinkler irrigation available in the software model.

Soil
The assignment description states that the study area of Badajoz is characterized by loamy soil. There is being assumed that the soil is deep and uniformly loam.

Simulation
The planting date every year is the first of April. Based on the Growth Degree Days it simulated the total growth period for that year. Literature suggest that the estimated total growth period for summer wheat in this region is 135 days, compared to 150 days for maize. For the initial conditions and field observations the default values are used.

Abbreviations in graphs
RF = Rain fed cropping
FU = Full irrigation using furrow technique
SP = Full irrigation using sprinkler technique
$WF_{Consumptive} = WF_{green} + WF_{blue}$

APPENDIX B: ASSUMPTIONS MADE APEX MODEL

This section explains the assumptions being made for simulating the output for the APEX model. Just as for the model itself, the assumptions are being categorized in crop data, operations and sub area files in the APEX editor. For every run, there are 3 options that need to be altered in the model, first the crop ID, then the potential heat unit and at last the management option for irrigation.

Climate
The climatic data are from my supervisor A.Chukalla. In the description of the file. The source of the rainfall and temperature data is from the European Climate Assessment and Dataset (ECA&D). The data provides information on the rainfall, minimum and maximum temperatures, and evaporative demand from the atmosphere for the study area between 1993 and 2012 per day. The whole period of 20 years is being simulated. The location of Badajoz is preselected in the model with the correct latitude and longitude.

Crop data
The scope of this study contains two types of crops: wheat and maize. The crop ID for maize or corn as it is called in the model is 2. The crop ID for summer wheat is 11.

Management options
For the management options *ns* file only the potential heat unit is changed. The potential heat unit is the equivalent of the growth degree day's option in the AquaCrop model. For maize the potential heat unit is 1700 and for wheat this is 2400. Compared to the AquaCrop model there are minor differences. Based on the Growth degree options maize is 1800 and wheat 2300.

Soil
The assignment description states that the study area of Badajoz is characterized by loamy soil. There is being assumed that the soil is deep and uniformly loam. Loam soil is preselected in the APEX model.

Subarea
The subarea.sub file contains the option to alter the irrigation strategy applied to the growth of the crops. There are 3 options that are being investigated; no irrigation (setting 0), sprinkler irrigation (setting 1) and furrow irrigation (setting 2).

Simulation
The planting date every year is the first of April. Based on the potential heat units it simulated the total growth period for that year. Literature suggest that the estimated total growth period for summer wheat in this region is 135 days, compared to 150 days for maize. For the initial conditions and field observations the default values are used. The output of the model has to be exported to Excel to make determine the water footprint of the different crop type and management option.

APPENDIX C: OUTPUT AQUACROP AND APEX MODELS PRE AND POST PROCESSED

The output of AquaCrop model is the total evaporation (E) and Transpiration (Tr). Together they form the evapotranspiration (E+Tr). For determining the blue and green components of the water footprint it is necessary to separate the evapotranspiration into a green and a blue component.

$$Full\ Irrigation\ strategy: Evaporation\ (E) + Transpiration\ (Tr) = Evapotranspiration\ (ET_{blue} + ET_{green})$$

For Rain Fed irrigation, no irrigation water is applied. Therefore, there can also no be blue evapotranspiration. The output of Rain Fed strategy therefore only gives the green evapotranspiration ET_{green}.

$$Rain\ Fed\ strategy: Evaporation\ (E) + Transpiration\ (Tr) = Evapotranspiration\ (ET_{green})$$

For Full Irrigation strategies (Furrow or sprinkler technique), irrigation water is applied. Therefore the output of the model contains both the green- and blue evapotranspiration. To separate these, it is assumed that the green evapotranspiration found in the rain fed strategy is also present in the output of the other strategies. So to determine the Blue water footprint of the full irrigation strategy, just subtract ET_{green} from the Rain fed strategy from the total evapotranspiration.

$$Full\ Irrigation\ strategy: ET_{blue} = \left(ET_{blue} + ET_{green}\right) - ET_{green}$$

Numerical example
To illustrate this separation of green and blue component we use one example to determine the results of Rain Fed strategy and Furrow technique for wheat production in the year 1993. These computations have been done for maize production as well. And can be found in tables 10 through 17.

Wheat production, rain fed strategy, 1993

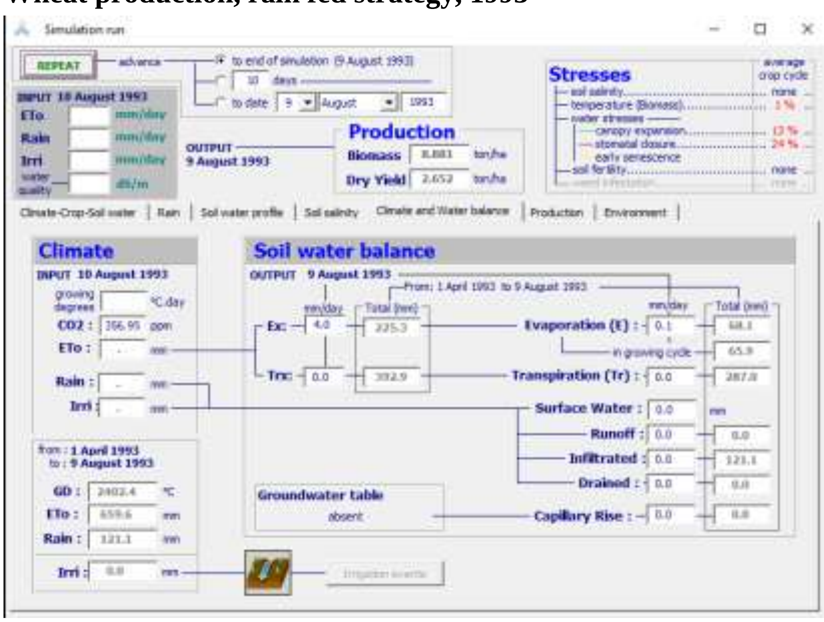

Figure 10: Example output AquaCrop simulation Wheat, Rain Fed, 1993

The climate and water balance gives an overview of the parameters we are interested in after the simulation. It shows the evaporative demand of the atmosphere (659.6 mm), the precipitation that has fallen during the growth period (121.1 mm), the irrigation water that has been applied (0 mm) but also the evaporation (68.1 mm) and transpiration (287 mm) of the crops during the growth period. The output also gives the total production of biomass (8,881 ton/ha) and the dry yield (2,652 ton/ha).

