Water footprint - Assessing efficiency of wheat production in New Zealand

Tim Doornkamp

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Tim Doornkamp
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Supervisors
Dr. R. Singh, external supervisor
A.D. Chukalla, internal supervisor

External place of research
Massey University
Institute of Agriculture & Environment
Palmerston North (NZ)

ABSTRACT

Since global water scarcity is increasing, raising awareness on the water consumption of activities, products and processes and the means to make the processes more sustainable becomes more important by the day. One of the methods to get an insight into the water use of a crop is by using the Water Footprint analysis. For this reason the research has been set up, and an assessment was made of the blue and green Water Footprint of wheat of the regions of Kiwitea, Dorie, Chertsey and Wakanui in New Zealand, with regard to the efficiency of the wheat production process.

To make the assessment, firstly local as well as global information was gathered to generate input for the consumptive local and global water footprint analysis for the periods of 2013-2014 and 2014-2015. The information consisted of climatic data, crop specific data, information on the management practices and the soil data. The AquaCrop tool (FAO, 2015) was used to generate the data needed for the Water Footprint calculation, consisting of the simulated yield, applied irrigation and crop evapotranspiration. After that, the same was done for different periods of time, depending on the availability of climatic data for each of the regions. The benchmarks as set by Hoekstra & Mekonnen (2013) were then used as comparison for the found local and global Water Footprints.

The Water Footprints that resulted from the analysis with local data are 509 m^3/ton for Kiwitea, 538 m^3/ton for Wakanui, 514 m^3/ton for Chertsey and 422 m^3/ton for Dorie. The Water Footprints that resulted from the analysis with global data are 409 m^3/ton for Palmerston North, 583 m^3/ton for Rakaia and 533 m^3/ton for Ashburton. This means that the local as well as the global water footprints estimated in this report perform better than the set benchmark for the 10th percentile of the world of 529 m^3/ton. The validation of the model assessing the simulated as opposed to the observed values for the crop yield resulted in the statistical values of a root mean square error of -0.02, a coefficient of mass residual of 0.44, an index of agreement of -15.54 and an average deviation of 12.03%.

The overall conclusion is that the wheat production process at the sites used for the research is very efficient, and should give a decent representation of the wheat production in the whole of New Zealand.

Keywords: Water productivity, water balance, modelling, AquaCrop, benchmark, irrigation, trial sites

PREFACE

With the completion of this research I hope that I have been able to contribute to the process of preserving the beautiful country of New Zealand, and to encourage people to be more aware of the role they can play in environmental issues.

Most of all, I am happy with the completion of this thesis, which is final chapter to my three months working experience at Massey University, and the Bachelor of Civil Engineering at the University of Twente. It was really interesting to work in a different environment, meet new people and explore New Zealand. I was very lucky to have had the privilege of being situated in an office with colleagues with whom I could share my experiences with.

In the beginning my interest went out to the subject of water footprint, sustainability and a product analysis. Since New Zealand has always been of personal interest to me, the choice seemed logical to come up with a research question that combined the previously mentioned elements. As for the 'product', the assessment for the production process of a crop seemed most interesting. After getting in contact with Dr. Singh of Massey University he suggested to take an arable crop as subject, which led me to wheat. My overall goals were learning to work in a different environment than I am used to, help to contribute in an environmental way to the country of New Zealand and enhance my knowledge about water management and sustainability. The reason I chose New Zealand was because I lived in New Zealand for some amount of time, and I absolutely loved everything about it. After my bachelor thesis I would like to continue with a master in water management.

During this research I quickly discovered the difficulties that can occur while conducting a research. The first few weeks I thought I was on the right track, collecting data and trying to implement this into AquaCrop. However, after a conversation with Dr. Singh it turned out that I had been going at it the wrong way, and had to use a different source. At first it was frustrating, because I felt like after those weeks I should have been able to have something to show for it, but I figured that this was just part of the process. With this in mind, I soon found the input data that I needed, and after getting familiar with using the AquaCrop tool I was able to make an estimate of the water footprints and complete my research. I started my research on the 3rd of June and handed in the final report on the 21st of August, 2015.

I'd like to thank, first of all, my supervisors Dr. Ranvir Singh from Massey University and Mr. Abebe Chukalla from the University of Twente for guiding me through the process and giving me advice at times when I encountered difficulties. They helped me to initialize the research and enabled me to present the report in its current form. Having Dr. Ranvir Singh as my supervisor was very helpful, since he was encouraging me in the way that he wanted me to get something out of the experience and learn new things. Furthermore, I'd like to thank my family in Palmerston North, in special Mrs. Caroline Hilderink, who provided me with a home to stay until I found a student dorm to live in. Also I'd like to thank my family in Auckland, who have always been there to welcome me coming to New Zealand and even provided me with a car which I used to travel around. Last but not least I'd like to thank all of the people in my office, in special Matt Hemler, who helped me in retrieving part of the data I needed. They gave me the chance to discover New Zealand and participate in all kinds of activities which I wouldn't have encountered without them.

Tim Doornkamp
Palmerston North, New Zealand
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CHAPTER 1 - INTRODUCTION

In this chapter the background of the research, its purpose and objectives are given, as well as a description of the research area.

1.1. Background

Water scarcity already affects every continent. New papers from the United Nations inter-agency coordination mechanism for all freshwater and sanitation related matters have shown that around 1.2 billion people (almost one-fifth of the world's population) live in areas of physical water scarcity, and another 500 million await the same fate (UN Water, 2014). The prediction is that almost half the world's population will have to endure water stress by 2030, given the existing climate change scenario. Water scarcity is both a natural and a man-made phenomenon. Even though there is enough freshwater on the planet for the seven billion people the unevenly distribution, pollution, wasting and unsustainable management continues to cause problems (UN Water, 2014).

A great deal of the consumption and pollution of water takes place by the influences of human activities, mostly for agricultural purposes. This can be associated with specific activities, such as irrigation, bathing, washing, cleaning, cooling and processing (Hoekstra & Mekonnen, 2013). People in general have little idea about the effect that influences in these fields can strongly affect the volume of water that can be associated with a final consumer product. With the earlier mentioned prediction for scarcity 2030 in the back of one's head it becomes clear something has to be done to ensure a more efficient use of the available water.

Hoekstra and Chapagain (2008) have shown that visualizing the hidden water use behind products can help in understanding the global character of fresh water and in raising overall awareness. The improved understanding can form a basis for better management of global freshwater resources. One way to achieve this goal is by applying the concept of Water Footprint analysis, as devised by Professor Arjen Y. Hoekstra. The water footprint is an indicator of freshwater appropriation, developed as an analogue to the ecological footprint, which is an indicator of use of biologically productive space. In essence, water footprint assessment is primarily about making the comparison of the human water footprint with what the earth can sustainably support (Hoekstra et al., 2011). It can be applied to the water consumption of a whole country (National Water Footprint), by analyzing the water consumption of a business (Corporate Water Footprint) or by analyzing the water consumption in the production process of food or other products (Product Water Footprint). The last one is adressed in this report.

The Product Water Footprint can be further divided into the blue, green and grey WFs, which can be estimated by following the calculation framework as set out in Hoekstra et al. (2011) "The Water Footprint Assessment Manual".

- The blue water footprint is an indicator of consumptive use of so-called blue water, in other words, fresh surface water or groundwater.
- The green water footprint is an indicator of the human use of so-called green water. Green water refers to the precipitation on land that does not run off or recharges the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation.
- The grey water footprint is an indicator of the degree of freshwater pollution that can be associated with the process step. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards.

The Water Footprint of a product is expressed as water volume per product unit. This can mean, for example, the water volume per unit of mass, unit of money, per piece or per unit of energy. For the assessment made in this report the water volume per ton is determined, since the yield of wheat production is expressed in ton/ha.

The input parameters needed to quantify the blue and green Water Footprint of a crop consist of the evapotranspiration and the crop yield. Since the measurement of the true value of crop evapotranspiration poses a variety of challenges and is susceptible to errors, modelling is being developed and used to make estimates. As the estimation of the yield response under water-limiting conditions remains one of the central issues, FAO has developed a yield-response to water model, AquaCrop, which simulates yields of the major herbaceous crops, including wheat. The difference of AquaCrop as compared to other models is that is has a smaller number of parameters, which makes for a better balance between simplicity and accuracy. It is a tool designed for making a prediction of crop production under different water-management conditions (including rain fed and supplementary, deficit and full irrigation) and for investigating different management strategies, under present and future climate change conditions. The way it works is firstly by simulating the root zone water content by keeping track of incoming and outgoing water fluxes at its boundaries, taking the soil water storage properties into account. Instead of the leaf area index the canopy ground cover is used. Canopy development, stomatal conductance, canopy senescence and harvest index are the key physiological crop responses to water stress. Secondly AquaCrop simulates the evapotranspiration as crop transpiration and soil evaporation. By using the normalized biomass water productivity of the wheat and the daily transpiration the daily biomass gain can be determined (Steduto, et al., 2015). The reference evapotranspiration ET_0 is converted to the crop evapotranspiration by multiplying ET_0 with the crop evapotranspiration coefficient K_c, after which a multiplication with the soil water evaporation coefficient K_s leads to the adjusted crop evapotranspiration ET_a (Allen et al., 1998). The output of AquaCrop consists of the simulated crop yield, applied irrigation and total adjusted crop evapotranspiration, and will be used to determine the green and blue Water Footprint.

The global Water Footprint benchmarks in their current form give an indication of the water efficiency within the production process of many different crops all over the world. The problem that occurs with this however is the fact that a global estimate is unable to account for local circumstances, which may lead to a distorted reflection of the true situation. Also, as not all data will be available for every region, assumptions have been made, leading to an even greater margin of error. By conducting research on the blue and green Water Footprint on a local scale a more accurate reflection of the situation can be generated and used to assess the efficiency.

1.2. Research purpose

Since wheat is one of the main crops of New Zealand, is seems like a logical choice to examine if the process is water efficient as it is, or that improvements can be made. One of the ways to determine if the water is being used as efficient as possible is by calculating the consumptive water footprints. By evaluating whether or not alterations within the wheat production process can be made to cut down the water usage one could potentially decrease the costs and the negative effect on the environment.

Measurements have shown that, especially with regard to the Canterbury region, an immense increase in irrigated area using groundwater has taken place (Environment Canterbury Regional Council, 2014). This, in turn, leads to the issue of New Zealand approaching its sustainable limits due to the relatively dry climate and the apparent low recharge rates. More knowledge could potentially allow more efficient allocation of water. Furthermore, the research will contribute to the global water footprint calculations in the way that it provides data which can be used for calibration. This will eventually lead to a model which is able to make a more precise estimate of different areas in the world in accordance with locally acquired data.

The main goal of the research is firstly to determine the blue and green Water Footprint of wheat production in different regions of New Zealand. After the calibration and validation of these results the long term influences of the input factors are simulated. Comparing these results with the globally made estimates will give an insight in to how accurate the global model is able to predict the local situation.

1.3. Research questions

The central question for the research is a combination of the sub questions, and can be formulated as follows:

- How would you value the efficiency of water use within the wheat production process in New Zealand?

To find an answer to this question, a couple of sub questions need to be addressed, namely:

1. What is the consumptive water footprint of wheat in the FAR trial sites of 2013-2014 and 2014-2015, based on local data?
   1.1. What effect does the input of local average climatic data have on the consumptive water footprints?
2. What is the consumptive water footprint of wheat in the FAR trial sites based on globally available data?
3. How do the local and global consumptive water footprints compare to each other and the global WF benchmarks?
4. What can be said about the efficiency of the wheat production process in its current form in New Zealand, and what recommendations can be made following previously conducted research on the topic?

1.4. Study area description

For the selection of the crop for the research wheat has been chosen, since it is one of the main seed crops produced by the New Zealand arable industry in the early 2000s (Ara, 2007). New Zealand arable production is centered on the Canterbury Region, although production also occurs in the Otago region and the Southland. In 2011, 88% of the total wheat areas were planted in Canterbury (Millner, 2011). One of the main foundations that focuses on wheat production in New Zealand is the FAR. The Foundation for Arable Research is an 'applied research and information transfer organization responsible primarily to New Zealand arable growers'. Every year they use trial sites to monitor the yield responses of wheat and barley in different regions of New Zealand, as shown in Figure 1. What is interesting is that they explore the possibility of wheat production on the North Island as well (Kiwitea on the map), which will provide an opportunity to compare the consumptive water footprint on the North Island as opposed to the South.

Figure 1: FAR Trial sites 2014-2015

With regard to the irrigation systems, most irrigation in New Zealand is applied with sprinklers of various types. Traditionally irrigation methods consisted of flood irrigation, particularly border-dyke. Up till 2007 no less than 64.000 ha in Canterbury was using this method (Statistics New Zealand, 2007). The main disadvantage of border-dyke irrigation is that the amount of water applied varies greatly with distance from the dyke, which in time will lead to a water deficit and drainage at the upper end once the water has finally reached the lower end of the borders. This makes this method very water inefficient. The drainage can lead to soil moisture reaching field capacity, so minimizing it by means of irrigation is key (Millner, 2011). Ideally, the irrigation is scheduled in such a way that ensures soil moisture does not fall below the point at which potential yield declines (trigger point) of the crop, usually about 50% of field capacity (Foundation for Arable Research, 2011). For this reason border-dyke systems have been steadily replaced with sprinkler systems. The current irrigation method used in the Canterbury region mainly consists of center pivot sprinklers (Millner, 2011)

As mentioned above, the study focusses on the trial sites as presented by FAR (2015). Since there is limited time available to conduct the research, four sites have been chosen to examine more closely. The selection of the areas is based on the fact whether or not any problems occurred during the growing period (such as logging or shattering), the presence/absence of daily climatic data and accurate soil descriptions. The selection procedure resulted in the sites of Kiwitea, Dorie, Chertsey and Wakanui. These areas represent a large portion of the New Zealand wheat production and a range of different input factors. Kiwitea is a relatively new site for crop production, which means that it has the potential to grow significantly, which makes an early water footprint analysis all the more interesting. Furthermore the differences in geographical locations can be compared and evaluated.

The reference period for the calculation of the global benchmarks is the average over the years 1996-2005. The research of this paper focuses on the results of trials conducted from 2013-2014 and 2014-2015.

CHAPTER 2 - RESEARCH METHODS AND MATERIALS

In this chapter the methods used during this research for gathering and processing information regarding the consumptive water footprints is described.

2.1. Water footprint calculation with local data

Firstly the local water footprints will need to be calculated. Therefore local data sources have to be found in order to get the most accurate data-set of the specific region. Once the initial water footprint of the regions has been calculated and callibrated for the period 2014-2015, the collected data on the previous period of 2013-2014 can be used to validate the outcome. By changing the time span of the climatic data the model can then be applied to other periods of time, to assess the influence of the climatic factors.

2.1.1. AquaCrop model input data

For the determination of the water footprint firstly the actual evapotranspiration and the yield response have to be estimated. For this the tool AquaCrop is used. The data that AquaCrop requires as input consists of:

- Climatic data (air temperature, reference evapotranspiration, rainfall and CO2 level),
- Soil texture data (sand, clay, loam, in %)
- Crop parameters (sowing rate, sowing and harvest dates, degree for the different stages of development, crop cop coefficient, harvest index, etc.)
- Management conditions (irrigation dates and amounts, groundwater level)
- Initial conditions (soil water level)

The data required has been gathered mostly from the National Institute of Water and Atmospheric Research (NIWA), the Foundation for Arable Research (FAR), the Home-Grown Cereals Authority (HGCA), the Landcare Research Informatics team and the Plant & Food research facility (Steve Green). Not to forget the Food and Agriculture Organization of the United Nations (FAO).

Climatic data

To acquire the climatic data the CliFlo database of the NIWA of New Zealand has been used. This database collects daily information from climatic monitoring stations spread through the country regarding the minimum/maximum air temperature (T_{min},T_{max}), the reference evapotranspiration (ET_0) and the rainfall. The reference evapotranspiration has been determined with the help of the Penman -Monteith Method, as advised by Allen et al. (1998). The method was devised as an improvement of the FAO Penman method, which was found to frequently overestimate ET_0.

