EFFECT OF DIFFERING DETAIL IN DATASET AND MODEL ON ESTIMATION OF WATER FOOTPRINT OF CROPS

July 2013 Bachelor Final Project

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BACHELOR FINAL PROJECT
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ABSTRACT

The concept of water footprint analysis has been devised by Professor Arjen Y. Hoekstra to assist with decision making for efficient, equitable and sustainable water use and its management. The water footprint can be calculated for different countries, businesses, crops and other products. To calculate the water footprints related to crop production the crop evapotranspiration and yield has to be known. The required variables can be calculated by using different models and different data sources over different temporal and spatial scales. Theoretically, each combination of model and dataset of a specific crop on a specific place should give the same results. This study has been done to identify if the use of different models and/or datasets will have effect on the estimation of the water footprint of crops.

The study area is the Sirsa district in the Indian state Haryana. This district is characterized as a dry area, caused by extremely high temperatures and little rainfall. Two crop rotations were studied namely a wheat – rice and a wheat – cotton field, where wheat is cultivated in the winter season and rice and cotton in the summer season. The study uses two different models, namely the CROPWAT model as being a simpler and commonly used model for water footprint studies and the SWAP model as being a complex agrohydrological model. The CROPWAT model used two different datasets, namely a dataset from global available sources and a locally available dataset. The SWAP model used local datasets, which have been collected on different times and places in the study area. With these models and datasets six different combinations have been assessed. All these combinations are calculated in this study, only the evapotranspiration values of the SWAP model combinations are taken from previous studies.

With the estimated crop evapotranspiration and yields calculated by the CROPWAT and SWAP models from different local and global data sources the water footprints of wheat, rice and cotton were calculated and compared to each other. The average water footprint in the Sirsa district for wheat is 0,84 m^3/kg, for rice 2,56 m^3/kg and for cotton 21,64 m^3/kg. The average water footprints of rice and cotton are high, caused by the high values calculated by the combination of CROPWAT model and global available data in comparison with the other values for wheat and rice. The coefficient of variation in the water footprints are largest with rice, namely about 46%. This means the water footprint of rice is the most sensitive to calculate, due to the preparation of the paddy fields. The evapotranspiration of wheat calculated by the different combinations are quite the same (ranging from 342 mm to 392 mm) except for the combination of CROPWAT model with global available data (237 mm). With this combination the evapotranspiration calculated for the different crops is much different than the average, for instance for wheat 237 mm by a mean value of 342 mm, for rice 1031 mm by a mean value of 864 mm and for cotton 1092 mm by a mean value of 745 mm. The coefficients of variation of the crop yields are quite large, namely 22% for wheat, 42% for cotton and 61% for rice. This is due to the manner of calculating the crop yields, which are different for almost all datasets, which all covers different time periods and different areas. This means therefore that the results show a discrepancy between practice and theory.

This study shows that several combinations of model and dataset are possible to estimate water footprints of crops, but the results are not the same. This is because of different data sources, different time periods considered, different methods used in models and different definitions of parameters. This means that it is very important that every parameter have to be defined very well in calculating the water footprint of crops. In drawing conclusions researchers should be very careful. The differences between the different combinations of model and dataset are too large to draw firm conclusions.

PREFACE

I am very glad to present you the report of my research study at the Massey University in New Zealand, which I did for the study Civil Engineering at the University of Twente, The Netherlands.

Before completing the bachelor degree of Civil Engineering at the University of Twente, a research project of at least 10 weeks has to be done. This Bachelor Final Project has to be done either at an external organization, an institute or a university. I liked the water part of my study the most and I wanted also to do this project abroad to improve my English language. After a long search for a water management research project in an English spoken country, I came into contact with Dr. Ranvir Singh from the Massey University in Palmerston North, New Zealand, and member of the Water Footprint Network. Together we formulated by e-mail conversation a project on the field of water footprint to do between May 2013 and the middle of July 2013. In the first week of the research, after I arrived in New Zealand, we formulated the research study a lot better. The next 11 weeks I did the research of which this report is about.

During this research I have worked most of the times on my own. Nevertheless, I couldn't do this research without the help of my supervisors. I would like to thank first Dr. Ranvir Singh, my supervisor at the Massey University. He has done a great job not only in helping to formulate this study, but also in helping me at the times when I struggled with the harder parts of this research. I hope this limited study will help him in doing further research and help other researchers too in doing their studies. I also want to thank my supervisor in The Netherlands, Dr. Mesfin Mekonnen, who helped me in the beginning with setting up this research and during this research in giving his comments, tips and tricks to write a good report.

I also would like to thank a few other people, who were not involved with this research, but nevertheless have been of great significance to me during this period. As there is my boarding family in Palmerston North, who let me all the time feel welcome, happy and at home at their house and in New Zealand. Also thanks to my parents for the support before and during this period, and especially thanks to my dad for correcting the English language in my report. And last but not least to my girlfriend who let me go for almost 4 months to the other side of the world to grant me this fantastic experience.

Teun Lassche
Palmerston North, New Zealand
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CONTENTS

1. INTRODUCTION

1.1 Background

Natural resources are becoming scarce on this planet because of its sometimes disproportionate use. For that reason we need to reduce the use of these resources or use them more efficiently, equitably and sustainably. This research project is about the natural resource water. In 1993 Peter H. Gleick concluded that less than 1 percent of the fresh water on the earth could be used, which is about 200.000 km^3 of which the biggest part is difficult to reach (Gleick, 1993). Beside this Gabi Spitz (2012) argues that fresh water is unequally distributed over the world and over the several populations. Therefore exact identification of the water use of people has become a big topic in the field of fresh water sustainability.

During daily life of people a lot of water is being used. Part of the water is being used directly, as for showering, toileting, cooking, drinking, etc. But by far the biggest part of the water consumption is getting used indirectly, in the producing of food, clothes and other products. Jefferies et al. (2012) argue that 86% of the water used is spent on producing food. Hoekstra and Mekonnen (2011) even argue that at least 92% of the water use is spent in agricultural production. This has become known through the application of the water footprint concept, through which the direct and the indirect use of water can be identified.

The concept of water footprint analysis has been devised by Professor Arjen Y. Hoekstra in the year 2002. He states that the water footprint is based on the recognition that human impacts on fresh water systems can ultimately be linked to human consumption, and that issues like water shortages and pollution can be better understood and addressed by considering production and supply chains as a whole (Hoekstra et al., 2011). Water footprint is measured in terms of water volumes consumed (evaporated) and/or polluted per unit of time. This can be done first by analyzing the water consumption of a whole country, the National Water Footprint, second by analyzing the water consumption of a business, the Corporate Water Footprint or third by analyzing the water consumption in the producing of food or other products, the Product Water Footprint, and so on (Hoekstra et al., 2011). With this latter water footprint we will proceed in this research.

The water footprint of certain products can be divided into three components, namely the blue, green and grey water footprint (Hoekstra et al., 2011). The blue water footprint refers to the consumption of surface and groundwater during the production processes. The green water footprint refers to the consumption of rainwater stored in the soil profile. The grey water footprint refers to a hypothetical volume of water need to dilute the pollutants load for maintaining the water quality according to agreed water quality standards. For the blue and green water footprint the consumption of water can be defined as a loss of water, which occurs when water evaporates, returns to another catchment area or the sea or is incorporated into a product.

In calculating the green and blue components of water footprints of the process of growing crops, the accumulation of daily evapotranspiration over the complete growing period must be known. This can be measured, which takes a lot of time and money, or it can be estimated by means of a model using easily measurable and available input parameters and climatic data (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011, p. 42). Several models or methods can be used for estimating the evapotranspiration and the crop growth. First, the EPIC model (Erosion-

Productivity Impact Calculator (Williams & Singh, 1995)) can be used. This model is primarily a soil hydrology model and is developed to track the impacts of erosion and soil productivity on crops (Gueneau, 2012). Secondly, the CROPWAT model (FAO, CROPWAT, 2009) can be used. This empirical process-based crop model is generic and requires very few input parameters for the plant or soil specifications (Gueneau, 2012), and therefore it is easy in use. This model is commonly employed in water footprint estimation studies, and provides relevant references to support such a statement. The evolution of CROPWAT is the model AquaCrop (FAO, AQUACROP, 2011). This model is an empirical process-based crop model as well and focuses on evaluating the irrigation need for crops (Gueneau, 2012). The last model mentioned here is the model SWAP (Soil Water Atmosphere Plant) (Dam, Groenendijk, Hendriks, & Kroes, 2008). This agrohydrological model simulates the transport of water, solutes and heat in unsaturated and saturated soils (Alterra, 2011).

1.2 Research purpose

As mentioned in the previous section, the models are commonly used to estimate the evapotranspiration and the crop yields to estimate water footprint of a particular crop on a specific place and at a specific time. In theory, each combination of model and dataset of a specific crop on a specific place should give the same results. However, there are differences in complexity between these models and there are differences in availability of input data for the models. There are models which need large datasets in order to do their calculations; other simpler models need less data to do their calculations. In addition, the datasets can differ therein that data is globally or locally available. In this research project we will assess the effects of differing models and data sources on the water footprint calculations of agricultural crops.

For the simpler model the CROPWAT model will be used. This is because of its relative ease of use and implementation. CROPWAT is a decision support tool developed by the Land and Water Development Division of FAO (Food and Agriculture Organization of the United Nations). With this tool it is possible to calculate reference evapotranspiration, crop water requirements and irrigation requirements based on soil, climate, irrigation and crop data. There are two options to calculate the blue and the green evapotranspiration (ET_{blue} and ET_{green}), namely with the Crop Water Requirements (CWR) and with the irrigation requirements. In this study only the CWR-option is used because it is the easiest one to implement with the local data available.

For the more complex model the SWAP model will be used. SWAP is a model developed by Wageningen University, sub-department Water Resources, and Alterra Green World Research, department Water and Environment (Dam, 2000). The model is designed to simulate flow and transport processes at field scale level. It simulates the vertical soil water flow and salt transport in close interaction with the crop growth (Singh, 2005). With this more complex model several researches have already been done, and that with the same (local) dataset as will be used in this study.

With these two models the water footprints of wheat, cotton and rice in the Sirsa district in Haryana (India) will be calculated. The global available data will be taken from data available in global databases that correspond with data of this Sirsa district. The local available data is more difficult to get, due to limited information available from specific areas. The local available data in this research will be taken from a few fields in the Sirsa district, which are made available through the WATPRO-study (Dam & Malik, 2003).