The following computations can be made to determine the green, blue and total water footprint of wheat for this particular irrigation strategy in this particular year. The sum of evaporation and Transpiration equals the sum of green and blue evapotranspiration:

$$ET_{green} + ET_{blue} = Evaporation\ (E) + Transpiration\ (T) = 68{,}1 + 278 = 355{,}1\ mm$$

For Rain Fed irrigation, we know that there is only a green water footprint:

$$ET_a = ET_{green} + ET_{blue} = 355{,}1 + 0\ mm = 355{,}1\ mm$$

To determine the green, blue and total water footprint, it is necessary to convert the evapotranspiration from mm into m^3/ha. This can be done by multiplying the green, blue and actual evapotranspiration by factor 10.

$$ET_{green} = 3351\ \frac{m^3}{ha}\ , ET_{blue} = 0\frac{m^3}{ha}\ and\ ET_a = 3351\ \frac{m^3}{ha}$$

Now it is possible to determine the green, blue and total water footprint, by dividing it by the yield. Because the yield is measured in ton/ha and the evapotranspiration in cubic meters per hectare, the unit is cubic meter per hectare.

$$WF_{green} = \frac{ET_{green}}{Yield} = \frac{3351}{2{,}652} = 1339\ \frac{m^3}{ha}\ , WF_{blue} = \frac{ET_{blue}}{Yield} = \frac{0}{2{,}652} = 0\ \frac{m^3}{ha}$$

$$WF_{consumptive} = WF_{green} + WF_{blue} = 1339 + 0 = 1339\ \frac{m^3}{ha}$$

Wheat production, Full Irrigation (Furrow technique), 1993

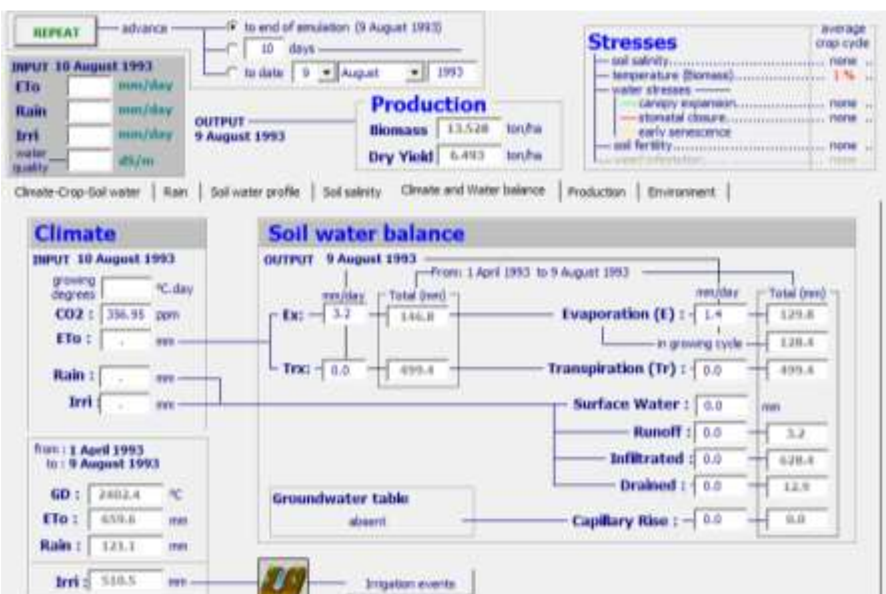

Figure 11: Example output AquaCrop simulation Wheat, Furrow, 1993

The climate and water balance gives an overview of the parameters we are interested in after the simulation. It now shows the irrigation water that has been applied (510.5 mm) but also the evaporation (129.8 mm) and transpiration (499.4 mm) of the crops during the growth period. The output also gives the total production of biomass (13,528 ton/ha) and the dry yield (6,493 ton/ha).

$$ET_{green} + ET_{blue} = Evaporation\ (E) + Transpiration\ (Tr) = 129{,}8 + 499{,}4 = 629{,}2\ mm$$

To determine the blue and green component, we can use the fact that we know the green evapotranspiration from the Rain Fed management option, which equals 355,1 mm.

$$ET_{blue} = \left(ET_{green} + ET_{blue}\right) - ET_{green} = 629{,}1 - 355{,}1 = 274{,}1\ mm$$

To determine the green, blue and total water footprint, it is necessary to convert the evapotranspiration from mm into m^3/ha. This can be done by multiplying the green, blue and actual evapotranspiration by factor 10.

$$ET_{green} = 3351\ \frac{m^3}{ha}\ , ET_{blue} = 2741\frac{m^3}{ha}\ and\ ET_a = 6292\ \frac{m^3}{ha}$$

Now it is possible to determine the green, blue and total water footprint, by dividing it by the yield. Because the yield is measured in ton/ha and the evapotranspiration in cubic meters per hectare, the unit is cubic meter per hectare.

$$WF_{green} = \frac{ET_{green}}{Yield} = \frac{3351}{6{,}493} = 546{,}9\ \frac{m^3}{ha}\ , WF_{blue} = \frac{ET_{blue}}{Yield} = \frac{2741}{6{,}493} = 422{,}1\ \frac{m^3}{ha}$$

$$WF_{consumptive} = WF_{green} + WF_{blue} = 546{,}9 + 422{,}1 = 969\ \frac{m^3}{ha}$$

This sequence of computations can be repeated for every year between 1993 and 2012 and for every irrigation strategy. The results are presented in the tables 10-17 on the next pages.

Tables 10 and 11 show the output of the AquaCrop model in terms of yield, actual evapotranspiration (ET_a), green evapotranspiration (ET_{green}) and blue evapotranspiration (ET_{blue}) for wheat and maize for all different management options. Tables 12 and 13 show the results in terms of Blue (WF_{blue}), green (WF_{green}) and consumptive water footprint for wheat and maize for all different irrigation strategies for the AquaCrop model.

Tables 14 and 15 show the output of the APEX model in terms of yield, actual evapotranspiration (ET_a), green evapotranspiration (ET_{green}) and blue evapotranspiration (ET_{blue}) for wheat and maize for all different management options. Tables 16 and 17 show the results in terms of Blue (WF_{blue}), green (WF_{green}) and consumptive water footprint for wheat and maize for all different irrigation strategies for the APEX model.

OUTPUT AQUACROP: WHEAT (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	*Yield_RF (ton/ha)*	ET_{a}_RF (mm)	ET_{green}_RF (mm)	ET_{blue}_RF (mm)	Yield_FU (ton/ha)	ET_{a}_FU (mm)	ET_{green}_FU (mm)	ET_{blue}_FU (mm)	Yield_SP (ton/ha)	ET_{a}_SP (mm)	ET_{green}_SP (mm)	ET_{blue}_SP (mm)
1993	**2.7**	355.1	355.1	0	6.5	629.2	**355.1**	274.1	6.5	576.3	355.1	221.2
1994	2.1	337.8	337.8	0	6.5	663.7	337.8	325.9	6.5	600.7	337.8	262.9
1995	1.1	283.9	283.9	0	6.2	615.1	283.9	331.2	6.2	559.0	283.9	275.1
1996	1.9	349.2	349.2	0	6.4	627.1	349.2	277.9	6.4	587.9	349.2	238.7
1997	3.8	377.2	377.2	0	6.6	560.4	377.2	183.2	6.5	509.2	377.2	132.0
1998	2.4	345.2	345.2	0	6.4	620.6	345.2	275.4	6.4	573.1	345.2	227.9
1999	1.8	318.6	318.6	0	6.4	627.7	318.6	309.1	6.5	585.9	318.6	267.3
2000	1.9	375.2	375.2	0	6.4	632.3	375.2	257.1	6.4	618.1	375.2	242.9
2001	1.2	288.7	288.7	0	6.5	631.6	288.7	342.9	6.5	583.7	288.7	295.0
2002	1.1	289.5	289.5	0	6.7	651.3	289.5	361.8	6.6	605.7	289.5	316.2
2003	0.7	125.7	125.7	0	6.4	652.3	125.7	526.6	6.5	604.0	125.7	478.3
2004	0.9	261.8	261.8	0	6.5	635.5	261.8	373.7	6.4	577.3	261.8	315.5
2005	1.0	264.8	264.8	0	6.4	623.2	264.8	358.4	6.3	566.4	264.8	301.6
2006	0.8	277.7	277.7	0	6.5	629.9	277.7	352.2	6.5	584.4	277.7	306.7
2007	1.9	336.7	336.7	0	6.7	626.6	336.7	289.9	6.7	593.4	336.7	256.7
2008	2.6	353.2	353.2	0	6.9	620	353.2	266.8	6.9	578.7	353.2	225.5
2009	0.9	289.5	289.5	0	6.8	656.5	289.5	367	6.7	598.9	289.5	309.4
2010	2.1	340.7	340.7	0	6.8	636.9	340.7	296.2	6.8	605.3	340.7	264.6
2011	3.8	385.5	385.5	0	6.7	614.4	385.5	228.9	6.7	564.9	385.5	179.4
2012	1.4	296	296	0	6.7	638.4	296	342.4	6.7	589.9	296	293.9
1993-2012	**1.8**	**312.6**	**312.6**	**0**	**6.6**	**629.6**	**312.6**	**317.0**	**6.5**	**583.1**	**312.6**	**270.5**

