Application of SWAP model to analyse the impact of drought and climate change on water demand and apple fruit crop yield in the Kromme Rijn area, The Netherlands

Master Thesis, 45 ECTS

By:
Susy Rita Wanti
3620735
SusyRitaWanti@students.uu.nl

Supervisors:
Dr. Aat Barendregt (Utrecht University)
Drs. Henk van Hardeveld (Hoogheemraadschap De Stichtse Rijnlanden, HDSR)

Second Reader:
Dr. Paul Schot (Utrecht University)

Master Sustainable Development
Track Global Change and Ecosystem
August, 2012

HOOGHEEMRAADSCHAP DE STICHTSE RIJNLANDEN

Universiteit Utrecht

"But blessed is the one who trusts in the LORD,
whose confidence is in him.
They will be like a tree planted by the water
that sends out its roots by the stream.
It does not fear when heat comes;
its leaves are always green.
It has no worries in a year of drought
and never fails to bear fruit."

Jeremiah 17:7-8

List of Acronyms

CBS	Centraal Bureau Statistics
CH	Crop Height
CGCM	Cliamte Global Circulation Model
CPRO-DLO	Central for Plant Breeding and reproduction research
DINOLoket	Data en Informatie van de Nederlandse Ondergrond
DVS	Development Stage
ET_a	Actual Evapotranspiration
ET_p	Potential Evapotranspiration
HDSR	Hoogheemraadschap De Stichste Rijnlanden
IPCC	Inter Panel of Climate Change
KNMI	Koninklijk Netherlands Meteorologisch Instituut
K_y	Yield Response Factor
LAI	Leaf Area Index
NAP	Normaal Amsterdam Peil
NHI	Nationaal Hydrologisch Instrumentarium
RCM	Regional Climate Model
RDepth	Root Depth
RDens	Root Density
SWAP	Soil Water Plant Atmosphere
SIMGRO	SIMulation of GROundwater and surface water
T_a	Actual Transpiration
T_p	Potential Transpiration
WOFOST	World Food Studies

Acknowledgment

This thesis is a big challenge to me; however, I am really grateful that I can be in the last stage of my journey on this as I present this thesis.

I would like to thank my daily supervisor in HDSR, Henk van Hardeveld, for the opportunity for doing this project. I would like to thank him for his guidance, encouragement, and challenges that always bring me one step forward.

I would like to thank Aat Barendregt as my supervisor in Utrecht University for his guidance and feedbacks. The 'question marks' in the reports helping me a lot to find the answer I was looking for.

My thanks also go to my roommates, Linda and Vanya of HDSR, for the laughs, coffee times and translation help. I would like to thank my colleagues in P&A department in HDSR that have supported me in one way or the other during the course of this work.

Special thanks goes to my husband, Rihard, who always be there for me. His love and encouragement always give my more power to move on. Also for my lovely children, Daniel and Darlene, I would like to thank them for their patient, love, and smiles. Jullie zijn echt super!

I would like to thank my parents, brothers and sisters in Indonesia for their support and prayers.

I am grateful for all my friends in WIN NL family, who support and pray for me.

Finally, all the gratitude and honor I give them to my Lord.

Abstract

Drought is defined as water shortage. Future climate scenario predicts that average daily temperature will rise with less rainfall leading to higher evapotranspiration. Many studies have shown that in the future, drought is expected to be more severe compared to the past. Drought will affect ground water level and water demand for irrigation of agricultural area in order to maintain optimum crop yield.

De Stichtse Rijnlanden (HDSR) is responsible to supply sufficient water for irrigation of Kromme Rijn area which is one of the important fruit crop plantations in The Netherlands. In order to ensure the capability of HDSR to supply sufficient water supply to the Kromme Rijn in the future, an estimation of water demand for irrigation is needed.

This thesis tried to analyze the impact of future climate changes on ground water level, water demand for irrigation and relative crop yield in the Kromme Rijn area. Soil-Water-Atmosphere-Plants (SWAP) program is used. A SWAP model for the study area is was built and calibrated.

The calculation using the calibrated model for the future climate scenario showed that, to maintain optimum apple crop yield in the Kromme Rijn area, surface irrigation will need to be increased from 0.05 to 1.5 mm per day (1.8 – 55 cm/year) in 1986 – 1995 to about 0.5 to 4 mm per day (18 – 150 cm/year) in 2046-2055. The water demand in the future predicted by the SWAP model is between 0.05 to 0.60 m3/sec. Compared to the maximum water supply applied today (0.3 m3/sec), based on the calculation results obtained during this study, HDSR need to double the amount for irrigation with a factor of 2 in the future.

Keywords: SWAP Model, Climate Change, Apple Crop, Water demand, Ground Water Level, Relative Crop yield

Table of content

Chapter 1
Introduction

1. 1 Background

In general, water shortage can be defined as drought. Crops will have less production yield compared to the normal condition when there is water shortage (Karl and Koscielny 1982; Quiering and Papakryiaku 2003). If there is too little water available for the plants, they will grow less high or perish. Therefore, one of the impacts of drought in agricultural sector, for example, is the increasing demands for a good management of water levels and a sufficient quantity of water for irrigation. Further, for nature, besides sufficient water, it is essential that the water quality stays in a close range with the characteristics of the local natural system. A drought could develop slowly and unnoticed for a long time (Tallaksen and van Lanen, 2004). Long period of drought can also lead to higher probability of forest fires (Pausas 2004), degradation and desertification of land (Bruins and Berliner 1998; Schlesinger et al. 1990, and Glantz 1994). This means that drought will not only impact crop yield but also further impacting the social-economic activities.

The average global temperature has been rising since 100 years ago from 1-6^{o}C (Bressers et al., 2005). Climate change partly explains the occurrence of dry spring-summer period. This increase is also expected in The Netherlands where the frequency of dry and warm springs and summers will increase. Koninklijk Netherlands Meteorologisch Instituut (KNMI) define drought as high precipitation deficit (i.e. precipitation minus evapotranspiration). The KNMI recorded that for the last 30 years, 1976, 1985, 1995, 1996, 2003, 2006, and 2008 are dry years. In 1976, extreme dry year occurred with precipitation deficit reach 360 mm in August/September and in 2003, a dry year occurred with precipitation deficit of 227,2 mm (see figure 1.2.).

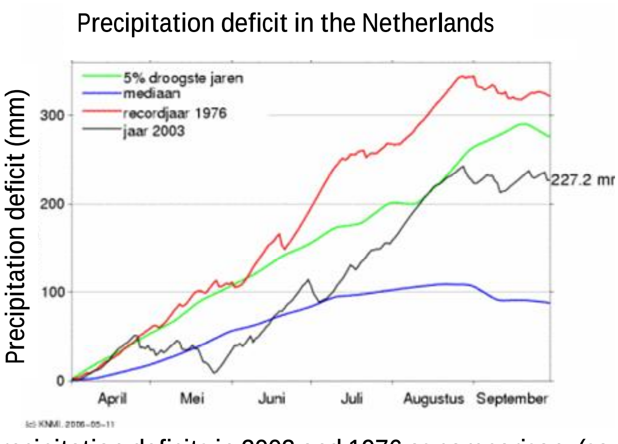


Figure 1.1 Precipitation deficits in 2003 and 1976 as comparison. (source: www.KNM.nl, 2012)

Intergovernmental Panel on Climate Change (IPCC, 2007) forecasted that climate change will cause large implications on water resources, water management and agricultural production in many part of the worlds, including The Netherlands. Water deficit changes regionally because of local meteorological conditions, soil profiles, land use, surface water level management, seepage, etc. Oosterbaan (2004) predicted that The Netherlands will experience more drought periods and water deficit can occur in surface water as well as in ground water. Further, Oosterbaan also estimated that the frequency and the duration of drought will increase due to climate change.

In a report by KNMI (Beersma et al., 2004), a prediction the frequency of extreme year (as in 1976, occurrence time in 100 years) and moderate dry year (as in 2003, occurrence time in 10 years) is presented. KNMI predicted that the occurrence of extreme dry and moderate dry year in the future will be more often particularly when the rapid climate change (W+) scenario is used in the simulation. The future climate change scenario therefore could be used to predict future precipitation that will occur in The Netherlands. Van den Hurk (2006) for instance showed the prediction of precipitation deficit in 2050 based on the future climate change scenario (see figure 1.2.). Precipitation deficit in moderate dry year toward the year of 2050, for instance, will be occurring every 6 to 8 years instead of every 10 years in the past (Oosterbaan, 2004).

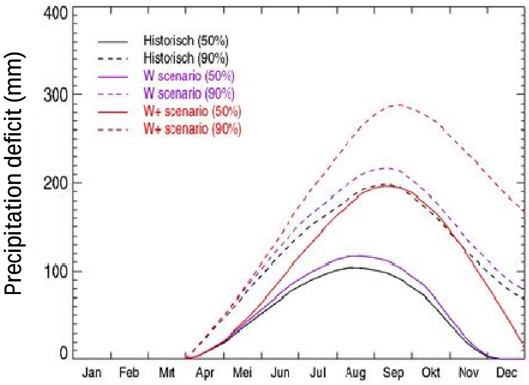


Figure. 1.2 Deficit precipitation according to the KNMI climate scenario

As the occurrence of draught is predicted to be more severe and more often in the future, it is very important therefore, to predict the demand of water in order to suffice agricultural need and to minimize the impact of drought on crop yield. In the past few years, there is numerous research activities carried out to study and predict the impact of drought on water demand and crop yields.

In The Netherlands, the impact of drought is apparent to the degree of nature degradation and agricultural yield. Some recent studies on modeling different aspect of drought in the Netherlands have also been reported. Van Walsum (2011, 2012) tried to develop a model to simulate the impact of climate change on crop growth and hydrologic condition with a case study in the area of Kromme Rijn. He simulated the groundwater level and crop growth by calculating leaves area index (LAI) based on the climate scenario given by Van den Hurk et al. (2006). The model developed by van Walsum (2011) simulated crop growth of grass and potatoes by using Simulation of groundwater and surface water model (SIMGRO) and MetaSWAP in one dimension (as a function of depth). Kroes and Supit (2011) evaluated the impact of drought, water excess and salinity on grass production in the Netherlands (Zegveld, Ruurlo, and Cranendock) using historical and future climate data using SWAP (Soil-Water-Air-Plant) model, originally developed by scientists in the Wageningen University; Soil Physics, Ecohydrology and Groundwater Management Group. All these studies suggest that water demand to satisfy the need for agricultural activities will be increasing in the future.

Water management in The Netherlands has to deal with shallow water tables and a strong interaction between groundwater and surface water. Hansen et al. (2006) stated that an integrated approach is required to model yield-limiting factors. Some researchers have clearly showed a strong correlation between drought, groundwater level and crop production (e.g Kroes and Supit 2011, Alexandrov and Hoogenboom 2000, van Walsum and Supit 2012). Therefore, it is important to know water demand in order to satisfy the need for irrigation in the agricultural area to maintain and obtain optimum crop yield. In addition, the supply of water in the future could become a problem resulting in insufficient water to meet the water demand in particular area, particular years, and particular climate scenario. For this, the responsible organizations to supply water to agricultural area needs to know whether with the current water management they applied, there will be sufficient amount of water to satisfy the demand of water for irrigation in the future, in particularly when the worst climate change scenario (W+) will occur. In case needed, the necessary actions could then be taken.

The water board, Hoogheemraadschap De Stichtse Rijnlanden (HDSR) is responsible of water management and to supply enough water to agricultural areas in Utrecht province, The Netherlands. One of the important agricultural areas in Utrecht province is Kromme Rijn. In Kromme Rijn, there are various crops plantation, e.g. apples, pears, grapes, etc. HDSR would like to know the demand of water for irrigation in the area of Kromme Rijn in response to future climate change in order to ensure optimum crop yield. The research presented here tried to answer the need of HDSR for water demand in the Kromme Rijn area, particularly in the area where fruit crops grow. Therefore, the main objective of the research presented here is to study the effect drought on water demand, groundwater level and crop yield in the area of study. To achieve this purpose, an available code that takes into account the interaction between soil, water, atmosphere and plants (SWAP) is used. The results of this study are presented here.

1.2 Problem definition

Water shortage can be different essentially between regions. As mentioned before, the HDSR is responsible to supply enough (surface) water to the Kromme Rijn area which is part of the water board. According to the KNMI, in the future, the precipitation deficit and temperature will rise. Therefore, the HDSR needs to know the impact of future climate prediction of water demand, ground water level and crop yield in the Kromme Rijn area in particular apple fruit plantation area. Further, in order to maintain the optimum crop yield in the future, HDSR also needs to know the water demand for the Kromme Rijn area.

It is expected that higher temperature and low precipitation during spring summer period (as predicted in the future climate scenario) will consequently reduce the available water in the soil, therefore water demand will increase to obtain maximum crop yield.

1.3 Objectives, research questions, and research hypothesis

1.3.1 Objectives

The objectives of this research are:

- to study the impact of drought on water demand, groundwater level, relative apple crop yield in the Kromme Rijn area based on historical data.
- to predict water demand, groundwater level, grass and fruit crops production in the future based on climate change scenario (W^+) in 2050 predicted by KNMI.
- to give recommendations to water board HDSR on the water irrigation need for the area based on the results of the research.

1.3.2 Research Question:

To address the aforementioned objectives, the following research question is posed:
What are the impacts of recorded drought (history) and future climate on water demand, groundwater level and apple fruit crops yield in the area of Kromme Rijn?

To be able to answer the research question, the sub questions should be first answered:

1. What are the impacts of the recorded drought on water demand, groundwater level, and apple crop yield in the last 30 years,

2. What are the impacts of future climate change scenario of KNMI in 2050 on water demand, groundwater level, and apple crop yield in the area of Kromme Rijn?
3. What do the results mean for the water board HDSR as suggestions for water irrigation management in the Kromme Rijn area?

1.3.3 Research Hypotheses

1. In the dry year, the groundwater level is deeper compare to the normal year. However, apple crop yield can be maintained if required water demand can be fulfilled.
2. In the future, due to the increase in average temperature, the severity of drought will rise causing an increase in transpiration and evaporation leading to an increase in water demand to maintain optimum apple crop yield. The HDSR may need to increase the water supply to the Kromme Rijn area due the increase irrigation water demand.

1.4 General methodology

A one dimensional hydrological model implemented in the SWAP code was used to assess the groundwater level and relative crop yield using historical and future climate data in the area of Kromme Rijn. The methodology implemented in this study was based on the objective of the study presented in the previous section and in general, the activities could be characterized into three main stages, i.e. pre-SWAP model building (literature study to find relevant input parameters), SWAP model calibration to check the validity of the model being developed and post-SWAP model activities to study the impact of future climate changes on water demand, ground water level and relative crop yield.

In the first stage a literature review was carried out to understand the process of soil water flow in the unsaturated zone, to study and learn how the SWAP model works for simulating groundwater level and relative crop yield in the unsaturated zone and to collect the necessary input data for the model, such as meteorological data, crop data, soil data, and hydrological data of the area (pre-SWAP model building). In the following stage the SWAP model was built. Calibration of the model using observed ground water level and apple crop yield data was carried out. In the next stage, the results of the model were analysed. Further, based on the future climate scenario, water demand was calculated and analysed. Finally, conclusion and recommendations for further study were made based on result obtained.

The figure below shows the schematic representation of general methodology taken in this thesis.