The different models with the different levels of information are depicted in figure 1.1. Therein the rule is the higher the layer number, the more complex the model and the manner of gathering information. Layer 3 (with the SWAP model) has already been investigated thoroughly in the PhD study of Singh (2005), wherefore this model is not further explained in this report. The focus is on the first two layers, which each will be compared with layer 3, in order to evaluate how accurate the results of the former two models and data combinations are.

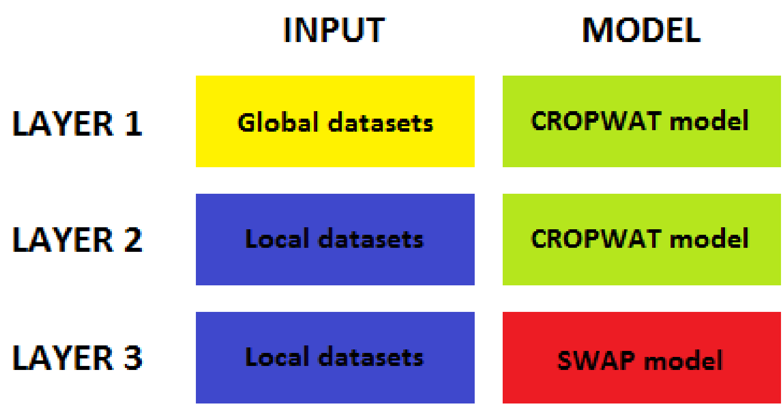

FIGURE 1.1: RANK OF COMPLEXITY WATERFOOTPRINT MODELS

1.3 Research questions

In correspondence with the purpose of this research three main questions are formulated, which are as follows.

1. What is the effect of difference in the detail of the datasets on the calculation of the water footprint of agricultural crops?
2. What is the effect of difference in the complexity of the models on the calculation of the water footprint of agricultural crops?
3. What is the effect of difference in the detail of the datasets and the complexity of the models on the calculations of the water footprint of agricultural crops?

1.4 Study area description

The Sirsa district is one of the districts of the Indian state Haryana and is located in the northwestern part of India (figure 1.2), near Pakistan and about 250 km from Delhi. Its surface area is about 4275 km^2 and it has a population of approximately 1.3 million. The density of the population is 303 inhabitants per square kilometer (Census2011, 2011). The Sirsa district is divided into seven administrative blocks: Dabwali, Odhan, Baragudha, Rania,

FIGURE 1.2: LOCATION OF SIRSA-DISTRICT (RED COLOUR)

Sirsa, Ellanabad and Nathusari (Singh, 2005) as shown in figure 1.3. The water management in the Sirsa district is complex because of scarce and erratic rainfall, high evaporative demand, marginal to poor groundwater quality in most parts of the district, rising groundwater levels, occasional flooding, low water holding capacity of soils and the absence of any perennial river (Dam & Malik, 2003). Only the ephemeral Ghagger River flows through the district. The district is completely covered by the Sirsa Irrigation Circle (SIC) water supply in the area. This limited water supply comes from Gobind Sagar Storage Reservoir, located at about 400 kilometers distance. The limited canal supply is supplemented by the groundwater use.

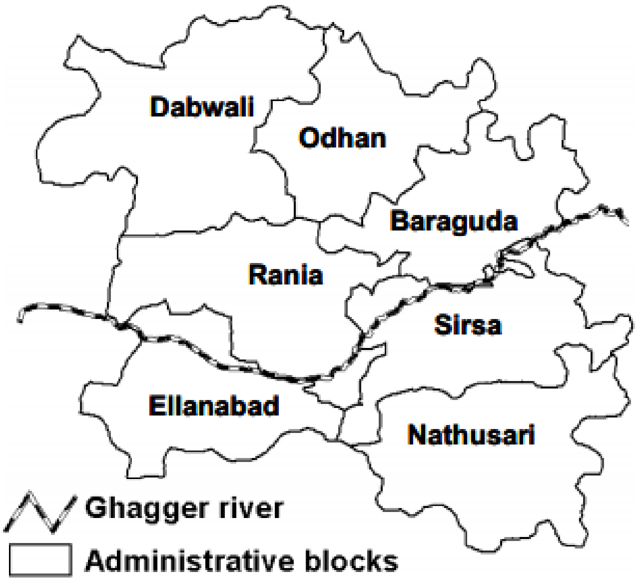

FIGURE 1.3: ADMINISTRATIVE BLOCKS SIRSA DISTRICT

The climate of the Sirsa district is very dry, characterized by extremely high temperatures and little rainfall. Temperatures vary from 5-21°C in winter to 41-49 °C in summer. The average rainfall varies from 100 to 400 mm per year, which is only 10 to 25% of the reference evapotranspiration.

The main occupation of the people living in this district is with agriculture. The main crops cultivated are wheat in winter season (rabi) and cotton and rice in summer season (kharif). The crop calendar of wheat, rice (National Food Security Mission, Ministry of Agriculture, 2013) and cotton (Barik, 2010) is given in table 1.1. In this table the planting periods and the harvesting periods are given in terms of months, whereby the beginning (B), the middle (M) and the end (E) of the month also is specified.

TABLE 1.1: CROP CALENDAR HARYANA

Crop	Planting time	Harvesting time
Wheat	October (E) – December (B)	April (M) – April (E)
Rice	June (B) – July (B)	October (M) – November (E)
Cotton	April (B) – April (M)	October (M) – November (M)

1.5 Report outline

The report is organized in four chapters, of which the first chapter is the introduction. Chapter 2 describes the basic method for calculating the water footprint. Beside this it presents the method of the CROPWAT model. Also, in this chapter is explained the calculation of the input parameters of the CROPWAT model, both for the global available data and for the local available data. The chapter closes with an explanation of the datasets used for the SWAP model. In chapter 3, the calculations of the water footprints are done for both models with help of the datasets explained in chapter 2. After this the results are compared with each other and discussed. The results which are presented in chapter 3 are summarized in chapter 4 with (key) conclusions and recommendations.

2. METHOD AND MATERIALS

2.1 Water footprint calculation

The total water footprint of a crop is the sum of the three (green, blue and grey) water footprint components as shown in formula 2.1.

$$WF_{crop} = WF_{crop,green} + WF_{crop,blue} + WF_{crop,grey} \text{ [mass/volume]} \quad (2.1)$$

Within this research the blue and green components of the water footprint (*WF*) of the growing of different crops shall be calculated, which means the grey component will be disregarded. The green and blue components shall be calculated by dividing the estimated crop evapotranspiration (ET, mm) by the crop yield (γ, ton/ha).

$$WF_{crop,green} = \frac{ET_{green}}{\gamma} \text{ [volume/mass]} \quad (2.2)$$

$$WF_{crop,blue} = \frac{ET_{blue}}{\gamma} \text{ [volume/mass]} \quad (2.3)$$

$$WF_{crop,blue\&green} = \frac{ET_{green}+ET_{blue}}{\gamma} \text{ [volume/mass]} \quad (2.4)$$

The water footprints will be calculated for two fields with different combination of crops and soils. Below these two fields are listed.

	Winter (*rabi*)		Summer (*kharif*)		Soil
Field 1 :	Wheat	-	Rice	on	Clay loam
Field 2 :	Wheat	-	Cotton	on	Loamy sand

2.2 CROPWAT model and its input parameters

The components of the crop evapotranspiration will be estimated with the help of the model CROPWAT, wherewith the actual crop evapotranspiration (ET_c, mm) and the effective precipitation (P_{eff}, mm) can be calculated. With these water fluxes the green and blue components of the crop evapotranspiration can be estimated by using the following formulas:

$$ET_{blue} = \max(0, ET_c - P_{eff}) \text{ [length/time]} \quad (2.5)$$

$$ET_{green} = \min(ET_c,\ P_{eff}) \text{ [length/time]} \quad (2.6)$$

The actual crop evapotranspiration will be calculated in the CROPWAT model by multiplying the reference crop evapotranspiration (ET_0, mm) with the crop coefficient (k_c) as is given in formula 2.7.

$$ET_c = k_c \times ET_0 \text{ [mm]} \quad (2.7)$$

The crop coefficient is a value that includes different crop characteristics as crop type, plant health and it differs through the growing period. Therefore, the crop growing period is divided in 4 stages, namely the initial, developing, middle and late stages. The initial, middle and late stages each have their own crop coefficients, which can either be searched for in case of global data or estimated and calculated in case of local data. The calculation and estimation of the crop coefficients for the local data shall be explained in the section 2.3.2.

The model also needs climatic data for the calculation of the reference crop evapotranspiration. This climatic data includes the mean monthly maximum and minimum temperatures (°C), the mean monthly relative humidity (in %), the mean monthly sunshine hours per day and mean monthly wind speed. The CROPWAT model calculates with these data the reference evapotranspiration, with help of the Penman-Monteith Method (Allen et al., 1998).

In addition to the climatic data and the crop coefficients the CROPWAT model requires some other crop characteristics, such as the water stress coefficient (K_s), the yield response factor (K_y) and the critical depletion level. These are not needed for the calculation of the crop water requirements, for which the model in this research will be used, but rather only as dummy inputs to run the model. These characteristics don't affect the calculations of the crop water requirements.

Only in the case of the calculation of the crop water requirements of rice the CROPWAT model needs soil data. The soil input data includes *inter alia* the total available soil water content, the maximum infiltration rate for runoff estimates, drainable porosity of the soil and the initial soil water content at the start of the season.

To calculate the effective rain with the actual rain data the effective rain method 'USDA SCS method' is used, because of the recommendation by Smith (1992) done in his book about the CROPWAT model and its use in most of the water footprint studies (Pongpinyopap & Mungcharoen, 2012). This method calculates the effective rain (P_{month}) with help of the actual rainfall per month (P_{month}) with the following formulas:

$$P_{eff} = P_{month} * (125 - 0{,}2 * P_{month})/125 \text{ for } P_{month} \leq 250\ mm \quad (2.8)$$

$$P_{eff} = 125 + 0{,}1 * P_{month} \text{ for } P_{month} > 250\ mm \quad (2.9)$$

With all these data, the CROPWAT model calculates the decadal crop water requirements for the different crops and also the crop water requirements per growing period.