By looking at NIWA's Environmental Information Browser it was possible to determine which stations were located closest to the Dorie, Kiwitea, Chertsey and Wakanui regions, compare the data and find the most accurate climatic input. The stations names considered to provide this input are respectively Dorie Cws @ Leferink, Palmerston North Aws, Chertsey Cws and Wakanui Cws. Within the data of the Wakanui station some days of minimum/maximum temperature and evapotranspiration were missing, which were manually estimated by comparing the data to that of nearby stations, in this case Ashburton Aws. Daily data proved to be more accurate than monthly data, since the AquaCrop tool doesn't account for partial months, and would take the rainfall of the entire month if, for example, the specific harvest date only required half. To make sure that the missing data from Wakanui doesn't affect the outcome of the assessment a reference calculation will be done for the location of Ashburton, using the Ashburton climatic data in combination with the Wakanui soil, irrigation and crop data.

As for the Atmospheric Carbon Dioxide level, it had to be checked whether or not the standard setting of AquaCrop could be applied to the situation in New Zealand. For this, information from

NIWA regarding the Carbon Dioxide Mixing Ratio (ppm) of the station at Baring Head was used, see Figure 2. Since both the standard setting from the MaunaLoa station used by AquaCrop and the Baring Head station followed the same curve and generated almost identical values the MaunaLoa data was applied to the yield response and evapotranspiration calculation.

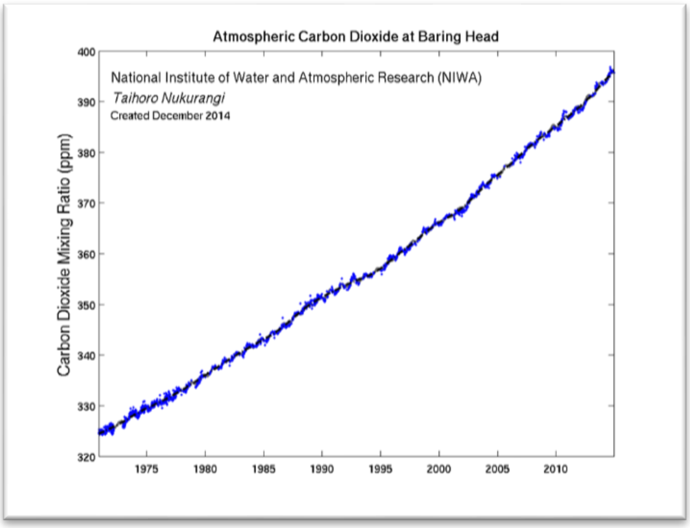

Figure 2: CO2 level Baring Head (NIWA, 2015)

To give an indication of the climatic data, the total reference evapotranspiration over the growing periods, the average minimum/maximum temperature and the rainfall over the growing periods have been presented in Table 1.

Table 1: Climatic data input

Region/growing season	ET_0 over growing period (mm)	Average T_{max} (°C)	Average T_{min} (°C)	Rainfall over growing period (mm)
Dorie				
2013-2014	713.7	16.9	7.1	483.6
2014-2015	686.4	16.9	7.0	333.4
Kiwitea				
2013-2014	823.5	18.6	9.0	713.2
2014-2015	701.1	18.7	9.0	608.8
Chertsey				
2013-2014	810.9	16.5	6.8	748.6
2014-2015	699.8	17.2	7.1	420.6
Wakanui				
2013-2014	759.1	16.9	7.1	494.0
2014-2015	804.7	16.9	7.0	263.6
Ashburton reference				
2013-2014	770.9	17.0	6.9	635.0
2014-2015	821.5	17.2	7.2	276.9

Soil texture data

The FAR trial site reports gave a definition of the specific soil types present at the location of the wheat production. As mentioned before, the specific regions have been chosen based on the availability of data, which includes the soil types. The soil names given by FAR consisted of regional names, some of which did not generate any results in the soil database of the Landcare Research Informatics Team. The regional names however could be converted to general terms by using the Soil

Factsheet (S-mapOnline, 2015), which contains information about the key properties of a particular soil, and interprets information derived from a suite of models that classify various environmental risks.

The soil types that resulted from this analysis can be seen in Table 2. Since the percentages are given by ranges or numbers, the mean of the numbers has been chosen as input value to preserve the ratios.

Table 2: Soil profiles

Region	Soil name	Horizons	Stones (%)	Clay (%)	Sand (%)	Thickness of the soil layer (cm)
Dorie	Templeton Silt Loam	1. Loamy Fine Slightly Firm	0	20-30	10-20	25-35
		2. Loamy Coarse Slightly Firm	0	25-35	15-40	40-50
		3. Clayey Coarse	0	30-45	10-20	20-30
Kiwitea	Kiwitea Silt Loam	1. Loamy Weak	0	18-30	5-15	20-28
		2. Loamy Weak	0	20-35	5-20	75-80
Chertsey	Chertsey Moderately Deep Silt Loam	1. Loamy Weak	0	15-25	5-15	25-35
		2. Loamy Fine Slightly Firm	0	15-25	5-15	0-50
		3. Loamy Course Slightly Firm	0	10-25	5-20	0-40
		4. Very Stony Loamy Compact	40-60	5-12	15-35	10-30
		5. Very Stony Sandy Loose	50-70	0-4	85-95	0-30
Wakanui	Wakanui Silt Loam	1. Loamy Fine Slightly Firm	0	15-30	10-30	25-35
		2. Loamy Course Slightly Firm	0	25-35	10-30	18-38
		3. Loamy Coarse Slightly Firm	0	10-25	30-60	35-50

The next step with regard to the soil input required by AquaCrop is the determination of the Field Capacity, Wilting and Stress points. For this, a model created by Dr. Steve Green of the Plant & Food Research Facility has been used, which withdraws data from the S-map database and uses this to estimate the needed soil hydraulic parameters. An example of the program output for Chertsey is given in Figure 3. The naming of the horizons differs from the naming in the S-map database, but they contain the same values. Since the program does not allow the option for 'Wheat' as crop, 'Maize' has been chosen, since this generates the similar properties. The root depth has been set to 1.40 m (HGCA, 2008). The Soil bulk density was set to 1.22 g/cm^3, in accordance with the S-map factsheets data.

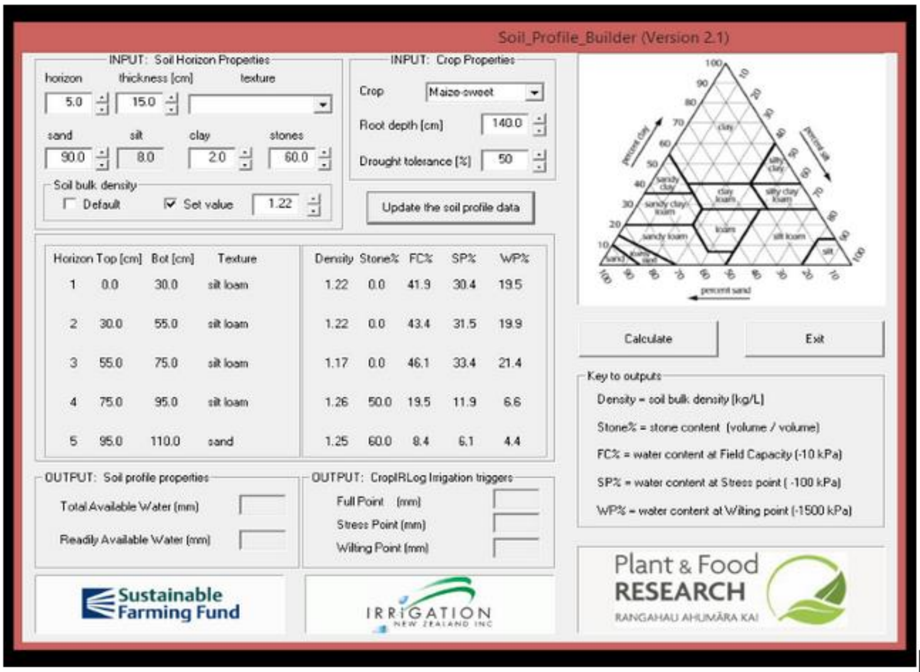

Figure 3: Example estimation FW, SP and WP for Chertsey

With regard to the groundwater table, monitoring networks within the Canterbury region have measured that the depth is more than ten meter deep, which means that no cappilary rise will occur (Environment Canterbury Regional Council, 2014). As for the Kiwitea Site, monitoring networks from Horizons have measured the same phenomenon, as the ground water table goes as deep as 50 meters at some occasions (Horizons, 2013).

Crop parameters

The crop specific parameters of AquaCrop require the most input of all. They consist of the crop development parameters, evapotranspiration parameters, crop production values, stress parameters and the growing cycle input.

Crop development parameters.

- The initial canopy cover is based on the plant density and the canopy size of the seedling. According to (FAO, 2012b), the soil surface covered by an individual seedling is 1.5 cm^2/plant.
- The generally established plant density target of the FAR trial sites is 150 plants/m^2 for feed wheat and 175 plants/m^2 for milling wheat (FAR, 2015).
- The thousand grain weight of the wheat used as described by the FAR research papers vary between 45 and 55, which results in a mean of 50 g.
- The Canopy growth coefficient (CGC) as given by FAO (2012b) is suggested to have a value between 0.5 - 0.7% (fraction per growing degree day). After running the model it was confirmed that these values lie within the boundaries.
- The Maximum canopy cover (CC$_x$) is suggested to lie between 80 – 99 %, and after calibration is set to 96%.
- The Canopy decline coefficient (CDC) is set at 0.4% (fraction per growing degree day), in accordance to the provided parameter sheet of FAO (2012b).

Furthermore, wheat has a slow canopy development in the initial stage (HGCA, 2008), which complies with the data generated from the AquaCrop tool.

Evapotranspiration parameters.

These parameters consist of the crop transpiration coefficient (K_{cTr}) and the soil evaporation coefficient (K_e). Differences in soil evaporation and crop transpiration between field crops and the reference surface are integrated within the crop coefficient. After rainfall or irrigation, the effect of evaporation is dominant when the crop is small of size and only shades the ground for a small percentage. For those low-cover conditions, the K_{cTr} coefficient is determined mostly by the frequency with which the soil surface is wetted. Where the soil is wet for most of the time from irrigation or rain, the evaporation from the soil surface will be considerable and Kc may exceed 1 (Allen et al., 1998).

Values of K_{cTr} for most crops increase from a minimum value at planting to maximum at about full canopy cover. The K_{cTr} tends to decline at a point after a full cover is reached in the crop season (Lazzaro & Rana, 2015). The declination primarily depends on the particular crop growth characteristics and the irrigation management during the late season (Allen et al., 1998).

What has to be noted with regard to the globally calculated average crop coefficient factors is that the K_{cTr} is affected by all the factors that influence soil water status, for instance, the irrigation method and frequency, the weather factors, the soil characteristics and the agronomic techniques that affect crop growth (Lazzaro & Rana, 2015). Because of this, the average crop coefficient values can vary significantly from the actual ones if growing conditions differ from those where the fore mentioned coefficients were obtained (Tarantino and Onofrii, 1991).

The AquaCrop model, as opposed to the older CROPWAT model, doesn't allow the crop coefficient factors for the different stages to be manually entered. Instead, it uses the mid-stage crop coefficient value and an age reduction factor to simulate the initial-, development- and late-stage. The suggested value for K_{cTr} is 1.10 (FAO, 2012b), but after calibration a value of 1 generated a more accurate reflection of the true yield and transpiration. The lower value could be caused by any of the fore mentioned factors, but will most likely be the result of differences in the length of crop growing stages and irrigation timing, as is discussed further on.

Crop production values.

These consist of the crop water productivity (WP) value, which was normalized for the climate and CO2, and the reference harvest index (HI). Since wheat is classified as a C3 and not as a C4 plant, the values of the WP range from 15-20 g/m^2 (FAO, 2012b).

C3 plants are regular everyday plants, they open their stomata during the day to breathe in CO2 and release O2. They go through the light and dark reactions normally since they are not exposed to extremely hot conditions. C4 plants have devised ways to overcome rough environments (Zundel, 2015). After using the climatic data as input and calibrating the model, a value for WP of 15g/m^2 was found to be most suitable.

The harvest index of winter wheat normally ranges from 45 to 55% according to Hsiao et al. (2012), while the crop parameter appendix of FAO (2012b) suggests a range from 45 to 50%. A harvest index of 48% has been chosen after calibration, since the specific harvest index of the wheat applied in the trial sites is unknown, and this value resulted in the most accurate prediction of actual yield.

Soil water, soil salinity and air temperature stresses.

Standard values provided by AquaCrop have been used, which complied with findings of Hsiao et al. (2012), who stated that wheat is considered to be moderately tolerant the fore mentioned stresses.

Calendar of the growing cycle.

The length of the total growing period (life cycle) of winter wheat normally ranges from 180 to 300 days (Hsiao et al., 2012), depending upon climate, seed type, and soil conditions (winter wheat lies dormant during a winter freeze) (NZGSTA, 2015). According to Mr. Rob Craigie, who was involved in the creation of the FAR trial site report, it takes about 150 degree days for the Canterbury wheat to emerge, and autumn sown wheat flowers mid to late November.

The sowing and harvesting dates of the crops as well as the attained yield, the type of wheat and the occurrence of special conditions are shown in Table 3.

Table 3: Crop details per region 2013-2014 and 2014-2015

Crop details per region					
Trial site name	**Sow date**	**Harvest date**	**Mean yield (t/ha)**	**Type of wheat**	**Special conditions**
Kiwitea	*19 May 2014*	*29 January 2015*	*11.4*	*Milling*	
	8 May 2013	*20 February 2014*	*9.7*	*Milling*	
Dorie	*11 May 2014*	*5 February 2015*	*11.9*	*Milling*	
	12 May 2013	*26 February 2014*	*8.5*	*Milling*	*Barley yellow dwarf*
Chertsey	*15 April 2014*	*4 February 2015*	*11.9*	*Feed*	
	25 March 2013	*21 February 2014*	*11.9*	*Feed*	
Wakanui	*25 May 2014*	*5 March 2015*	*16.0*	*Feed*	
	31 May 2013	*12 March 2014*	*8.5*	*Milling*	*Shattering, lodging and Barley yellow dwarf*

The definite length of the different growth stages, consisting of the initial stage, canopy development stage, mid- and late-season stage were determined by using the previously mentioned dates and the guidelines as set out by HGCA (2008) and Hsiao et al. (2012).

Management conditions

The management conditions of the trial sites differ from each other, in the sense that not one requires as much irrigation as the other. The FAR reports state the amount of irrigation in millimeters that the farmers have applied, and the number of passes of the center pivot irrigator they needed to disperse the water. According to FAR (2015), the farmers rely on data from lysimeters in the surrounding area. The way these lysimeters work is by calculating the evapotranspiration (ET) as the change in storage (ΔS) minus the precipitation (P), the drainage (Q) and the amount of irrigation (I) (Singh, 2015). They measure the soil water content, and base the timing of the irrigation on that. As mentioned before, ideally the irrigation is scheduled in such a way that ensures soil moisture does not fall below about 50% of field capacity.

To translate the input data into AquaCrop the specific dates of application need to be known. However, these are not given by the FAR reports, since the timing and depth are specified by the user according to Mr. Rob Craigie. To solve this issue, firstly the option ‘Generation of irrigation schedule’ was selected in AquaCrop, with the allowable depletion of the field capacity set to 50%.

After running the model with the input data as mentioned before, this resulted in an automatically generated irrigation schedule. The dates suggested by AquaCrop were then used as a guideline and, combined with the occurrence of drought, manually calibrated to fit the information provided by FAR, which delivered the set amount in the specific number of passes. The assumption was made that the center pivot systems deliver 100% surface wetting with water of excellent quality.

In case of Kiwitea where there is a rain-fed agriculture and no irrigation is applied, the 'no irrigation' setting in AquaCrop is used.