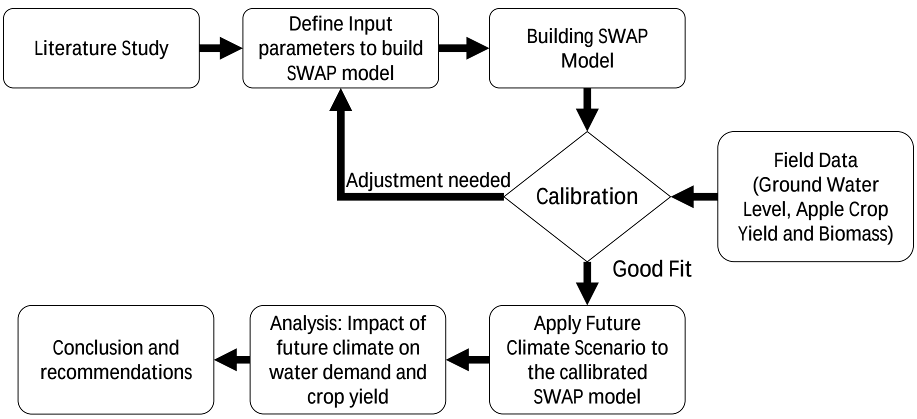


Figure 1.3. Major steps of the study

1.5 Thesis outline

The content of this thesis is concisely outlined as follows:
Chapter 1 explains background of the research, problem definition, objective of the study, research questions, and proposed hypotheses. Chapter 2 presents literature review studies about drought and its impact of water demand and crop yield. Chapter 3 presents a short description of the study area in terms of location, climate and weather, topography, soil type, land use, and hydrogeology. Chapter 4 gives a short summary of the theory behind SWAP model. In this chapter a short description about the model, relevant soil water flow mathematical equations, the required model input and parameters is given. In chapter 5, all the relevant input parameters that are used in building the SWAP model is presented. Chapter 6 discusses results and analysis of the model calibration. Chapter 7 discusses the results and analysis of the simulation for the future climate on groundwater level, relative crop yield, and water demand. In chapter 8 a discussion about the model calibration, crop yield, remote sensing, and water demand are presented. Finally, conclusions and recommendations for further research and water management for HDSR are presented in chapter 9.

Chapter 2
Literature Review

2.1 Drought

Generally drought is defined as lack of water, i.e. water that ordinarily would be available for nature and mankind. Droughts are commonly classified in four different forms (see figure 2.1). Even though diversion from the normal amount of precipitation over particular period of time is generally accepted as the main cause for drought, there is no universally accepted definition of drought (Vazifedoust, 2007). Increasing of water demand, subsequent to a growing global population and the widely use of water for irrigation and industry practices, has raised the awareness of our vulnerability to drought (Tallaksen and van Lanen, 2004).

Drought is an inevitable consequence of earth's climate that occurs regularly. Drought is the result of many complex factors, including activities of human being, which acting and interacting in the environment. The impacts of drought vary by the sector affected, making different definitions of drought relevant for specific groups (Chimpanshi, 1995). When the meteorological conditions is not favourable, e.g. low precipitation and high temperature causing high evapotranspiration, then the soil moisture will decrease. If drought is happening in a longer period, significant hydrological changes (lower surface and ground water level) will occur. This will immediately impact crop yield and ecosystem in the area that experience drought. In a later stage will cause impact to the economical situation of the region. This chain of impact of drought could be visualised in figure 2.1.

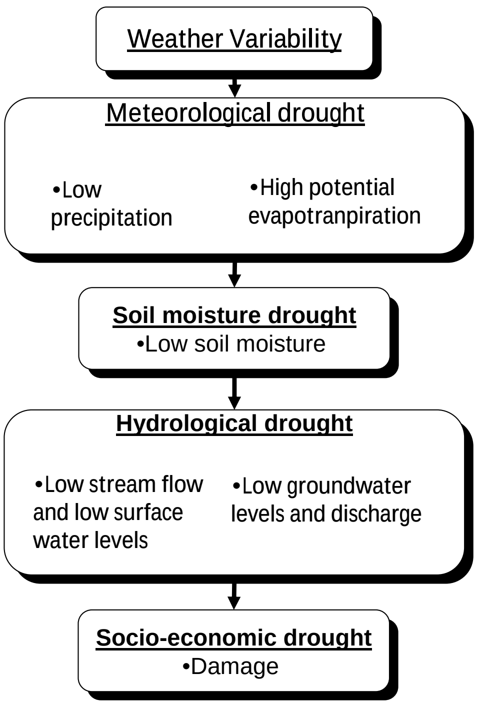


Figure 2.1. Classification of drought (Vazifedoust, 2007, after Peters 2003)

Period of drought is also difficult to define since the variation of precipitation and evapotranspiration is different each year, therefore it is important to analyse and compare the historical climate data and to build physical model to further predict future occurrence. In the sunny weather with warm and windy weather the evapotranspiration will be high causing water shortages to increase rapidly. This condition is defined as drought period by KNMI where the precipitation shortage (precipitation minus evapotranspiration) calculated during the summer period (April-September). This drought definition is used generally in The Netherlands (Bot, 2011) beside the discharge deficit amount of the Rijn River during dry periods (Beersma et al., 2004). The latter drought characteristic is determined by calculating the difference between a given threshold value (1800 m3/s) and the average discharge during April-September period (Beersma et al, 2004). The dry period then is defined if the average discharge is lower than the threshold value.

In this study drought definition using the precipitation deficit value (KNMI, Beersma 2004, Bot 2011) is adopted. Dry year is defined as if the value of potential evapotranspiration exceeds precipitation in the spring summer months (April-September) in the particular year. Table 2.1 shows the precipitation deficit of recorded dry years since 1980-2010.

Year	Precipitation deficit (April-Sept) (mm)
1985	36
1995	199,9
1996	199,2
2003	217,1
2006	175,7

Table 2.1 Precipitation deficit of recorded dry years.

According to the report Droog, Droger, Droogst (Beersma, 2004) by using a model one can calculate the occurrence time of dry year in The Netherlands, based on historical precipitation deficit. It is found that the occurrence time for extreme dry year like in 1976 is about 100 year while for dry year like in 2003 is about 10 years. And due to climate change, the occurrence of dry year will be shorter than that in the past. Dry year as 2003, for instance, will be occurring every 6-8 years instead of every 10 years in the past (Oosterbaan, 2004)

Large impact of drought on economic sector is through agriculture area. A short-term drought at critical development stage of crops can give severe result on crop yield (Wu and Wilhite, 2004). Climate scenario presented by KNMI shows that the Netherlands will face drought for longer period compared to the history which will cause the increase in water demand to maintain the optimum crop yield. Therefore, to deal with drought properly, monitoring, assessment, and mitigation of drought impacts are very important factors of drought preparedness plan (Wilhite and Svoboda, 2000). One of the ways to minimize the impact of drought is to predict the necessary water demand in the future by applying the understanding of interactions between soil, atmosphere, plant and water, and take necessary actions based on the prediction and the available infrastructures.

2.2. Impact of drought and climate change on crop yield, groundwater level and irrigation water demand (observation and model)

In the future, as explained in the chapter 2.1, due to climate change drought problem will occur more frequent and in a longer period, in global scale as well as regional scale such as in The Netherlands. Being able to model the impact of climate change on ground water level, water demand and crop yield is of vital importance because with the model, one can simulate many possible scenarios to minimize impact of drought.

There are some studies have been done to model the effect of climate change on crop yield, groundwater level, and water demand for agricultural purposes, all over the world including The Netherlands. In the following paragraphs, the application of some models, including the SWAP model to study the impacts of drought and climate change in some countries are reviewed.

Sensitivity to climate change in Mediterranean regions is projected to be more severe. In Turkey, for instance, that has Mediterranean environment, the impacts of climate change have been studied to assess the full range of the impacts and to search adaptations strategies (Yano et al., 2007). Yano et al. (2007) implemented a SWAP model to describe effect of climate change on crop growth and irrigation water demand for wheat and maize crops. The simulation was carried by two future climate scenarios given by IPCC: CGCM2 and RCM. The result of the model showed that for the period 2070-2079 irrigation water demand by wheat and maize would be higher due to the decrease of precipitation and increase actual evapotranspiration (ETa). Furthermore, regarding to the yield production, wheat production will increase by 16-36% (CGCM2 and RCM climate respectively) and small increase of 3% (CGMCM2) and decrease of 25% (RCM) for maize yield.

Vazifedoust et al. (2008) searched on-farm strategies which result in higher economic benefits and water productivity in Iran which is an arid/semi-arid region area with water scarcity and regularly faces drought. To assess on-farm strategies, an agrohydrological model, the SWAP model was carried out. The simulation was done for some crops, i.e wheat, fodder maize, sunflower, and sugar beat. The results showed that during the limited water supply period, on-farm strategies that were investigated, such as deficit irrigation scheduling and reduction of the cultivated area can give higher economics benefits. Under the conditions that water shortage occur, reduction of cultivated area gained higher water productivity values compared with deficit irrigation strategy.

In The Netherlands, Kroes and Supit (2011) did study of effects of drought and climate change, increasing salinity in groundwater, and water excess on grass production. The study applied SWAP and WOFOST (World Food Study) to simulate crop growth, water transport, solute transport, and heat transport. The result indicated that the salinity effects on grass production are limited. During the wet year, however, the rainfall excess will reduce the salt water seepage. By applying the future climate scenario given by IPCC; Global Circulations Models (GCMs), in 2050 due to higher temperature, the drought stress occur, however the grass production reduction under salt water stress is limited. As a main conclusion from this research, drought stress is higher than stress causes by water excess, and water excess stress is higher that salt water stress. In the future climate scenario, water demand on irrigation on grassland may increase to 9-10% and deliver in water scarcity in the situation that water supply is insufficient.

Another study in The Netherlands regarding to drought and climate change was done by van Walsum (2011) and van Walsum and Supit (2012). He applied regional hydrological modeling framework SIMGRO and coupling it with soil moisture model MetaSWAP and the crop growth simulation model WOFOST. Using future climate change scenario in combination with higher CO_2 concentrations the model was done for potatoes and grassland in the area of Kromme Rijn. To study the effect of warm and dry situation, the year of 2003 data; and for future climate scenario, the meteorological time series data of 2050; were used. As result for the W+ climate scenario (in 2063) irrigation water demand in the area Kromme Rijn is about 0.5-0.8 mm/day. For the dry year (2003) the level of groundwater declined about 1-3 cm. In respect to the dependency of crop yield on groundwater level, van Walsum and Supit (2012) stated that the locations with shallow groundwater have higher relative crop yield compare to the area with deep groundwater. This is in accordance with the situations with high evapotranspiration and low recharge.

2.3. Apple crop

Irrigation water demand in the area of Kromme Rijn is important to investigate. In order to simulate this factor, the relationship between plant and water has to be discovered. Since a big part of the area of study is planted with fruit crops, therefore in the SWAP model apple crop is chosen to simulate the crop growth and thereby calculate the water demand for irrigation. Following paragraph describe some information about apple.

Living and growing trees need air, sunshine, and water in appropriate amount and duration. They also need good soil and nutrient to produce optimal fruit. There are 5 main growth stages of the fruit trees: budburst and flowering, beginning of rapid shoot growth, beginning of fruit fill, harvesting, and the last stage is leaf fall. During stage 1 to stage 3 irrigation and nutrition are critical demands. Monitoring of these stages is important because it allow the farmers to work out soil moisture requirements for the crops. There are some important management practices that generally affect the crop productions, such as management in irrigation, salinity, nutrient, and soil. With respect with the weather, warm weather during flowering is very important. Therefore, one day frozen spring will affect the production because it damages the flowering process (Boland et al, 2002).

2.4 Contribution of the present work

Apple crop is one of the crops planted in the Kromme Rijn area. There is hardly any SWAP model that has been developed to asses the impact of future climate scenario on water demand and crop yield in apple plantation area. The work presented here therefore contribute to the knowledge of modeling future water demand in apple plantation, with particular emphasis in apple plantation in Kromme Rijn area, in the Netherlands.

Chapter 3
Description of Study area

3.1 Location

In this study, Kromme Rijn area is chosen. This area is one of agricultural areas in the Netherlands. The Kromme Rijn area is the area between Kromme Rijn river and Amsterdam Rijn Kanaal. There are farmlands, grasslands, orchards, and some forest on this area. It lays in the central part of The Netherlands (Fig 3.1). The *Kromme Rijn* River is a fork of the Rhine branches. At the north-eastern side, the area is bordered by the sandy soil hills, Utrechtse Heuvelrug, which is at elevation of 65 m above sea level. The seepage from Utrechtse Heuvelrug influence the groundwater level of the downside area, i.e. the Kromme Rijn area.

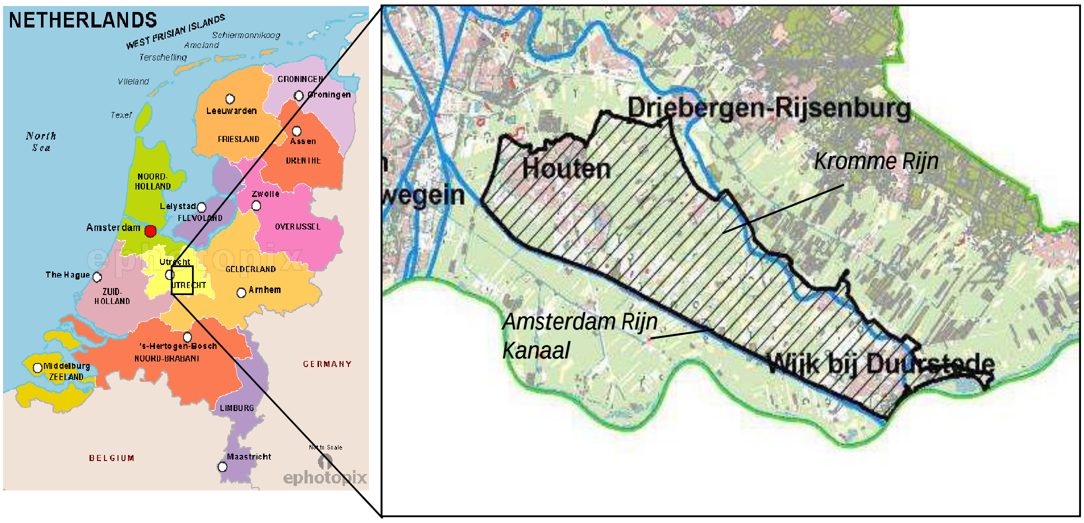


Figure 3.1 Location of the study area

Source : HDSR, 2008

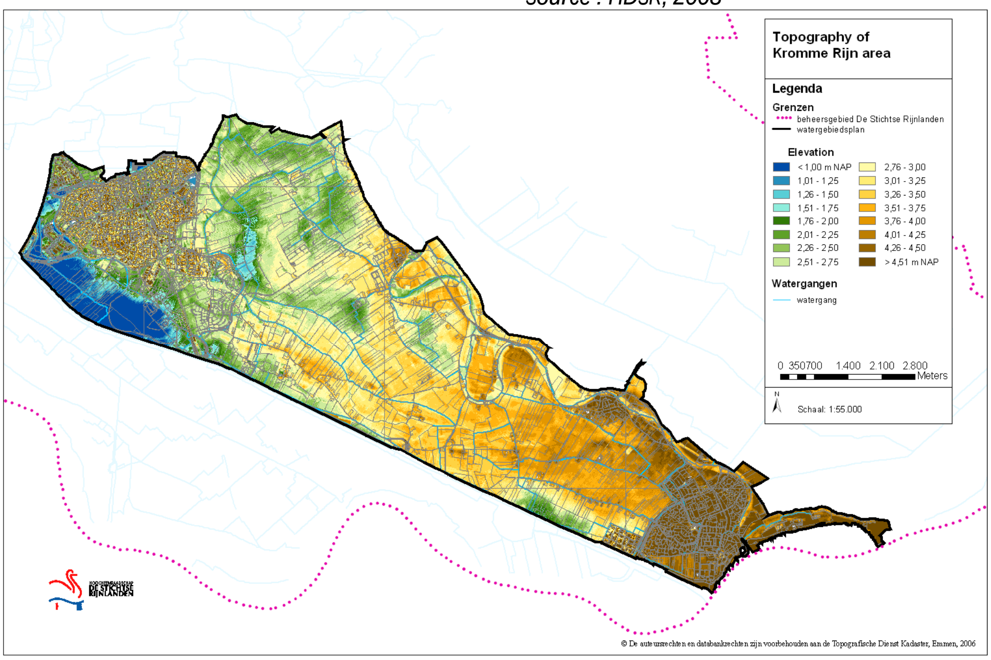


Figure 3.2 Topography of the study area (Source: Koenraadt, 2008)

The area between Amsterdam Rijn Kanaal and Kromme Rijn has variety in landscape. In Topography, the south-western part of the area (Wijk bij Duurstede) is +4.50m from NAP (Normaal Amsterdam Peil), and around +2.50 from NAP between Houten and Odijk (figure 3.2).