Table 5: Output AquaCrop model Wheat production

Post processed output AquaCrop: Maize (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	Yield_RF (ton/ha)	ET_a_RF (mm)	ET_{green}_RF (mm)	ET_{blue}_RF (mm)	Yield_FU (ton/ha)	ET_a_FU (mm)	ET_{green}_FU (mm)	ET_{blue}_FU (mm)	Yield_SP (ton/ha)	ET_a_SP (mm)	ET_{green}_SP (mm)	ET_{blue}_SP (mm)
1993	5.4	404	404	0	12.7	692.4	404	288.4	12.7	620.8	404	216.8
1994	4.4	375.2	375.2	0	13.0	702.7	375.2	372.5	12.9	614.2	375.2	239
1995	5.1	334	334	0	12.8	635.1	334	301.1	12.5	536.5	334	202.5
1996	4.8	394.3	394.3	0	12.5	666	394.3	271.7	12.5	611.1	394.3	216.8
1997	12.4	465.7	465.7	0	13.8	595.7	465.7	130	13.6	523.2	465.7	57.5
1998	6.4	399.7	399.7	0	12.7	672.9	399.7	273.2	12.6	602	399.7	202.3
1999	4.6	370.2	370.2	0	12.7	661	370.2	290.8	12.6	584	370.2	213.8
2000	4.7	413.9	413.9	0	12.7	666.8	413.9	252.9	12.6	642.3	413.9	228.4
2001	3.5	322.2	322.2	0	12.7	671.1	322.2	348.9	12.3	563	322.2	240.8
2002	3.3	320.1	320.1	0	13.0	676.5	320.1	356.4	12.8	587.7	320.1	267.6
2003	3.3	312.7	312.7	0	12.8	683.0	312.7	367.6	12.5	577.1	312.7	264.4
2004	3.4	304.7	304.7	0	12.2	661.1	304.7	356.4	11.9	538.7	304.7	234
2005	5.3	315.7	315.7	0	12.4	638.3	315.7	322.6	12.2	532.3	315.7	216.6
2006	4.9	333.3	333.3	0	12.7	629.8	333.3	296.5	12.5	549.3	333.3	216
2007	6.6	396.2	396.2	0	13.4	656.8	396.2	260.6	13.1	578.4	396.2	182.2
2008	6.5	409.5	409.5	0	13.4	654.5	409.5	245	13.3	588.9	409.5	179.4
2009	5.0	343	343	0	13.0	683.1	343	340.1	12.7	570.9	343	227.9
2010	5.9	391.8	391.8	0	12.8	665.1	391.8	273.3	12.6	597.3	391.8	205.5
2011	10.2	447.9	447.9	0	13.2	621.6	447.9	173.7	13.2	558	447.9	110.1
2012	3.7	173.6	173.6	0	12.7	668.1	173.6	488.2	12.5	568.3	173.6	394.7
1993-2012	**5.5**	**361.4**	**361.4**	**0**	**12.9**	**659.6**	**361.4**	**298.2**	**12.7**	**577.2**	**361.4**	**215.8**

Table 6: Output AquaCrop model maize production

POST PROCESSED OUTPUT AQUACROP: WHEAT (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	*Yield_RF (ton/ha)*	*WF green_RF (m3/ton)*	*WF blue_RF (m3/ton)*	*WF cons_RF (m3/ton)*	Yield_FU (ton/ha)	WF green_FU (m3/ton)	WF blue_FU (m3/ton)	WF cons_FU (m3/ton)	Yield_SP (ton/ha)	WF green_SP (m3/ton)	WF blue_SP (m3/ton)	WF cons_SP (m3/ton)
1993	2.7	1339.0	0	**1339.0**	6.5	546.9	422.1	**969.0**	6.5	547.4	341.0	888.4
1994	2.1	1610.1	0	1610.1	6.5	522.3	503.9	1026.3	6.5	522.8	406.9	929.7
1995	1.1	2611.8	0	2611.8	6.2	456.4	532.5	988.9	6.2	457.9	443.7	901.6
1996	1.9	1827.3	0	1827.3	6.4	544.3	433.2	977.6	6.4	544.4	372.2	916.6
1997	3.8	990.5	0	990.5	6.6	575.4	279.4	854.8	6.5	576.7	201.8	778.5
1998	2.4	1417.7	0	1417.7	6.4	539.5	430.4	970.0	6.4	540.3	356.7	897.0
1999	1.8	1788.9	0	1788.9	6.4	494.0	479.3	973.3	6.5	494.0	414.4	908.4
2000	1.9	2028.1	0	2028.1	6.4	586.0	401.5	987.5	6.4	586.0	379.4	965.3
2001	1.2	2436.3	0	2436.3	6.5	441.0	523.8	964.7	6.5	441.7	451.3	893.1
2002	1.1	2695.5	0	2695.5	6.7	434.6	543.1	977.6	6.6	435.7	475.8	911.5
2003	0.7	1729.0	0	1729.0	6.4	194.0	812.5	1006.5	6.5	194.4	739.7	934.1
2004	0.9	2876.9	0	2876.9	6.5	404.5	577.4	981.9	6.4	406.0	489.2	895.2
2005	1.0	2546.2	0	2546.2	6.4	415.8	562.8	978.6	6.3	417.1	475.0	892.1
2006	0.8	3282.5	0	3282.5	6.5	427.5	542.2	969.7	6.5	428.7	473.5	902.3
2007	1.9	1730.2	0	1730.2	6.7	498.9	429.5	928.4	6.7	499.6	380.9	880.4
2008	2.6	1340.9	0	1340.9	6.9	513.7	388.0	901.7	6.9	514.8	328.7	843.5
2009	0.9	3092.9	0	3092.9	6.8	428.6	543.4	972.0	6.7	429.9	459.5	889.4
2010	2.1	1638.0	0	1638.0	6.8	503.8	438.0	941.7	6.8	504.0	391.4	895.4
2011	3.8	1007.3	0	1007.3	6.7	572.2	339.8	912.0	6.7	572.0	266.2	838.3
2012	1.4	2124.9	0	2124.9	6.7	439.5	508.4	947.9	6.7	440.3	437.2	877.4
1993-2012	**1.8**	**2005.7**	**0**	**2005.7**	**6.6**	**476.9**	**484.6**	**961.5**	**6.5**	**477.7**	**414.2**	**891.9**