In Table 4 and Table 5 the irrigation details as specified by the report as well as the input data for AquaCrop after calibration is shown. What has to be noted is the fact that the sprinkler system needs to be able to deliver an irrigation amount of only 5 mm in one passing. The application as suggested by DairyNZ (2011) is 4 mm/day with an application depth of 12 mm, which would mean the center pivot installation would need three days to return, depending on the size of the field. Since the amounts and timing of the application have been determined manually these values could be changed to 12 mm, by lowering the next application by 7 mm. For the purpose of this research however, the values of 5 mm were chosen since they gave the most accurate estimate of the yield in combination with the other crop parameters.

Table 4: Irrigation details per region 2014-2015

Irrigation details per region	As specified by the report	Input data AquaCrop after calibration	
Trial site name	**Dryland/ Irrigation**	**Irrigation date**	**Irrigation amount (mm)**
Kiwitea	*Dryland*	' No irrigation'	' No irrigation'
Dorie	*240 mm in 6 passes*	16 June	30
		8 July	30
		7 August	35
		29 August	65
		16 September	65
		27 October	15
Chertsey	*371 mm in 13 passes*	19 July	5
		1 August	35
		8 August	5
		13 August	5
		23 August	45
		28 August	5
		7 September	40
		22 September	40
		2 October	26
		19 October	50
		6 November	25
		3 December	45
		6 January	45
Wakanui	*187 mm in 10 passes*	11 September	20
		16 September	20
		17 September	5
		27 September	21
		3 October	20
		17 October	10
		21 October	37
		27 October	34
		9 November	15
		28 November	5
		21 January	52

Table 5: Irrigation details per region 2013-2014

Irrigation details per region	As specified by the report	Input data AquaCrop after calibration	
Trial site name	**Dryland/ Irrigation**	**Irrigation date**	**Irrigation amount (mm)**
Kiwitea	*Dryland*	‘ No irrigation’	‘ No irrigation’
Dorie	*255 mm in 3 passes*	*9 June*	*50*
		19 July	*90*
		28 August	*115*
Chertsey	*290 mm in 10 passes*	*20 July*	*10*
		29 July	*10*
		13 August	*40*
		23 August	*48*
		14 September	*10*
		27 September	*10*
		17 October	*10*
		6 November	*25*
		12 November	*50*
		6 December	*25*
		21 January	*52*
Wakanui	*180 mm in 4 passes*	*3 July*	*20*
		29 August	*60*
		27 September	*50*
		5 November	*50*

2.1.2. AquaCrop model output data

Green and blue water evapotranspiration during crop growth can be estimated with the Food and Agriculture Organization’s AquaCrop model. There are two different ways to do this: using the crop water requirement option (assuming optimal conditions) or the irrigation schedule option (including the possibility to specify actual irrigation supply in time). The latter has been chosen since the irrigation schedules of the specific trial sites have been determined already.

In the second option the crop evapotranspiration can be calculated under both optimal and non-optimal conditions over the total growing season using the daily soil water balance approach. The calculated adjusted crop evapotranspiration ET_a may be smaller than ET_c due to non-optimal conditions. The water movements in the soil, the water holding capacity of the soil and the ability of the plants to use the water can be influenced by different factors, such as physical condition, fertility and biological status of the soil (Hoekstra et al., 2011).

As mentioned before, the reference evapotranspiration ET_0 collected from the climatic stations is converted automatically by AquaCrop to the adjusted crop evapotranspiration by using the following formula:

$$ET_a = K_s * ET_c = K_c * ET_0$$

$Where$
$ET_a \; = \; adjusted\ crop\ evapotranspiration$
$K_s \; = \; water\ stress\ coefficient$
$ET_c = crop\ evapotranspiration$
$K_c = \; crop\ transpiration\ coefficient$

$ET_0 = reference\ evapotranspiration$

By filling in the gathered data as mentioned above in the AquaCrop tool an estimate of the yield response and adjusted evapotranspiration can be made. The data that could not be obtained from local sources is run at standard settings, according to the wheat calculation guidelines provided by FAO.

Under the scenario of a rain-fed agriculture, the green water evapotranspiration (ET_{green}) is equal to the total evapotranspiration as simulated by the model and the blue water evapotranspiration (ET_{blue}) is zero.

In the cases where irrigation practices have taken place the blue water evapotranspiration is equal to the 'total net irrigation' as specified in the model output. The green evapotranspiration is equal to ET_a minus ET_{blue}. The assumption is made that the percolation of the water into the soil is neglect able for this estimation.

Since the outcome data (ET_{blue} and ET_{green}) is given in mm, it needs to be converted to m^3/ha by applying the factor 10. By dividing ET_{green} and ET_{blue} to the yield, the green and blue water footprint can be determined. The formula for this calculation is shown below:

$$WF_{Blue} = \frac{Adjusted\ ET_{Blue}}{Y} [m^3/ton]$$

$$WF_{Green} = \frac{Adjusted\ ET_{Green}}{Y} [m^3/ton]$$

Since these calculations refer to the evapotranspiration from the field, the water that has been incorporated into the wheat has not yet been accounted for. This water is part of the green and blue water footprint, but does not influence the yield. The water fraction of wheat lies in the range of 10-15%. The percentage that the incorporated water contains with regard to the evaporated water needs to be checked (FAO, 2012b).

2.1.3. Validation model

After the calibration has taken place and the water footprints of the 2013-2014 and 2014-2015 trial sites have been determined the model has to be validated. This is done by assessing the AquaCrop yield simulation as compared to the observed yields of the trial sites.

Statistical measures can be used to quantify the differences between the simulated and observed yield, and with that evaluate the performance of the model. Since a single measure is unable to give a proper indication as to how well a simulation model performs, a combination of statistical indices is preferred. In this study, the following formulas were used to ensure the quality and reliability of AquaCrop predictions of crop yield for the trial sites:

$$Percent\ deviation = (Si - Oi) * 100/Oi$$

The percent deviation is the most basic indicator of the degree to which the simulated values agree with the observed data (Shodor, 2015).

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}$$

The RMSE is considered to be one of the best overall measures of the model performances. It gives an estimate of average absolute error in the units of the predicted and observed crop yield. The closer the outcome is to zero the better the models performance (Holmes, 2000).

$$\text{Coefficient of mass residual (CRM)} = \frac{\sum_{i=1}^{N} S_i - \sum_{i=1}^{N} O_i}{\sum_{i=1}^{N} O_i}$$

The CRM gives an indication of the relative size and nature of the error. In case of a negative value of CRM the model tends to simulate a value lower than the observation, and in case of a positive value tends to simulate a higher value than the observation (Wallis & Todini, 1974).

$$\text{Index of agreement (IoA)} = 1 - \frac{\sum_{i=1}^{N}(S_i - O_i)^2}{\sum_{i=1}^{N}(|O_i - O| + |S_i - O|)^2}$$

The IoA measures the agreement between the simulated and observed crop yield. The closer it is to 1 the higher the agreement (Krause et al., 2005).

$$\text{Model efficiency (EF)} = \frac{\sum_{i=1}^{N}(O_i - O)^2 - \sum_{i=1}^{N}(S_i - O_i)^2}{\sum_{i=1}^{N}(O_i - O)^2}$$

The EF evaluates the error relative to the natural variation of the observed values and can vary from -∞ to 1. When the square of errors between the predictions and observations equals the variation of the observations, EF becomes zero. Values between 0.50 and 1 are considered acceptable (Nash & Sutcliffe, 1970).

For all formulas:

$$N = total\ number\ of\ observations$$
$$O_i = observed\ value\ of\ the\ i_{th}\ observation$$
$$S_i = simulated\ value\ of\ the\ i_{th}\ observation$$
$$O = mean\ of\ the\ observed\ values$$
$$i\ varies\ from\ 1\ to\ N$$

In addition to these statistical measures, the reliability of model outputs is judged through the graphical presentations of the simulated and observed yield.

2.1.4. Application model

For the application of the model over multiple years the climatic input factors will be seen as a variable. What has to be noted is the fact that the Dorie, Chertsey and Wakanui stations were founded only a couple of years ago or in case of the last one are already shut down, which mean they cannot provide the data needed for a the longest time period of Kiwitea (23 years). Still a decent estimate can be made with the years that are available. By using the ClifFlo database to determine the period of measurements of the weather data stations time periods have been established over which the mean precipitation, minimum and maximum temperature and the Penman-Monteith evapotranspiration have been calculated. The data consists of daily averages, taken from multiple years, as shown in Table 6. The choice for averages instead of the actual daily data for the multiple years is based on the fact that complete days were missing, as well as values for a specific date of certain years. By using the average values of the years the missing data was supplemented and the error was minimized.

The growing period in case of the multiple years' averages equals the growing cycle period of the 2014-2015 crops. The data from the Ashburton climatic station has been used only as a comparison to the Wakanui station, as mentioned before, and uses the growing period of the Wakanui 2014-2015 crop.

Table 6: Climatic data input multiple years

Region	Reference evapotranspiration over growing period (mm)	Average maximum temperature (°C)	Average minimum temperature (°C)	Rainfall over growing period (mm)
Dorie				
2011-2015	574.6	17.1	7.2	416.2
Kiwitea				
1992-2015	642.1	17.9	8.6	699.8
2005-2015	654.5	18.2	8.8	713.3
2010-2015	673.7	18.3	8.9	731.6
Chertsey				
2013-2015	718.8	16.6	6.8	547.4
Wakanui				
2012-2015	721.8	17.0	6.9	403.7
Ashburton reference				
2006-2015	776.6	16.7	5.7	556.0
2010-2015	774.1	16.7	5.8	561.6

2.2. Water footprint calculation global data

Since the previously established benchmarks by Hoekstra & Mekonnen (2013) of the water footprints were based on globally available data-sets, a comparison can provide insight into what this causes. Therefore, global data will be gathered from similar sources as used by Hoekstra & Mekonnen (2013) to estimate the water footprint of the regions closest to the trial sites.

The input data required by AquaCrop for the estimation of the global water footprints equals that of the determination of the local water footprints, consisting of climatic, soil, management and crop data.

Climatic data

To gather the global climatic data the Climate Information Tool (AQUASTAT - FAO, 2015) has been used. This tool allows the user to enter the latitude and longitude of a specific location to generate a spatial data-set containing mean monthly climate data. Since it concerns data from locations all over the world, daily input is unavailable. The data-set covers the global land surface at a 10 minute spatial resolution for the period 1961-1990. It generates the climate variables needed for the assesment, consisting of precipication in mm, minimum and maximum temperature in °C and the reference evapotranspiration in mm/d. All data, apart from the reference evapotranspiration, originate from the CRU CL 2.0 data-set which is described by New et al. (2002). The data are available through the School of Geography Oxford, the International Water Management Institute World Water and Climate Atlas and the Climatic Research Unit of the University of East Anglia. For the calculation of the reference evapotranspiration the Irrigation and Drainage Paper 56 of FAO has been used (Allen et al., 1998), applying the Penman-Monteith method. The data available refers to mean circumstances that are obtained by interpolating data from different climate stations.

As it turned out, data sets of locations near the trial sites generated the best result at:

Ashburton (Latitude: -43.906°, Longitude: 171.746°),
Rakaia (Latitude: -43.756°, Longitude: 172.023°),
Palmerston North (Latitude: -40.352°, Longitude: 175.608°).

The coordinates of these were used to determine the climatic input for AquaCrop, as can be seen in Table 7, Table 8 and Table 9.

Table 7: Palmerston North Global Climate Data

Palmerston North	Monthly average precipitation	Average max. temperature	Average min. temperature	ET_0
Month	**mm**	**°C**	**°C**	**mm/d**
Jan	102	21.7	11.8	3.7
Feb	87	22.1	11.6	3.3
Mar	108	20.6	10.7	2.5
Apr	102	17.5	8.2	1.6
May	138	14.3	5.6	1.0
Jun	148	11.8	3.7	0.6
Jul	155	11.2	3.1	0.7
Aug	132	12.2	4.0	1.0
Sep	137	13.8	5.8	1.7
Oct	137	15.8	7.1	2.4
Nov	112	17.8	8.6	3.0
Dec	126	20.2	10.6	3.5

Table 8: Rakaia Global Climate Data

Rakaia	Monthly average precipitation	Average max. temperature	Average min. temperature	ET_0
Month	**mm**	**°C**	**°C**	**mm/d**
Jan	48	23.0	11.2	4.1
Feb	46	22.4	11.0	3.4
Mar	53	20.5	9.7	2.5
Apr	57	17.7	6.7	1.7
May	56	14.0	3.9	1.0
Jun	49	11.3	1.3	0.7
Jul	62	10.8	1.2	0.7
Aug	63	12.1	2.3	1.1
Sep	34	14.8	4.1	1.9
Oct	46	17.4	6.1	2.8
Nov	49	19.3	7.9	3.4
Dec	47	21.4	10.1	3.9

Table 9: Ashburton Global Climate Data

Ashburton	Monthly average precipitation	Average max. temperature	Average min. temperature	ET_0
Month	**mm**	**°C**	**°C**	**mm/d**
Jan	58	23.6	11.1	4.1
Feb	54	22.9	10.8	3.4
Mar	62	20.9	9.5	2.6

Apr	64	17.7	6.4	1.7
May	61	13.8	3.5	1.0
Jun	50	11.1	0.9	0.7
Jul	62	10.6	0.6	0.7
Aug	65	12.3	1.8	1.1
Sep	42	15.0	3.7	1.9
Oct	56	17.9	6.0	2.9
Nov	57	19.7	7.9	3.4
Dec	55	21.8	9.8	3.9

When comparing the global climatic data to the local climatic data a couple of remarks can be made. First of all, the global data of Palmerston North suggests a higher annual rainfall than the local data from Kiwitea. The average temperatures however are similar. The global data for Ashburton and Rakaia suggest about the same amount of rainfall as the local data for Dorie, Chertsey and Wakanui. What is striking however is the fact that the suggested ET_0 of all of the locations with global data is significantly lower than the values given by the local data.

Soil texture data
For the soil data the ISRIC-WISE (Batjes, 2006) database was used. This provided grid-based data on a 5-by-5 arc-minute resolution. From the summary file, as used by Hoekstra & Mekonnen (2010), firstly the identification code (also called SUID) of a specific location on the map has been determined by using ArcGIS, after which the soil properties of that location were assessed, consisting of the sand, silt and clay fraction for the five different layers. The layers ranged from 0-20, 20-40, 40-60, 60-80 to 80-100 cm. Also the FAO texture classification was used to determine what class the soil was appointed to, ranging from **C**ourse, **M**edium, **M**edium **F**ine, **F**ine, to **V**ery **F**ine. With the known fractile percentages the Soil classification triangle (Figure 5) could be combined with the Soil textural classes triangle (Figure 4) to generate the needed input for AquaCrop.

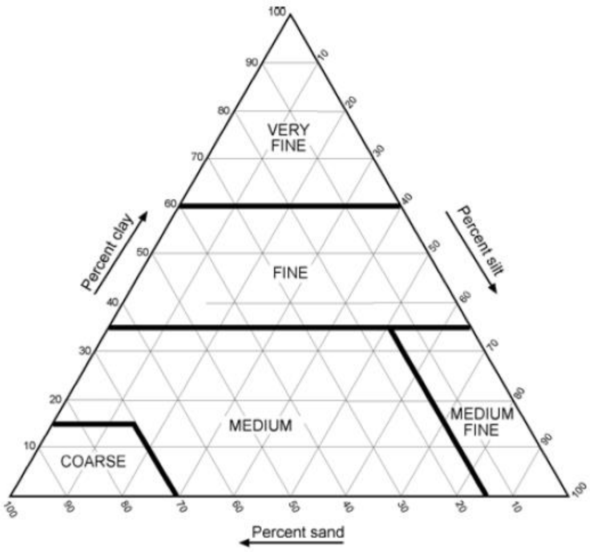

Figure 8. Soil textural classes

Figure 4: Soil textural classes

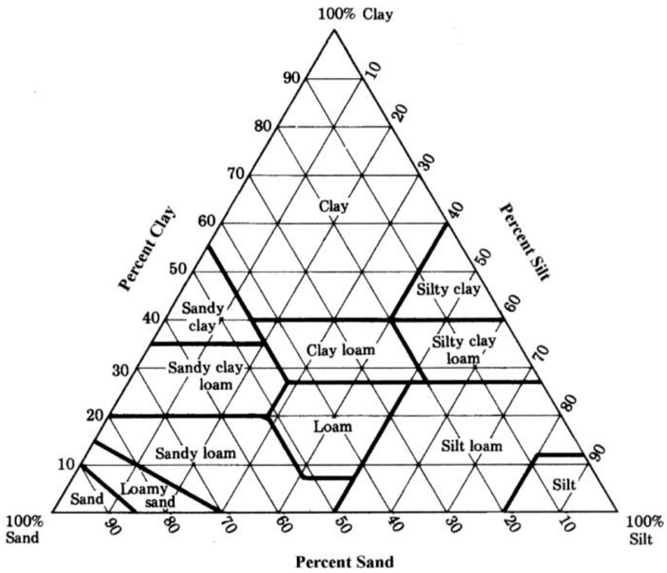

Figure 5: Soil classification triangle

The result of the soil property analysis for the different areas can be seen in Table 10, Table 11 and Table 12. By importing the found soil layers in AquaCrop the soil water content at PWP, FC, SAT and the k_{sat} value are automatically generated, according to the global standards as set by FAO (2015b).