2.3 CROPWAT model input data

2.3.1 Global data

In the first layer defined in the research purpose the water footprint of wheat, rice and cotton is to be calculated using the CROPWAT model with global available data (figure 1.1). These global available data can be found in standard CROPWAT data and in the CLIMWAT database, which is also used in several other water footprint studies as Bulsink, Hoekstra & Booij (2009), Gerbens-Leenes & Hoekstra (2009) and Chapagain & Hoekstra (2011). This climatic database provides for monthly data like the minimum and maximum temperatures, humidity and sunshine hours and the monthly rainfall for more than 5000 stations in the world over the period 1971-2000 (FAO, 2009). In the following paragraph, the data are given and explained and the calculations are done.

REFERENCE EVAPOTRANSPIRATION (ET_0)

In order to determine the reference evapotranspiration (ET_0) in the CROPWAT model the Penman-Monteith Method has been used. This method determines ET_0 from the following climatic data:

- Temperature
- Humidity
- Sunshine
- Wind speed

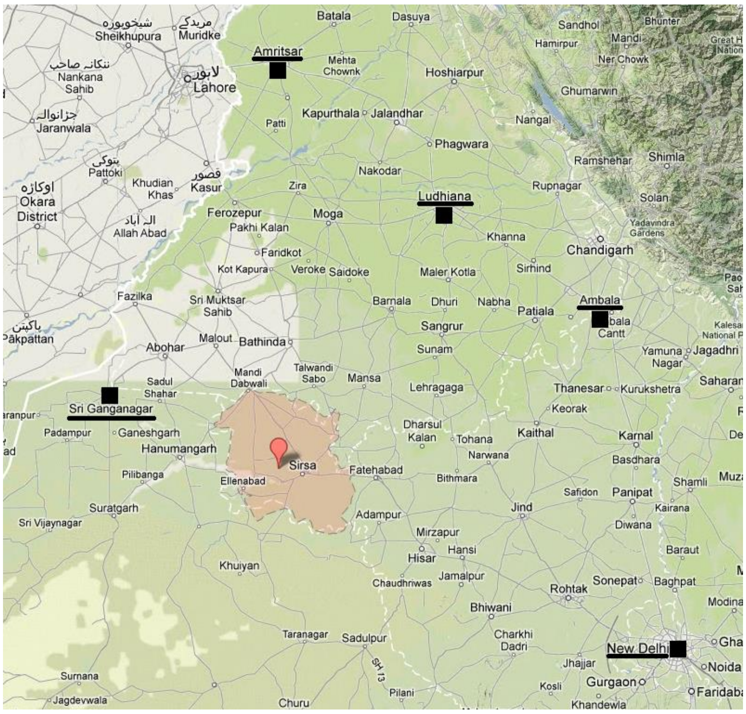

FIGURE 2.1: LOCATIONS OF METEOROLOGICAL STATIONS AROUND SIRSA DISTRICT (GOOGLE MAPS)

These data should be collected from the most representative meteorological station in the Sirsa district. The data from this station are to be found in the CLIMWAT database. However, in this database no meteorological station has been incorporated that is known in the Sirsa district, rather there are five meteorological stations in the area surrounding the Sirsa district. Looking for the most representative and nearest meteorological station it is helpful to look on the terrain map for the locations of these stations to find the most representative station, and further to the distance between the stations and the Sirsa-district to find the nearest station.

In figure 2.1, a geographical and topographical map with the five meteorological stations nearest to the Sirsa district is shown. The figure shows the geographical and topographical area of the three northern stations, Amritsar, Ludhiana and Ambala, which in terms of different terrain colours are a bit different, from the areas of Sri Ganganagar and New Delhi. These stations are therefore the most representative stations to gather the climatic data for the Sirsa-district.

TABLE 2.1: DISTANCE FROM STATIONS TO BORDER OF SIRSA-DISTRICT

Station	Km to border
Sri Ganganagar	60 km
Amritsar	185 km
Ludhiana	135 km
Ambala	160 km
New Delhi	200 km

Table 2.1 shows the distance between the border of the Sirsa district and the meteorological station, for each station, from west to east. The meteorological station in New Delhi is more than 3 times further away from the Sirsa district than the station in Sri Ganganagar is. This means that the most representative and the nearest meteorological station is that in Sri Ganganagar, from which the climatic data contained in the CLIMWAT database will be used.

After importing the monthly climatic data file of the CLIMWAT database from the meteorological station in Sri Ganganagar into the CROPWAT model, the sunshine radiation ($MJ/m^2/day$) and the reference evapotranspiration (ET_0) (mm/day) are calculated with the

Penman Monteith Method. In table 2.2, all these data and calculations are given. The altitude, latitude and longitude, the minimal and maximal temperature, the humidity, the wind speed and the sunshine hours are from the CLIMWAT database. The radiation and the ET_0 are calculated in the CROPWAT model as already noted.

TABLE 2.2: MONTLY ET_0 WITH DATA OF STATION GANGANAGAR WITH PENMAN-MONTEITH METHOD

Country: INDIA | Station: GANGANAGAR
Altitude: 177 m. | Latitude: 29.91 °N | Longitude: 73.91 °E

Month	Min Temp °C	Max Temp °C	Humidity %	Wind m/s	Sun hours	Rad MJ/m²/day	ETo mm/day
January	4.7	20.5	60	0.8	6.9	12.5	1.74
February	7.5	24.1	53	1.1	7.8	15.6	2.62
March	11.1	29.6	48	1.4	8.5	19.3	3.99
April	18.2	36.3	33	1.5	9.6	23.1	5.74
May	24.0	41.5	27	1.7	10.2	25.1	7.27
June	28.0	42.1	35	2.3	10.5	25.8	8.50
July	28.1	38.8	54	2.8	9.3	23.8	7.65
August	26.9	37.3	59	1.7	9.0	22.5	6.11
September	24.1	36.6	54	1.3	8.9	20.5	5.25
October	17.0	35.0	44	0.9	9.1	17.9	4.00
November	8.9	29.4	47	0.7	8.2	14.3	2.58
December	5.5	23.3	57	0.7	7.3	12.2	1.82
Average	17.0	32.9	48	1.4	8.8	19.4	4.77

RAINFALL

Part of the crop water use comes from the water through rainfall. Not all the water through rainfall can be used because of losses due to surface runoff or deep percolation below the root zone. Therefore, the effective rainfall, or in other words the rainfall that the crops use, should be calculated. This is done with USDA Soil Conservation Service method, which is explained in the section 2.2.

TABLE 2.3: MONTHLY RAIN WITH DATA OF STATION GANGANAGAR

	Rain mm	Eff rain mm
January	8.0	7.9
February	5.0	5.0
March	13.0	12.7
April	3.0	3.0
May	7.0	6.9
June	22.0	21.2
July	66.0	59.0
August	65.0	58.2
September	41.0	38.3
October	1.0	1.0
November	1.0	1.0
December	5.0	5.0
Total	237.0	219.3

The data of the actual rain per month is taken from the CLIMWAT database from the metrological station in Sri Ganganagar and is given in table 2.3. Also, the effective rain per month, which is calculated in the CROPWAT model, is given in this table.

The table shows that about 92% of the rainfall has been estimated as effective rainfall, which means that the biggest part of the rainfall is used by the crops. These values are as expected because of the low rainfall per month. The crops use the water more effectively when there is less rainfall, especially in winter (rabi) season, as Rahman, Islam and Hasanuzzaman (2008) conclude in their study of Effective Rainfall in Bangladesh.

CROP CHARACTERISTICS

In this research three crops, namely wheat, rice and cotton will be studied. The CROPWAT model requires the characteristics of these crops in to calculate the crop water requirements. These characteristics are taken from the CROPWAT database, which contains the characteristics of approximately 40 different crops, which are taken from selected FAO publications (Allen et al., 1998).

For rice and cotton there exists only one set of characteristics, but for wheat there are three sets of characteristics available, two sets of winter wheat and one set of common or spring wheat. The spring wheat set is chosen in this research because of the planting date in November, which Smith provides in his book about the CROPWAT model for the of Central India (1992, p. 56), to which the study area is located the nearest of the mentioned areas, and the length of the growing period (130 days for spring wheat, 240 and 335 days for the sets of winter wheat). The tables 2.4 and 2.5 show the characteristics per crop.

The rooting depth, critical depletion and the yield response factor are not needed for the calculation of the crop water requirements, rather only as dummy inputs to run the CROPWAT model. The values for these crop characteristics don’t affect the crop water requirements and therefore aren’t given.

TABLE 2.4: GLOBAL AVAILABLE DATA FOR WHEAT AND COTTON CROPS

Crop	Parameter	Stages					Planting
		initial	develop	mid	late	total	date
Spring wheat	Length per stage (days)	30	30	40	30	130	15-11
	K_c values	0.30	→	1.15	0.30		
	Cropheight (m)			1.00			
Cotton	Length per stage (days)	30	50	60	55	195	15-4
	K_c values	0.35	→	1.20	0.60		
	Cropheight (m)			1.30			

TABLE 2.5: GLOBAL AVAILABLE DATA FOR RICE CROP

Crop	Parameter	nursery	landpreparation		growth stages				total	Planting
			total	puddling	initial	develop	mid	late		date
Rice	Length per stage (days)	30	20	5	20	30	40	30	150	20-6
	K_c dry	0.70	0.30		0.50	→	1.05	0.70		
	K_c wet	1.20	1.05		1.10	→	1.20	1.05		
	Puddling depth (m)			0.40						
	Nursery area (%)	10								
	Cropheight (m)						1.00			

In this research, two different fields are chosen in the combinations of crop and yield. The crops on field 1 are wheat (in winter) and rice (in summer). The crops on field 2 are wheat (in winter) and cotton (in summer). In figure 2.2 the cropping pattern for both fields is shown, based on the planting times from table 1.1 in the section 1.4, and the harvesting times calculated by the CROPWAT model, as shown in the tables 2.4 and 2.5.