Table 7: Results post processing output AquaCrop for wheat production

POST PROCESSED OUTPUT AQUACROP: MAIZE (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	Yield_RF (ton/ha)	WF green_RF (m3/ton)	WF blue_RF (m3/ton)	WF total_RF (m3/ton)	Yield_FU (ton/ha)	WF green_FU (m3/ton)	WF blue_FU (m3/ton)	WF total_FU (m3/ton)	Yield_SP (ton/ha)	WF green_SP (m3/ton)	WF blue_SP (m3/ton)	WF total_SP (m3/ton)
1993	5.4	740.7	0	740.7	12.7	317.0	226.3	543.2	12.7	318.8	171.1	489.9
1994	4.4	851.6	0	851.6	13.0	289.7	252.8	542.5	12.9	291.3	185.6	476.9
1995	5.1	659.6	0	659.6	12.8	261.1	235.4	496.6	12.5	266.3	161.5	427.8
1996	4.8	820.8	0	820.8	12.5	314.5	216.7	531.2	12.5	315.7	173.6	489.3
1997	12.4	375.1	0	375.1	13.8	338.0	94.3	432.3	13.6	341.4	42.2	383.6
1998	6.4	628.6	0	628.6	12.7	314.3	214.8	529.1	12.6	317.3	160.6	477.9
1999	4.6	798.5	0	798.5	12.7	291.0	228.6	519.6	12.6	293.8	169.7	463.5
2000	4.7	876.0	0	876.0	12.7	326.8	199.7	526.4	12.6	328.3	181.2	509.4
2001	3.5	933.1	0	933.1	12.7	254.3	275.4	529.6	12.3	262.0	195.8	457.8
2002	3.3	983.7	0	983.7	13.0	245.6	273.5	519.1	12.8	250.3	209.2	459.5
2003	3.3	955.1	0	955.1	12.8	245.0	288.0	532.9	12.5	249.6	211.0	460.6
2004	3.4	899.4	0	899.4	12.2	249.7	292.1	541.8	11.9	256.7	197.2	453.9
2005	5.3	600.9	0	600.9	12.4	254.2	259.8	514.0	12.2	258.6	177.4	436.0
2006	4.9	680.1	0	680.1	12.7	263.3	234.3	497.6	12.5	267.2	173.1	440.3
2007	6.6	604.1	0	604.1	13.4	296.7	195.1	491.8	13.1	301.4	138.6	439.9
2008	6.5	627.6	0	627.6	13.4	306.4	183.3	489.7	13.3	309.0	135.4	444.4
2009	5.0	690.0	0	690.0	13.0	263.4	261.2	524.5	12.7	269.9	179.3	449.2
2010	5.9	668.5	0	668.5	12.8	306.8	214.0	520.7	12.6	310.7	163.0	473.7
2011	10.2	438.7	0	438.7	13.2	338.7	131.4	470.1	13.2	339.7	83.5	423.1
2012	3.7	473.0	0	473.0	12.7	137.0	385.4	522.4	12.5	138.9	315.9	454.9
1993-2012	**5.5**	**715.2**	**0**	**715.2**	**12.9**	**280.7**	**233.1**	**513.8**	**12.7**	**284.3**	**171.2**	**455.6**

Table 8: Results post processing output AquaCrop for maize production

Output APEX: Wheat (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	*Yield_RF (ton/ha)*	ET_a_RF (mm)	ET_{green}_RF (mm)	ET_{blue}_RF (mm)	Yield_FU (ton/ha)	ET_a_FU (mm)	ET_{green}_FU (mm)	ET_{blue}_FU (mm)	Yield_SP (ton/ha)	ET_a_SP (mm)	ET_{green}_SP (mm)	ET_{blue}_SP (mm)
1993	0.23	288.6	288.6	0	0.3	343.1	288.6	54.5	0.3	343.1	288.6	54.5
1994	0.32	252.8	252.8	0	0.32	252.8	252.8	0	0.32	252.8	252.8	0
1995	0.33	236.5	236.5	0	0.33	236.5	236.5	0	0.33	236.5	236.5	0
1996	0.32	304.2	304.2	0	0.32	304.2	304.2	0	0.32	304.2	304.2	0
1997	0.39	298.3	298.3	0	0.39	298.3	298.3	0	0.39	298.3	298.3	0
1998	0.33	265.8	265.8	0	0.33	265.8	265.8	0	0.33	265.8	265.8	0
1999	0.29	279.1	279.1	0	0.29	279.1	279.1	0	0.29	279.1	279.1	0
2000	0.32	286.5	286.5	0	0.32	286.4	286.5	0	0.32	286.4	286.5	0
2001	0.32	283.1	283.1	0	0.32	283.1	283.1	0	0.32	283.1	283.1	0
2002	0.34	269.3	269.3	0	0.34	269.3	269.3	0	0.34	269.3	269.3	0
2003	0.31	270.9	270.9	0	0.31	270.9	270.9	0	0.31	270.9	270.9	0
2004	0.28	237.7	237.7	0	0.28	237.7	237.7	0	0.28	237.7	237.7	0
2005	0.27	201.1	201.1	0	0.27	201.1	201.1	0	0.27	201.1	201.1	0
2006	0.29	274.0	274.0	0	0.29	274.0	274.0	0	0.29	274.0	274.0	0
2007	0.35	288.1	288.1	0	0.35	288.1	288.1	0	0.35	288.1	288.1	0
2008	0.34	283.8	283.8	0	0.34	283.8	283.8	0	0.34	283.8	283.8	0
2009	0.33	231.5	231.5	0	0.33	231.5	231.5	0	0.33	231.5	231.5	0

2010	0.29	315.1	315.1	0	0.29	315.1	315.1	0	0.29	315.1	315.1	0
2011	0.32	294.8	294.8	0	0.32	294.8	294.8	0	0.32	294.8	294.8	0
2012	0.3	233.8	233.8	0	0.3	233.8	233.8	0	0.3	233.8	233.8	0
1993-2012	***0.314***	***269.7***	***269.7***	**0**	***0.317***	***272.5***	***269.7***	**0**	***0.317***	***272.5***	***269.7***	**0**

Table 9: Output wheat production APEX

Output APEX: Maize (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	Yield_RF (ton/ha)	ET_a_RF (mm)	ET_{green}_RF (mm)	ET_{blue}_RF (mm)	Yield_FU (ton/ha)	ET_a_FU (mm)	ET_{green}_FU (mm)	ET_{blue}_FU (mm)	Yield_SP (ton/ha)	ET_a_SP (mm)	ET_{green}_SP (mm)	ET_{blue}_SP (mm)
1993	0.300	*277.3*	*277.3*	0	10.0	811.3	*277.3*	534.0	10.0	811.3	*277.3*	534.0
1994	0.790	*315.6*	*315.6*	0	11.2	830.3	*315.6*	514.7	11.2	830.3	*315.6*	514.7
1995	0.380	*216.0*	*216.0*	0	11.7	797.1	*216.0*	581.1	11.7	797.1	*216.0*	581.1
1996	0.820	*367.9*	*367.9*	0	10.9	848.5	*367.9*	480.6	10.9	848.5	*367.9*	480.6
1997	2.320	*364.8*	*364.8*	0	12.7	817.8	*364.8*	453.0	12.7	817.8	*364.8*	453.0
1998	0.930	*337.5*	*337.5*	0	10.9	835.2	*337.5*	497.7	10.9	835.2	*337.5*	497.7
1999	0.430	*261.0*	*261.0*	0	10.7	801.5	*261.0*	540.4	10.7	801.5	*261.0*	540.4
2000	0.840	*358.5*	*358.5*	0	11.3	854.0	*358.5*	495.5	11.3	854.0	*358.5*	495.5
2001	0.730	*326.1*	*326.1*	0	11.1	822.0	*326.1*	495.9	11.1	822.0	*326.1*	495.9
2002	0.760	*316.0*	*316.0*	0	11.7	827.1	*316.0*	511.1	11.7	827.1	*316.0*	511.1
2003	0.710	*318.3*	*318.3*	0	11.3	842.2	*318.3*	523.9	11.3	842.2	*318.3*	523.9