Table 10: Global soil properties Palmerston North

Palmerston North					
Identification code	6380				
Layer	**Sand (%)**	**Silt (%)**	**Clay (%)**	**FAO class**	**Soil triangle**
0-20	52	27	21	M	Sandy Clay Loam
20-40	47	26	27	M	Sandy Clay Loam
40-60	42	25	33	M	Clay Loam
60-80	40	25	35	F	Clay Loam
80-100	39	27	34	M	Clay Loam

Table 11: Global soil properties Rakaia

Rakaia					
Identification code	6348				
Layer	**Sand (%)**	**Silt (%)**	**Clay (%)**	**FAO class**	**Soil triangle**
0-20	44	33	23	M	Loam
20-40	43	32	25	M	Loam
40-60	44	31	25	M	Loam
60-80	46	30	24	M	Loam
80-100	47	31	24	M	Loam

Table 12: Global soil properties Ashburton

Ashburton					
Identification code	6371				
Layer	**Sand (%)**	**Silt (%)**	**Clay (%)**	**FAO class**	**Soil triangle**

0-20	44	28	28	M	Clay loam
20-40	43	28	29	M	Clay Loam
40-60	44	27	29	M	Clay loam
60-80	46	26	28	M	Sandy Clay Loam
80-100	47	26	27	M	Sandy Clay Loam

When comparing the global soil data to the local soil data a couple of remarks can be made. The global data of Palmerston global suggests a high sand percentage, while the local data of Kiwitea suggests high silt percentage. The Rakaia data suggests that the soil is made up mostly of sand, followed by silt and clay. The local data of Chertsey however suggests an equal distribution of sand and clay, but has stones in the lower layer. The local data from Dorie states that there is a higher clay percentage than sand, as opposed to the global data.
Ashburton global data suggests mostly sand, about equal silt/clay percentage, which concurs more or less with the local data from Wakanui with regard to the sand, but the silt percentage is higher than the clay.

Overall the global data has a high sand percentage, while silt is the predominant substance in the local data.

Crop parameters
FAO has calibrated crop parameters for major agriculture crops, and provides them as default values in the model. When selecting a crop, for example wheat, its crop parameters are downloaded into AquaCrop (FAO, 2012b). The parameters used can be seen in Figure 6, Figure 7 and Figure 8. In this case, the selected file is 'WheatGDD' under standard settings, to reflect the growing degree days as was done in the calculation of the local water footprints.

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

Figure 6: Wheat global phenology parameters

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

Figure 7: Wheat global transpiration and production parameters

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

Figure 8: Wheat global stress parameters

The last thing that is needed are the crop planting dates and lengths of the cropping season. The report of Hoekstra & Mekonnen (2010) states that the input data was obtained from FAO (2015c). However, the tool used only accounts for a specific number of countries, excluding New Zealand. Therefore, to ensure that the comparison between the local and global water footprints can be made, the actual sowing dates as reported in the FAR reports of 2014-2015 have been used as input in the AquaCrop model. For Palmerston the sowing date of Kiwitea has been used, for Rakaia that of Dorie and for Ashburton that of Wakanui, since those areas are nearest. The harvest dates will differ, since they are based on the standard values for the growing cycle as provided by FAO (2012b).

This results in the sowing and harvesting dates as shown in Table 13

Table 13: Global sowing and harvesting dates

Site name	Sow date	Harvest date
Palmerston North	*19 May*	*4 January*

Rakaia	*11 May*	*5 January*
Ashburton	*25 May*	*13 January*

The largest difference between the global crop data and the local crop data lies in the sowing and harvesting dates. The Palmerston North and Rakaia site with global data suggest a harvest date in January as opposed to February for the local data of Kiwitea, Dorie and Chertsey. The harvest index of 45 instead of 48 will have its impact on the simulated yield, and the crop coefficient of 1.10 instead of 1 will have its effect on the evapotranspiration. The data that hasn't been mentioned in paragraph 2.1.1 is equal for both global as well as local data.

Management conditions
To determine whether or not the areas of interest are undergoing irrigation practises the AquaStat database was used (FAO, 2015). The database is a collaboration between the university of Bonn and AquaStat and allows the user to determine in what areas of a country irrigation is being used. From this data is can be derived that the Canterbury area is fully equipped for irrigation, and the Palmerston North area is considered dryland. Since it is known that the current irrigation system in New Zealand mostly consists of sprinklers of various types, this will be used as input for AquaCrop (Millner, 2011). The global data assumes that the area is recieving optimal irrigation, and when run under standard settings will provide irrigation once the readily available soil water reaches a depletion of 20%. This value has been determined by FAO (2015) and is used as standard generation scedule of AquaCrop, so will have the highest chance to have been used in the global benchmark calculations.

Initial conditions
To run the model the initial condition of the soil water level needs to be used as input. For this AquaCrop was run at standard settings, meaning the soil water content at field capacity of 30%.

2.3. Comparison local and global data/benchmarks

After the estimation of the local and global water footprints for the periods as previously described it is possible to make a comparison between the local and global data and the local and benchmark data, based on the input parameters and output of AquaCrop.

The benchmarks have been established based on the variability of water footprints found across regions and amongst producers within regions. They act as a reference and target for producers that perform below the benchmark, as well as a guide for the government in the allocation of water permits.

The water footprint benchmark for a certain process can be chosen, for example, by looking for a water footprint that is not exceeded by the best 20% of the producers. This has been done on a regional basis as well as a global basis, to account for the differences in environmental conditions, such as climate and soil, and development conditions. Looking at the best 20% of global production is one way of establishing water footprint benchmarks for water-consuming activities. Another way is to identify the 'best-available technology' and take the water footprint associated with that technology as the benchmark. According to Hoekstra & Mekonnen (2013), using precision irrigation techniques for agricultural purposes as opposed to using less advanced sprinklers could be chosen to function as a crop benchmark. Business associations within the different sectors of economy could develop their own regional or global water footprint benchmarks, following the governmental regulations and legislation. This will aid to improve the efficiency of water allocation (WIREs Water, 2014).

The paper describing the water footprint benchmarks for crop production of Hoekstra & Mekonnen (2013) provides the following arrangement, with regard to the green-blue WF of wheat on a grid cell basis:

Table 14: Global water footprint benchmarks

Green-blue water footprint benchmarks	
Percentile of the world	**Water footprint benchmark of Wheat**
10^{th}	592 m^3/ton
20^{th}	993 m^3/ton
25^{th}	1069 m^3/ton
50^{th}	1391 m^3/ton
Global average	1620 m^3/ton

Furthermore, an estimation of the WF has been made by Hoekstra & Mekonnen (2010) on a regional scale for most of the countries in the world to form the base for the benchmark determination of different crops. This includes the production of wheat in the Ashburton and Dannevirke region. For this estimation data from 1996 till 2005 was used, and the same calculation procedures as for the previously mentioned global data sets have been applied. It states that the Water Footprint in the Ashburton region equals 761 m^3/ton, and the Water Footprint of the Dannevirke area (closest to Kiwitea) 528 m^3/ton. The country average of New Zealand is considered to be 719 m^3/ton.

2.4. Efficiency evaluation

Since the water footprint can be measured per unit of production it forms an ideal measure of resource efficiency. As the water footprint goes down, this indicates a more efficient use of water in producing the wheat or any other product. If the water footprint exceeds the benchmarks, this indicates that there is the opportunity for water footprint reduction through a change in practices or technology. Besides the evaluation of the Water Footprints a review of literature has been made to formulate suggestions/recommendations for future wheat production.

CHAPTER 3 - RESULTS AND DISCUSSION

The simulated yields, adjusted evapotranspiration and the estimated water footprints for the different time periods will be shown in this chapter. The total outcome of AquaCrop can be found in

APPENDIX A: Output of Aquacrop.

3.1. Water footprints

The consumptive water footprints of the wheat grown in the FAR trial sites of 2013-2014 and 2014-2015 can be seen in **Fout! Verwijzingsbron niet gevonden.**.

Table 15: Local WF FAR sites

Site	Local WF 2013-2014 (m^3/ton)	Local WF 2014-2015 (m^3/ton)
Kiwitea	607	511
Dorie	389	567
Chertsey	494	539
Wakanui	562	642

The consumptive water footprints of the wheat under input of local average climatic data can be seen in
Table 16. The WFs with average climatic data tend to be lower than the WFs for specific years.

Table 16: Local WF average climatic data

Area	Average WF over time period (m^3/ton)
Kiwitea	476
Dorie	309
Chertsey	509
Wakanui	410

The consumptive water footprints of the wheat under input of global average climatic data of the areas closest to the FAR trial sites can be seen in Table 17.

Table 17: Global WF average climatic data

Area	Average WF over time period (m^3/ton)
Palmerston	409
Rakaia	583
Ashburton	533

An overview of the main results for the local water footprints per trial site can be found in Table 18. Following the formulas given in paragraph 2.1.2 the green and blue Water Footprint for the specific regions and time periods were calculated. The ET_{green} and ET_{blue} in millimeters have been transformed to Total ET_{green} and Total ET_{blue} in m^3/ha by multiplying by the factor ten.

Table 18: Water footprints with local data

Kiwitea	Total rainfall (mm)	Irrigation applied (mm)	ET Green (mm)	ET Blue (mm)	ETa (mm)	Total ET Green (m^3/ha)	Total ET Blue (m^3/ha)	Total ET (m^3/ha)	Simulated yield (t/ha)	WF Green (m^3/ton)	Wf Blue (m^3/ton)	Wf Total (m^3/ton)
2014-2015	608.8	0	595.0	0	595.0	5950	0	5950	11.65	511	0	511
2013-2014	713.2	0	665.0	0	665.0	6650	0	6650	10.96	607	0	607
2010-2015	731.6	0	594.7	0	594.7	5947	0	5947	12.22	487	0	487
2005-2015	713.3	0	582.0	0	582.0	5820	0	5820	12.21	477	0	477
1992-2015	699.8	0	566.6	0	566.6	5666	0	5666	12.22	464	0	464
											Average	**509**

Chertsey	Total rainfall (mm)	Irrigation applied (mm)	ET Green (mm)	ET Blue (mm)	ETa (mm)	Total ET Green (m^3/ha)	Total ET Blue (m^3/ha)	Total ET (m^3/ha)	Simulated yield (t/ha)	WF Green (m^3/ton)	Wf Blue (m^3/ton)	Wf Total (m^3/ton)
2014-2015	420.6	371	248.5	371	619.5	2485	3710	6195	11.50	216	323	539
2013-2014	748.6	290	388.1	290	678.1	3881	2900	6781	13.73	283	211	494
2013-2015	547.4	371	257.0	371	628.0	2570	3710	6280	12.35	208	300	509
											Average	**514**

Wakanui	Total rainfall (mm)	Irrigation applied (mm)	ET Green (mm)	ET Blue (mm)	ETa (mm)	Total ET Green (m^3/ha)	Total ET Blue (m^3/ha)	Total ET (m^3/ha)	Simulated yield (t/ha)	WF Green (m^3/ton)	Wf Blue (m^3/ton)	Wf Total (m^3/ton)
2014-2015	263.6	187	450.7	187	637.7	4507	1870	6377	9.94	453	188	642
2013-2014	494.0	180	491.2	180	671.2	4912	1800	6712	11.95	411	151	562
2012-2015	403.7	187	468.7	187	655.7	4687	1870	6557	16.00	293	117	410
											Average	**538**

Wakanui-Ashburton	Total rainfall (mm)	Irrigation applied (mm)	ET Green (mm)	ET Blue (mm)	ETa (mm)	Total ET Green (m^3/ha)	Total ET Blue (m^3/ha)	Total ET (m^3/ha)	Simulated yield (t/ha)	WF Green (m^3/ton)	Wf Blue (m^3/ton)	Wf Total (m^3/ton)
2014-2015	276.9	187	461.2	187	648.2	4612	1870	6482	9.43	489	198	687
2013-2014	635.0	180	507.9	180	687.9	5079	1800	6879	11.80	430	153	583
2010-2015	561.6	187	323.8	187	510.8	3238	1870	5108	11.88	273	157	430
2006-2015	556.0	187	332.7	187	519.7	3327	1870	5197	12.08	275	155	430
											Average	**533**

An overview of the main results for the global water footprints per area can be found in Table 19.

Table 19: Water footprints with global data

Region	Total rainfall (mm)	Irrigation applied (mm)	ET Green (mm)	ET Blue (mm)	ETa (mm)	Total ET Green (m^3/ha)	Total ET Blue (m^3/ha)	Total ET (m^3/ha)	Simulated yield (t/ha)	WF Green (m^3/ton)	Wf Blue (m^3/ton)	Wf Total (m^3/ton)
Palmerston 1961-1990	1019.1	0	396.3	0	396.3	3963	0	3963	9.68	409	0	**409**
Rakaia 1961-1990	394.9	132.9	326.6	132.9	459.5	3266	1329	4595	9.36	349	142	**583**
Ashburton 1961-1990	424.6	112.6	376.2	112.6	488.8	3762	1126	4888	9.17	410	123	**533**

As mentioned before, since wheat is considered to have a water content of 10 to 15% the green and blue water that has been incorporated into the harvested crop needs to be accounted for. Based on this, the water footprint of wheat is 0.10-0.15 m^3/ton if we look at incorporated water alone. This is less than 1 percent of the water footprint related to evaporated water.

3.1.1. Validation of the model

The validation of the model results in the values for the RMSE, IoA, CRM, EF and the procentual deviation between the simulated and observed values for wheat yield. However, since there were cases of the Barley Yellow Dwarf Virus and shattering/lodging distorted values might be generated. Therefore the same validation methods were applied while leaving those cases out of the equation. The values and results can be seen in Figure 9 and Table 20. The * marker indicates special conditions during the cropping season. For the validation only the sites that provide an actual observed crop yield value were assessed, with the exception of Chertsey 2013-2014, where the average observed yield of the periods 2013-2014 and 2014-2015 is used.