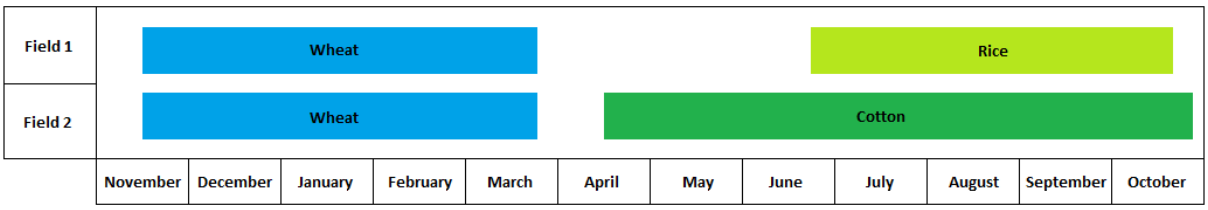

FIGURE 2.2: CROPPING PATTERN FIELDS 1 AND 2 WITH GLOBAL DATA

SOIL CHARACTERISTICS

The last step before we can calculate the crop water requirements is to define the soil type of field 1. This is necessary in the CROPWAT model, otherwise the Crop Water Requirement of rice cannot be calculated. The soils for the fields have already been defined in the section 2.1, namely a clay loam soil type in field 1 and a loamy sand soil type in field 2. There is few data globally available, because the soil types differs a lot per regions. So in this part of the research the soil types available in CROPWAT are used. The soil types black clay, red loamy, red sandy loam and red sandy soil are available in the CROPWAT database. The clay loam soil, which is the soil type of field 1, is a heavy soil type just as black clay soil. Therefore, the black clay soil is used in this part of the research. In table 2.6 the soil data of field 1 is shown. The maximum rooting depth, the critical depletion for puddle cracking, the water availability at planting and the maximum water depth does not affect the calculation of the crop water requirements, therefore are not shown in table 2.6. However, the CROPWAT model needs these values to run the calculations, but these values can be chosen randomly.

TABLE 2.6: GLOBAL AVAILABLE SOIL DATA FOR CALCULATION CWR RICE

Total available soil moisture (FC - WP)	200.0	mm/meter
Maximum rain infiltration rate	30	mm/day
Initial soil moisture depletion (as % TAM)	50	%
Initial available soil moisture	100.0	mm/meter
Drainable porosity (SAT - FC)	10	%

2.3.2 Local data

The second layer defined in the research purpose is to calculate the water footprint of wheat, rice and cotton by using the CROPWAT model with local available data. Most of these data have been collected in the Water Productivity 'WATPRO'-project and are from the sources as shown in table 3.4 of (Singh, 2005, p. 35). In this section the data needed for the calculation of the crop water requirements of wheat, cotton and rice in the CROPWAT model are given and explained.

REFERENCE EVAPOTRANSPIRATION (ET_0)

The local available climatic data are from the meteorological station at the Cotton Research Station (CRS) in Sirsa except in some cases, due to missing data and occurring errors, from the meteorological station at the CCS Haryana Agricultural University (HAU), Hisar, which is about 90 km from Sirsa. These data have already been collected in the WATPRO project (Dam & Malik, 2003) and stem from the years 1990 – 2002.

All the climatic data can be taken directly from this resource. Only the relative humidity should be calculated with the available data. The relative humidity contained in the local available dataset consists of the relative humidity in the morning (RH_M) and the relative humidity (RH_E) in the evening. Within the CROPWAT model a relative humidity (RH) of the whole day is needed, so that the average relative humidity is calculated as following:

$$RH = \frac{RH_M + RH_E}{2} \tag{2.10}$$

All the climatic data are given in table 2.7 and also the altitude, latitude and longitude of the meteorological station of Sirsa.

TABLE 2.7: MONTLY ET_0 WITH DATA OF STATION CRS IN SIRSA WITH PENMAN-MONTEITH METHOD

Country: India | Station: CRS, Sirsa
Altitude: 205 m. | Latitude: 29.33 °N | Longitude: 75.20 °E

Month	Min Temp °C	Max Temp °C	Humidity %	Wind m/s	Sun hours	Rad MJ/m²/day	ETo mm/day
January	5.5	19.0	67	1.0	6.3	12.0	1.73
February	7.9	22.1	65	1.2	7.3	15.2	2.40
March	11.8	27.7	55	1.4	8.2	19.0	3.70
April	18.0	36.1	40	1.6	9.3	22.7	5.69
May	24.4	41.0	36	2.3	8.3	22.3	7.55
June	27.0	40.2	47	2.6	7.5	21.4	7.50
July	27.0	36.2	61	2.5	6.0	19.0	5.98
August	26.2	34.9	66	2.0	6.7	19.2	5.30
September	23.8	34.3	64	1.5	8.3	19.7	4.93
October	16.2	32.9	52	0.9	8.3	17.1	3.73
November	10.1	28.5	50	0.7	7.8	14.0	2.53
December	6.2	22.6	59	0.8	6.4	11.5	1.86
Average	17.0	31.3	55	1.5	7.5	17.8	4.41

RAINFALL

The effective rainfall needs to be calculated with the actual rainfall, with help of the USDA Soil Conservation Service method, explained in the section 2.2.

TABLE 2.8: MONTHLY RAIN WITH DATA OF STATION CRS IN SIRSA

	Rain mm	Eff rain mm
January	11.8	11.6
February	19.8	19.2
March	5.4	5.4
April	10.6	10.4
May	30.5	29.0
June	47.0	43.5
July	106.0	88.0
August	67.6	60.3
September	46.3	42.9
October	17.1	16.6
November	2.8	2.8
December	1.9	1.9
Total	366.8	331.5

The local available data of actual rainfall is also from the meteorological station at the CRS in Sirsa, in some cases added with data from the meteorological station at CCS HAU, Hisar. This data from 1990 – 2002 was already collected in the WATPRO project (Dam & Malik, 2003). The local available data of the actual rain per month and the effective rain per month is given in table 2.8.

The effective rainfall is estimated at about 90% of the actual rainfall, as can be seen in the table 2.8. This is a bit less than the effective rainfall estimated with the global data (92%), but not significantly less. This can be attributed by the higher rainfall estimated with local data, which means the crops use the water a bit more ineffectively than by lower rainfall.

CROP CHARACTERISTICS

Three crops are being used in this research, namely wheat, rice and cotton. These crops have each different characteristics. Some of these characteristics have to be calculated before putting them into the model, which applies for the crop coefficients. The other characteristics needed for the calculation of the crop water requirements are taken from the sources shown in table 2.9.

TABLE 2.9: LOCAL SOURCES OF CROP CHARACTERISTICS

Information	**Source**
Planting and harvesting data	Average crop calendar (Singh, 2005)
Length stages	Estimated with WATPRO data (Dam & Malik, 2003)
Crop height	WATPRO data (Dam & Malik, 2003)

The additional data needed for rice, as nursery area and puddling depth are taken from the CROPWAT database (Allen et al., 1998).

Crop coefficients (K_c)

For each crop different crop coefficients exist for different stages of the growing period. These are the crop coefficients for the initial, middle and late stages. For each of these crop coefficients different formulas are used. For the calculation of the crop coefficient of the initial stage alone even more than one formula exist. This is because the original crop coefficients are developed for certain conditions and therefore Allen et al. (1998) suggest to adjust them to be used for different climatic conditions. In this research the formula for raining events less than 10 mm is used, due to the climatic condition of the Sirsa district. In this case it is not a formula but a figure (figure 2.3) from where the crop coefficient ($K_{c\ ini}$) can be read, by knowing the ET_O and the interval between irrigations or rain events.

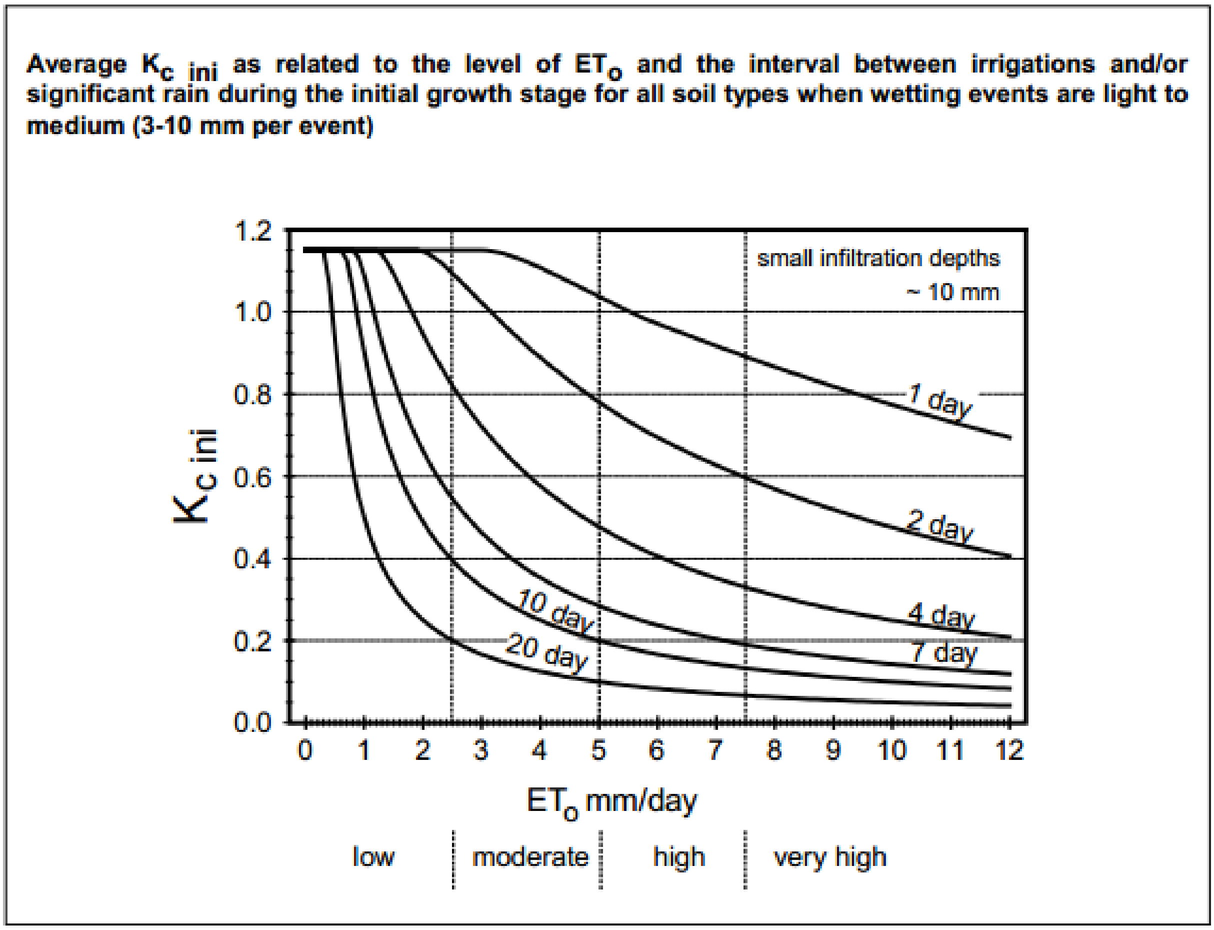

FIGURE 2.3: FIGURE FOR CALCULATING CROP COEFFICIENT INITIAL STAGE (ALLEN, PEREIRA, RAES, & SMITH, 1998)

In table 2.10 the estimated crop coefficients of the initial stage for the crops are given.