2004	0.680	*298.2*	*298.2*	0	10.0	820.2	*298.2*	522.0	10.0	820.2	*298.2*	522.0
2005	0.320	*194.5*	*194.5*	0	10.4	792.1	*194.5*	597.5	10.4	792.1	*194.5*	597.5
2006	0.570	*288.9*	*288.9*	0	10.7	778.4	*288.9*	489.4	10.7	778.4	*288.9*	489.4
2007	0.920	*339.6*	*339.6*	0	11.7	845.8	*339.6*	506.2	11.7	845.8	*339.6*	506.2
2008	0.880	*320.0*	*320.0*	0	11.5	826.9	*320.0*	506.9	11.5	826.9	*320.0*	506.9
2009	0.750	*265.4*	*265.4*	0	11.3	757.0	*265.4*	491.5	11.3	757.0	*265.4*	491.5
2010	0.970	*351.2*	*351.2*	0	10.5	786.2	*351.2*	435.0	10.5	786.2	*351.2*	435.0
2011	1.230	*369.2*	*369.2*	0	11.9	816.9	*369.2*	447.7	11.9	816.9	*369.2*	447.7
2012	0.370	*231.0*	*231.0*	0	11.1	782.1	*231.0*	551.1	11.1	782.1	*231.0*	551.1
1993-2012	*0.785*	***305.9***	***305.9***	**0**	*11.1*	*814.6*	***305.9***	*508.8*	*11.1*	*814.6*	***305.9***	*508.8*

Table 10: Output maize production APEX

Output APEX post processed Wheat (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	*Yield_RF (ton/ha)*	*WF green_RF (m3/ton)*	*WF blue_RF (m3/ton)*	*WF cons_RF (m3/ton)*	Yield_FU (ton/ha)	WF green_FU (m3/ton)	WF blue_FU (m3/ton)	WF cons_FU (m3/ton)	Yield_SP (ton/ha)	WF green_SP (m3/ton)	WF blue_SP (m3/ton)	WF cons_SP (m3/ton)
1993	0.23	12548	0	12548	0.3	9620	1816	11436	0.3	9620	1816	11436
1994	0.32	7901	0	7901	0.32	7901	0	7901	0.32	7901	0	7901
1995	0.33	7168	0	7168	0.33	7168	0	7168	0.33	7168	0	7168
1996	0.32	9508	0	9508	0.32	9508	0	9508	0.32	9508	0	9508
1997	0.39	7649	0	7649	0.39	7649	0	7649	0.39	7649	0	7649

1998	0.33	8054	0	8054	0.33	8054	0	8053	0.33	8054	0	8053
1999	0.29	9624	0	9624	0.29	9624	0	9624	0.29	9624	0	9624
2000	0.32	8952	0	8952	0.32	8952	0	8952	0.32	8952	0	8952
2001	0.32	8847	0	8847	0.32	8847	0	8846	0.32	8847	0	8846
2002	0.34	7920	0	7920	0.34	7920	0	7919	0.34	7920	0	7919
2003	0.31	8738	0	8738	0.31	8738	0	8738	0.31	8738	0	8738
2004	0.28	8489	0	8489	0.28	8489	0	8488	0.28	8489	0	8488
2005	0.27	7448	0	7448	0.27	7448	0	7448	0.27	7448	0	7448
2006	0.29	9448	0	9448	0.29	9448	0	9447	0.29	9448	0	9447
2007	0.35	8232	0	8232	0.35	8232	0	8232	0.35	8232	0	8232
2008	0.34	8346	0	8346	0.34	8346	0	8346	0.34	8346	0	8346
2009	0.33	7015	0	7015	0.33	7015	0	7015	0.33	7015	0	7015
2010	0.29	10865	0	10865	0.29	10865	0	10865	0.29	10865	0	10865
2011	0.32	9213	0	9213	0.32	9213	0	9212	0.32	9213	0	9212
2012	0.3	7794	0	7794	0.3	7794	0	7794	0.3	7794	0	7794
1993-2012	***0.314***	***8688***	**0**	***8688***	***0.317***	***8541***	***91***	***8632***	***0.317***	***8541***	***91***	***8632***

Table 11: Output wheat production APEX post processed

OUTPUT APEX POST PROCESSED MAIZE (1993-2012)

	Rain Fed strategy				Full Irrigation strategy/ Furrow technique				Full Irrigation strategy/Sprinkler technique			
Year	Yield_RF (ton/ha)	WF green_RF (m3/ton)	WF blue_RF (m3/ton)	WF total_RF (m3/ton)	Yield_FU (ton/ha)	WF green_FU (m3/ton)	WF blue_FU (m3/ton)	WF total_FU (m3/ton)	Yield_SP (ton/ha)	WF green_SP (m3/ton)	WF blue_SP (m3/ton)	WF total_SP (m3/ton)
1993	0.300	9243	0	9243	10.0	276.2	531.9	808.0	10.0	276.2	531.9	808.0
1994	0.790	3995	0	3995	11.2	281.3	458.7	740.0	11.2	281.3	458.7	740.0
1995	0.380	5684	0	5684	11.7	184.9	497.5	682.4	11.7	184.9	497.5	682.4
1996	0.820	4486	0	4486	10.9	338.1	441.7	779.9	10.9	338.1	441.7	779.9
1997	2.320	1573	0	1573	12.7	286.6	355.9	642.4	12.7	286.6	355.9	642.4
1998	0.930	3629	0	3629	10.9	309.3	456.2	765.5	10.9	309.3	456.2	765.5
1999	0.430	6071	0	6071	10.7	244.0	505.1	749.0	10.7	244.0	505.1	749.0
2000	0.840	4268	0	4268	11.3	317.3	438.5	755.8	11.3	317.3	438.5	755.8
2001	0.730	4467	0	4467	11.1	293.7	446.8	740.5	11.1	293.7	446.8	740.5
2002	0.760	4158	0	4158	11.7	270.6	437.6	708.2	11.7	270.6	437.6	708.2
2003	0.710	4483	0	4483	11.3	282.4	464.8	747.3	11.3	282.4	464.8	747.3
2004	0.680	4385	0	4385	10.0	299.4	524.1	823.5	10.0	299.4	524.1	823.5
2005	0.320	6079	0	6079	10.4	187.2	575.1	762.3	10.4	187.2	575.1	762.3
2006	0.570	5069	0	5069	10.7	271.3	459.6	730.8	10.7	271.3	459.6	730.8
2007	0.920	3691	0	3691	11.7	291.3	434.1	725.4	11.7	291.3	434.1	725.4
2008	0.880	3636	0	3636	11.5	278.0	440.4	718.4	11.5	278.0	440.4	718.4