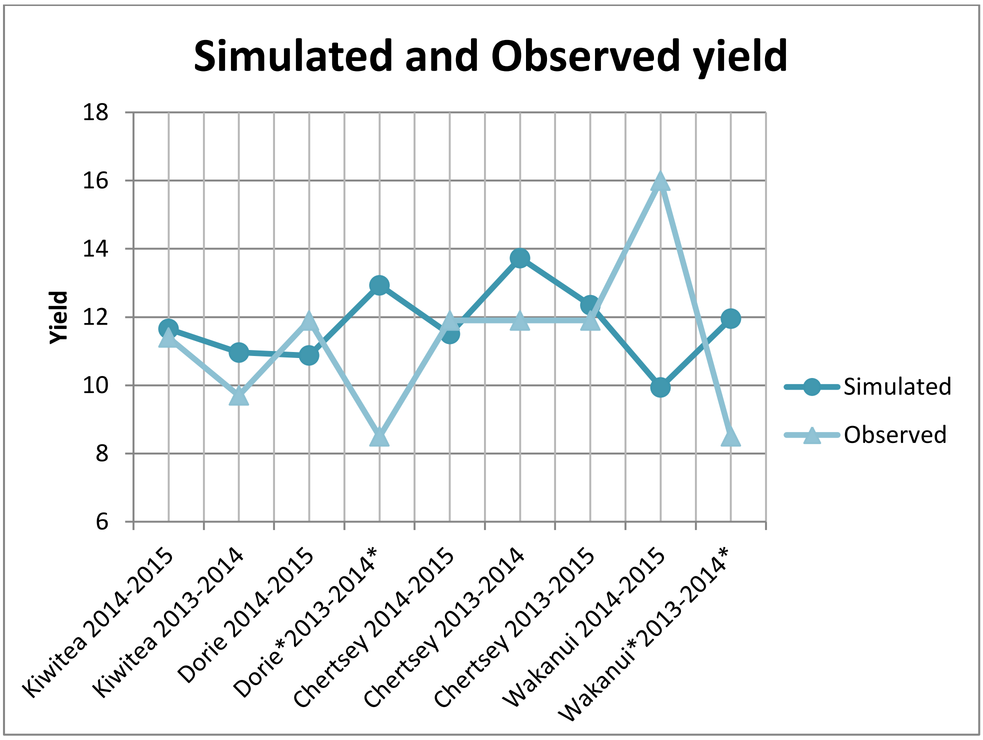

Figure 9: Simulated and Observed yield

Table 20: Model validation

Statistical measure	Variable	With special conditions	Without special conditions	Ideal value
RMSE	Yield	2.88	2.48	0
CRM	Yield	0.09	-0.02	Negative = underestimation Positive = overestimation
IoA	Yield	0.40	0.44	1
EF	Yield	-2.65	-15.54	0.50-1. Range (-∞ , 1)
Average Deviaton (%)	Yield	19.66	12.03	...

The analysis shows that there is a difference between the statistical measures with and without special conditions. This discrepancy is caused by the fact that the model is unable to account for the occurrence of diseases and other crop growth influencing factors. Research has shown that the virus can potentially lead to a yield loss of 34 to 55% (Perry, Kolb, Sammons, & Lawson, 2000), which is confirmed by the difference between the simulated and observed yield values, assuming that the models' prediction is reasonably accurate in a situation without a virus.

The biggest case of underestimation however lies with the Wakanui site with data from 2014-2015, since it had the highest actual yield and the lowest simulated yield. This difference could be attributed to the fact that some of the climatic data was missing during that period, which mostly has been replaced with data from nearby stations. This is illustrated by the fact that the model, run with the average climatic data for Wakanui, predicts the yield perfectly. The index of agreement is on the low side, which can be caused by the models' oversensitivity to extreme values due to the squared differences. The fact that the model efficiency value is very low means that there is an error relative to the natural variation of the observed values. An average deviation of 19.66% for the situation including special conditions and 12.03% for the situation without them are acceptable values for a model with this many input factors.

The conclusion that can be drawn from the analysis is that the model provides the user with a decent means of predicting the yield under normal conditions, but is not yet optimal.

3.2. Comparison of water footprints

The differences between the region's local water footprints and between the water footprints using global data as determined in this report will be presented, as well as a comparison to the global benchmarks and the estimated values by Hoekstra & Mekonnen (2010) for nearby regions, consisting of Ashburton and Dannevirke.

The globally calculated area nearest to Kiwitea is Palmerston North, and the estimated area Dannevirke.
The globally calculated area nearest to Dorie and Chertsey is Rakaia.
The globally calculated area nearest to Wakanui is Ashburton, which is also the estimated area.

Table 21: Water Footprint comparison

Area	Local WF (m^3/ton)	Global WF (m^3/ton)	Estimated value by Hoekstra & Mekonnen (2010) (m^3/ton)
Kiwitea	509		
-Palmerston		409	
-Dannevirke			528
Dorie	422		
Chertsey	514		
-Rakaia		583	
Wakanui	538		
-Ashburton	533	533	761

What immediately becomes clear is the fact that both the consumptive water footprint calculations using local data and global data for the specific areas perform at the highest level according to the green-blue water footprint benchmarks. Going by these results the New Zealand wheat production is part of the 10th percentile of the world with a consumptive water footprint under 592 m^3/ton. Furthermore, the country average for New Zealand according to Hoekstra & Mekonnen is 719 m^3/ton, and resulting from the analysis made in this report and the average taken over the local consumptive water footprints is 502.8 m^3/ton. The estimated value for Dannevirke is very similar to the locally estimated consumptive water footprint of Kiwitea, with a deviation of 3.7%. For the situation of Ashburton however the estimated value differs 42% from the locally estimated consumptive water footprint.

What is striking is the fact that the local consumptive water footprint of Ashburton, which was used as a reference for the Wakaniu region, is exactly the same as the global consumptive water footprint. What has to be noted however is that, even though they have the same value, the separate input and output factors differ from each other. The average yield, for example, that was simulated using the local data was 11.28 m^3/ton as opposed to simulated yield of 9.17 m^3/ton for the global data. This could be caused by the fact that the crop parameters used in the global estimate haven't been calibrated to the specific regions, or the fact that the global rainfall averaged 424.6 mm instead of the 507.4 mm of the local data. Judging by the similarity of the local consumptive water footprint of Wakanui and Ashburton it can be said that the low value of the simulated yield of 2014-2015 isn't caused by missing data, rather than differences between actual and simulated management practices and perhaps inaccurate data from used sources.

The main reason for the difference between local and global results however is caused by the simulated evapotranspiration. In all of the cases the locally simulated ET is higher than the globally simulated values, caused by the distinction between the calibrated and non-calibrated crop parameters and the in-accuracy of the global weather stations.

As for the trial sites, the site that stands out is that of Dorie, since it is the only area with a consumptive water footprint under 500 m^3/ton. This is most likely caused by the fact that the soil of Dorie is able to contain the water used during the crop growing period to a greater degree than that of the other regions.

Lastly, what can be noted is the fact that Wakanui and Kiwitea tend to have a higher green water footprint than blue, as opposed to Chertsey and Dorie, where the two are about equally accounted for. For Kiwitea this is because it concerns a dryland, which means that no irrigation is applied. As for Wakanui, the amount of irrigation is the lowest of the irrigated areas, since Chertsey and Dorie both use more than 200 mm.

3.3. Efficiency evaluation

As stated above, the estimated water footprints for local as well as global data in this report perform better than the 10^{th} percentile benchmark of 592 m^3/ton. This means that the opportunity for water footprint reduction through a change in practices or technology will be limited, and the wheat production process in its current state is very efficient. However, since the irrigation timing and amount plays such a big role in the crop production and water footprint establishment, as was illustrated by the AquaCrop model calibration, even slight changes could have a big impact. Adjusting the irrigation practises to the specific situation should be done by closely monitoring the lysimeters/installing lysimeters at locations where that hasn't happened already. One has to be careful not to cause excess water, as it could lead to water logging. The irrigation has to take the stages of wheat growth into account, since the timing of moisture stress determines three different aspects, namely the number of ears per unit area, the number of grains per ear, and the size of the grains.

Some pointers, as given by HGCA (2008) for achieving optimum canopy size consist of pre-management strategies:

- Try to sow as early as possible
- Have a high sowing rate
- Make sure there are enough soil nutrients present before sowing
- Make sure the pH level of the soil is at the correct level before you sow

During the growing season canopy can be managed by:

- The amount and timing of fertiliser applied
- The disease control measures

Of course, the efficiency doesn't only mean decreasing the consumptive water footprint, but could mean maintaining the current water footprint while increasing the yield. Since the achievement of optimal canopy size is important for good yield, pre-sowing management is needed. The factors that play an important part in the successful establishment of the crop and need to be monitored/could be altered are as follows, according to (FAR, 2015):

- The state of the seedbed needs to be checked, since a trashy seedbed may reduce seed/soil contact while a compacted seedbed may restrict emergence. It depends on the situation which one is preferable, and which state bears the least restrictions for the crop growth.
- The sowing depth, as well as the time of sowing are equally important factors in the crop development. If the seed is sown too shallow, it may be exposed to environmental hazards such as drought or sudden heavy rainfall. If the seed is sown too deep the plants might experience difficulties emerging from the ground, and be more prone to diseases. The optimal sowing depth needs to be determined by using trial crops. As for the timing of sowing, this can be crucial for the crop development. If the crops are sown when soil temperatures are warm and moisture is ideal, germination should occur rapidly and the

emergence rate of the seedlings will be high. The moisture level is important especially right after the germination, since the seedling will be fragile then.
- To ensure the most efficient production fertilizers can be applied that will supply the seedlings with the nutrients they need to grow.
- Last but not least there is the issue of disease, weed and pest control. Diseases will have the most devastating effect on the overall crop production, and need to be dealt with by using fungicides appropriate to the situation, taking into account some of the possible negative effects, such as delayed crop emergence. The crop needs to be monitored to make sure that, if pests occur, immediate actions can be taken.

3.4. Discussion

Since there are so many parameters involved in the estimation of the water footprint a couple of remarks need to be made.

First of all, while using the AquaCrop tool it became clear that some parameters had a bigger effect on the outcome than others. For example, the specific dates for the start and end of each of the stages of the crop growth had to be estimated according to other sources and previous research. However, by only changing some of the days already a reasonable change in yield/precipitation could be noticed, depending on the climatic file that was used at the time. Since there was no way to know the exact growing degree days of the different stages the best estimate was chosen. Same goes for the determination of the specific irrigation applications, which has been done manually.

Furthermore, even though the AquaCrop tool is able to make a decent estimate of the crop yield, it fails to incorporate some important factors in the process. For example there is the wind speed, the previous use of the paddock and the effect of fertilizers on the crop growth, which in the case of the FAR trial sites differs from each other. Also, as mentioned before, the tool fails to account for diseases and weed, which will have a big impact on the yield response. These factors might explain the difference between the different trial sites.

With regard to the climatic data, the main problem was that of missing data. The data has been supplemented or estimated in most cases, but it is possible that some in-accuracy still occurred. To minimize the risk the reference site of Ashburton has been used. Besides that, the climatic stations had different start- and end-dates for their measurements, which lead to an uneven distribution of time periods with climatic data. An example of this is the fact that it was possible to use climatic data from Kiwitea over the period 1992-2015, as opposed to that of Dorie of 2011-2015. Since it concerns average values however, the sets should not vary a lot.

There are multiple factors that could cause the differences between the benchmarks/estimated values as determined by Hoekstra & Mekonnen (2010 and 2013), as opposed to the locally estimated green-blue water footprints.
- First of all, since the preferred method of irrigation changed from border-dyke to sprinkler during the last couple of years, as stated before, it could be that the benchmarks and estimates were made based on that assumption. The center pivot sprinkler installations they use nowadays disperse the water more efficiently.
- Secondly, the soil data collected by using the global database differs from the region specific data, meaning that the calculations will proceed with different values for the water storage capacity and total runoff.
- Thirdly, there is the fact that the global climatic databases used for the estimation of the benchmarks cover a different time period than the local and global estimates made in this report, and can't provide a region specific analysis, or use data from only one year. This in combination with the differences in sowing and harvesting dates can lead to differences in ET_0 and total rainfall during the simulated period. Since there is always the possibility of a

climate change the daily averages calculated over one year/period from a long time ago can be different from that of another period further in the future.

- Last but not least, the benchmarks and estimated values for Dannevirke and Ashburton have been based on the CROPWAT model instead of the newer and improved AquaCrop model. The latter will most likely be more accurate in making a prediction of the actual yield and ET_a.

CHAPTER 4 - CONCLUSION AND RECOMMENDATION

The overall conclusion, consisting of the answer to the main question asked in chapter one, as well as a recommendation will be addressed in this chapter.

4.1. Conclusion

Based on the research conducted in this report the following conclusions can be drawn.

With regard to the consumptive water footprints of the wheat grown in the FAR trial sites of 2013-2014 and 2014-2015 all of the areas performed well, ranging from a water footprint of 389 to 642 m^3/ton. After performing the same calculations with average climatic data slightly lower values for the water footprint were determined, ranging from 309 to 509 m^3/ton. The regions of Palmerston, Rakaia and Ashburton under global data resulted in a water footprint of respectively 409, 583 and 533 m^3/ton. Comparing the average local and global blue-green water footprints of wheat production to the 10^{th} percentile benchmark of 529 m^3/ton results in the conclusion that the trial sites perform well enough to be part of the top ten percent of the world. Of the sites Dorie has the overall best performance, while the others generate similar results. Since the blue-green water footprints that were estimated in this report already perform better than the benchmark an increase in efficiency in the form of lowering it even further will prove to be difficult. As for the main question "How would you value the efficiency of water use within the wheat production process in New Zealand?" it can be put that wheat production process in the sites used for the research is very efficient, and should give a decent representation of the wheat production in the whole of New Zealand.

4.2.Recommendation

Based on the results/issues discussed in the previous chapters and on the overall concept of the water footprint analysis a couple of recommendations can be made.

Firstly, research has shown that the current irrigation systems in the Canterbury area allow farmers to top up according to their personal notion. This leads to the fact that only a small percentage of irrigation in Canterbury uses soil water. By monitoring the timing and amounts of irrigation per site water reduction can be achieved and less stress will be put on the groundwater level.

With regard to the actual irrigation systems, centre pivot has proven to be more efficient than travelling sprinklers, though it can lead to an increase in drainage near the pivot due to excessive irrigation at that point. Another reason for the occurence of drainage could be attributed to the topograhical layout, as the water flows to low areas once irrigation exceeds the infiltration. This effect will increase if the soils have poor structures and low infiltration rates. All of these factors have to be taken into account for the area of interest when determining how, when and if irrigation needs to be applied. A global solution will be less effective than those targeting a specific area.

Further research on a couple of areas is needed to increase the accuracy of the prediction by AquaCrop an increase the overall efficiency of wheat production. These consist of:

- Research on the prior use of paddocks and their effect on the growth of different types of wheat.
- Since research of Amec Foster Wheel (2015) has shown that high temperatures and wind in spring will accelerate plant water use considerably, finding ways to deal with these phenomenon's, for example by using vegetation to block the wind, will provide an interesting topic for further research.
- Research on the effect of differences in sowing depth as well as rate on the biomass establishment and actual yield.
- Research on the ideal timing of irrigation and the specific amount for different types of wheat in specific areas of New Zealand. This has to include all the system types that are

available, such as border-dyke irrigation and sprinkler installations, by assessing their efficiency and, for example in the case of center pivot installations, trying to decrease drainage caused by excessive irrigation.

But most importantly, further research is needed on the water footprint of wheat in other areas of New Zealand/the world to create an updated and more complete database of the water footprints, based on the latest tools, such as AquaCrop, which allows the data to be compared to one another.