TABLE 2.10: ESTIMATING CROP COEFFICIENTS INITIAL STAGE

Crop	**Interval** (days)	**ET$_0$** (mm/day)	**K$_{c\ ini}$** (-)
Wheat	15	2,5	0,3
Cotton	5-6	7,5	0,3
Rice	3	7,5	0,5

For the calculation of the crop coefficient for the middle stage ($K_{c\ mid}$) the following formula is used:

$$K_{c\ mid} = K_{c\ mid\ (Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \qquad (2.11)$$

where $K_{c\ mid\ (Tab)}$ value for $K_{c\ mid}$ taken from Table 12 from Allen et al. (1998)
u_2 mean value for daily wind speed at 2m height over grass during the mid-season growth stage from WATPRO data (2003) (m/s)
RH_{min} mean value for daily minimum relative humidity during the mid-season growth stage from WATPRO data (%)
h mean plant height during the mid-season stage from WATPRO data (m)

In table 2.11 the calculation of the crop coefficients of the middle stage for the crops is given.

TABLE 2.11: CALCULATING CROP COEFFICIENTS MIDDLE STAGE

Crop	$K_{c\ mid\ (Tab)}$ (-)	u_2 (m/s)	RH_{min} (%)	h (m)	$K_{c\ mid}$ (-)
Wheat	1,15	1,3	46	0,85	1,13
Cotton	1,15-1,20	1,9	59	1,10	1,13
Rice	1,20	1,7	56	0,90	1,16

For the calculation of the crop coefficient for the end stage ($K_{c\ end}$) the following formula is used:

$$K_{c\ end} = K_{c\ end\ (Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \qquad (2.12)$$

where $K_{c\ end\ (Tab)}$ value for $K_{c\ end}$ taken from Table 12 from Allen et al. (1998)
u_2 mean value for daily wind speed at 2m height over grass during the end-season growth stage from WATPRO data (2003) (m/s)
RH_{min} mean value for daily minimum relative humidity during the end-season growth stage from WATPRO data (%)
h mean plant height during the end-season stage from WATPRO data (m)

In table 2.12 the calculation of the crop coefficients of the end stage for the crops is given.

TABLE 2.12: CALCULATING CROP COEFFICIENTS END STAGE

Crop	$K_{c\ end\ (Tab)}$ (-)	u_2 (m/s)	RH_{min} (%)	h (m)	$K_{c\ mid}$ (-)
Wheat	0.25	1,6	30	1,00	0,28
Cotton	0.70-0.50	0,9	38	1,30	0,59
Rice	0.90-0.60	0,9	38	1,00	0,74

The crop coefficients for rice for the stages before the transplantation (initial stage) and the wet crop coefficients are taken from the CROPWAT database for rice (Allen et al., 1998).

All crop characteristics calculated or taken from local available data, which are needed for the calculation of the crop water requirements for wheat, cotton and rice are given in tables 2.13 and 2.14. The lengths of the stages are estimated from the different defined stages in the local data.

TABLE 2.13: LOCAL AVAILABLE DATA FOR WHEAT AND COTTON CROPS

Crop	Parameter	Stages					Planting
		initial	develop	mid	late	total	date
Wheat	Length per stage (days)	40	46	50	30	166	16-11
	K_c values	0.30	→	1.13	0.28		
	Cropheight (m)			1.00			
Cotton	Length per stage (days)	30	45	55	50	180	5-5
	K_c values	0.30	→	1.13	0.59		
	Cropheight (m)			1.30			

TABLE 2.14: LOCAL AVAILABLE DATA FOR RICE CROP

Crop	Parameter	nursery	landpreparation		growth stages				total	Planting
			total	puddling	initial	develop	mid	late		date
Rice	Length per stage (days)	30	20	5	28	30	45	30	163	21-6
	K_c dry	0.70	0.30		0.50	→	1.16	0.74		
	K_c wet	1.20	1.05		1.10	→	1.20	1.05		
	Puddling depth (m)			0.40						
	Nursery area (%)	10								
	Cropheight (m)						1.00			

SOIL CHARACTERISTICS

For the calculation of the crop water requirements for rice the CROPWAT model needs the soil data of the rice-field. Some of the soil characteristics are available in the WATPRO-project, but most of the data that the CROPWAT model needs has to be calculated, and a few other data is standard data. The percentages of the clay and sand for the soil type can be taken from the WATPRO-project. With these percentages the field capacity (FC), the wilting point (WP) and the saturated soil (SAT) can be calculated with help of the online 'Soil Hydraulic Property' calculator (Global Soil Science Educators and Knowledge Managers, 2009), which is showed in table 2.15 for the clay loam soil. With this information the following soil characteristics can be calculated.

Percent Sand	36
Percent Clay	34
	Calculate
Percent Silt	30
Texture (US System)	Clay loam
Bulk density *(g/cm³)*	1.32
Saturated hydraulic conductivity *(cm/hr)*	0.27
Saturation *(cm³ water/cm³ soil)*	0.5
Field capacity *(cm³ water/cm³ soil)*	0.32
Wilting point *(cm³ water/cm³ soil)*	0.19
Plant Available water *(cm³ water/cm³ soil)*	0.13
(inches water/foot soil)	1.57

TABLE 2.15: SOIL HYDRAULIC PROPERTIES FOR CLAY LOAM

The total available soil moisture can be calculated with the following formula:

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \quad \text{[mm]} \tag{2.13}$$

where TAW the total available soil water in the root zone (mm)
θ_{FC} the water content at field capacity (cm^3/cm^3)
θ_{WP} the water content at wilting point (cm^3/cm^3)
Z_r the rooting depth (m)

The maximum rain infiltration rate, which is the rate at which the soil is completely dry, can be calculated by converting the saturated hydraulic conductivity calculated in table 2.15 from cm/hr to mm/day.

The initial soil moisture depletion is the average fraction of Total Available Soil Moisture that can be depleted from the root zone before moisture stress (reduction in evapotranspiration) occurs in the initial stage, and ranges from 0 – 1. Table 22 of Allen et al. (1998) contains depletion fractions for an evapotranspiration of approximately 5 mm/day. The initial available soil moisture is the moisture left after depletion.

The drainable porosity can be calculated with this formula:

$$DP = (SAT - FC) * 100 \quad \text{[\%]} \tag{2.14}$$

where SAT the saturation (mm)
FC the field capacity (mm)

Table 2.16 contains all the soil data that the CROPWAT model need for the calculation of the crop water requirements of rice. The maximum rooting depth, critical depletion for puddle cracking, water availability at planting and the maximum water depth, which the CROPWAT model needs but does not affect the crop water requirement calculations are not shown in this table.

TABLE 2.17: LOCAL AVAILABLE SOIL DATA FOR CALCULATION CWR RICE

Total available soil moisture (FC - WP)	130.0	mm/meter
Maximum rain infiltration rate	65	mm/day
Initial soil moisture depletion (as % TAM)	20	%
Initial available soil moisture	104	mm/meter
Drainable porosity (SAT - FC)	18	%

2.4 SWAP model and its input data

The calculation of the water footprints of the crops with help of the CROPWAT model and a global available as well as a local available dataset will be compared with the calculations with help of the SWAP model and local available datasets. The calculations with help of the SWAP model have been done already in a study of R. Singh (2005). In Singh's study three different datasets can be defined, which are explained in the following paragraphs.

The first dataset is from irrigated crops at field scale. These inputparameters have been measured directly in the field. In the study five fields were chosen in the Sirsa district, namely two wheat-rice fields and three wheat-cotton fields. These fields were monitored in the agricultural year 2001 – 2002. Some of the parameters that were too difficult to measure in the field have been found with the help of field experiments conducted at the Cotton Research Station (CRS) in Sirsa in the agricultural year 2001 – 2002. These field experiments have also been used for calibrating and validating the SWAP model. An overview of the data collected for the calibration and validation of the model by the field experiments is given in table 3.3 of the study 'Water productivity analysis from field to regional scale' (Singh, 2005). In the current study the calculated evapotranspiration (*ET*) values and the crop yield (*Y*) values are used for the calculation of the water footprints of wheat, cotton and rice with help of the SWAP model and the dataset from the field measurements.

The second dataset is a one year dataset of irrigated crops at regional scale. This calculation is based on different combinations of soil-crop-irrigation types in the whole of the Sirsa irrigation district. This dataset is generated by the SWAP model, which is calibrated and validated with the field measurements as described above. The dataset for calculating the water footprints of wheat, rice and cotton is collected and aggregated from satellite remote sensing techniques in Sirsa district and from the State Government agencies in Sirsa district. An overview of these data is given in table 3.4 of the study of Singh (2005). For this second dataset only the data of the agricultural year 2001 – 2002 is used. Also from these calculations the evapotranspirations and the crop yields for the different crops are used in this study.

The third and last dataset that can be defined from Singh's study is a 10 year dataset of irrigated crops at regional scale. This is the same dataset as the dataset mentioned before, extended with data of the years before. This is therefore a dataset of a longer period. The different data in the set are from different periods between 1990 and 2002, but the meteorological data is from the whole period 1990 – 2002. In table 3.4 of the study of Singh an overview of the data is given with the associated period and source per data. With this data the evapotranspiration of wheat, rice and cotton is calculated with the SWAP model, which is used in this study, just as the crop yielp per crop.

3. RESULT AND DISCUSSION

3.1 Water footprints

3.1.1 CROPWAT model with global available data

With the data collected from global available resources the most important part of the calculations can be performed: the calculation of the crop water requirements. The module Crop Water Requirement ***CWR*** in CROPWAT calculates the irrigation water requirement of the crop on a decadal basis and over the total growing season, as the difference between crop evapotranspiration under standard conditions (***ETc***) and the Effective rainfall (Allen et al., 1998). The outputs of the ***CWR*** calculations for the crops in this research are given in Appendix A. Table 3.1 shows a summary of the green and blue evapotranspiration calculations for the cropping pattern for both fields.