2009	0.750	3539	0	3539	11.3	234.9	435.0	669.9	11.3	234.9	435.0	669.9
2010	0.970	3621	0	3621	10.5	334.2	413.9	748.0	10.5	334.2	413.9	748.0
2011	1.230	3001	0	3001	11.9	311.0	377.2	688.2	11.9	311.0	377.2	688.2
2012	0.370	6243	0	6243	11.1	208.1	496.5	704.6	11.1	208.1	496.5	704.6
1993-2012	***0.785***	***4566***	**0**	***4566***	***11.1***	***275.0***	***459.5***	***734.5***	***11.1***	***275.0***	***459.5***	***734.5***

Table 12: Output maize production APEX post processed

Appendix D: Climatic data study area

Introduction

The climatic data for this case study was provided by A.Chukalla and included daily minimum and maximum temperatures, precipitation, the reference evapotranspiration of the atmosphere for the period 1993-2012. The AquaCrop model uses the climatic data for the simulation of the crop growth. The AquaCrop model itself uses assumptions about the CO_2 development of the atmosphere.

Numerical output

Month	Rain (mm/month)	ET_0 (mm/month)	Tmin (degrees)	Tmax (degrees)	GGD (degree-days/month)
January	48,9	39,1	3,6	14,1	107,4
February	40,5	54,7	4,2	16,5	138,1
March	31,8	91,1	6,7	20,4	250,1
April	42,2	111	9	22,1	300,8
May	42,8	146,9	12,2	26,1	413,3
June	11,1	181,1	15,8	31,9	505,9
July	2,4	203,3	17,3	34,9	559,7
August	4,4	183,1	17,6	34,7	564,4
September	25,5	127,5	15,2	30	487,9
October	65,5	83,7	11,9	24,4	388,6
November	66,3	48,2	7,3	18	213,7
December	65,3	36,1	4,9	14,3	130,6

Table 13: Monthly average data study area

Year	Rain (mm/year)	ET_0 (mm/year)	Tmin (degrees)	Tmax (degrees)	GGD (degree-days/year)
1993	404,7	1277,8	9,3	22,4	3605,1
1994	326,9	1336,4	9,8	24,1	3973,3
1995	414	1358	11,4	25,2	4435,9
1996	635,2	1247,7	10,7	23,2	4003,4
1997	736,9	1255,7	11,5	24,1	4334,8
1998	334,1	1295,4	10,4	24	4052,4
1999	386,6	1302,7	10,3	23,8	3981,6
2000	564	1314	10,1	23,9	3975,3
2001	491,1	1288	10,9	23,8	4098,2
2002	461,5	1291,5	10,8	23,9	4128,4
2003	476,1	1324	10,8	24,2	4123,3
2004	328,1	1303,5	10,5	23,9	4021,3
2005	228,8	1370,7	9,7	24,4	3956,3
2006	452,1	1337,5	10,9	24,5	4171,3
2007	314,8	1284	9,8	23,5	3890,1
2008	431	1295,3	10,1	23,7	3968,8
2009	436	1382,5	10,8	25	4259,9
2010	774,3	1304,3	10,8	23,8	4021,6
2011	454,9	1331,2	11	24,5	4224,8
2012	331	1307,7	10,2	23,9	3984,3
20 year average	449,1	1307,9	10,5	24,0	4060,5

Table 14: Yearly average data study area

PRECIPITATION

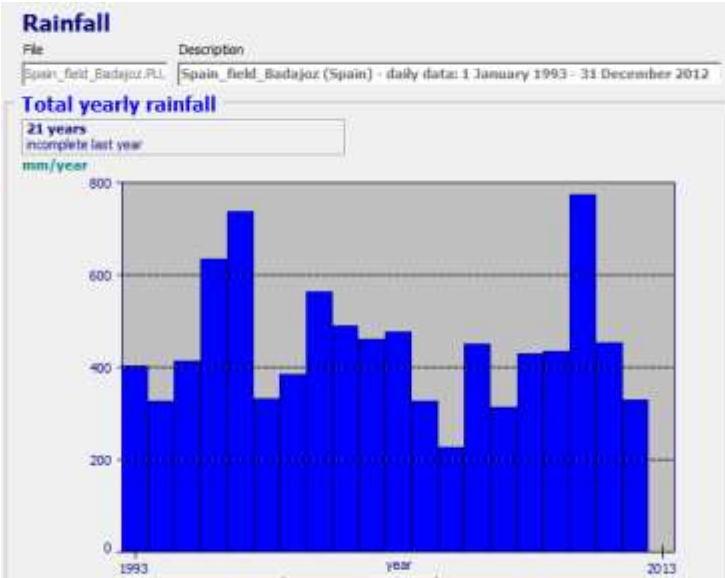

Figure 12: Yearly rainfall study area (1993-2012) in mm/year

Figure 17 shows the total yearly rainfall over the period 1993-2012 in mm/year. The precipitation data show that there is an average of almost 450 mm/year over the period 1993-2012. We can categorize the years into wet, normal and dry years. There have been 3 wet years (>600 mm/year; 1996, 1997 and 2010), 10 normal years (400-600 mm/year; 1993, 1995, 2000, 2001, 2002, 2003, 2004, 2006, 2008, 2009 and 2011) and 7 dry years (<400 mm/year; 1994, 1998, 1999, 2004,2005,2007 and 2012).

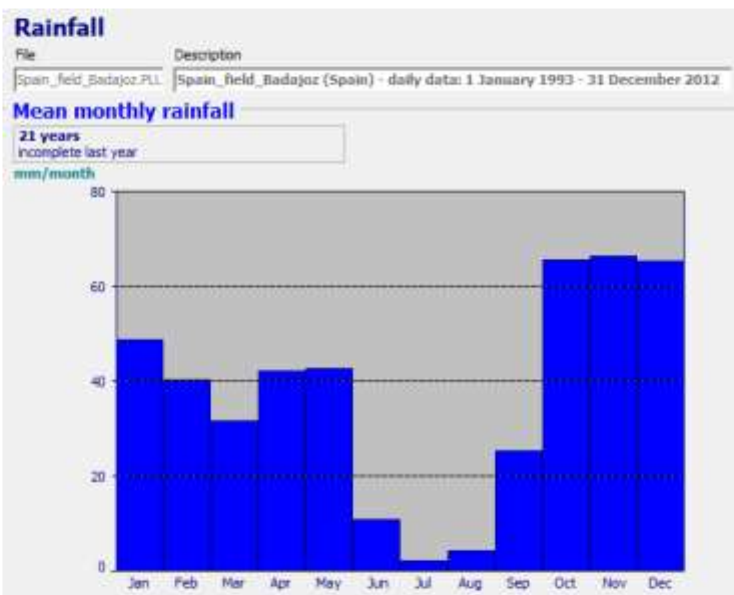

Figure 13: Mean monthly precipitation (1993-2012)

Figure 18 shows the mean monthly rainfall over the period 1993-2012 in mm/month. This shows that there are four dry summer months (<30 mm/month; June, July, August and September). The wettest months are the winter months October, November and December with an average precipitation of 65 mm/month.