GLOSSARY

Term.	Meaning.
Lodging	The process by which shoots of cereals are displaced from their vertical orientation. Two forms of lodging have been recognized: stem lodging/breakage or root lodging.
Shattering	The seeds being dispersed as soon as they are ripe.
Barley yellow dwarf virus	A plant disease which is the most widely distributed viral disease of cereals.
Canopy Cover	The above ground portion of a plant community or crop, formed by plant crowns.
Transpiration	Transpiration is the process by which moisture is carried through plants from roots to small pores on the underside of leaves, where it changes to vapor and is released to the atmosphere.
Soil horizon	A distinct layer in a soil profile, with different physical, chemical and biological properties from adjacent layers.
Evaporation	The process, by which water changes from a liquid to a gas or vapor, can happen on any free surface.
Permanent Wilting Point	The soil water content at which plants stop extracting water and will permanently wilt.
Field Capacity	The total amount of water that a soil contains after water has drained away by gravity over a period of two days after it has been saturated by rainfall.
Saturation	When the total pore volume is filled with water, the soil water content is at saturation.
TAW	Total Available Soil Water. The amount of water a crop can theoretically extract from the root zone and be used for transpiration.
PAW	Plant available water is the water content difference between field capacity and permanent wilting point of your soil at any given depth.
Dry Bulk Density	The mass of oven-dry soil contained in a sample of known volume. Soils with low bulk density generally have fewer problems of root penetration and water permeability than soils with high bulk density.
K_{sat}	Saturated hydraulic conductivity. The hydraulic conductivity expresses the property of the soil to conduct water through a soil.
TGW	Thousand grain weight. Determination of the TGW is essential to enable accurate control of the seed rate when sowing to obtain the correct plant population target.
NIWA	National Institute of Water and Atmospheric Research
FAR	Foundation for Arable Research
HGCA	Home-Grown Cereals Authority
FAO	Food and Agriculture Organization of the United Nations
Lysimeter	Measuring device which can be used to measure the amount of actual evapotranspiration which is released by plants, usually crops or trees. By recording the amount of precipitation that an area receives and the amount lost through the soil, the amount of water lost to evapotranspiration can be calculated.
RAW	Readily Available soil Water is the maximum amount of water that a crop can extract from its root zone without inducing stomatal closure and reduction in crop transpiration.
GDD	Growing degree days, or heat units, can be used in AquaCrop to describe crop development. With this method, the duration of a process or the time required to reach a particular stage is expressed in GDD (°C day) instead of number of days.
WP	Crop water productivity, efficiency term, expressing the amount of marketable product (for example kilograms of grain) in relation to the amount of input needed to produce that output (cubic meters of water)
HI	Harvest Index, a measurement of crop yield, the weight of a harvested product as a percentage of the total plant weight of a crop.
Germination	The process by which a plant grows from a seed.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and Drainage Paper no. 56.*

Amec Foster Wheel. (2015). *GRDC Publication Irrigated Wheat.* GRDC.

AQUASTAT - FAO. (2015). *Climate Information Tool*. Retrieved from AQUASTAT website: http://www.fao.org/nr/water/aquastat/climateinfotool/index.stm

Ara, T. (2007). *Story: Arable farming*. Retrieved from Map of grain-growing areas, 2007: http://www.teara.govt.nz/en/interactive/17577/map-of-grain-growing-areas-2007

Batjes, N. (2006). *ISRIC-WISE derived soil properties on a 5-by-5 arc-minutes global grid.* ISRIC.

DairyNZ. (2011). *Guide to Good Irrigation. Part 1: good irrigation practices on-farm.* DairyNZ Limited.

Environment Canterbury Regional Council. (2014). *Groundwater levels*. Retrieved from Groundwater levels: http://ecan.govt.nz/services/online-services/monitoring/groundwater-levels/pages/default.aspx

FAO. (2012a). *Crop yield response to water.* FAO.

FAO. (2012b). *Crop parameters*. Retrieved from Food and Agriculture Organization of the United Nations: http://www.fao.org/nr/water/docs/aquacropv40annexes.pdf

FAO. (2015). *Aquacrop*. Retrieved from Aquacrop: http://www.fao.org/nr/water/aquacrop.html

FAO. (2015b). *Crop Water Information: Wheat*. Retrieved from FAO - Water development and mangement unit - crop water information: wheat: www.fao.org/nr/water/cropinfo_wheat.html

FAO. (2015c). *Crop Calendar*. Retrieved from Crop Calendar: www.fao.org/agriculture/seed/cropcalendar/welcome.do

FAO. (2015c). *Global Map of Irrigation Areas (GMIA)*. Retrieved from AQUASTAT - FAO irrigation information: http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm

FAR. (2006). *No. 167 Guide to sowing rates & dates for autumn /winter wheat & barley.* FOUNDATION FOR ARABLE RESEARCH.

FAR. (2015). *Autumn sown wheat and barley 2014-2015.* Foundation for Arable Research.

Foundation for Arable Research. (2011). *Irrigation management for cropping - Foundation for Arable Research 2011b. Issue 4.* Retrieved from Irrigation management for cropping – : http://www.far.org.nz

HGCA. (2008). *The Wheat Growth Guide.* Agriculture and Horticulture Development Board.

Hoekstra, A., & Mekonnen, M. (2010). *The green, blue and grey water footprint of crops and derived crop products.*

Hoekstra, A., & Mekonnen, M. (2013). *Water Footprint Benchmarks for Crop Production.* UNESCO-IHE Institute for Water Education.

Hoekstra, A., Chapagain, A., Mekonnen, M., & Aldaya, M. (2011). *The Water Footprint Assesment Manual.* London: Earthscan.

Holmes, S. (2000). *RMS Error*. Retrieved from RMS error: http://statweb.stanford.edu/~susan/courses/s60/split/node60.html

Horizons. (2013). *Report on Horizons Groundwater Level Monitoring Network.* Pattle Delamore Partners LTD.

Hsiao, T., Steduto, P., Fereres, E., & Raes, D. (2012). *Crop yield response to water - FAO irrigation and drainage paper. Issue 66.* FAO.

Krause, P., Boyle, D., & Base, F. (2005). *Comparison of different efficiency criteria for hydrological model.* Department for Geoinformatics, Hydrology and Modelling, Friedrich-Schiller-University.

Landcare Research. (2015). *S-mapOnline*. Retrieved from S-mapOnline: http://smap.landcareresearch.co.nz/smap#layers=text_cache_nztm,water,transport,text,topobasemap_notext,topo_hyb_relief,topo_mono_hyb_relief,smap_overview,topobasemap_monochrome_notext,landscape_eco_painted_relief,landscape_shaded_relief,coastpoly,smap_paw

Lazzaro, P., & Rana, G. (2015). *The crop coefficient (Kc) values of the major crops grown under Mediterranean climate.* CRA- Research Unit for Agricultural in Dry Environments.

Mekonnen, M., Hoekstra, A., Pahlow, M., Aldaya, M., & Zarate, E. (2014). *Water Footprint Assessment for Latin America and the Caribbean.* UNESCO-IHE Institute for water education.

Millner, J. P. (2011). *THE NEW ZEALAND ARABLE INDUSTRY.* Palmerston North.

Nash, J., & Sutcliffe, J. (1970). *RIVER FLOW FORECASTING THROUGH CONCEPTUAL MODELS PART I- A DISCUSSION OF PRINCIPLES.* North-Holland Publishing Co.

New Zealand Government. (2015). *Geographic boundary viewer*. Retrieved from Geographic boundary viewer: http://www.stats.govt.nz/StatsMaps/Home/Boundaries/geographic-boundary-viewer.aspx

New, M., Lister, D., Hulme, M., & Makin, I. (2002). *A high-resolution data set of surface climate over.* School of Geography and the Environment, University of Oxford.

NIWA. (2015). *Carbon dioxide*. Retrieved from Carbon Dioxide | NIWA: https://www.niwa.co.nz/atmosphere/our-data/trace-gas-plots/carbon-dioxide

NZGSTA. (2015). *New Zealand grain and seed trade association*. Retrieved from About us|NZGSTA: http://www.nzgsta.co.nz/

Perry, K., Kolb, F., Sammons, B., & Lawson, C. (2000). *Yield Effects of Barley yellow dwarf virus in Soft Red Winter Wheat.* National Center for Biotechnology Information.

Regional Council Environment Canterbury. (2011). *Maps of the Canterbury region*. Retrieved from http://ecan.govt.nz/services/online-services/pages/maps-canterbury-region.aspx

Shodor. (2015). *Simple Statistics*. Retrieved from Simple Statistics: http://www.shodor.org/unchem/math/stats/

Singh, R. (2015). Lecture 10: Evaporation and Transpiration. Palmerston North, New Zealand.

S-mapOnline. (2015). *Regional Factsheets*. Retrieved from S-map Online - Regional Factsheets: http://smap.landcareresearch.co.nz/factsheet

Statistics New Zealand. (2007). *Agricultural production census 2007 - Statistics New Zealand 2008b*. Retrieved from Agricultural production census 2007: www.stats.govt.nz

Steduto, P., Raes, D., Hsiao, T., Fereres, E., Heng, L., Izzi, G., & Hoogeveen, J. (2015). *AquaCrop: a new model for crop prediction under water deficit conditions.* FAO.

Te Ara. (2007). *Story: Arable farming*. Retrieved from Map of grain-growing areas, 2007: http://www.teara.govt.nz/en/interactive/17577/map-of-grain-growing-areas-2007

UN Water. (2014). *Water Scarcity*. Retrieved from Water Scarcity - International Decade for Action ' Water for Life': http://www.un.org/waterforlifedecade/scarcity.shtml

Wallis, J., & Todini, E. (1974). *Comment upon the residual mass curve coefficient.* Centro Scientifico IBM.

Water Footprint Network. (2015). *What is Water Footprint Assessment?* Retrieved from What is Water Footprint Assessment?: http://waterfootprint.org/en/water-footprint/water-footprint-assessment/

WIREs Water. (2014). *Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation.* Wiley Periodicals.

Zundel, J. (2015). *C3 and C4 Plants: Definition, Types & Examples*. Retrieved from C3 and C4 Plants: Definition, Types & Examples: http://study.com/

APPENDIX A: Output of Aquacrop

The output of Aquacrop used to make the water footprint calculation for the regions of Kiwitea, Dorie, Chertsey and Wakanui can be found below.