The Kromme Rijn River has an important role in the history of the area. This river formed the northern border of the Roman Empire (Limes) and also in the Middle Ages as a transport artery between market town of Wijk bij Duurstede and Utrecht. The Amsterdam Rijn Kanaal is 72.4 km long and it is divided in two parts which is the area of study at the first part; the northern part of de Lek (60.5 km) and southern part of de Lek (Koendraadt, 2008).

Today, Kromme Rijn river plays an important role in water management in the Kromme Rijn area. It is largely fed with inlet water from the Nederijn river. During summer time, the water demand from the agricultural area is high therefore, the water level of this river in the summer is regulated so that it has a higher level than in the winter.

3.2. Climate and weather.

In the present time, The Netherlands climate is classified as a semi-humid maritime climate with cool summers and mild winters. This type of climate is influenced by the southwest predominant wind direction. Rainfall occurs during almost the whole year. The climate in the Netherland got also a significant influence from the north sea. The weather is mainly affected by frequent appearances of depressions of westerly winds, resulting in variable weather conditions over short time range. Westerly winds occur during the whole year and take humid marine air on land.

Recorded temperatures at De Bilt meteorological station indicates that there are visible rise of temperature since 1990s and this is mainly due to climate change on global level (Bressers, 2005).

3.2.1 Temperature, relative humidity and global radiation.

The mean monthly temperature of the study area (1986-2011) is between 3,3 ^{o}C in January and 17, 9 ^{o}C in July (figure 3.3). As we can see from the graph below, July and August are the warmest month with the average maximum temperature reach up 22,5 ^{o}C. The month of January, February, and December the coldest month in the area with the average minimum temperature about 0,5 ^{o}C-1^{o}C.

Figure 3.3 shows the average relative humidity of the Kromme Rijn area is 87% in the winter and 77% in the summer. The values vary from 74.5% in May to 89% in December.

The amount of energy available to vaporize the water determines the evapotranspiration process and solar radiation is the largest source of energy. The potential amount of this energy that can reach the evaporating surface is determined by its location and the time of the year. Figure 3.4 shows the mean monthly difference of the solar radiation in the area of Kromme Rijn. It is clear that the study area receives high value of energy solar radiation in the summer and lower in the winter season.

In each year, however, the fluctuation of temperature and global radiation can be different. As recorded by KNMI, the year of 2007, for instance, had dry spring with high temperature relatively. In April and Mei 2007 the temperature were 13.1^{o}C and 14.1 ^{o}C respectively with 662 sunshine hours (normal long duration amount is 485) and this year recorded as an extremely soft weather and very sunny spring with normal precipitation amount (166 mm).

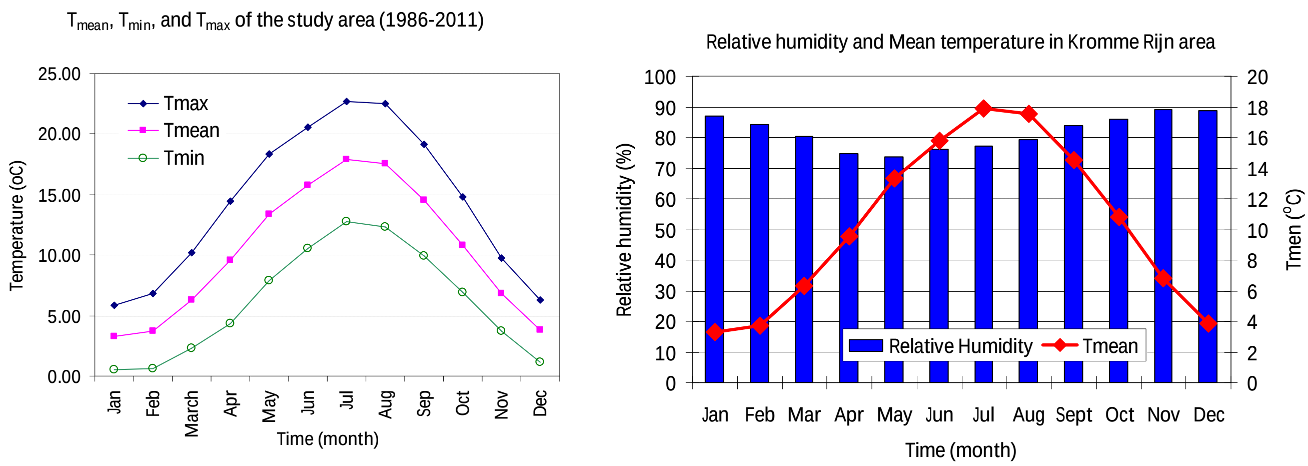


Figure 3.3 T_{mean}, T_{min}, T_{max} and relative humidity in the Kromme Rijn area

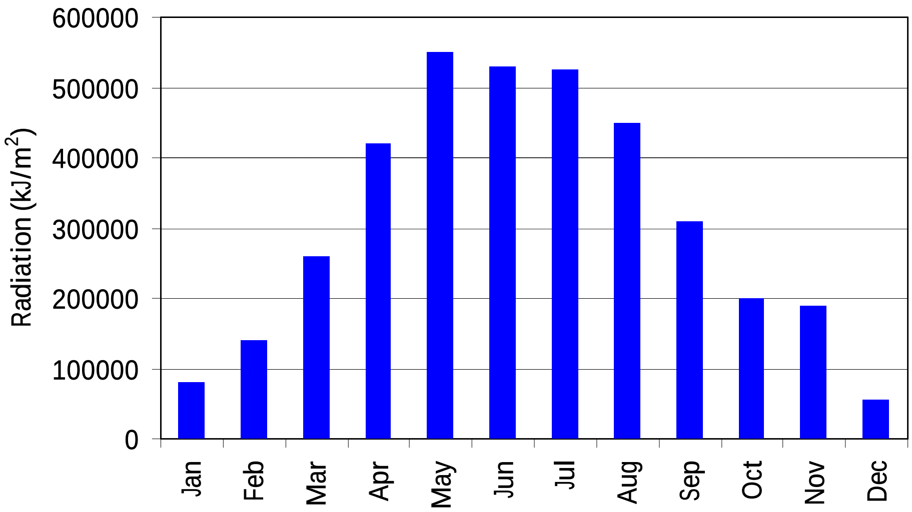


Figure 3.4. Mean monthly solar radiation obtained from weather station de Bilt (1986-2011).

3.2.2 Rainfall and evapotranspiration

The mean yearly precipitation for The Netherlands from 1980-2010 is 832.5 mm and the average number of days with rain is 234 days (KNMI, 2012). In the study area, annual precipitation (station de Bilt) is found about 844 mm with the minimal rainfall is about 576 mm in 1996 and the wettest year reach the value of 1235 mm in the year of 1998 (see figure 3.5). However, in each year the fluctuations of the rainfall can be bigger. In 2011 for instance, as the KNMI reported, the precipitation amount during spring was 49 mm (normal long duration amount is 172 mm). This value is recorded as the driest spring in the last 100 years. In addition, the sunshine hours was 713 hours and compare to the normal long duration value, spring 2011 is also recorded as the sunniest spring in the last 100 years. Furthermore, the small amount of precipitation in combination with high evaporation usually caused by the sunny weather, lead to potential precipitation deficit. At the end of spring period the average of precipitation was recorded as 135 mm, higher than 110 mm as recorded in 1976.
The mean annual reference crop evapotransporation value of about 565.5 mm and the mean annual precipitation for the study area is 839 mm. Figure 3.6 shows the mean monthly rainfall and reference

evapotranspiration variation in the study area. From figure 3.6, one can see that the mean monthly rainfall distribution of the area shows the lowest rainfall value falls in April (41 mm) and the wettest month is July (89 mm).

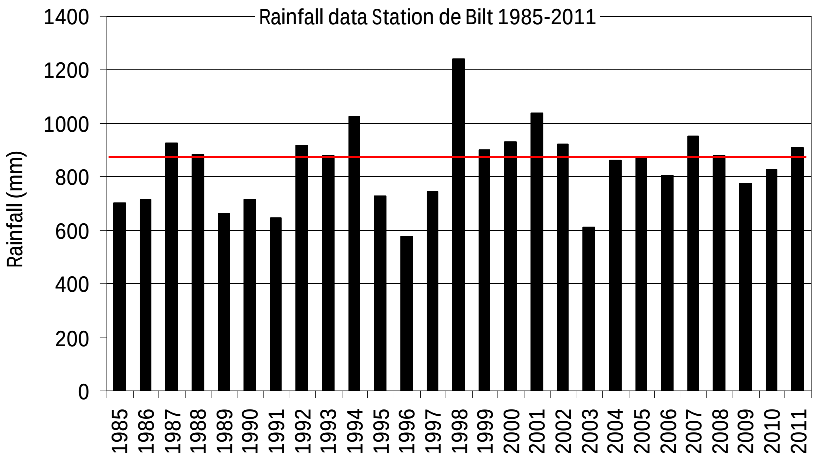


Figure 3.5 Rainfall data recorded from weather station De Bilt (1985-2011)

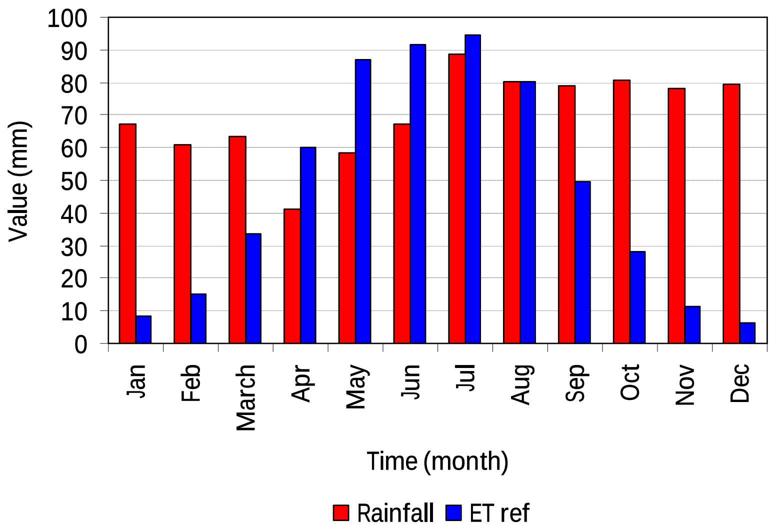


Figure 3.6 Mean monthly rainfall rate and reference evapotranspiration (1986-2011)

In the annual cycle the monthly evapotranspiration is 16.47 mm in January and reach up to 108 mm in July (figure 3.7). The value of seasonal variation of evapotranspiration is mainly depending on solar radiation, wind speed, and temperature (Allen et.al, 1998).

As described in chapter 2, the severity of drought defined here is the difference between precipitation and evapotranspiration. Rainfall shortage is defined when the evapotranspiration is higher than precipitation. As can be seen from figure 3.7, rainfall shortage mainly occurs during the growing season in the month (April-August). It means that during these months dry period may occur. This is a very importance stage for crop growth. Therefore, in these months, extra effort is needed to supply sufficient water to the crops by irrigation in order to ensure optimum crop yield.

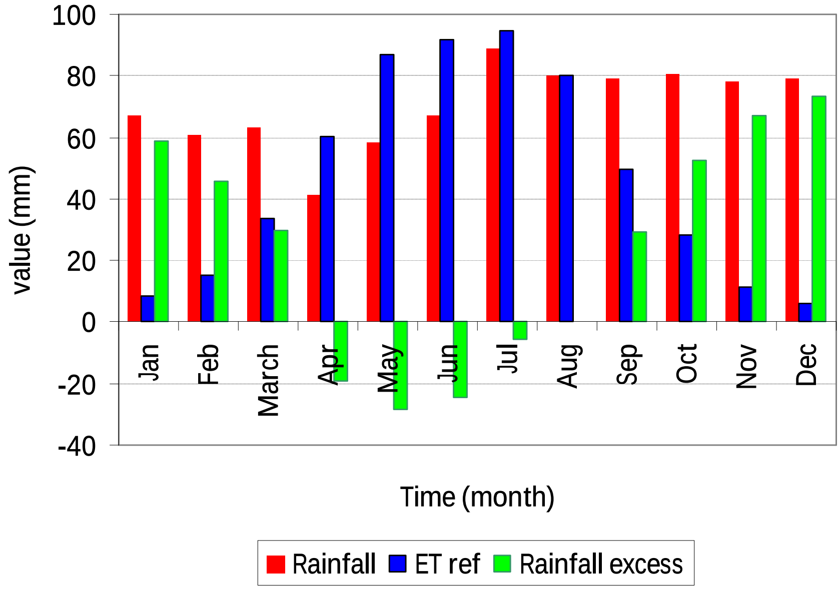


Figure 3. 7 Mean monthly rainfall, evapotranspiration and rainfall excess in Kromme Rijn area (1986-2011)

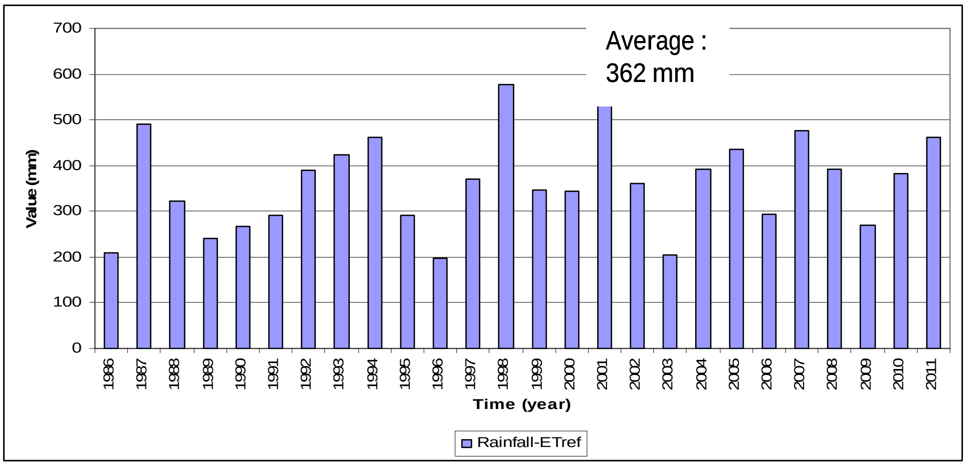


Figure 3.8. Annual rainfall excess (Apr-Sept) in Kromme Rijn area (1986-2011)

If normal rainfall excess during spring summer time in the period 1986-2011 is defined as average of the rainfall excess then the value is 362 mm. From figure 3.7, one can see that the year of 1986, 1996, 2003 are dry years (i.e. low rainfall excess). The year of 1998 and 2001 is wet year (i.e. high rainfall excess) while 1999 and 2000 are some of the normal years (i.e. average rainfall excess).

3.3 Hydrogeology.

The geology of The Netherlands was heavily modified in the glacial stage when the iced pushed soil material. Therefore ridges were formed by lobes of the ice sheets. The area between the Kromme Rijn and Amsterdam Rijn Kanaal is located at the border of a ridge area (Heuvelrug). The soil layers consist of clay, peat and sand in the Holocene layer. The streambeds of the river Rhine is also important in shaping the soil type in the Kromme Rijn.