EVAPOTRANSPIRATION

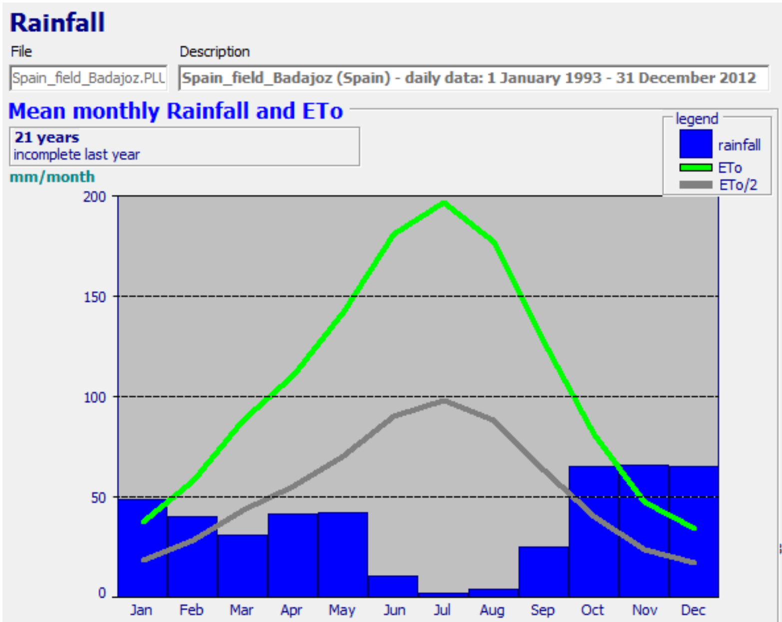

Figure 14: Mean monthly Rainfall and ET0 (1993-2012)

Figure 19 is a copy of the mean monthly rainfall just like figure 2 but now also the demand of evapotranspiration by the atmosphere. The green line shows the ET_0 and the grey line the $ET_0/2$. For most months the evaporative demand is higher than the precipitation, with exceptions for January, November and December. During the summer the evaporative demand is the highest, with a peak of over 200 mm/month in July.

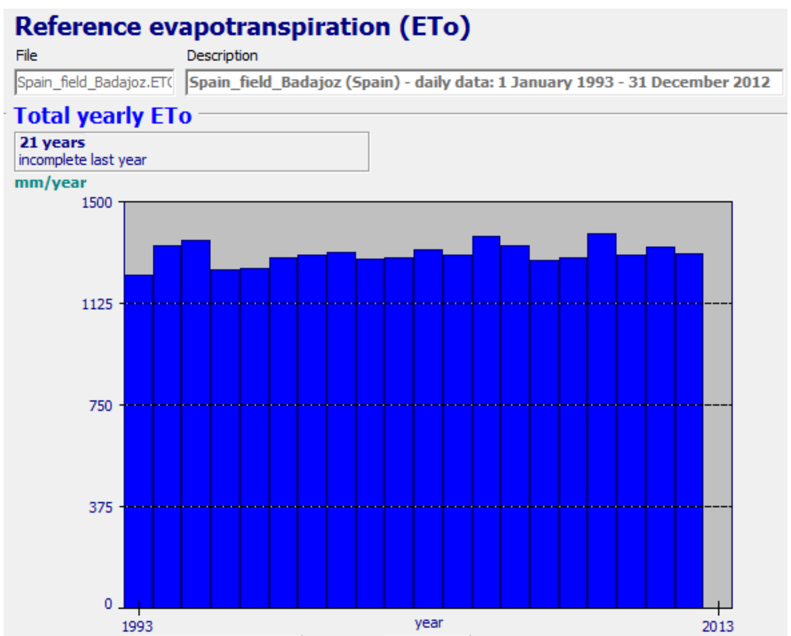

Figure 15: Reference evapotranspiration ET0 (1993-2012)

Figure 20 shows the total yearly reference evapotranspiration (ET_0). The average reference evapotranspiration over the period 1993-2012 is 1308 mm/year. This graph has a similar shape as the mean yearly air temperatures (see figure 6).

TEMPERATURE

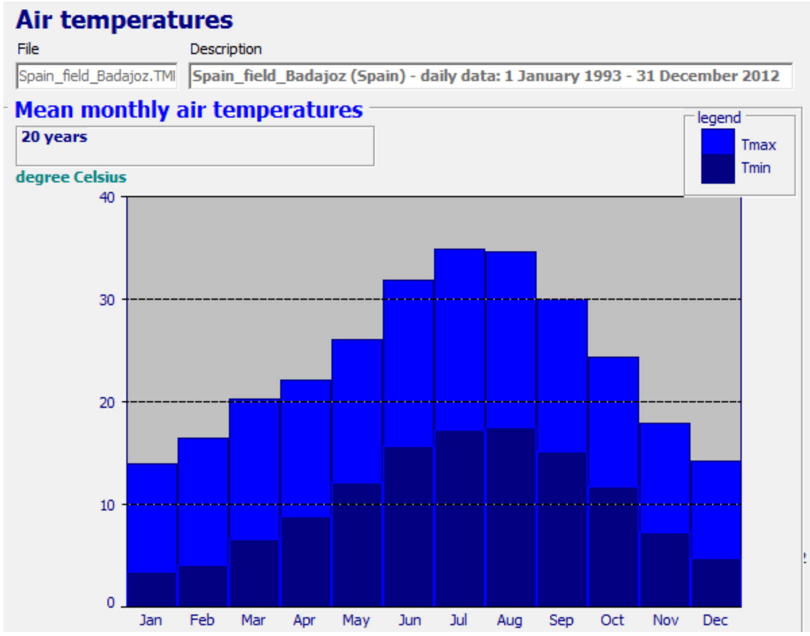

Figure 16: Mean monthly air temperatures Tmin and Tmax (1993-2012)

Figure 21 shows the mean monthly minimum and maximum air temperatures over the period 1993-2012. The average between the minimum and maximum temperatures forms the mean monthly temperature. The warmest months have a mean maximum temperature above the 30 *°C* (June, July, August and September). The coldest months have a mean minimum temperature of below the 5 *°C* (December, January, and February).

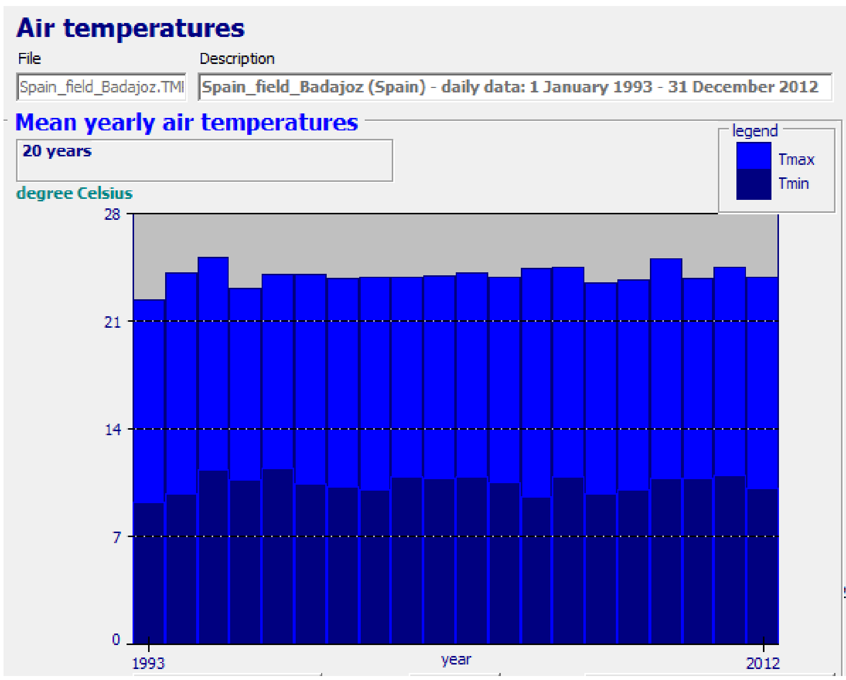

Figure 17: Mean yearly air temperatures Tmin and Tmax (1993-2012)

Figure 22 shows the mean yearly minimum and maximum air temperatures over the period 1993-2012. The graph has the same shape as figure 4, indicating that the temperature has a large impact on the reference evapotranspiration. The mean yearly minimum temperature (10.5 °C) and maximum temperature (24 °C) give a mean yearly temperature of 17,25 °C for the period 1993-2012.