Local data

Kiwitea

2014-2015

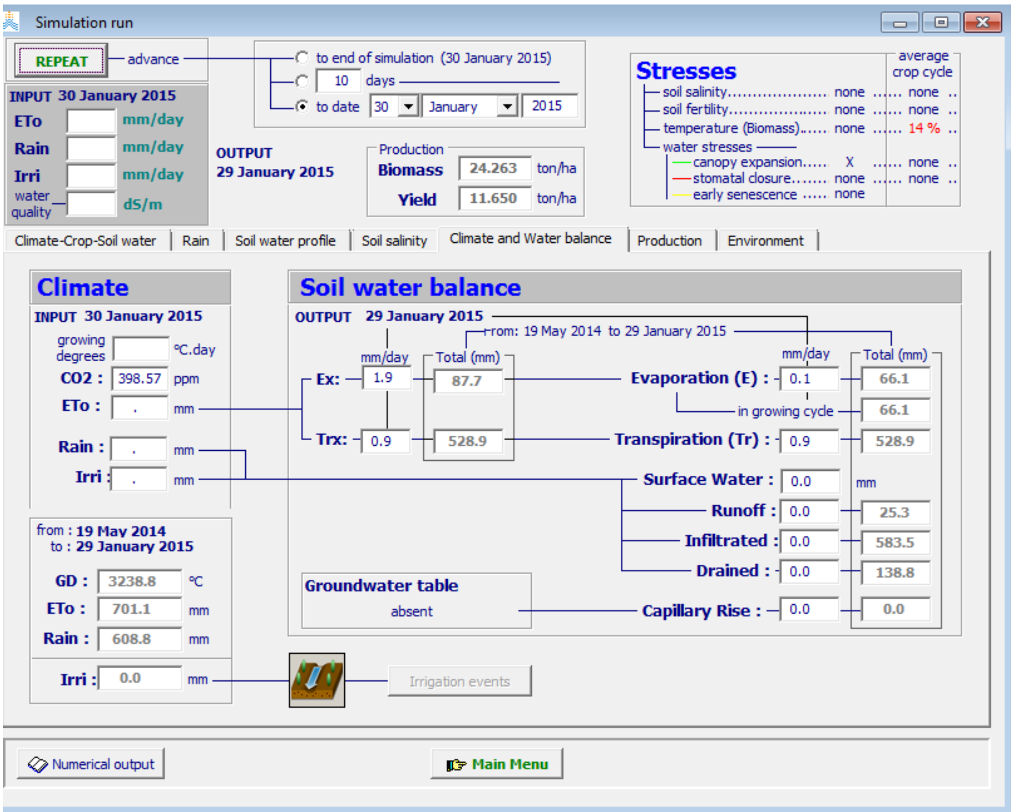

Figure 10: AquaCrop output Kiwitea 2014-2015

2013-2014

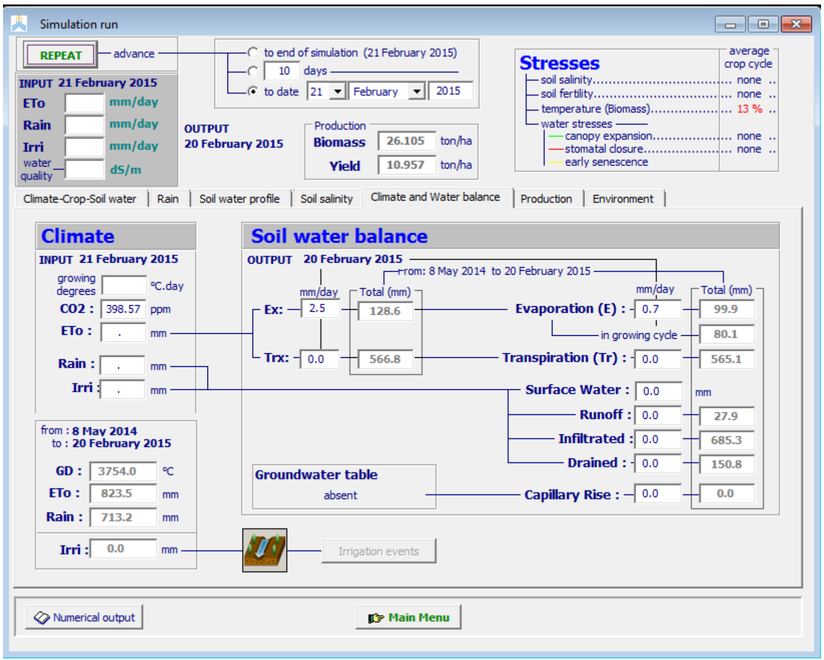

Figure 11: AquaCrop output Kiwitea 2013-2014

2010-2015

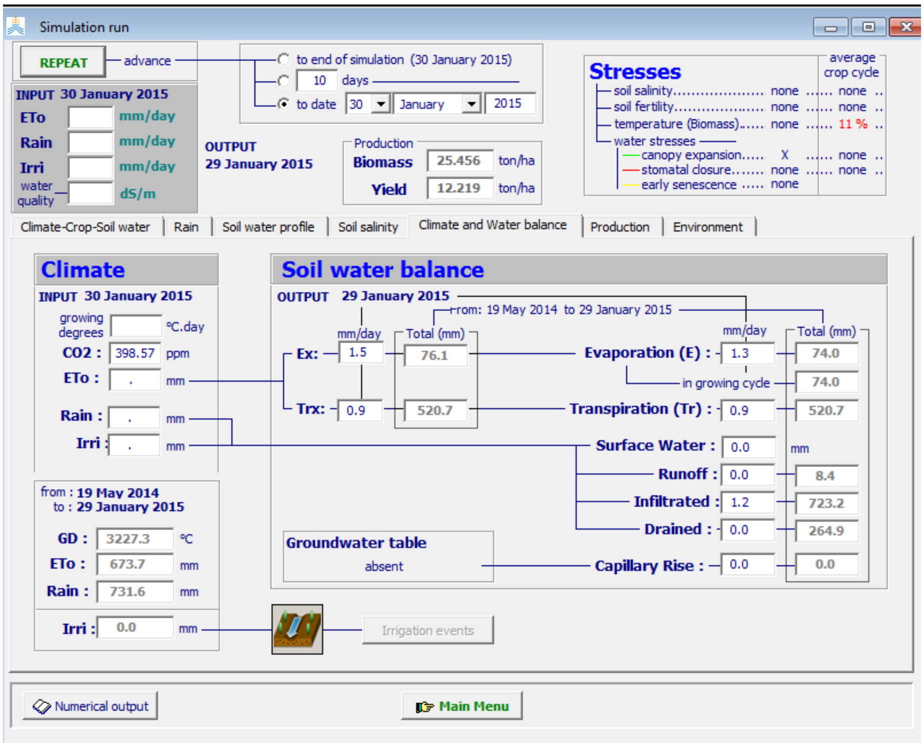

Figure 12: AquaCrop output Kiwitea 2010-2015

2005-2015

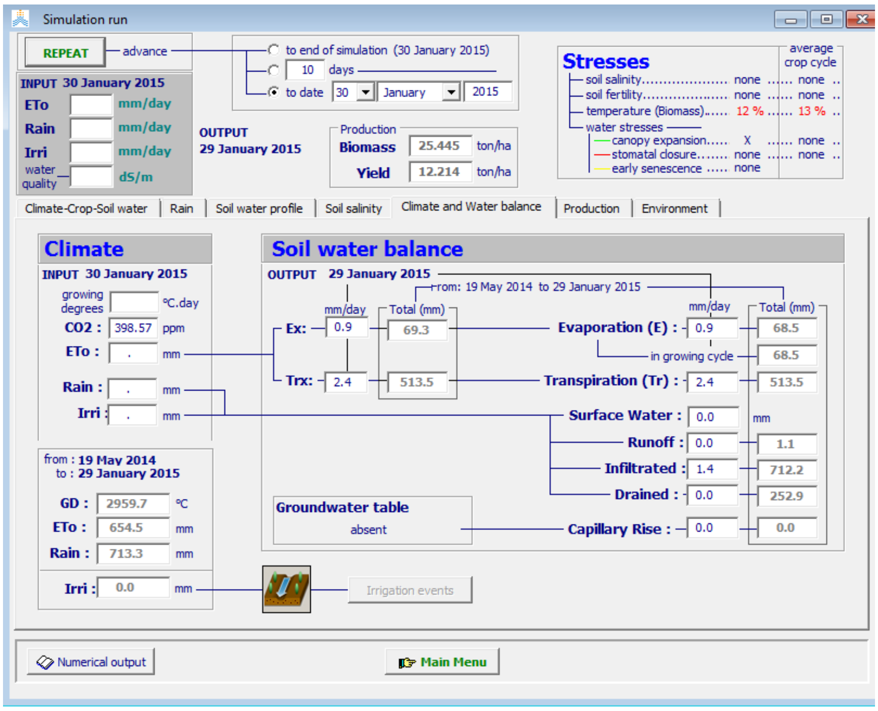

Figure 13: AquaCrop output Kiwitea 2005-2015

1992-2015

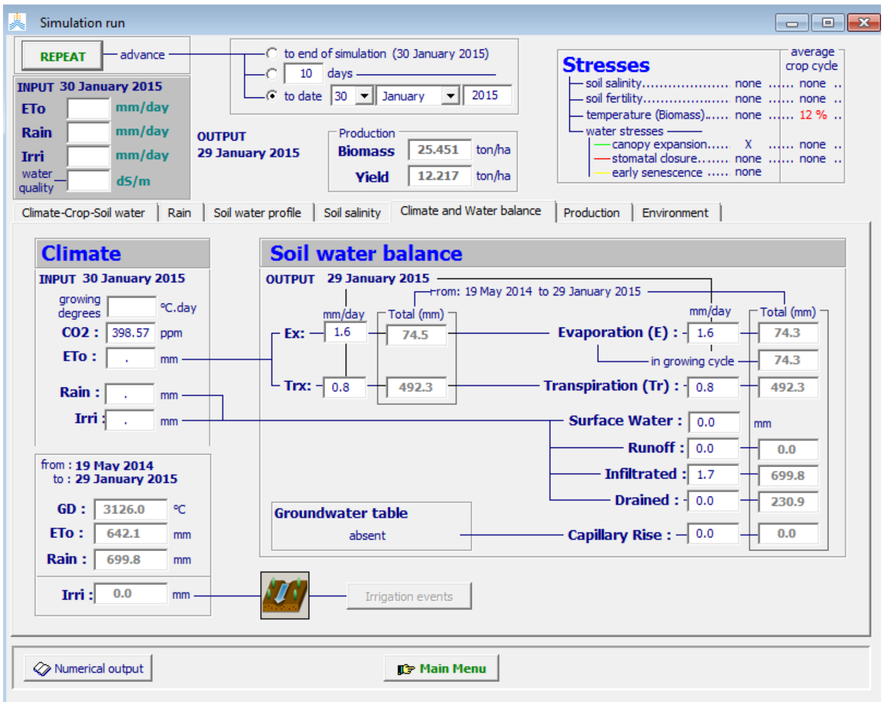

Figure 14: AquaCrop output Kiwitea 1992-2015

Dorie

2014-2015

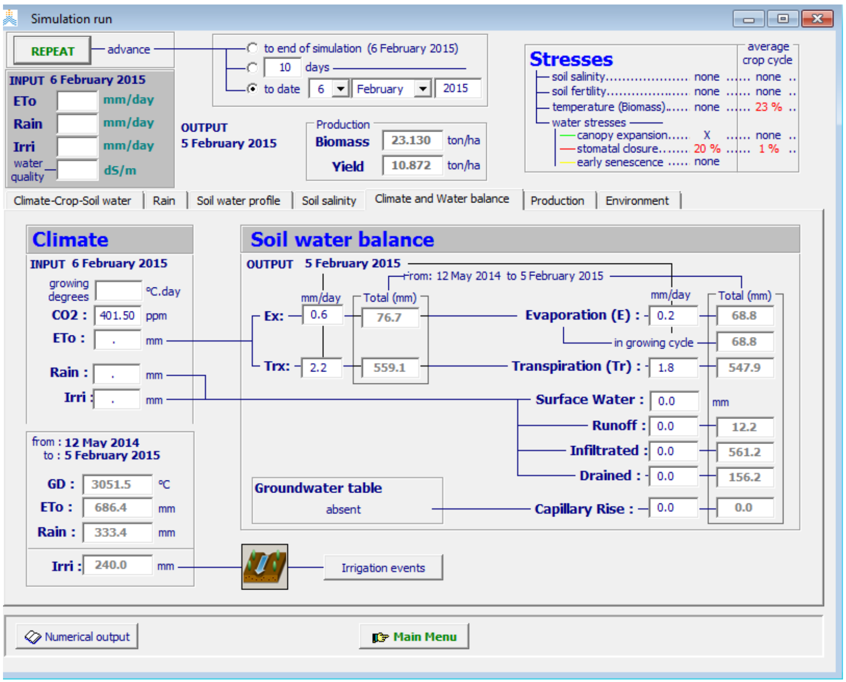

Figure 15: AquaCrop output Dorie 2014-2015

2013-2014

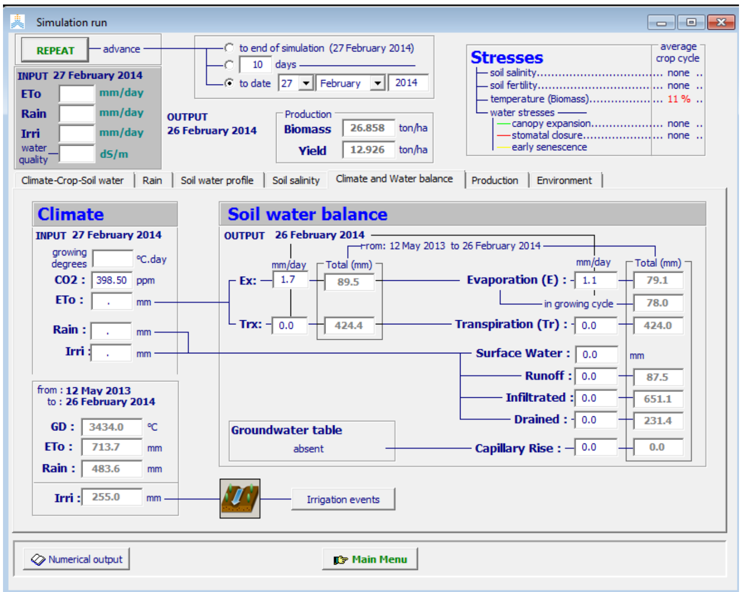

Figure 16: AquaCrop output Dorie 2013-2014

2011-2015

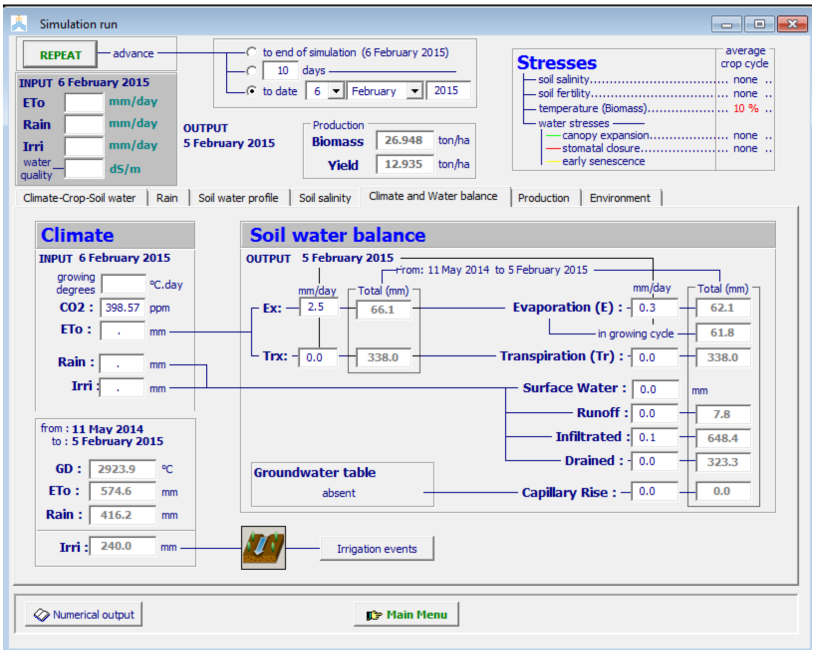

Figure 17: AquaCrop output Dorie 2011-2015

Chertsey

2014-2015

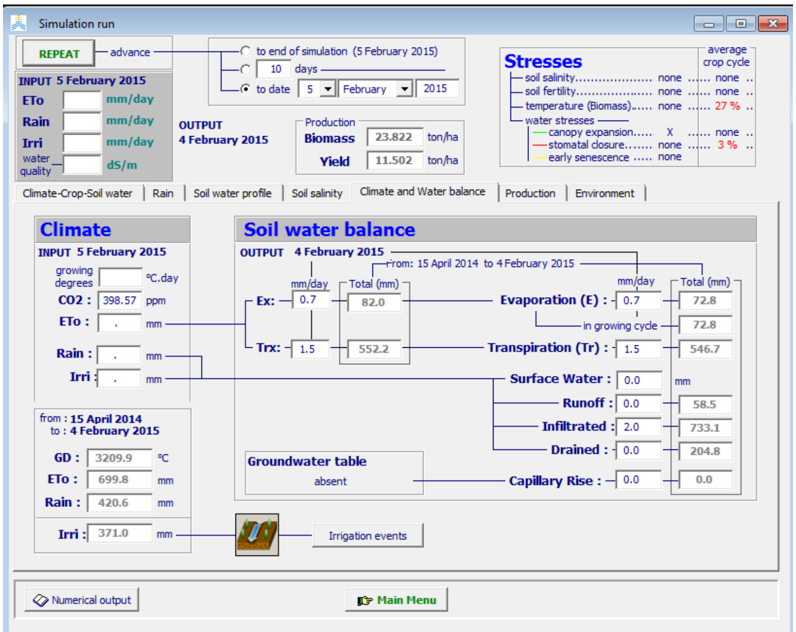

Figure 18: AquaCrop output Chertsey 2014-2015

2013-2014

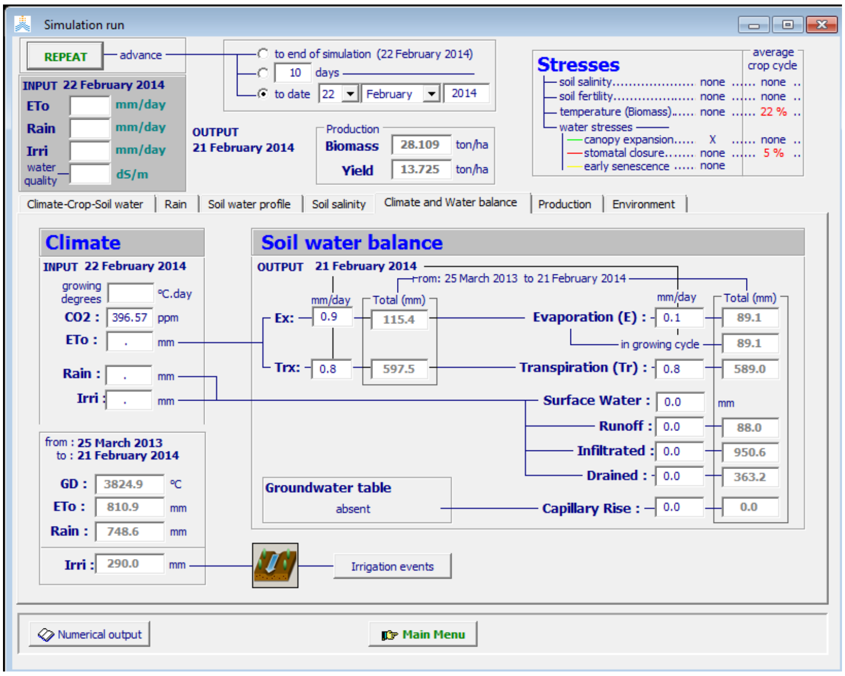

Figure 19: AquaCrop output Chertsey 2013-2014

2013-2015

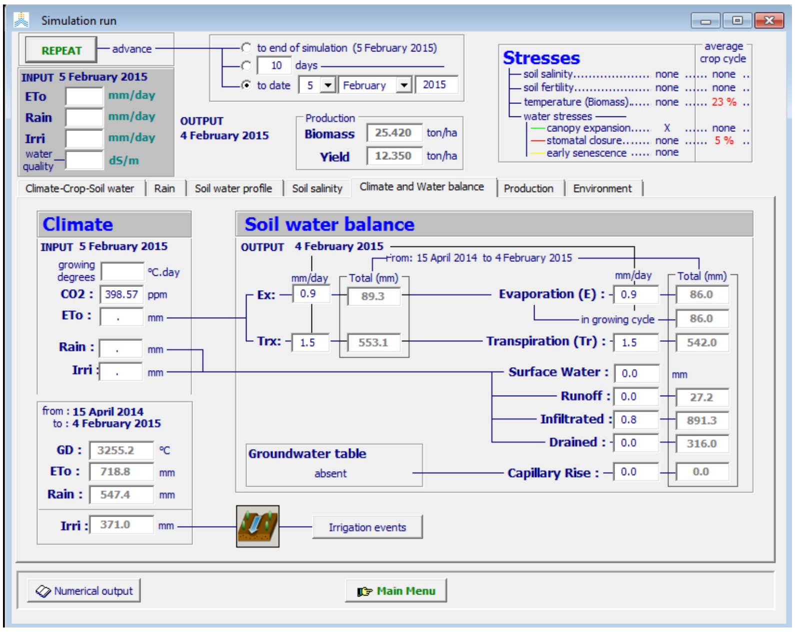

Figure 20: AquaCrop output Chertsey 2013-2015