TABLE 3.1: CROP WATER REQUIREMENTS (IN MM), CALCULATED WITH GLOBAL AVAILABLE DATA

Field	Crop	Planting date	Harvest date	Etc	Eff. Rain	Irr. Req.	ET_{green}	ET_{blue}
				mm/growing period				
1	Wheat	15-11	24-03	236,7	28,9	207,4	28,9	208,1
1	Rice	20-06	17-10	1031,3	181,2	1129,5	181,2	849,9
2	Wheat	15-11	24-03	236,7	28,9	207,4	28,9	208,1
2	Cotton	15-04	26-10	1091,9	185,9	906,0	185,9	905,8

These calculations show that compared to cotton and rice, wheat does not need a large amount of water. Therefore, it is possible for this crop to grow in winter, also due to favourable temperature and radiation. Nevertheless, the effective rainfall is only 12% of the crop water requirement. Therefore, more than 85% has to be delivered by irrigation. In summer, there is more rainfall, but cotton and rice need both a lot of water. This means the irrigation requirement is still more than 80%. The difference between the ***ETc*** minus Effective Rainfall and the Irrigation Requirement by rice can be explained by the fact that at the beginning of the growth season the land for rice needs to be prepared with a water level, which is not included in the ***ETc***.

With these calculations and estimations the water footprint of the crops can be calculated as explained in the section 2.1. The crop yields are taken from the Department of Agriculture, Haryana (2012). These are average crop yields over the whole Haryana State including Sirsa district from 1971 to 2000. The results of these calculations are shown in table 3.2.

TABLE 3.2: CALCULATION OF GREEN & BLUE COMPONENTS WATER FOOTPRINT WITH GLOBAL DATA

Crop	ET_{green}	ET_{blue}	ET_{total}	Y	$WF_{crop,green}$	$WF_{crop,blue}$	$WF_{crop,green\&blue}$
	mm/growing period			ton/ha		m^3/kg	
Wheat	28,9	208,1	237,0	2,83	0,10	0,74	0,84
Rice	181,2	849,9	1031,1	2,39	0,76	3,55	4,31
Cotton (lint)	185,9	905,8	1091,7	0,35	5,36	26,11	31,46

The water footprint of cotton is much larger than the water footprint of wheat and rice. This is due to the low cotton lint yield compared to the yield of rice and wheat.

3.1.2 CROPWAT model with local available data

Table 3.3 shows a summary of the calculations for the cropping pattern for both fields using locally available data. The outputs of the ***CWR*** calculations of CROPWAT for the crops in this research are given in Appendix B.

TABLE 3.3: CROP WATER REQUIREMENTS (IN MM), CALCULATED WITH LOCAL AVAILABLE DATA

Field	Crop	Planting date	Harvest date	Etc	Eff. Rain	Irr. Req.	ET_{green}	ET_{blue}
				mm/growing period				
1	Wheat	16-11	30-04	392,2	49,2	343,0	49,2	343,2
1	Rice	21-06	31-10	941,1	261,7	1040,8	260,5	680,6
2	Wheat	16-11	30-04	392,2	49,2	343,0	49,2	343,2
2	Cotton	5-05	31-10	775,2	277,2	498,7	277,2	498,1

The difference between the ***ETc*** minus Effective Rainfall and the Irrigation Requirement by rice is the same as indicated above by the CROPWAT model with global available data. In these calculations there is more effective rainfall than with the global data. Also, the ***ETc*** of rice and especially of cotton is quite lower than with the global dataset calculations. However, this still means that there is large irrigation requirements of for about 87%, 72% and 65% of the total ***ETc*** for wheat, rice and cotton, respectively.

With this information the water footprint of the crops was calculated and shown in table 3.4. The average crop yields are from the agriculture statistics records of the Deputy Director of Agriculture (DDA), Government of District Sirsa (2012) for the years 1991-2001. The water footprints of the crops wheat and rice are now closer together, with cotton still having the far largest water footprint.

TABLE 3.4: CALCULATION OF GREEN & BLUE COMPONENTS WATER FOOTPRINT WITH LOCAL DATA

Crop	ET_{green}	ET_{blue}	ET_{total}	Y	$WF_{crop,green}$	$WF_{crop,blue}$	$WF_{crop,green\&blue}$
	mm/growing period			ton/ha	m^3/kg		
Wheat	49,2	343,2	392,4	4,04	0,12	0,85	0,97
Rice	260,5	680,6	941,1	3,20	0,81	2,13	2,94
Cotton (lint)	277,2	498,1	775,3	0,40	6,89	12,37	19,26

3.1.3 SWAP model with local available data

The crop evapotranspiration and yields of wheat, rice and cotton has been simulated by using SWAP model at both field and regional scale in the study 'Water productivity analysis from field to regional scale' (Singh, 2005). In these simulations there is no difference between the blue and green evapotranspiration, only the sum of these values is simulated as crop evapotranspiration. Also note that in this study (Singh, 2005), the simulated crop yields are water and salt limited yields, not the actual yields. The actual crop yields recorded in the Sirsa district are significantly lower than the simulated water and salt limited yields, due to substantial nutritional, pest or disease stress on crop production in Sirsa district (Singh, 2005). However, in this study the recorded actual crop yields are used in combination with the SWAP simulated crop evapotranspiration for each crop season to estimate the water footprint of different crops (table 3.5). In the case of 'Field scale' estimation the average crop yields are based on the measured crop yields at five farmer fields in Sirsa district during the agricultural year 2001-02, while the average crop yields in case of 'Regional scale' estimation are taken from the agriculture statistics records of the Deputy Director of Agriculture (DDA), Government of District Sirsa for the year 1990-2002.

TABLE 3.5: CALCULATION OF WATER FOOTPRINTS WITH SWAP MODEL

Dataset	*Field scale, 1 year*			*Regional scale, 1 year*			*Regional scale, ± 10 years*		
Crop	**ET** mm/period	**Y** ton/ha	**WF** m^3/kg	**ET** mm/period	**Y** ton/ha	**WF** m^3/kg	**ET** mm/period	**Y** ton/ha	**WF** m^3/kg
Wheat	384	5,37	0,72	353	4,16	0,85	342	4,04	0,85
Rice	911	8,55	1,07	751	3,19	2,35	687	3,20	2,15
Cotton	666	0,64	10,41	570	0,18	31,67	622	0,40	15,55

3.2 Comparison of water footprints

Overall, the water footprints of wheat, rice and cotton are calculated in 6 different ways. Each calculation option uses a different dataset and/or a different model. All these options are compared in table 3.6, which also shows the mean value and the standard deviation of the evapotranspiration, the crop yield and the water footprint per crop.

Option 1 uses the crop evapotranspiration simulated by SWAP model and average crop yields recorded at five fields in Sirsa district during the agricultural year 2001 – 2002. This combination is noted as 'Singh, SWAP, field scale, 1 year'.

Option 2 uses the crop evapotranspiration simulated by SWAP model and the average crop yields recorded over the entire Sirsa district during the agricultural year 2001 – 2002. This combination is noted as 'Singh, SWAP, regional scale, 1 year'.

Option 3 uses the crop evapotranspiration simulated by SWAP model and the average crop yields recorded over the entire Sirsa district during the years 1991 – 2001. This combination is noted as 'Singh, SWAP, regional scale, $\pm$ 10 years'.

Option 4 uses the CROPWAT model with a globally available climatic dataset from the years 1971 – 2000 and the average crop yield recorded over the Haryana State including Sirsa district during the same years 1971-2000.

Option 5 uses the CROPWAT model with a local available climatic dataset from the years 1990 – 2002 and the average crop yields recorded over the entire Sirsa district during the years 1991 – 2001.

TABLE 3.6: COMPARISON OF CALCULATIONS OF WATER FOOTPRINTS OF WHEAT, RICE AND COTTON IN THE SIRSA DISTRICT

Model and dataset combinations	Wheat			Rice			Cotton (lint)		
	ET mm	Y ton/ha	WF m³/kg	ET mm	Y ton/ha	WF m³/kg	ET mm	Y ton/ha	WF m³/kg
1 Singh, SWAP, field scale	384	5,37	0,72	911	8,55	1,07	666	0,64	10,41
2 Singh, SWAP, regional scale, 1 year	353	4,16	0,85	751	3,19	2,35	570	0,18	31,67
3 Singh, SWAP, regional scale, ± 10 years	342	4,04	0,85	687	3,20	2,15	622	0,40	15,55
4 Current study, CROPWAT, global data	237	2,83	0,84	1031	2,39	4,31	1092	0,35	31,20
5 Current study, CROPWAT, local data	392	4,04	0,97	941	3,20	2,94	775	0,40	19,38
Mean	342	4,09	0,84	864	4,11	2,56	745	0,39	21,64
Standard deviation	62	0,90	0,09	142	2,51	1,19	208	0,16	9,49
Coefficient of variation	18	22	11	16	61	46	28	42	44

In the following sections these results are discussed. This shall be done first for all the options together, and after that for each research question individually, which have been given in the section 1.3. For the discussion about the effect of the model in the calculations only option 3 is used. This is because of the comparison with options 4 and 5, which are calculated with data from a period of 10 years. Only option 3 from the calculations with the SWAP model calculates with a dataset of more than one year and the options 1 and 2 use data from a period of only one year.

3.2.1 Interpretation overall result

The water footprint of wheat varies between 0,72 and 0,97 m³/kg with a mean value of 0,84 m³/kg and a coefficient of variation ***COV*** of 11%. This variation is quite low. By looking only to the water footprint, it might be said that all options are that close to each other, that each option is appropriate to calculate the water footprint. However, when taking into account the values of evapotranspiration ***ET*** and yield ***Y*** it shows a remarkable thing with option 4, the CROPWAT model in combination with a global available data set, namely a low value for ***Y*** but also a low value for ***ET*** and therefore a normal value for the water footprint. If this option is not taken into account the ***COV*** of ***ET*** is only 7%, which is very good. However, the fact remains that the yield used by CROPWAT in combination with global available data is still a lot lower than the estimations with the SWAP model with the different data sets.