A thickness of about 5 to 10 m below the first aquifer consist of moderate fine to coarse sands of the formations of Boxtel, Kreft Heije, Urk and Sterksel. The thickness of the layer is approximately 50 m, and the permeability rate is generally around 25 m/d. The second layer is 15-20 m thick and consists of Waalre clay. The resistance of this layer is about 1000 to 1500 days. Located below the 2nd and 3rd aquifers are not separated from each other and have a joint thickness of approximately 75 m. These layer consist of clayey sands and Peize Waalre. The permeability of the sand is around 15 m/d. At a depth of 140 to 160 m below NAP starts separating layer 3, consisting of the clay deposits of Maassluis. This layer has a thickness from about 50 to 100 m and below this layer the base of hydrogeology of the area lays. The hydrogeology of the area is shown in figure 3.9 below.

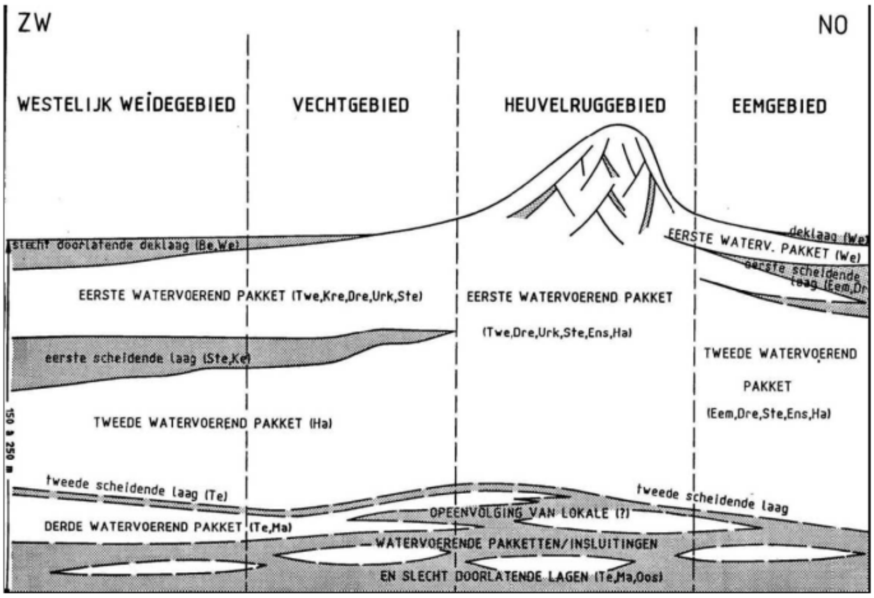


Figure 3.9 Hydrogeology profile of Utrecht area including the area of study.(source: Koenraadt et al., 2008)

3.3.1 Groundwater level fluctuations.

With respect to groundwater level fluctuations, a distinction is made between the mean highest groundwater (GHG) and mean lowest groundwater (GLG). In The Netherlands which has shallow groundwater, GHG and GLG are classified into seven groundwater regime which called groundwatertrap (Gt). Thus the Gt is determined by GLG and GHG value as shown in figure 3.10.

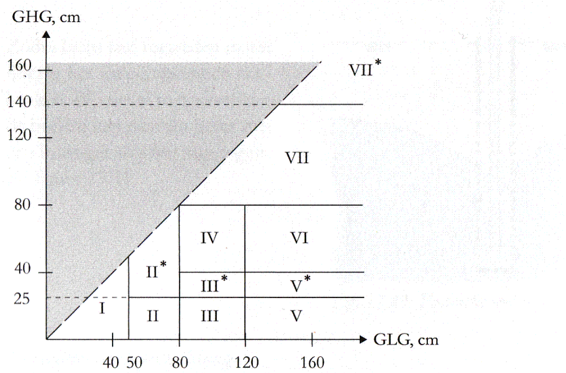


Figure 3.10 Groundwater regime (Gt), Bot (2011)

Example:
For GHG : 33 cm and GLG : 168 cm, then Gt : V*
For GHG : to surface level and GLG : 70 cm, then Gt : II

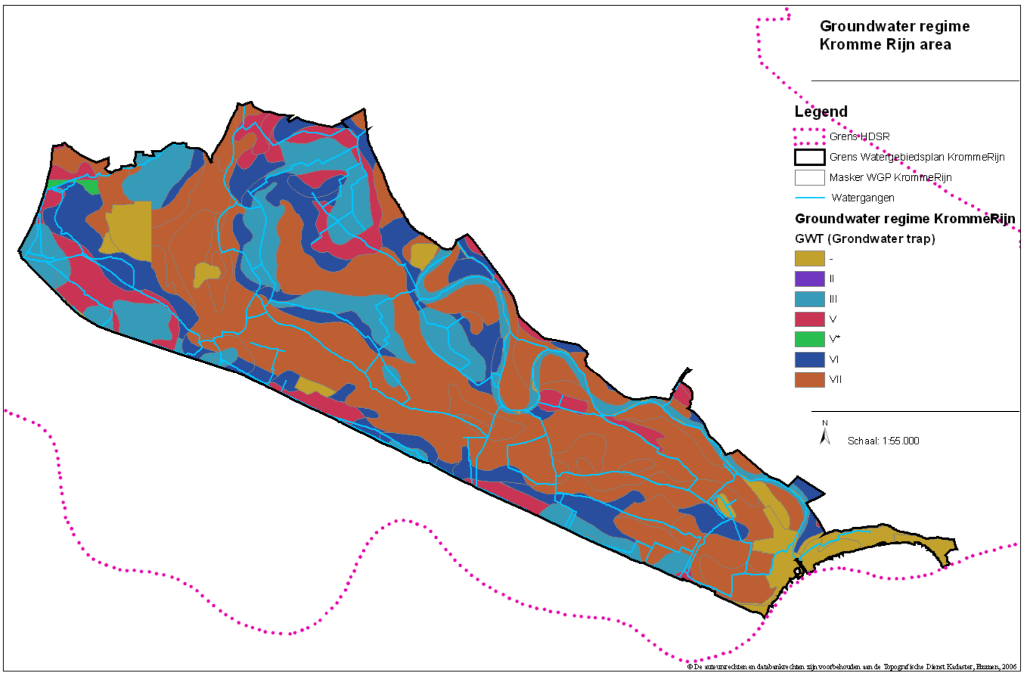


Figure 3.10 groundwater regime in the Kromme Rijn area (source: HDSR, 2008)

The average highest groundwater (GHG) in the low area are around 25-50 cm below the surface level while in the higher area is more than 1 m below surface level. The mean lowest groundwater (GLG) levels occur in the summer and in the most area the groundwater levels are below 1.75 m (below surface level). The difference between the GHG and GLG is approximately 75 cm in the most area. The groundwater regime in the study area is shown by figure 3.10.

Table 3.1 below shows the data of GLG and GHG of the Kromme Rijn area at the selected sites, data was obtained from GIS map available in HDSR.

	Point							
Parameter	176	187	219	270	280	314	350	556
GHG [cm] below surface level	-84	-102	-97	-119	-135	-93	-97	-61
GLG [cm] below surface level	-164	-238	-224	-262	-236	-248	-183	-146
Groundwater regime	VII	VII	VII	VII	VII	VII	VII	VI

Table 3.1 Groundwater regime in the area of study at points.

As we can see from table 3.1 the ground water regime on the selected points are mainly Gt VII.

3.3.2 Seepage and infiltration.

Originally, the deep seepage in this area is coming from local infiltration of precipitation on the hill ridge Utrechtse Heuvelrug, but it is significantly reduced comparison to the past. With the commissioning of Amsterdam Rijn Kanaal this seepage in a large area is disappeared. The reduction is also caused by heavy groundwater pumping for drinking water (van Walsum, 2011). The low level of Amsterdam Rijn Kanaal (-0.40 NAP) causes a strong infiltration of groundwater from almost the entire Kromme Rijn area. There are some seepage at the surface at the some lower areas, particularly southwest of the area and till along the Kromme Rijn river. Figure 3.11 shows where there is seepage and where infiltration of the study area. The range value of the infiltration is mainly between -1.00 – -2.00 mm/day.

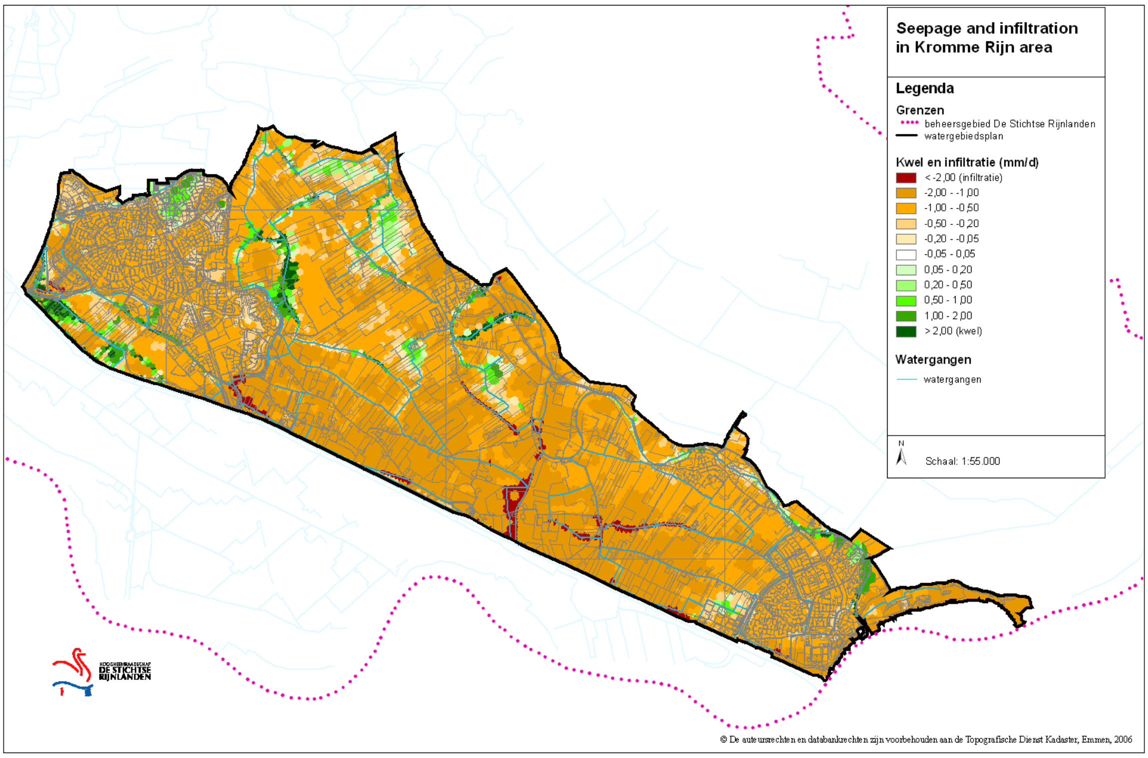


Figure 3.11 Seepage and infiltration map in the Kromme Rijn area

3.3.3 Water management in the agricultural area

The watercourses in the area are mainly divided into primary and tertiary watercourses. The main watercourses have the function of water supply (''aanvoer'') and water drainage/disposal (''afvoer). The main water courses in the rural area are less than 8 m and usually small than 3 m with average depth are about 75 cm. Because of relatively shallow water depth, the water plants present at almost all the watercourses.

For irrigation purposes in the agricultural area much water is needed. Partly it has to do with strong infiltration into the canal and other reason is because the practice of frost control 'nachtvorstbestrijding' in the orchards area (Koendraat et al, 2008). Furthermore, the groundwater level is in the most area goes lower during summer. To prevent the damage in the agriculture area, an irrigation practice is necessary to apply. This is possible by extracting water from the ditches. To meet the water demand in the orchards area in the recent years, due to the changes of existing orchard, the irrigation systems are not only extended but also replaced. To make sure that there is always water available in the area, especially in the agricultural area, surface water management is applied. Surface water level in the winter and in the summer has difference of 10-20 cm, which is higher during summer period. Figure 3.12 shows an example of surface water level ("drooglegging") during summer time.

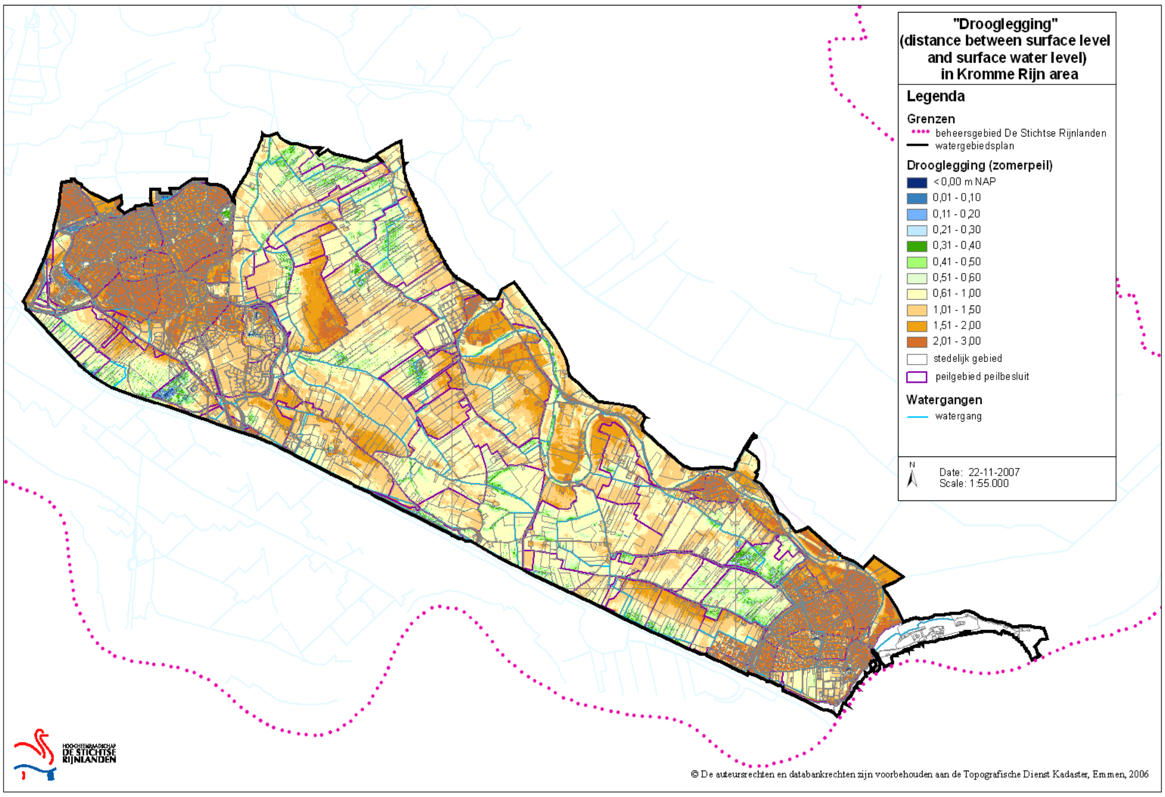


Figure 3.12 Surface water level in Krommer Rijn area.

3.4 Soil types, land use and vegetation.

Figure 3.13 shows the types of soils in the study area which are mostly loam soil and clay soil; vary from light to heavy clay on sandy soil. This material is built in centuries in Kromme Rijn. In the small area at south-western, part the clay on peat is found.