CO_2 - CONCENTRATION

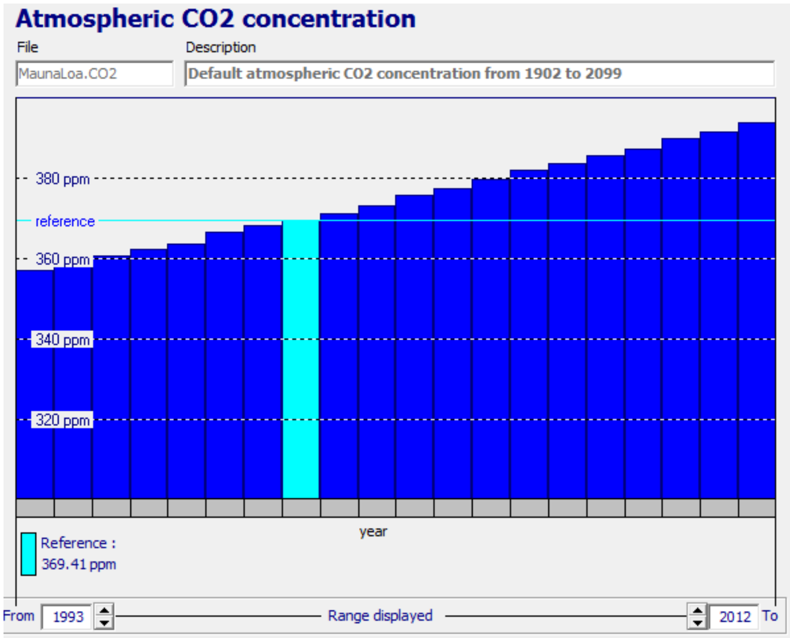

Figure 23 shows the development of the atmospheric CO_2 concentration. We use the default option that simulates the CO_2 concentration from 1902 to 2099. By selecting the years 1993 to 2012 we can see the development of the atmospheric concentration. It shows a reference concentration of 369.41 parts per million (ppm) for the year 2000.

Figure 18: Atmospheric CO2 concentrations (1993-2012).

CLIMATE CLASSIFICATION

Based on the numerical output of the data and the graphs from AquaCrop we can determine the climate of the study area. The most frequently used climate classification map is that of Vladimir Koppen, presented in its latest version 1961 by Rudolf Geiger (Kottek et al., 2006). By having a first look on the data, our hypothesis is that the study area has a BSk (Cold semi-arid) climate or Csa (Hot dry summer) climate. There is not a BSk climate, because the precipitation threshold is lower than the average precipitation. This leaves the Csa climate, which has the following conditions:

- ‘C zones’ or temperate climates have an average temperature above -3 °C, but below 18 °C in their coolest months.
- The second letter indicates the precipitation pattern (‘S’ represents dry summers). Koppen has defined a dry summer month as a month with less than 30 mm of precipitation and with less than one-third of the wettest winter month.
- The third letter indicates the degree of summer heat: "*a*" represents an average temperature in the warmest month above 22 °C.

For the study area the months: November, December, January, February, March and April fit the first criterion, so there is a temperate climate. The wettest winter month is December with 66,3 mm. There are 3 months that meet both criteria of the second mark: June, July and August are all dry summer months. The average temperature in the warmest month is August with 26.2 °C. According to the Koppen-climate classification and based on the data provided for the study area over the period 1993-2012 we can speak of a hot dry-summer climate (Csa) for the region of Badajoz, Spain.

GLOSSARY

Blue water footprint: volume of surface and groundwater consumed as a result of the production of a good or service. Consumption refers to the volume of freshwater used and then evaporated or incorporated into a product. It also includes water abstracted from surface or groundwater in a catchment and returned to another catchment or the sea. It is the amount of water abstracted from groundwater or surface water that does not return to the catchment from which it was withdrawn.

Consumptive water footprint: The consumptive water footprint is defined as the sum of the green and blue component of the water footprint. It excludes the grey water footprint.

Crop water requirement: The total water needed for evapotranspiration, from planting to harvest for a given crop in a specific climate regime, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield.

Crop yield: Weight of harvested crop per unit of harvested area. The yield is measured in ton/ha.

Evapotranspiration: Evaporation from the soil and soil surface where crops are grown, including the transpiration of water that actually passes crops.

Green water footprint: Volume of rainwater consumed during the production process. This is particularly relevant for agricultural and forestry products (products based on crops or wood), where it refers to the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested crop or wood.

Water footprint: The water footprint is an indicator of freshwater use that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater used to produce the goods and services consumed by the individual or community or produced by the business. Water use is measured in terms of water volumes consumed (evaporated or incorporated into a product) and/or polluted per unit of time. A water footprint can be calculated for a particular product, for any well-defined group of consumers (for example, an individual, family, village, city, province, state or nation) or producers (for example, a public organization, private enterprise or economic sector). The water footprint is a geographically explicit indicator, showing not only volumes of water use and pollution, but also the locations.

Water Footprint Accounting: The step in Water Footprint Assessment that refers to collecting factual, empirical data on water footprints with a scope and depth as defined earlier.

Water Footprint Assessment: Water Footprint Assessment refers to the full range of activities to: (i) quantify and locate the water footprint of a process, product, producer or consumer or to quantify in space and time the water footprint in a specified geographic area; (ii) assess the environmental, social and economic sustainability of this water footprint; and (iii) formulate a response strategy.

Water Footprint Benchmark: A measure of water productivity or its inverse: water footprint (m3/product units) of a process or a product. It is the highest water footprint of process or product produced most efficiently using the best available practices and technologies for a fixed percentile of production in the region or the globe.

Water footprint of a product: The water footprint of a product (a commodity, good or service) is the total volume of freshwater used to produce the product, summed over the various steps of the production chain. The water footprint of a product refers not only to the total volume of water used; it also refers to where and when the water is used.

Water productivity: Product units produced per unit of water consumption or pollution. Water productivity (product units/m3) is the inverse of the water footprint (m3/product unit). Blue water productivity refers to the product units obtained per cubic meter of blue water consumed. Green water productivity refers to the product units obtained per cubic meter of green water consumed. Grey water productivity refers to the product units obtained per cubic meter of grey water produced. The term ‘water productivity’ is a similar term as the terms labor productivity or land productivity, but now production is divided over the water input. When water productivity is measured in monetary output instead of physical output per unit of water, one can speak about ‘economic water productivity’.