In looking to the ***COV***'s for the ***ET***, the yield ***Y*** and the water footprint for rice it can be said that these are very high for the yield and the water footprint, which make these values very uncertain and therefore also the water footprint value turns out to be uncertain. The ***COV*** of the water footprint of rice is very high, being 46%. The values for water footprint of rice vary between 1,07 and 2,94 m³/kg for the options 1 to 3 and 5, and the value of option 4 is much larger (4,31 m³/kg), which makes the ***COV*** very high. This value can be explained by the high value of ***ET*** and the low value of ***Y***. However, when option 4 is not taken into account the range of the ***Y*** is still high, due to the high ***Y*** value of option 1, which is far higher than the mean value ***Y*** of rice. This means the calculation of the water footprint of rice is still quite uncertain.

The estimation of the crop yield of cotton (lint) is for the options 3, 4 and 5 quite the same, but the yields used with manner 1 and 2 make the ***COV*** of the yield of cotton very high. Beside this is the fact of the higher range of ***ET***, namely from 570 mm to 1092 mm with a mean value of 745 mm and a ***COV*** of 28%. This together means that the range of the water footprint values is also wide, with a ***COV*** of 44%. Two water footprint calculations stand out, namely the water footprint calculated with option 2 and option 4. The water footprint of option 2 is high because of a very low yield. The water footprint of option 4 is high because of a very high ***ET***. This ***ET*** is 48% higher than the mean value. When this option is not taken into consideration, the values of ***ET*** are more equal, then with a ***COV*** of 12%.

Beside these considerations, it has to be remarked that the SWAP model calculates with an ***ET*** of a whole season and the CROPWAT model calculates with an ***ET*** of the period between planting and harvesting. For example in the case of the crop wheat the SWAP model calculates with the period from 1st of November till 30th of April. The CROPWAT model uses the period between 16th of November (planting date) till 30th of April (harvesting date). The SWAP model takes therefore a longer period for ***ET*** than the CROPWAT model does. This makes that the ***ET*** values calculated by the SWAP model, should be higher than the ***ET*** values that CROPWAT calculated. However, this is not the case with any of the crops. In this case this means that the CROPWAT model always makes a higher estimation of the ***ET*** than the SWAP model. This could be explained by the fact that CROPWAT did not consider the water stress in calculating the ***ET***, but the SWAP model did it, which reduces a crop potential ***ET*** to the actual ***ET*** under field conditions.

3.2.2 Effect of different datasets on water footprint

Table 3.6 shows a big difference between the water footprint calculated with a global available dataset and the one calculated with a local available dataset, whereby both calculations are done with the use of the CROPWAT model. For wheat, the model with the global dataset calculates an evapotranspiration ***ET*** that is almost 40% lower than the ***ET*** calculated with the local dataset. With rice and cotton it is the inverse, the ***ET*** calculated with the global dataset is about 10% higher than calculated with the local data in case of rice and 40% bigger in case of cotton. The crop yields for wheat calculated with the different datasets are quite different, which applies to a lesser extent for rice. The crop yields for cotton (lint) are almost the same. All this means that the calculated water footprints of cotton vary about 60% from each other, the water footprints of rice differ about 45% of each other and the water footprints of wheat differ about 15% of each other.

The values of ***ET*** should be higher while calculating with global available data because of the higher reference evapotranspiration ***ETo***. However, the value of the global calculated ET of wheat is lower than the value of the local calculated ET of wheat. This can be explained by the fact that the global crop data provides for a growing period that is one month less than the growing period calculated with the local crop data. In addition, the global calculated growing period of rice is some weeks less than the local calculated growing periods, but this is not reflected in the results as in terms of a lower ***ET*** with global data. The higher ***ET*** of cotton calculated with global data can also be explained by using a two weeks longer growing period. Beside this, it has also a lower crop coefficient at middle stage calculated with local data than the crop coefficient from the global data source, which results in a higher ***ET*** by option 4.

The lower value of global calculated crop yield is probably caused by the period from 1971 – 2000. Especially with rice the crop yield is increased a lot during the latter years. The crop yield of rice from local sources has been calculated from the years 1999 – 2001, in which the yield is increased compared with the 1970's. Further, the crop yield used in option 4 is calculated from resources of Haryana, where the crop yield used in option 5 is calculated from resources of Sirsa district. The crop yields of Sirsa district are generally the highest crop value of the state Haryana.

3.2.3 Effect of different models on water footprint

The datasets used for option 3 and for option 5 are the same for the calculation of the evapotranspiration ***ET***. These two options are compared in order to see the effect of the model on the water footprint calculation. The differences between the water footprints of the different crops are quite low. The water footprint of wheat calculated with the CROPWAT model is a bit higher than calculated with the SWAP model due to the higher with the CROPWAT model calculated ***ET***, which is only about 14% higher than the ***ET*** calculated with the SWAP model. The same defined percentages for rice and cotton are higher than for wheat. For rice this percentage is about 37% and for cotton about 25%. This makes a mean difference between the two calculations of about 25% higher ***ET*** calculated by CROPWAT in comparison with ***ET*** calculated with SWAP. This means the SWAP model uses some standards or calculations, which is primarily the consideration of water stress, in calculating the ***ET***, which always result in lower ***ET*** than the ***ET*** calculated with the CROPWAT model. The crop yields are the same, because of the use of the same dataset to calculate it.

3.2.4 Effect of different datasets and models on water footprint

The global available dataset used with the CROPWAT model in option 4 has a lack in accuracy to the local conditions in contrast to the local dataset used with the SWAP model in option 3. In these options, both the dataset and the model are different. This can be seen at the results where the different calculated water footprints of the crops differ a lot of each other. The difference between the water footprints is very small for wheat, but this does not mean that these calculations are quite the same, which already has been explained in the section 3.2.1. The water footprints calculated with the CROPWAT model are for both rice and cotton 100% higher than the values calculated with the SWAP model. These differences are far too great to accept. All this can be attributed to the higher ET calculation and mainly the lower crop yield calculation by use of the CROPWAT model. Hereby are two exceptions, namely the ET of wheat and the crop yield of cotton (lint). The lower CROPWAT calculated ET of wheat is due to the shorter length of the growing period of wheat that the global data calculates, which has been explained in the section 3.2.2. Between the crop yields calculated for cotton (lint) exists only a slight difference of about 10%.

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusions

In theory, a certain crop in a certain region has a specific water footprint. Nobody knows the real water footprint of a certain crop in a certain region. However, this can be calculated or estimated with the help of a model in combination with a dataset. For such a model, there are different options and different ways to gather data. In theory, each combination of model and dataset should have the same result in terms of water footprint. In this research different datasets have been gathered and used in the calculation of the water footprint of wheat, rice and cotton in the Sirsa District, India. Two different models, namely the CROPWAT model and the SWAP model are used in combination with the global and local available datasets to estimate the water footprints. The results of this research do not agree with the theory. The results show in some cases even quite a great difference between each combination of model and dataset. This means there is an inconsistency between theory and practice.

The effect of the dataset on the water footprint is big; it causes a mean difference between the different calculated evapotranspiration's of 30% by using the CROPWAT model. With the global available dataset the CROPWAT model calculates a lower evapotranspiration in the case of wheat and a higher evapotranspiration in the case of rice and cotton than calculated by the CROPWAT model with a local available dataset. There is also a big difference in crop yields of rice recorded in different databases. This means that detailed information about the meteorological circumstances, the crop characteristics and the yields is very important in calculating a reliable water footprint of a crop. There are too many differences between the global and local available dataset to calculate the reliable water footprint of a specific crop in the study area using globally available datasets.

The complexity of models also affects the water footprint, however this effect is a lot smaller than the differing of the datasets. The crop yields of both options are the same, because of the same dataset. Therefore, the differences in the water footprint are due to the calculation of the evapotranspiration. The evapotranspiration is meanly 25% higher with the CROPWAT model than with the SWAP model, but this is mainly caused by the high difference between the calculations of the evapotranspiration of rice. This shows the calculation of evapotranspiration of rice is quite difficult due to the preparation of the land and keeping the field wet during the whole period of growing.

The effect of differing the dataset and the complexity of the models shows the biggest differences, with even differences of 100% in case of rice and cotton. This is the effect of differences that are described above. It is therefore not possible to calculate reliable water footprints of crops with a global available dataset and a less complex model as the CROPWAT model.

The discussion of the results of this study done in chapter 3 and the conclusions drawn above brings us to the following key conclusions:

It is very important to define how the calculations are done and how the data is collected. In the case of collecting data, for example the length of the period of the dataset and the place of collecting the data is important for the calculation of the water footprint. The length of the period of data for calculating the crop yield is important by knowing the fact that the crop yield has increased a lot in the latter years. It is important to make a balanced choice of the years of which the mean value is calculated. The exact location of gathering the data is important by the fact it is possible to gather the yield data from a location that is either very productive or not productive. All this can affect the calculations a lot and a good description of this is therefore really important.

This study concludes that the researchers should be very careful in making their conclusions about water footprints of different crops in different regions. A calculation with one combination of dataset and model of the water footprint of a specific crop in a specific region is not sufficient to make firm conclusions. Therefore, the differences between the combinations are too large. It is only possible to make careful conclusions by clearly indicating the techniques followed.

4.2 Recommendations

A complex model as the SWAP model with a complex local available dataset is recommended especially to calculate water footprints of crops. Due to the costs of money and time of gathering data for a complex model this is not an easy option. Instead of this it is recommended on the basis of this study to do the water footprint calculations with a less complex model (CROPWAT model) in combination with a local available dataset. With this combination, there still is a degree of uncertainty, but there is no other possibility when taking time and costs in consideration.

This study can be extended at some points. In this research only the Crop Water Requirement option of the CROPWAT model is used. The model has another option to calculate the evapotranspiration, namely the Irrigation Scheduling option. Also, the differences in the climatic data calculated from the global and local resources can be studied further, in order to help to explain better the differences in simulated ET_{green} and ET_{blue} for different crops with different climatic datasets. Beside these several models, the model AquaCrop can be used and compared in calculating the evapotranspiration and water footprints of the crops.