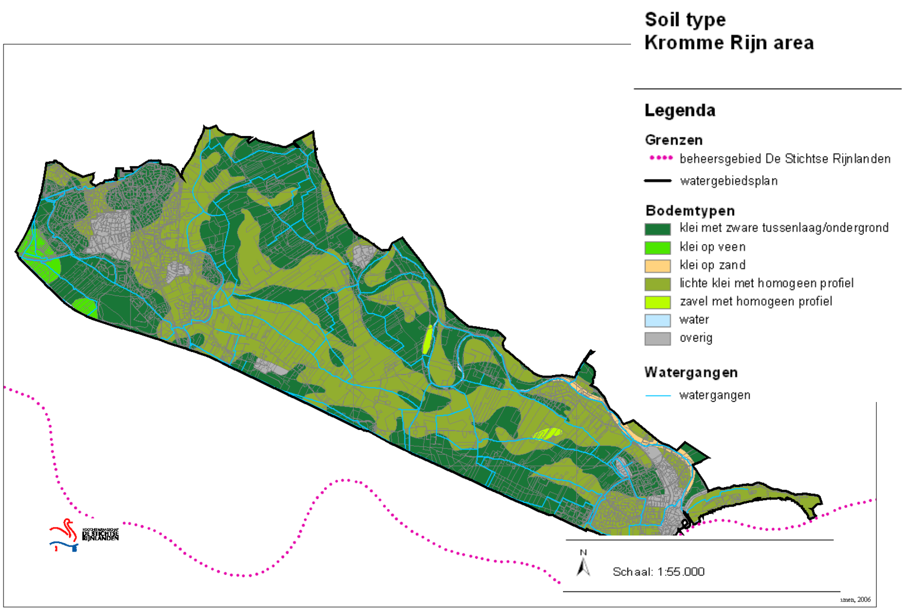


Figure 3.13 Soil type in the study area. Source: HDSR

At the present situation, the agricultural land use includes grassland and fruit crop activity. model will be done for Table 3.1 and figure 3.14 show the land use in the Kromme Rijn area.

Land use	Area (ha)	Area (%)
Built-up area and roads	1673	28
Grassland	2616	44
Fruit	816	14
Arable land	637	11
Nature	144	2
Fresh water	74	1
Total	5924	100

Table 3.1. Land use in the Kromme Rijn area (HDSR, 2011)

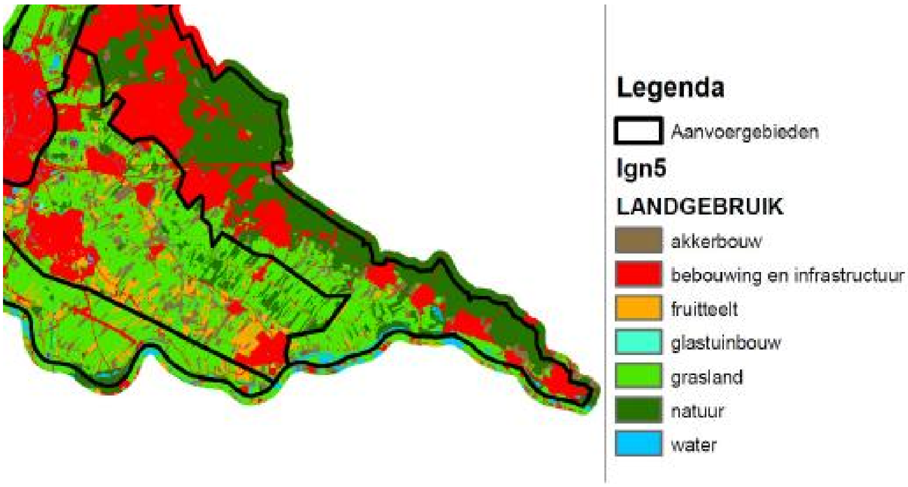


Figure 3.14. Land use map of the study area. Source : HDSR

Grassland is the most land use of the area, cover 44% of the total area where is mostly used for dairy farm. Orchards which grow on sandy streambeds cover 14% of the area. At this moment, in the Kromme Rijn area is approximately 5% of entire of The Netherlands orchards present. Beside that built up area and roads cover 28% of the area.

As we can see in figure 3.13, orchards grow mainly on loamy soil ('lichte klei met homogen profile' and 'klei op zand').

Chapter 4
SWAP model

4.1. Introduction

As described in chapter 1 & 2, water demand for plants is significantly influence crop yield. In order to have a good prediction of the impact of water management and meteorological conditions, understanding and mathematical models are needed to optimise crop yield. This has been a subject of study for many years. One of the mathematical models that could describe the interaction between atmospheric conditions, water, soil and plants is SWAP (Soil-Water-Atmosphere-Plant) model.

Transport of water in the unsaturated zone primarily vertical and can be simulated with one dimensional direction (van Dam et al., 1997). SWAP (Soil-Water-Atmosphere-Plant) is a model to simulate transport of water in the unsaturated zone in interaction with vegetation development. This is an integrated model developed by researched at DLO Winand Staring Centre and Wageningen Agricultural University in the Netherlands. SWAP was developed based on earlier models, e.g. SWATRE, SWACROP, etc. This model has been implemented in a computer code to calculate water flow, solute transport and crop growth. This model is proven to be powerful in predicting the interaction between soil, water, atmosphere and plants. This software has been used by several researchers (e.g. Kroes and Supit 2011, van Walsum 2011 in the Netherlands, Vazifedoust (2007) in Iran, and Yano (2007) in Turkey) to predict the impact of drought and future climate on crop yield and water demand. Therefore, this model is chosen here to analyse the impact of drought and future climate on water demand and crop yield in the area of Kromme Rijn.

This chapter will give a brief principle of SWAP model. The readers are referred to SWAP user guide and theory (Van Dam et al. 1997, Kroes et al 2000) for further detail on the model.

4.2 SWAP model description (Van Dam et al. 1997, Kroes et al. 2000)

The SWAP model integrates the interaction between soil, water, atmosphere and plant during the whole growing season and at field scale level. Graphically, the principle of theSWAP model is shown in figure 4.1.

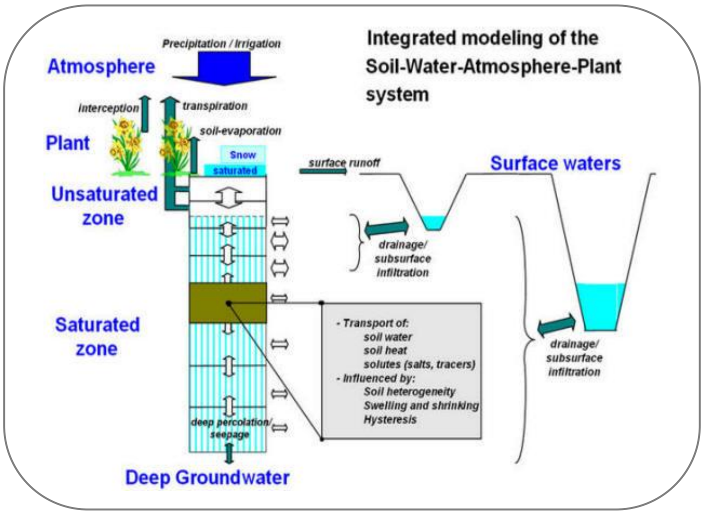


Figure 4.1. Schematic principle of SWAP model (Groenendijk et al., 1999)

The system modeled in the SWAP model has three boundaries, i.e. top boundary, bottom boundary and lateral boundary. The top boundary is defined by the soil surface water with atmospheric conditions. The bottom boundary describes the interaction of the soil system being modelled with regional ground water. This bottom boundary is the upper part of the groundwater. The lateral boundary describes the interaction of the soil system being studied with the surface water system. All these boundaries together with the properties of the soil and the growth model of the plants being studied will be integrated and used in the model to calculate the desired output like ground water level fluctuation, crop yield, irrigation and water demand during the defined time domain.

4.2.1. Soil Water Flow

To analyse water flow in a SWAP model system, one need to know the three boundaries mentioned earlier (i.e. top, bottom and lateral boundaries). For the top boundary (i.e. interaction between soil and atmosphere), the amount (available data or prediction) of rainfall and irrigation. Based on the meteorological data (i.e. rain, temperature, humidity, radiation, and wind speed) and crop model, the amount of water intercepted by the crop leafs and the amount of water extracted by the crop roots can be modeled. Further, based on the properties of the soil and meteorological data, the amount of water infiltration into the soil and surface run-off can be model. For the lateral boundary (i.e. interaction between soil and surface water level), the depth of surface water level and the depth of the ditches should be given. When the ground water level is well below the surface water and depth of the ditches, lateral infiltration will occur and if otherwise, drainage will occur. The rate of infiltration or drainage is very much influenced by the infiltration and drainage resistance of the soil being modeled. For the bottom boundary (i.e. upper part of saturated zone), depending on the spatial distribution of water pressure head, water recharge (water flow from unsaturated zone to saturated zone) or discharge (water flow from saturated zone to unsaturated zone) could occur. These entire mechanisms can be schematically shown in figure 5.2.

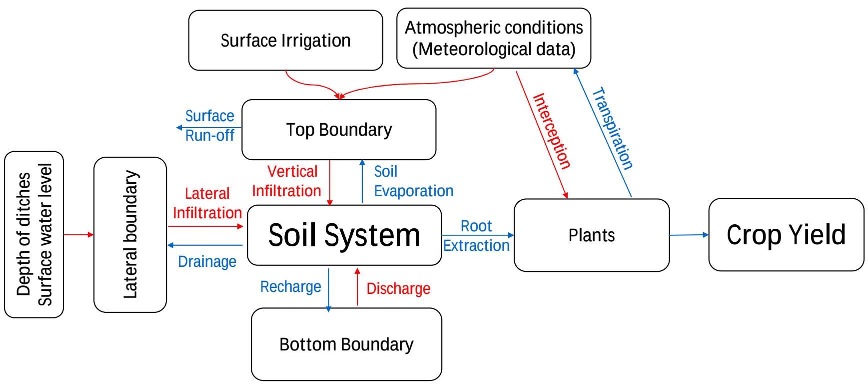


Figure 5.2. Schematic representation of mechanisms of water flow in SWAP model.

Depending on the given boundary conditions, SWAP model will calculate soil water flow due to the spatial differences of soil water potential. Soil consists of different organic matters and can be modeled as porous media with permeability properties as described by Darcy's low:

$$q = -K(h)\frac{\partial(h+z)}{\partial z} \qquad (5.1)$$

where q [cm/day] is the soil water flux density (positive upward), K is hydraulic conductivity of the soil [cm/day], h is soil water pressure head [cm] and z is the vertical coordinate [cm] taken positively upward.

When water content changes with time under transient conditions, conservation of matter is formulated by the continuity equation for soil water:

$$\frac{\partial q}{\partial t} = \frac{-\partial q - S(h)}{\partial z} \qquad (5.2)$$

where q is volumetric water content (cm^3 cm^{-3}), *t* is time (d) and S is soil water extraction rate by plant roots and drain discharge (cm3 cm-3 d-1).

By combining equation (5.1) and (5.2) one could derive the partial differential equation that describes the soil-water-atmosphere interactions in unsaturated zone which is the well-known Richard's equation:

$$\frac{\partial q}{\partial t} = C(h)\frac{\partial h}{\partial t} = \partial\left[\frac{K(h)(\partial h/\partial z + 1)}{\partial t}\right] - S(h) \qquad (5.3)$$

where *C* is the water capacity (∂θ/dh) (cm^{-1}), *h* soil water pressure head (cm), *K* is hydraulic conductivity (cm d^{-1}), *S* root water extraction rate (cm^3 cm^{-3} s^{-1}) and *z* soil depth (cm).

Hydraulic conductivity is an intrinsic representative property of the soil being studied. This soil property depends very much on the type and structure of the soil. In addition, atmospheric temperature and thus soil temperature will also have an impact on this hydraulic property of soil, which all are included the SWAP model. Root water extraction rate depends on the crop model and the atmospheric conditions, while the water pressure head depends on the initial condition and further calculated spatial distribution of water pressure head depending on all the boundary conditions and soil properties.

Richard's equation (equation (5.3)) is solved by SWAP numerically given the initial conditions, the boundary conditions and the relations between volumetric water content (q), soil water pressure head and hydraulic conductivity of the soil being studied. The reader is referred to SWAP manual for further detail on the numerical methods implemented in SWAP program.

4.2.2. Drainage and Bottom boundary system

In Kromme Rijn area, there are ditches that are used to control ground water level. In SWAP model the depth of the surface water level, the depth of the bottom of the channel is modeled and is influencing the ground water level. In this study basic drainage system with single drainage was applied since the model was applied for the field scale and only limitation data were available. The drainage flux relation conducted Hooghoudt or Ernest equation:

$$q_{drain} = \frac{\left(j_{gwl} or j_{avg}\right) - j_{drain}}{g_{drain}} \qquad (5.4)$$

where: j_{gwl} is phreatic groundwater level midway between the drains of the ditches (cm), j_{avg} is averaged phreatic groundwater level between the drains or ditches (cm), j_{drain} is drainage level, and g_{drain} is drainage resistance (d).

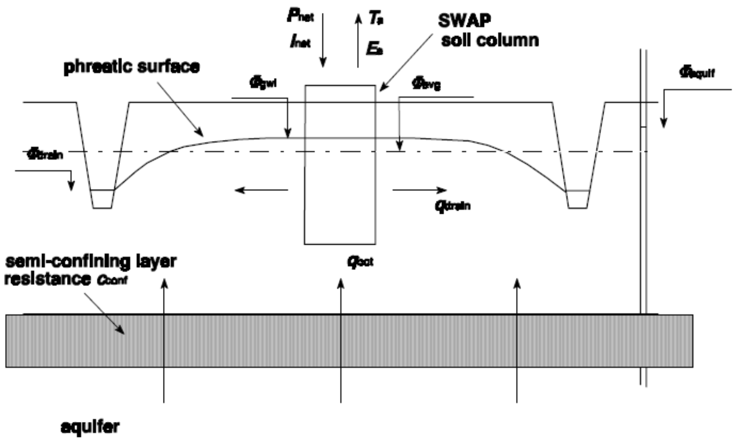


Figure 5.3. Schematic representation of soil water balance with single level drainage.

Bottom boundary could be defined as the transition between un-saturated and saturated zone in vertical direction. Between the aquifer and the ground water level is a semi confining layer with a certain thickness and a certain resistance. Bottom flux (q_{bot}) can be calculated as

$$q_{bot} = \frac{f_{aquif} - f_{ave}}{C_{conf}} \qquad (5.5)$$

where ϕ_{aquif} is the hydraulic head of the drain (cm) and ϕ_{ave} is the average ground water level (cm) and C_{conf} is the semi confining layer resistance.

4.2.3. Rainfall interception, evapotranspiration and relative crop yield

As described earlier, crops leafs intercept water from rain and irrigation. In SWAP, the amount of intercepted precipitation is calculated based on a formula proposed by Von Hoyningen-Hune (1883) and Branden (1985):

$$P_i = a \cdot LAI \left(1 - \frac{1}{1 + \frac{b \cdot P_{gross}}{a \cdot LAI}} \right) \qquad (5.6)$$

where P_i is intercepted precipitation (cm/day), *LAI* is leaf area index, P_{gross} is gross precipitation (cm/day), *a* is an empirical coefficient (cm/day) and *b* represents the soil cover fraction. Equation (5.6) shows that the amount of intercepted precipitation will asymptotically reaches the saturation amount (i.e. a·LAI) for increasing amounts of precipitation.

It is generally accepted that the daily water fluxes passing through a canopy are large compared to the amounts of water stored in the canopy itself. Therefore, it can be assumed that root water extraction in the soil is equal to plant transpiration. On the other hand, due to meteorological conditions, water from the soil or ponding on the soil surface can evaporate. The total amount of transpiration (from plant) and evaporation (from soil surface) can be referred to as evapotranspiration. Evapotranspiration can be calculated by using Penman-Monteith equation (Monteith, 1981):

$$ET_p = \frac{\frac{\Delta_v}{\lambda_w}(R_n - G) + \frac{p_1 \rho_{air} C_{air}}{\lambda_w} \frac{e_{sat} - e_a}{r_{air}}}{\Delta_v + \gamma_{air}\left(1 + \frac{r_{crop}}{r_{air}}\right)} \qquad (5.7)$$

where ET is the transpiration rate of the canopy (mm/day), Δ_v is the slope of the vapour pressure curve (kPa/°C), λ_w is the latent heat of vaporization (J/kg), R_n is the net radiation flux at the canopy surface (J/(m^2 day), G is the soil heat flux (J/(m^2 day), p_1 account for unit conversion (= 86400 s/day), ρ_{air} is the air density (kg/m^3), C_{air} is the heat capacity of moist air (J/(kg °C), e_{sat} is the saturation vapor pressure (kPa/°C), e_a is the actual vapor pressure (kPa), γ_{air} is the psychrometric constant (kPa/°C), r_{crop} is the crop resistance (s/m) and r_{air} is the aerodynamic resistance (s/m).