Wakanui

2014-2015

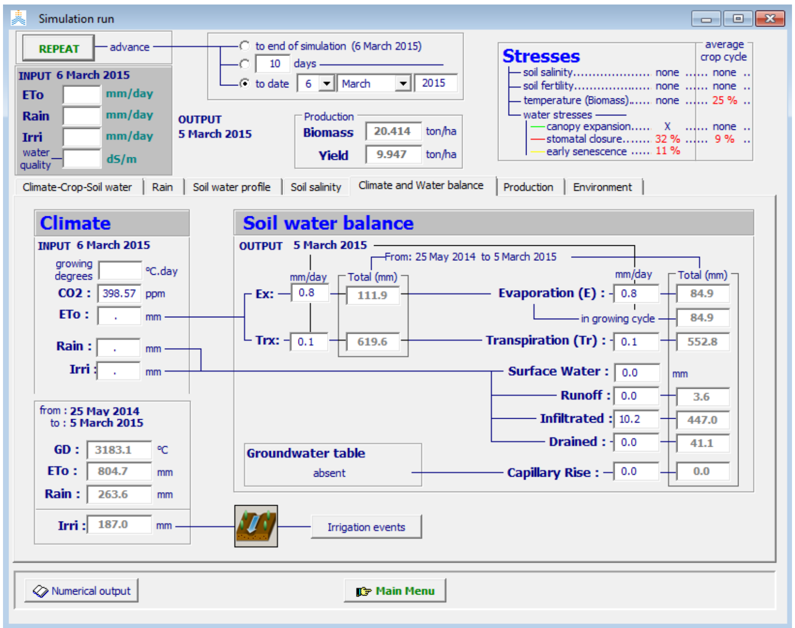

Figure 21: AquaCrop output Wakanui 2014-2015

2013-2014

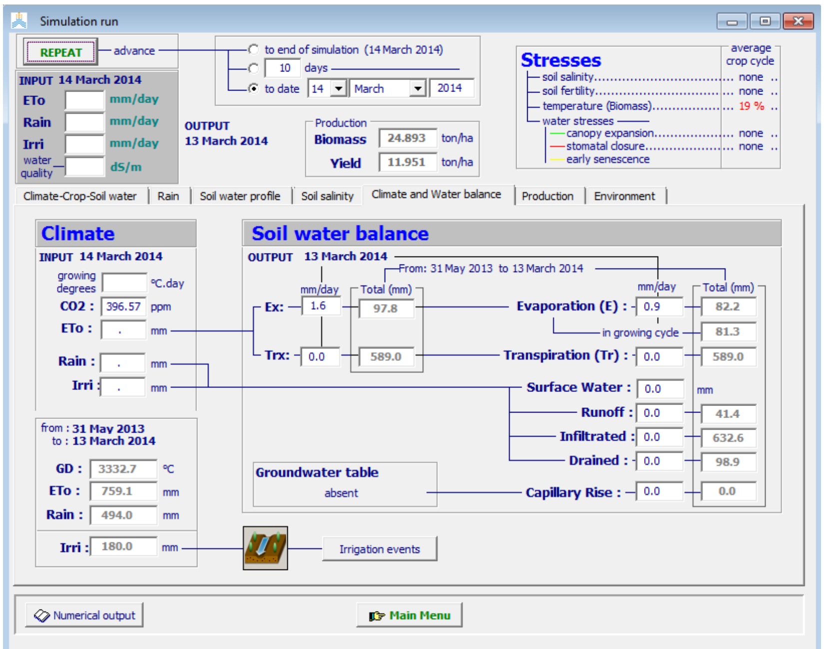

Figure 22: AquaCrop output Wakanui 2013-2014

2012-2015

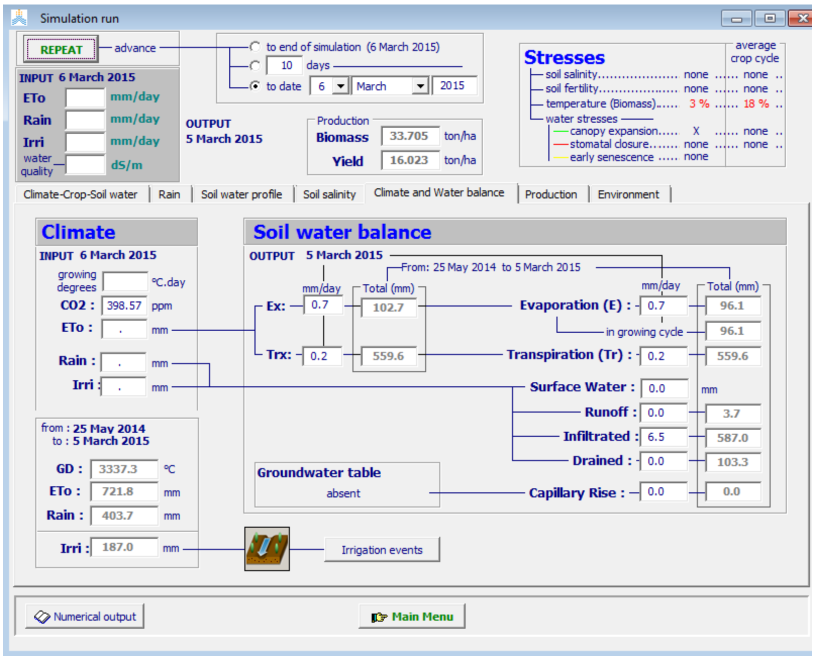

Figure 23: AquaCrop output Wakanui 2012-2015

Wakanui-Ashburton

2014-2015

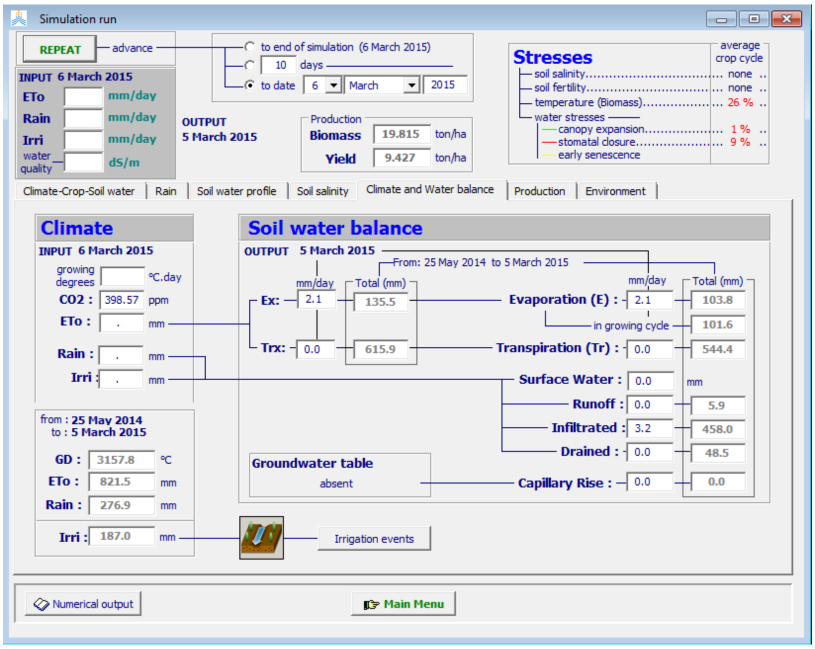

Figure 24: AquaCrop output Wakanui-Ashburton 2014-2015

2013-2014

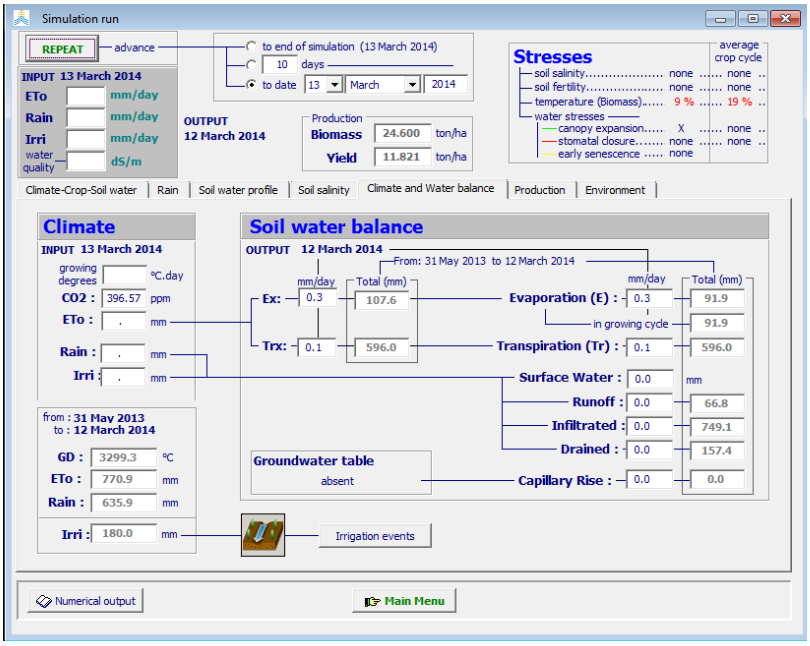

Figure 25: AquaCrop output Wakanui-Ashburton 2013-2014

2010-2015

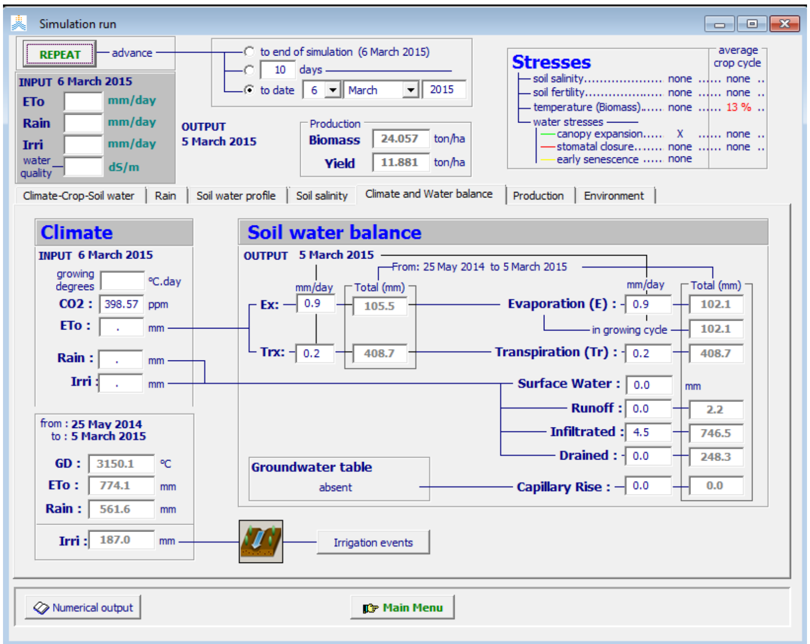

Figure 26: AquaCrop output Wakanui-Ashburton 2010-2015

2006-2015

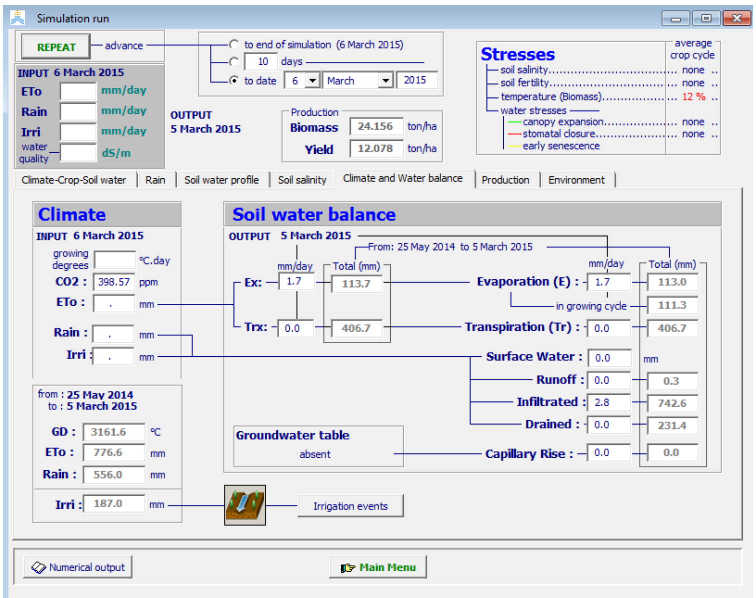

Figure 27: AquaCrop output Wakanui-Ashburton 2006-2015

Global data

Palmerston North

1996-1990

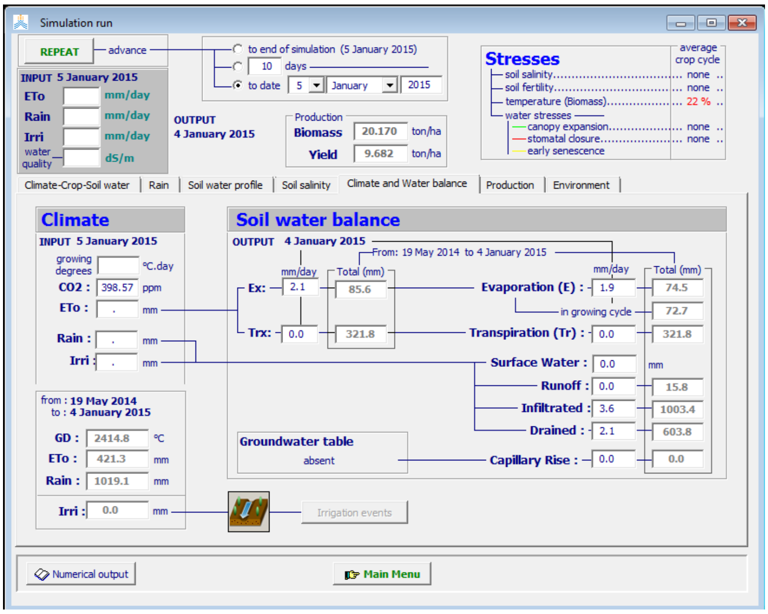

Figure 28: AquaCrop output Palmerston North 1996-1990

Rakaia

1996-1990

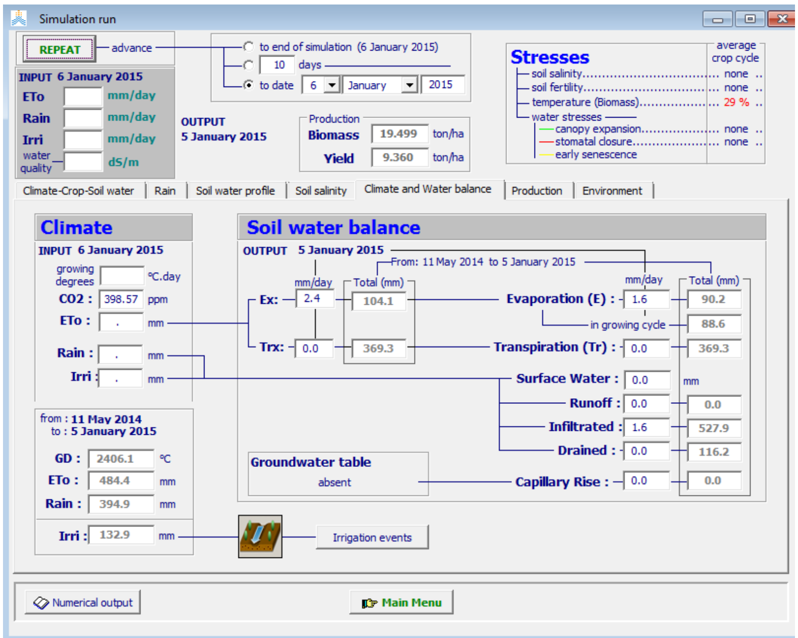

Figure 29: AquaCrop output Rakaia 1996-1990

Ashburton

1996-1990

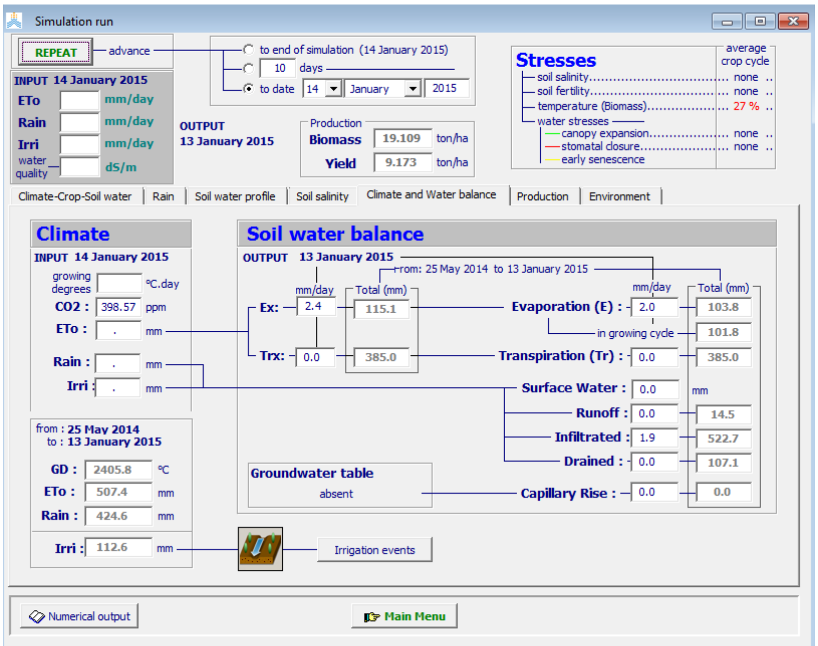

Figure 30: AquaCrop output Ashburton 1996-1990