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APPENDIX A: CROP WATER REQUIREMENTS WITH GLOBAL AVAILABLE DATA

TABLE A.1: CROP WATER REQUIREMENTS OF WHEAT

Eto station: GANGANAGAR
Rain station: GANGANAGAR

Crop: Wheat
Planting date: 15-11
Harvesting date: 24-03

Month	Decade	Stage	Kc coeff	Etc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec	Et_{green} mm/dec	Et_{blue} mm/dec
Nov	2	Init	0,30	4,7	0,1	4,6	0,1	4,6
Nov	3	Init	0,30	7,0	0,7	6,3	0,7	6,3
Dec	1	Init	0,30	6,2	1,2	5,0	1,2	5,0
Dec	2	Deve	0,36	6,5	1,7	4,9	1,7	4,8
Dec	3	Deve	0,64	12,6	2,0	10,6	2,0	10,6
Jan	1	Deve	0,94	15,9	2,5	13,4	2,5	13,4
Jan	2	Mid	1,14	18,7	2,9	15,8	2,9	15,8
Jan	3	Mid	1,15	24,9	2,5	22,4	2,5	22,4
Feb	1	Mid	1,15	26,8	1,7	25,1	1,7	25,1
Feb	2	Mid	1,15	30,2	1,2	29,0	1,2	29,0
Feb	3	Late	1,07	26,5	2,2	24,3	2,2	24,3
Mar	1	Late	0,82	29,1	3,9	25,2	3,9	25,2
Mar	2	Late	0,54	21,6	5,0	16,5	5,0	16,6
Mar	3	Late	0,34	6,3	1,3	4,4	1,3	5,0
				236,7	28,9	207,4	28,9	208,1

TABLE A.2: CROP WATER REQUIREMENTS OF RICE

Eto station: GANGANAGAR
Rain station: GANGANAGAR

Crop: Rice
Planting date: 20-06
Harvesting date: 17-10

Month	Decade	Stage	Kc coeff	Etc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec	Et_{green} mm/dec	Et_{blue} mm/dec
May	3	Nurs/LPr	1,19	17,4	3,6	104,7	3,6	13,8
Jun	1	Nurs/LPr	1,06	87,6	4,8	122,8	4,8	82,8
Jun	2	Init	1,07	93,0	6,0	235,5	6,0	87,0
Jun	3	Init	1,10	91,9	10,5	81,3	10,5	81,4
Jul	1	Deve	1,10	87,3	16,7	70,6	16,7	70,6
Jul	2	Deve	1,11	85,2	21,5	63,8	21,5	63,7
Jul	3	Deve	1,14	89,2	20,8	68,4	20,8	68,4
Aug	1	Mid	1,16	76,7	20,1	56,6	20,1	56,6
Aug	2	Mid	1,16	71,1	20,3	50,9	20,3	50,8
Aug	3	Mid	1,16	74,6	17,8	56,8	17,8	56,8
Sep	1	Mid	1,16	64,5	15,5	48,9	15,5	49,0
Sep	2	Late	1,16	61,0	13,6	47,4	13,6	47,4
Sep	3	Late	1,13	54,5	9,2	45,4	9,2	45,3
Oct	1	Late	1,08	48,0	1,1	46,9	1,1	46,9
Oct	2	Late	1,05	29,4	0,0	29,4	0,0	29,4
				1031,3	181,2	1129,5	181,2	849,9

TABLE A.3: CROP WATER REQUIREMENTS OF COTTON

Eto station: GANGANAGAR					Crop:		Cotton	
Rain station: GANGANAGAR					Planting date:		15-04	
					Harvesting date:		26-10	
Month	Decade	Stage	Kc coeff	Etc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec	Et_{green} mm/dec	Et_{blue} mm/dec
Apr	2	Init	0,35	12,1	0,2	11,9	0,2	11,9
Apr	3	Init	0,35	21,9	1,0	20,8	1,0	20,9
May	1	Init	0,35	23,7	1,6	22,1	1,6	22,1
May	2	Deve	0,38	28,0	1,9	26,1	1,9	26,1
May	3	Deve	0,55	46,3	3,6	42,7	3,6	42,7
Jun	1	Deve	0,72	59,3	4,8	54,6	4,8	54,5
Jun	2	Deve	0,89	77,1	6,0	71,1	6,0	71,1
Jun	3	Deve	1,05	87,8	10,5	77,2	10,5	77,3
Jul	1	Mid	1,17	92,8	16,7	76,2	16,7	76,1
Jul	2	Mid	1,17	89,9	21,5	68,4	21,5	68,4
Jul	3	Mid	1,17	92,2	20,8	71,5	20,8	71,4
Aug	1	Mid	1,17	77,8	20,1	57,7	20,1	57,7
Aug	2	Mid	1,17	71,8	20,3	51,5	20,3	51,5
Aug	3	Mid	1,17	75,2	17,8	57,5	17,8	57,4
Sep	1	Late	1,13	62,4	15,5	46,8	15,5	46,9
Sep	2	Late	1,02	53,5	13,6	39,9	13,6	39,9
Sep	3	Late	0,91	44,0	9,2	34,9	9,2	34,8
Oct	1	Late	0,80	35,5	1,1	34,3	1,1	34,4
Oct	2	Late	0,69	27,8	0,0	27,8	0,0	27,8
Oct	3	Late	0,61	12,9	0,0	12,9	0,0	12,9
				1091,9	185,9	906,0	185,9	905,8

APPENDIX B: CROP WATER REQUIREMENTS WITH LOCAL AVAILABLE DATA

TABLE B.1: CROP WATER REQUIREMENTS OF WHEAT

Eto station: SIRSA
Rain station: SIRSA

Crop: Wheat
Planting date: 16-11
Harvesting date: 30-04

Month	Decade	Stage	Kc coeff	Etc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec	Et_{green} mm/dec	Et_{blue} mm/dec
Nov	2	Init	0,30	3,8	0,2	3,6	0,2	3,6
Nov	3	Init	0,30	6,9	0,4	6,5	0,4	6,5
Dec	1	Init	0,30	6,3	0,4	5,8	0,4	5,9
Dec	2	Init	0,30	5,6	0,2	5,4	0,2	5,4
Dec	3	Deve	0,33	6,7	1,4	5,3	1,4	5,3
Jan	1	Deve	0,51	9,0	2,8	6,2	2,8	6,2
Jan	2	Deve	0,69	11,9	3,9	8,0	3,9	8,0
Jan	3	Deve	0,88	18,9	4,7	14,1	4,7	14,2
Feb	1	Mid	1,06	23,2	6,2	17,0	6,2	17,0
Feb	2	Mid	1,13	27,2	7,4	19,8	7,4	19,8
Feb	3	Mid	1,13	25,6	5,5	20,1	5,5	20,1
Mar	1	Mid	1,13	37,0	2,8	34,2	2,8	34,2
Mar	2	Mid	1,13	41,9	0,9	40,9	0,9	41,0
Mar	3	Mid	1,13	54,3	1,8	52,5	1,8	52,5
Apr	1	Late	0,97	49,0	2,5	46,5	2,5	46,5
Apr	2	Late	0,69	39,3	2,9	36,4	2,9	36,4
Apr	3	Late	0,41	25,7	5,1	20,6	5,1	20,6
				392,2	49,2	343,0	49,2	343,2

TABLE B.2: CROP WATER REQUIREMENTS OF RICE

Eto station: SIRSA
Rain station: SIRSA

Crop: Rice
Planting date: 21-06
Harvesting date: 31-10

Month	Decade	Stage	Kc coeff	Etc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec	Et_{green} mm/dec	Et_{blue} mm/dec
May	3	Nurs	1,20	9,2	10,3	0,0	9,2	0,0
Jun	1	Nurs/LPr	1,06	80,8	11,9	229,0	11,9	68,9
Jun	2	Nurs/LPr	1,06	80,9	13,1	268,0	13,1	67,8
Jun	3	Init	1,10	77,7	18,5	59,1	18,5	59,2
Jul	1	Init	1,10	71,3	26,7	44,7	26,7	44,6
Jul	2	Deve	1,10	65,8	32,7	33,0	32,7	33,1
Jul	3	Deve	1,12	70,5	28,5	42,0	28,5	42,0
Aug	1	Deve	1,14	62,7	22,9	39,9	22,9	39,8
Aug	2	Mid	1,15	61,1	19,6	41,5	19,6	41,5
Aug	3	Mid	1,16	65,9	17,9	48,1	17,9	48,0
Sep	1	Mid	1,16	58,5	16,5	42,0	16,5	42,0
Sep	2	Mid	1,16	57,1	14,7	42,4	14,7	42,4
Sep	3	Mid	1,16	52,5	11,6	40,8	11,6	40,9
Oct	1	Late	1,14	47,1	8,1	39,0	8,1	39,0
Oct	2	Late	1,10	41,1	5,0	36,1	5,0	36,1
Oct	3	Late	1,06	38,9	3,6	35,2	3,6	35,3
				941,1	261,7	1040,8	260,5	680,6

TABLE B.3: CROP WATER REQUIREMENTS OF COTTON

Eto station: SIRSA						Crop:		Cotton
Rain station: SIRSA						Planting date:		5-05
						Harvesting date:		31-10

Month	Decade	Stage	Kc coeff	Etc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec	Et_{green} mm/dec	Et_{blue} mm/dec
May	1	Init	0,30	12,7	4,6	8,9	4,6	8,1
May	2	Init	0,30	23,2	9,8	13,4	9,8	13,4
May	3	Init	0,30	25,3	11,4	13,9	11,4	13,9
Jun	1	Deve	0,35	26,5	11,9	14,5	11,9	14,6
Jun	2	Deve	0,52	39,4	13,1	26,3	13,1	26,3
Jun	3	Deve	0,69	48,9	18,5	30,4	18,5	30,4
Jul	1	Deve	0,87	56,3	26,7	29,6	26,7	29,6
Jul	2	Mid	1,04	62,0	32,7	29,3	32,7	29,3
Jul	3	Mid	1,09	68,7	28,5	40,2	28,5	40,2
Aug	1	Mid	1,09	60,0	22,9	37,1	22,9	37,1
Aug	2	Mid	1,09	57,5	19,6	37,9	19,6	37,9
Aug	3	Mid	1,09	61,8	17,9	44,0	17,9	43,9
Sep	1	Mid	1,09	54,9	16,5	38,4	16,5	38,4
Sep	2	Late	1,04	51,3	14,7	36,6	14,7	36,6
Sep	3	Late	0,94	42,4	11,6	30,8	11,6	30,8
Oct	1	Late	0,83	34,4	8,1	26,3	8,1	26,3
Oct	2	Late	0,73	27,2	5,0	22,2	5,0	22,2
Oct	3	Late	0,62	22,7	3,6	19,0	3,6	19,1
				775,2	277,2	498,7	277,2	498,1