Penman-Monteith equation is recognized as one of the best formula to predict evapotranspiration under different climatic conditions. This equation has become an international standard to calculate potential evapotranspiration for a dry, horizontally-uniform vegetated surface. Penman-Monteith equation is applied in SWAP to calculate potential evapotranspiration.

The maximum potential root water extraction rate could be reduced by the stress due to dry or wet conditions. The maximum possible root water extraction rate could be calculated as follow:

$$S_p(z) = \frac{\lambda_{root}(z)}{\int_{-D_{root}}^{0} \lambda_{root}(z)\,dz} T_p \qquad (5.8)$$

where λ_{root} is root layer thickness (cm) and T_p is potential evapotranspiration.

The amount of $S_p(z)$ is strongly influenced by stresses due to dry or wet condition and/or high salinity concentration. In the SWAP model, the water stress is described by the function given by Feddes et al. (1978), which is shown in figure 5.3. It is shown that the root water uptake is optimal in the range $h_3 < h < h_2$ and below h_3 root water uptake linearly declines due to drought until zero at h_4 (wilting point). Furthermore, due to insufficient aeration, the water uptake above h_2 declines until zero at h_1. The critical pressure head h_3 increase for higher potential transpiration T_p.
In this study the salinity stress was not taken into account, therefore the actual root water flux ($S_a(z)$ (d^{-1}) become :

$$S_a(z) = \alpha_{rw} S_p \qquad (5.9)$$

where α_{rw} is dimensionles s water stress coefficient.

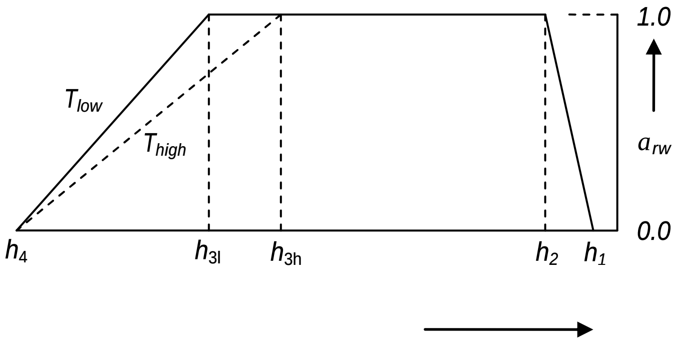


Figure 5.3 Reduction coefficient for root water uptake, a_{rw} as function soil water pressure head h and potential transpiration T_p (after Feddes et al. 1978).

The maximum evaporation value that to soil can sustain is calculated using Darcy's law:

$$E_{\max} = K_{1/2}\left(\frac{h_{atm} - h_1 - z_1}{z_1}\right) \tag{5.10}$$

Soil water pressure head

Where $K_{1/2}$ is average hydraulic conductivity (cm/d) between the soil surface and the first node, h_{atm} is the soil water pressure head (cm) in equilibrium with the air relative humidity, h_1 is the soil pressure head at the first node, and z_1 is the soil depth (cm) at the first node. The value of E_{max} depends on the thickness of the top soil compartments. SWAP recommends therefore for more accurate simulation, the thickness of the top compartments is maximum 1 cm.

By calculating the potential and actual transpiration one can then calculate the relative crop yield based on a simple model defined in SWAP. For each growing stage *k* the actual yield $Y_{a,k}$ (kg/ha) relative to the potential yield $Y_{p,k}$ (kg/ha) is calculated in the SWAP model using the following equation:

$$1 - \frac{Y_{a,k}}{Y_{p,k}} = K_{y,k}\left(1 - \frac{T_{a,k}}{T_{p,k}}\right) \tag{5.11}$$

where $K_{y,k}$ is the yield response factor of growing stage *k*, and $T_{p,k}$ (cm) and $T_{a,k}$ (cm) are the potential and the actual transpiration respectively, during growing stage *k*.

4.2.4. Soil Heat Flow and Solute Transport

The SWAP program could be used to calculate soil heat flow and solute transport to enable simulation of transport of fertilizer pesticide, for instance. These topics are not discussed in this thesis. The reader is therefore referred to the SWAP manual for further information on soil heat flow and solute transport.

4.3. SWAP program structure

The SWAP model described briefly in the previous sections has been implemented in a computer code. The SWAP model version 2.0 with its graphical user interface is used in this thesis. Once the input parameters for all the boundaries (e.g. meteorological data, irrigation, drainage, and bottom boundary data), soil data and the crop data (see chapter 5) are defined. The user could assign the program to calculate the desired output available within the SWAP program. In this thesis, a simplified structure of the SWAP program covering the input parameters, calculation and the desired outcome is shown in figure 5.4.

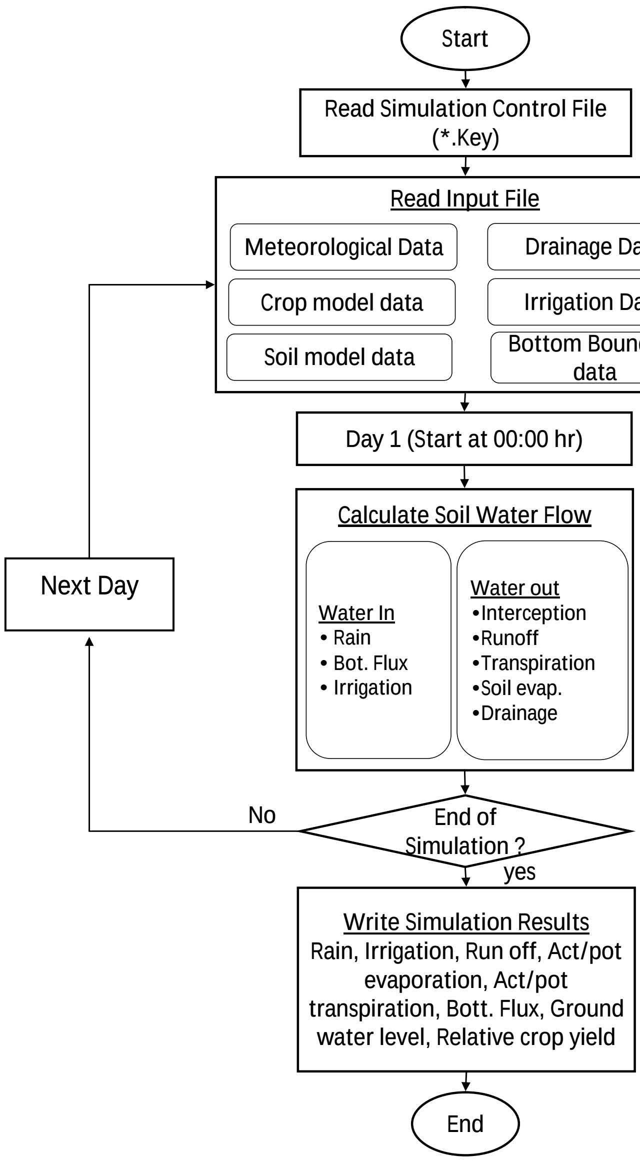


Figure 5.4. A simplified structure of the SWAP program covering the input parameters, calculation and the desired outcome used in this thesis.

Chapter 5
Input Data for SWAP Model

5.1. Introduction

As described in chapter 4, SWAP users need to define the boundaries (i.e. top, bottom and lateral boundaries of the soil system being studied), the intrinsic properties of the soil and the crop in order to calculate and simulate desired outcome like ground water level, irrigation, relative crop yield etc. In this chapter, all the parameters defined in SWAP model and the arguments for the chosen parameters are presented.

5.2. Meteorological data and bore holes

Daily meteorological data, i.e. precipitation, solar radiation, air temperature, air humidity and wind speed is needed to calculate the evapotranspiration rate with Penman-Monteith equation described in chapter 4. In addition, the amount of water from precipitation is needed as an input to calculate water interception by the plants, surface water run-off and rain infiltration into the soil.

The closest weather station to Kromme Rijn is De Bilt station. It is assumed here that the recorded data in De Bilt station is the same as that in the Kromme Rijn area. The meteorological data used in this study is obtained from KNMI recorded in De Bilt weather station. KNMI has been collecting meteorological data daily for the last twenty six years (1986-2011) from several weather stations in the Netherlands.

In SWAP model, daily meteorological data for all the year of interest is given. One can obtain the recorded meteorological data in the Netherlands from KNMI website. A screenshot of a meteorological data input in SWAP is shown in figure 5.1 and an example of a meterological data obtained from KNMI is shown in table 5.1.

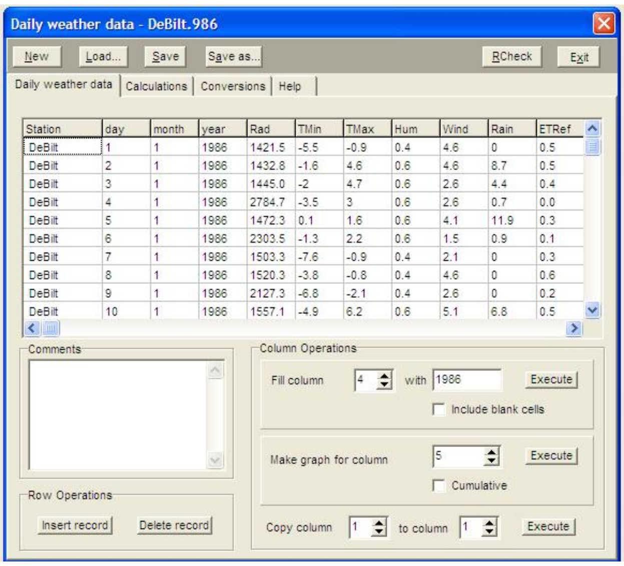


Figure 5.1. A screenshot of Meterological data of 1986 from De Bilt station as input.

Day	Month	Year	Radiation kJ/m2	TMin [?C]	TMax [?C]	Humidity [kPa]	Wind [m/s]	Rain [mm]	ETref [mm]
1	1	1986	1421.5	-5.5	-0.9	0.4	4.6	0	0.5
2	1	1986	1432.8	-1.6	4.6	0.6	4.6	8.7	0.5
3	1	1986	1445	-2	4.7	0.6	2.6	4.4	0.4
4	1	1986	2784.7	-3.5	3	0.6	2.6	0.7	0
5	1	1986	1472.3	0.1	1.6	0.6	4.1	11.9	0.3
6	1	1986	2303.5	-1.3	2.2	0.6	1.5	0.9	0.1
7	1	1986	1503.3	-7.6	-0.9	0.4	2.1	0	0.3
8	1	1986	1520.3	-3.8	-0.8	0.4	4.6	0	0.6
9	1	1986	2127.3	-6.8	-2.1	0.4	2.6	0	0.2
10	1	1986	1557.1	-4.9	6.2	0.6	5.1	6.8	0.5
11	1	1986	2026.1	2.5	6.3	0.8	4.6	0	0.2
12	1	1986	1748.7	2.6	6.4	0.7	5.7	0	0.8
13	1	1986	1619.4	5	9.8	0.9	6.7	5.2	0.8
14	1	1986	1795.9	4.3	9.7	0.8	7.7	4.9	1.2
15	1	1986	2183.4	0	6.7	0.7	5.1	2.1	0.5
16	1	1986	2997.3	0.8	4.8	0.6	3.6	0	0.6
17	1	1986	3141.6	-1.7	5.2	0.6	2.1	0	0.3
18	1	1986	1742.5	0	9.5	0.8	5.7	8.5	0.6
19	1	1986	1770.1	5.4	11	1	8.7	15.3	0.7
20	1	1986	4086.4	4.5	7.8	0.8	6.7	0	0.7
21	1	1986	1828	5.4	7.1	0.8	7.2	3.7	0.9
22	1	1986	3472.8	3.1	8.3	0.8	7.2	9.2	0.7
23	1	1986	3747.4	2.7	8.4	0.7	6.2	4.4	1.1
24	1	1986	3288.4	1.4	5	0.6	5.1	2.4	0.9
25	1	1986	4488.9	-0.1	5.4	0.6	4.1	0.3	0.6
26	1	1986	5134.8	-4.4	4.6	0.5	1.5	0	0.3
27	1	1986	2025.1	-5.3	-0.1	0.5	3.1	0	0.1
28	1	1986	4922.6	-1.4	4.3	0.6	4.1	2	0.4
29	1	1986	3184.2	0.1	3.4	0.5	5.7	0	1.1
30	1	1986	2746.9	-1.7	2.5	0.5	4.6	0	0.7
31	1	1986	2175.6	0.9	2.5	0.5	7.7	0	1.2
1	2	1986	2215.6	0.8	3.7	0.6	7.7	0	0.8
2	2	1986	2256.6	0	3.3	0.6	5.7	0	0.6
3	2	1986	2298.4	-1.2	0	0.5	5.7	0	0.6
4	2	1986	5063.3	-4	0.1	0.4	5.7	0	0.8
5	2	1986	5992.9	-6.2	0	0.4	3.6	0	0.5
6	2	1986	2429.5	-6.3	-2.1	0.3	4.6	0	0.9
7	2	1986	6238.7	-5.8	0.1	0.4	4.1	0	0.5
8	2	1986	5038.4	-7.3	-2.8	0.3	3.6	0	0.6
9	2	1986	5254	-10.5	-5.9	0.3	2.6	0	0.2
10	2	1986	2616.8	-7.2	-0.8	0.4	4.6	0	0.4
11	2	1986	3582.8	-2.6	0.7	0.5	3.6	0	0.4
12	2	1986	7927	-5.5	2.6	0.4	3.6	0	0.8
13	2	1986	8401.6	-7.7	3	0.3	4.6	0	1.3
14	2	1986	3402.8	-6.4	0	0.4	5.7	0	0.6
15	2	1986	6199.6	-6.1	1.1	0.4	5.1	0	0.7
16	2	1986	2923.4	-6.6	-0.6	0.4	5.1	0	0.5
17	2	1986	5931.6	-5.3	2.3	0.4	7.7	0	1.1
18	2	1986	3032	-6.6	-0.6	0.4	4.6	0	0.5
19	2	1986	3087.5	-6.9	-1.5	0.4	4.1	0	0.4
20	2	1986	6281	-11.6	-1.3	0.3	1.5	0	0.4
21	2	1986	7484.8	-14.6	-1.9	0.3	1	0	0.3
22	2	1986	3819.9	-14.4	-1.8	0.3	2.1	0.4	0.4
23	2	1986	9808.7	-9.6	-2	0.3	3.6	0	0.7
24	2	1986	8709.7	-13.1	1.4	0.3	3.1	0	0.8
25	2	1986	7750.1	-7.6	-0.9	0.3	4.6	0	1
26	2	1986	11129.8	-10.4	-0.2	0.3	5.1	0	0.9
27	2	1986	11189.3	-11.3	1.9	0.2	5.1	0	1.6
28	2	1986	6446.9	-6.7	2.5	0.2	7.7	0	2.3
1	3	1986	3679.9	-2.6	0.4	0.3	6.2	0	1.6
2	3	1986	10660.2	-6.8	3.1	0.4	4.6	0	1

Day	Month	Year	Radiation kJ/m2	TMin [?C]	TMax [?C]	Humidity [kPa]	Wind [m/s]	Rain [mm]	ETref [mm]
1	7	1986	26397.7	15.7	30.7	1.8	2.6	0	6
2	7	1986	21864.5	15.4	30.5	2	2.1	0	4.9
3	7	1986	22527.1	14.8	26.8	1.8	3.1	0	4.7
4	7	1986	20182.3	12.3	24.1	1.4	4.1	0	4.6
5	7	1986	8964.4	14	22.1	1.7	3.6	4.8	2.4
6	7	1986	15495.5	13	20.6	1.6	2.6	1.8	2.8
7	7	1986	17244.7	9.9	20.3	1.2	3.1	1.3	3.5
8	7	1986	25803.5	9.9	20.8	1.1	2.6	0	4.6
9	7	1986	20731.7	11.2	19.3	1.1	3.1	0	4.1
10	7	1986	12263.8	12.1	19	1.3	3.1	0	2.8
11	7	1986	20530.9	8.6	20.6	1.2	2.6	0	3.6
12	7	1986	20224.4	6.1	19.4	1	2.6	0	3.6
13	7	1986	26160.2	9.4	19.9	1.1	2.6	0	4.3
14	7	1986	8760	9.2	21.4	1.5	2.1	0.5	2
15	7	1986	12524.7	13.3	24.8	1.8	1.5	0	2.7
16	7	1986	22505.6	12.7	29.1	1.8	1.5	0	4.4
17	7	1986	20162.1	9.9	25.1	1.5	3.1	0	4
18	7	1986	17822	9.2	20.3	1.2	2.6	0	3.4
19	7	1986	17239	8.8	20.5	1.2	1.5	0	3.1
20	7	1986	10459.7	8.1	21.7	1.3	3.1	0	2.7
21	7	1986	9480.9	12.9	22.1	1.6	2.6	0	2.4
22	7	1986	11996.3	11.3	20.4	1.5	2.1	2.2	2.3
23	7	1986	17588.6	9.6	20.5	1.3	2.6	0.9	3.2
24	7	1986	17135.4	9.5	18.6	1.3	4.1	23	2.9
25	7	1986	8390.4	12.3	16.6	1.5	3.1	8.2	1.5
26	7	1986	8751.3	14	19.9	1.7	3.1	0.5	1.9
27	7	1986	22838.6	16	23.4	1.8	3.6	0	4.1
28	7	1986	13856.7	15.8	26.9	1.9	2.1	0	3.3
29	7	1986	13803.9	16.5	21.7	1.6	5.1	0	3.7
30	7	1986	18521.7	11.8	22.9	1.5	2.1	0	3.4
31	7	1986	13429.7	13.6	22	1.4	4.6	0	3.7
1	8	1986	22482.7	13.7	21.6	1.3	3.1	0	4.4
2	8	1986	16345.8	10.2	23	1.3	3.6	0	3.8
3	8	1986	19960.6	10.1	29.8	1.7	3.1	3.2	4.6
4	8	1986	12279.1	13.8	21.1	1.7	3.1	3.9	2.4
5	8	1986	20985.2	9.4	19.8	1.3	3.6	0	3.3
6	8	1986	24165.7	8.1	25.1	1.2	2.6	0	4.6
7	8	1986	15612.6	14.1	20.7	1.4	5.1	0	3.7
8	8	1986	10477.7	9.6	19.4	1.4	3.6	0	2.1
9	8	1986	12230.7	9	21.8	1.4	1.5	0	2.3
10	8	1986	17199.8	11	23.8	1.3	3.6	0	4.1
11	8	1986	13642.8	11.1	23.2	1.4	3.6	0	3.4
12	8	1986	14340.2	11.5	20.8	1.5	4.1	0	2.7
13	8	1986	20660.3	10.1	22.9	1.4	1.5	0	3.4
14	8	1986	16354.1	11.9	25.8	1.5	2.6	0	3.7
15	8	1986	17284.7	15.2	22.2	1.4	4.1	0	4.2
16	8	1986	19853.4	12.6	20.6	1.3	4.1	0	3.9
17	8	1986	11169.2	12.3	21.2	1.5	2.6	0	2.4
18	8	1986	9461.8	12.3	18.8	1.2	3.6	0	2.8
19	8	1986	9895.4	11.7	18.4	1.4	3.1	2.2	2.1
20	8	1986	16065.1	6.9	17.7	1.2	3.1	3.9	2.3
21	8	1986	15099.2	4.8	20.3	1	2.1	0	2.8
22	8	1986	8072.8	11.9	20.9	1.7	2.1	6.3	1.6
23	8	1986	13554.5	8.7	18.8	1.3	2.6	0.7	2.2
24	8	1986	15673.5	7.5	18	1.2	2.6	1.6	2.4
25	8	1986	10194.9	7.8	19.7	1.2	2.1	0	2.2
26	8	1986	8656.6	12.2	20.5	1.5	6.7	13	2.5
27	8	1986	6646.8	11.1	14.2	1.2	7.2	17	1.8
28	8	1986	12006.2	9.3	16	1.2	4.1	1.1	2.1
29	8	1986	11195.9	9.4	16.1	1.2	4.6	11.1	2.1
30	8	1986	8243.9	10.3	16.7	1.4	3.1	11.6	1.4

Table 5.1. An example of a meteorological data (year 1986) obtained from KNMI website.

Biweekly groundwater level data for the interest area was accessed from Dino Loket website (www.dinoloket.nl). A total of around 100 boreholes data for the Kromme Rijn area were retrieved but only 9 boreholes (on fruit plantation land use) were selected based on the plausible groundwater fluctuation and availability of recent record data (1985 onward, see table 5.2.).

Borehole number	Coordinate (Dutch RD)		Elevation above NAP (m)	Soil type	Dutch surface layer
	X	Y			
B39A0176	145000	445560	3,32	heavy loam	lichte klei met homogen profiel
B39A0187	149313	444324	3,92	light loam	klei op zand
B39A0219	149270	444751	2,79	heavy loam	lichte klei met homogen profiel
B39A0270	148802	444769	3,66	heavy loam	lichte klei met homogen profiel
B39A0314	147680	446100	3,85	light loam	klei op zand
B39A0350	144700	449260	2,96	heavy loam	lichte klei met homogen profiel
B39B0280	151290	444200	4,55	light loam	klei op zand
B39C0556	141073	452313	2,33	heavy loam	lichte klei met homogen profiel
B39C0705	144710	450200	3,27	heavy loam	lichte klei met homogen profiel

Table 5.1. selected boreholes and their location

To simplify the borehole number from this point forward, the number of the boreholes will be written with only the last three numbers, thus for example B39A0176 become 176, and so on.

5.3. Irrigation

Based on the agreement between HDSR and the farmers, HDSR will supply 1.5 m^3/day per hectare and the amount of water supply will be increased to maximum 9 m^3/day per hectare for dry period. Unfortunately, the real scheduled irrigation applied in the field is not recorded. In most cases the irrigation type applied in the field is surface irrigation. For simplicity reason, based on the information and provided by HDSR, the irrigation water amount is set to be 0.15 mm/day for normal month and 0.6 mm/day for dry month. Dry period is defined here as precipitation deficit, i.e. when the total precipitation is below the potential evapotranspiration. For the entire period of interest, the amount of irrigation per day can be realized by calculating the difference between precipitation and potential evapotranspiration for every month based on the meteorological data and applied the criteria defined above (i.e. 0.15 mm/day for normal month and 0.6 mm/day for dry month. The irrigation is applied during the month of April till October.
A screenshot of irrigation data input for the year 1986 is shown in figure 5.3. The year 1986 is known as dry year and in most of the month, the amount of precipitation is well below the potential evapotranspiration. Therefore, the amount of irrigation for the year 1986 is set in SWAP program as 0.6 mm/day. This criterion was applied to every year of interest.

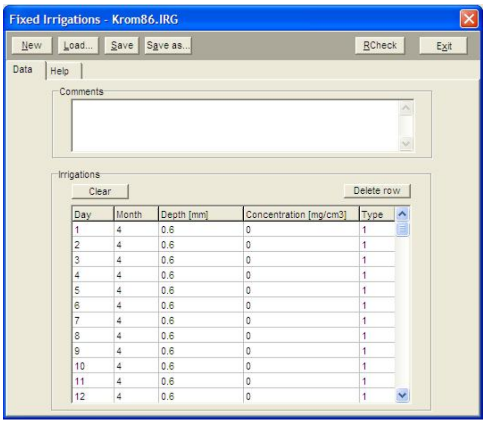


Figure 5.2. A screenshot of irrigation data input for the year 1986.

5.4. Crop Data

As described in chapter 3, in the area of Kromme Rijn, apple is the most fruit vegetation planted. To date, unfortunately, there is no crop parameters that can be readily be used as input to build SWAP crop model for apple crop. The National Hydrologisch Instumentarium (NHI) in their report, ‘*Deelraport Gewaskenmerken’* (2008). Suggested the users to use the crop parameters for oak tree as the closest parameters to model apple trees. Therefore, in this thesis the model parameters for apple are defined as that for oak tree defined NHI.

With respect to crop growth development, a simple crop development model is chosen because the crop growth input data is not available to simulate a detailed crop model. This model represents a green canopy that intercepts precipitation, transpires, and shades the ground which requires data of leaf area index (LAI), crop height (CH), and rooting depth (RD) as a function of development stage. The DVS is phonological stage of the plant which is expressed as 0 < DVS < 2. For many annual crops DVS value of 0 means at seedling emergence, goes to 1 at flowering, and 2 at maturity. The most essential phonological change is the one from vegetative (0 < DVS < 1) to reproductive stage (1< DVS < 2). Below are the explanations of these parameters.

a. Leaf Area Index (LAI)
   Leaf Area Index is the ratio of total leaf area surface of the vegetation and the surface area of the land where the vegetation grows. This parameter need to be specified as a function of development stage to divide the potential evapotranspiration over the potential (crop) transpiration and potential (soil) evapotranspiration.
b. Crop height
   As described before, in this model evapotranspiration is calculated using the Penman-Monteith equation. The crop height is one of the important physical parameter to apply this method in calculating evapotranspiration.
c. Rooting depth
   Root depth is one of the factors that determine the amount of soil water available for transpiration. The rooting depth for the model was taken from NHI report Table xx shows the value of rooting depth and root density that are applied in the model.

In the simple crop model routine, there are many input parameters to be defined. Following sections describe the input crop parameters in the simple crop model.

5.4.1 Crop development and root distribution

According to NHI report, the extinction coefficient for diffuse visible light and the extinction coefficient for direct visible light were set to be 0.73. The root density as a function of depth is also given by NHI and the values are shown in the screenshot of the crop parameters defined in the SWAP model shown in figure 5.3.

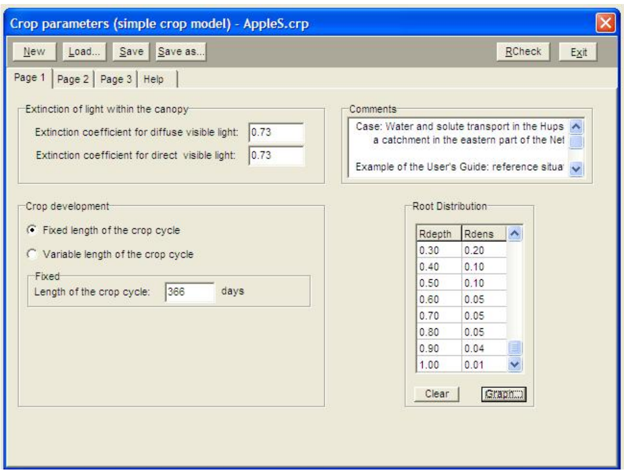


Figure 5.3. A screenshot apple crop parameters defined in the SWAP model.

5.4.2 Function of development stage

Further, NHI also provides the data for LAI as a function of development stage (DVS)(see figure 5.4.). According to FAO irrigation and drainage paper no. 56 (Allen et al, 1998), the maximum height of an apple tree is 4 meters. In this thesis, the average height of apple tree is assumed to be 3 m (average) and the rooting depth is assumed to be 100 cm as suggested by NHI. Yield response factor is the most difficult factor to estimate. In this thesis, a simple crop yield model is selected since there is no available data could be used to estimate crop yield factor for apple and it is not easy to be measured. For simple model, the SWAP manual suggests to use crop yield factor equal to 1 for the whole growing season which is adopted here (see figure 5.4).

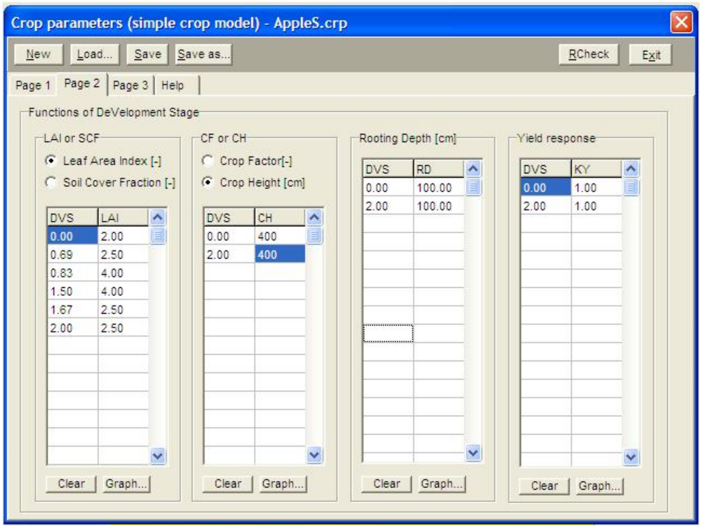


Figure 5.4 The screenshot apple crop parameters defined in SWAP (function of development stage).

5.4.3 Water stress response function

Finally, for water stress response function, different parameters are defined based on the data suggested by NHI report (See figure 5.5). In this study, salinity stress is not taken into account since the water in the area of study is fresh water. This is realized by deactivating the function of water stress in the simulation option.

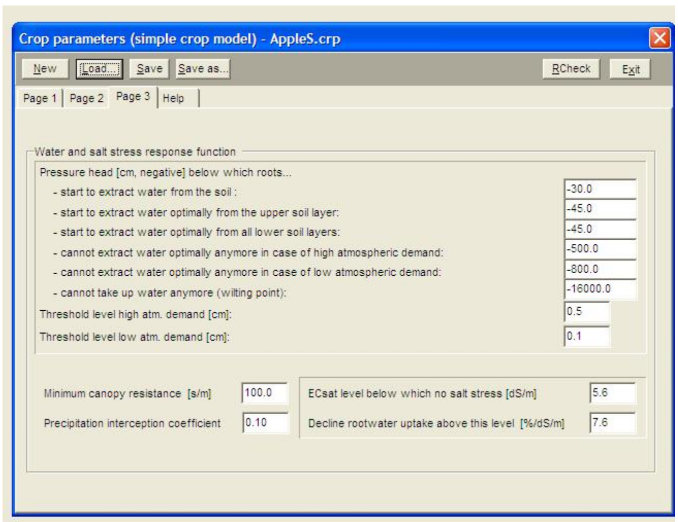


Figure 5.5. Parameters defined for water stress response function as suggested by NHI report.

5.5. Soil

Soil water section is one of the main input file beside other files that have been describe in the previous sections. In the following sections, the input parameters for soil properties are described.

5.5.1 Ponding

The maximum ponding layer thickness (cm) is the threshold of water layer thickness on top of the soil surface before run-off starts. Here the maximum thickness of ponding water layer is set at 0.2 cm.

5.5.2 Soil Evaporation and numerical scheme

Soil evaporation is calculated using Penman-Monteith equation described in chapter 4. In some cases however, calculation of actual soil evaporation using soil hydraulic function could be overestimated. Therefore, SWAP allows users to select empirical functions with different coefficients that need to be defined. Here, SWAP manual recommends users (default) to use the combination of reduction to maximum Darcy flux and maximum black. Default soil evaporation coefficient for black equals to 0.35 cm/day$^{0.5}$. Default minimum rainfall for model reset (cm) is used here (= 0.5). Further, default parameters for numerical scheme to discretize Richard's equation are used here (see figure 5.6.).

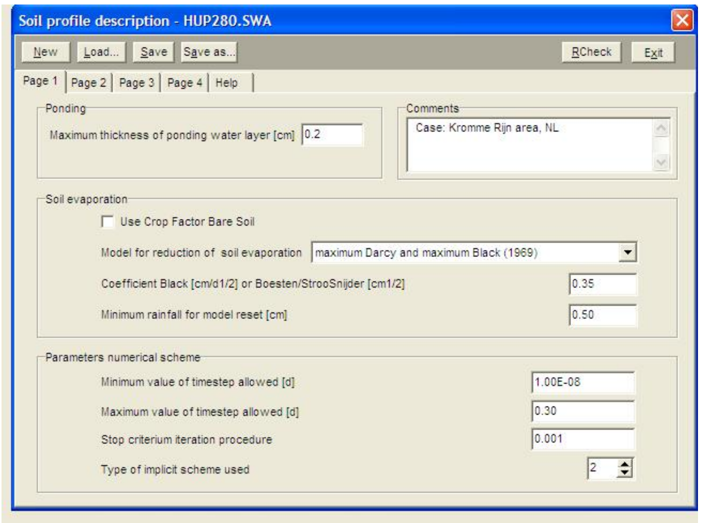


Figure 5.6. Parameters defined for ponding, soil evaporation and parameters for numerical scheme.

5.5.3 Soil hydraulic properties

In this thesis, soil types are grouped into two types of soil, light loamy soil and heavy loamy soil. These two soil types have different hydraulic properties. The light loamy soil is modeled with two layers, i.e. at the top loam (B8) and at the bottom loam (O10). Heavy loam is also modeled with 2 layers i.e. at the top clay (B10) and at the bottom is loam (O10). The soil of hydraulic functions of the soil layers to a depth of 4 m (the depth of soil domain chosen here) and soil water retention parameter was taken from Van Genuchten-Mualem parameters (i.e. saturated moisture content (θ_{sat}), residual moisture content θ_r, saturated hydraulic conductivity K_s, and shape parameters n, α, and λ were obtained from Wosten et al., 1994)). The parameters used to define the soil hydraulic properties of top soil loam (B8), top soil Clay (B10) and sub soil loam (010) is shown in table 5.3. below.

Soils	θres (cm3 cm-3)	θsat (cm3 cm-3)	Ksat	α (cm-1)	λ (-)	n (-)
(Top) Loam (B8)	0	0,43	2,25	0,0096	-2,733	1,284
(Top) Clay (B10)	0,1	0,42	1,17	0,0118	-4,795	1,224
(Sub) Loam (O10)	0	0,49	2,22	0,0107	-2,123	1,28

Table 5.3. Top and sub soil properties.

5.5.4 Soil Geometry and Texture

The soil in the area of study is simply modeled with 2 layers, i.e. top layers (14 cm thick) are divided into 10 compartments (vertical descretization) with 1 cm thick plus 2 compartments with 5 cm thick. The sub soil layer is modeled with 44 compartments with 5 cm thick and 18 compartments with 10 cm thick. The soil texture is defined as shown in figure 5.7.

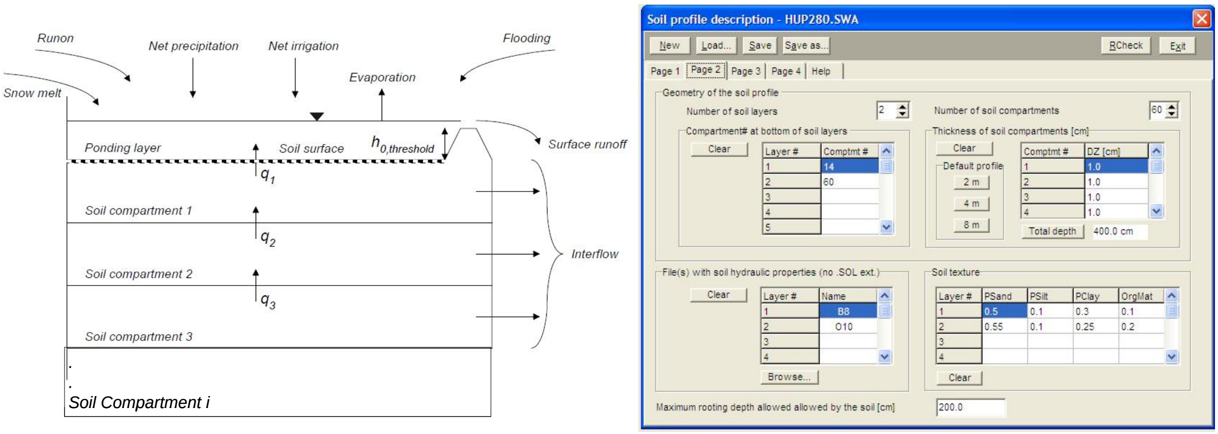


Figure 5.7. Geometry of soil profile and soil texture defined here (left: schematic representation and right: input parameters).

5.6 Drainage and bottom boundary

In this thesis, the surface water system takes into account only one channel order which is main ditch which are the most watercourses occur in the study area. In the Krommerijn area, there are ditches with average distance between ditches as 300 m (Gerretsen 1993, HDSR). The depth of water level and the depth of the bottom of the ditches for the selected areas are shown in table 5.4. The data was obtained from GIS map available in HDSR. The basic drainage routine is chosen here for simplicity reason.

Location	Water Level in Channel Summer [cm]	Water Level in Channel Winter [cm]	Depth of Bottom of Channel [cm]	Drainage Resistance [days]	Infiltration Resistance [days]
A0176	-92	-112	-187	1000	1500
A0187	-80	-100	-200	1000	1500
A0219	-100	-120	-195	900	1350
A0270	-60	-80	-155	950	1425
A0314	-120	-120	-220	800	1200
A0350	-75	-95	-190	1000	1500
B0280	-120	-120	-195	800	1200
C0556	-95	-115	-205	900	1350
C0705	-100	-120	-215	1000	1500

Table 5.4. Input parameters for drainage.

The exact values of drainage resistance and infiltration resistance are very difficult to determine. These values strongly depend on the phreatic groundwater level and drainage level as described by equation 5.4 and soil type. In addition the value of drainage resistance is also average for a certain

region. Based on the type of soil described in chapter 3, the values of drainage resistance for light and heavy loamy are estimated to be between 700 and 1000 days. The value of infiltration resistance is assumed to be 1.5 times greater than the drainage resistance (as suggested by SWAP model). The values of drainage resistance are iterated between 700 and 1000 days to fit the measured ground water level (see chapter 6). A sensitivity analysis on this parameters on bottom flux and infiltration is discussed in chapter 8.
The values of drainage and infiltration resistance that best fit the measured ground water level for each location is shown in table 5.3.

The SWAP model offers 8 options for the lower boundary conditions. Here, the lower boundary conditions that calculate bottom flux from hydraulic head of deep equifier is chosen. The parameter mean drain base to correct the ground water level is chosen to be the depth of surface water level in the ditches (see table 5.3). The vertical resistance of semi-permeable layer is assumed to be 200 days. The value of average hydraulic head in the equifer is difficult to determine. Here, the values are iterated to fit the measured ground water level (see chapter 6). These values (after the iteration) are shown in table 5.5.

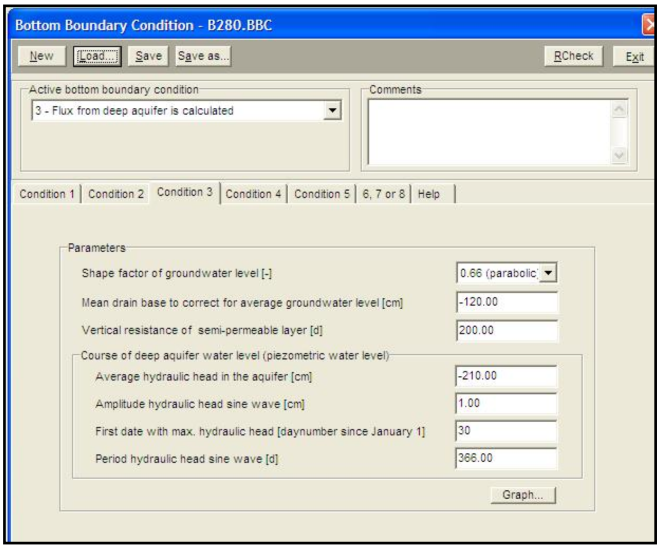


Figure 5.8. Screenshot of bottom boundary parameters input defined here.

Location	Average hydraulic head in equifer [day]
A0176	-250
A0187	-220
A0219	-170
A0270	-175
A0314	-220
A0350	-170
B0280	-210
C0556	-150
C0705	-170

Table 5.5. Values of hydraulic head in equifer for all the locations.

Chapter 6
Results and Analysis - Model calibration

6.1. SWAP model calibration

Based on all the input parameters described in chapter 5, SWAP program can calculate some desired output like ground water level, crop yield, and water balance. In this chapter, the results of SWAP model described here are calibrated against the measured ground water level recorded by DINO *loket* provided by TNO *(www.dinoloket.nl)*. DINO *loket* is the central gateway data and information of subsurface of The Netherlands. From the archive data one can extract data of groundwater, well logging, seismic data, etc for deep and shallow subsurface in the Netherlands.

The calculation of crop yield based on the simple model described here is also callibrated by using the recorded apple yield in the area of Kromme Rijn obtained from Centraal Bureau Statistic (CBS). Finally, the results of the model are also calibrated with the value of biomass recoded by HDSR in 2011.

6.2. Ground water level calibration

Data of ground water level presented here is obtained from DINO *loket* website. As described in chapter 3, there are 9 boreholes locations of ground water level selected based on the available data. Two points representing light loam (location B0280) and heavy loam (location C0556) soils were selected (see figures 6.1 and 6.2.). The rest of the results of the calibration are shown in appendix A.

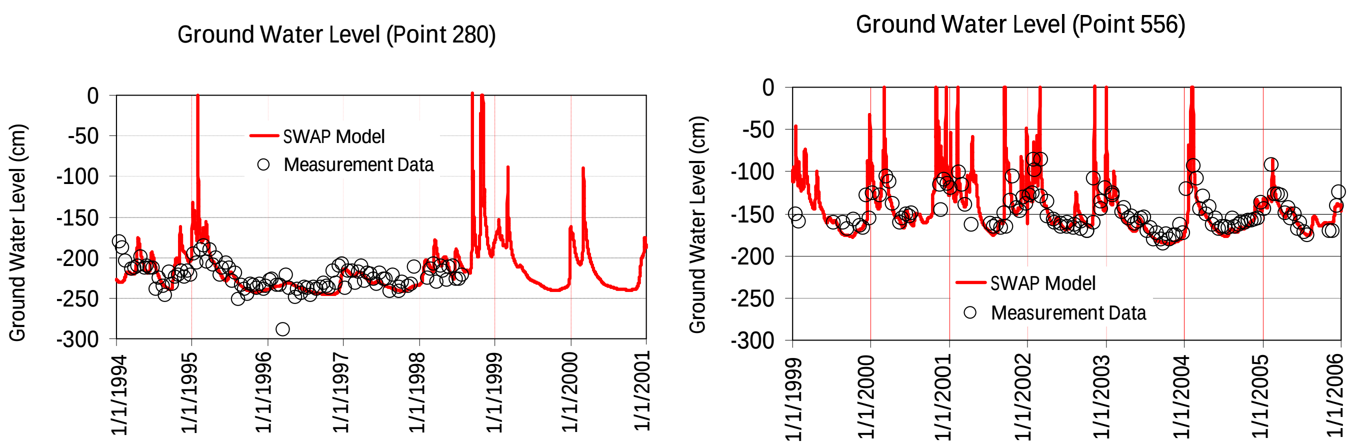


Figure 6.1. Ground water level calculated with SWAP model described here and ground water level measurements for location 280 and 556.

	Point 280								
	Water in (cm)			Water Out (cm)					
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-57.99	4.59	6.38	41.84	11.17	-26.83
1995	72.95	8.7	-57.88	3.94	5.11	45.86	11.47	-26.79
1996	57.57	8.68	-31.29	3.49	0.95	44.84	9.77	-33.69
1997	74.35	7.3	-48.71	3.99	1.06	43.62	11.12	-29.18
1998	123.96	4.69	-89.02	5.45	12.46	27.48	10.5	-18.34
1999	90.15	7.35	-58.45	4.8	1.5	47.01	11.23	-26.68
2000	93.24	5.96	-55.1	5.12	16.79	41.52	10.88	-27.63
	Point 556								
	Water in (cm)			Water Out (cm)					
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1999	90.15	7.31	-40.18	4.8	8.87	44.89	9.98	-12.14
2000	93.24	8.7	-56.22	5.12	6.12	33.79	9.63	-8.18
2001	103.89	7.31	-55.29	5.07	12.5	35.71	9.77	-8.42
2002	92.4	7.3	-42.84	4.3	14.65	39.2	10.22	-11.47
2003	61.27	8.68	-15.96	3.43	7.3	55.37	10.74	-17.7
2004	85.94	7.35	-31.15	4.45	12.38	45.75	10.66	-14.23
2005	87.29	5.96	-30.59	4.44	16.28	46.4	10.42	-14.51

Table 6.1. Water balance obtained from SWAP model described here.

The SWAP model with input parameters defined here shows good fit with measured ground water level (see figure 6.1 and appendix A). Further, based on the data available in HDSR, it is known that depending on the location, the bottom flux of ground water recharge to equifer is between 1 to 2 mm/day (36 to 72 cm/year). The calculation of water balance presented in table 6.2. (see also appendix A) that the calculated bottom fluxes for all the locations of interest are within the range observed by HDSR. These all shows that the model with the defined parameters described in chapter 5 could predict the ground water dynamics in the selected location described here.

6.3. Relative crop yield calibration

After obtaining the right input parameters that fits the ground water level data (section 6.2), the model could then be extended to calculate the relative crop yield at each point for the year of interest. To calibrate this results, the apple yield per year from the area of Kromme Rijn obtained from CBS is used. The apple yield from 1997 to 2011 recorded by CBS is shown in table 6.2.

Year	Apple Yield [ton]	Area of plantation [ha]	Apple Yield/Area [ton/ha]	Relative Yield [normalised to 2011]
1997	2.13E+05	7014	30.37	0.60
1998	2.29E+05	6994	32.74	0.64
1999	2.62E+05	6721	38.98	0.77
2000	2.15E+05	6129	35.08	0.69
2001	1.97E+05	5571	35.36	0.69
2002	1.65E+05	5225	31.58	0.62
2003	1.72E+05	4884	35.22	0.69
2004	2.14E+05	4928	43.43	0.85
2005	1.79E+05	4706	38.04	0.75
2006	1.76E+05	4640	37.93	0.74
2007	1.87E+05	4603	40.63	0.80
2008	1.89E+05	4554	41.50	0.81
2009	2.01E+05	4467	45.00	0.88
2010	1.73E+05	4232	40.88	0.80
2011	2.07E+05	4063	50.95	1.00

Table 6.2 Apple crop yield from Kromme Rijn area reported by CBS.

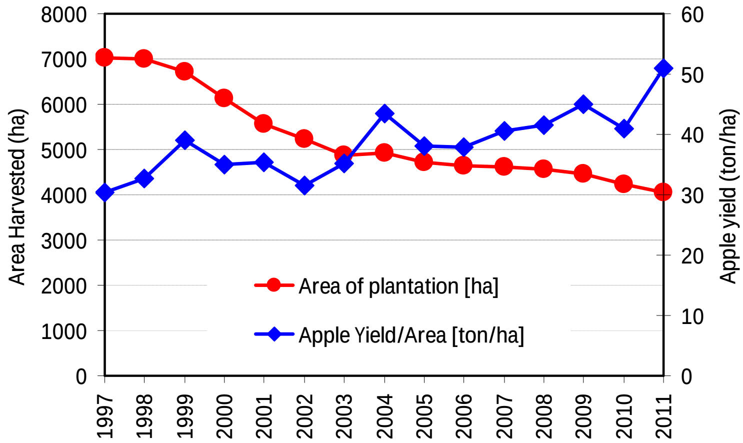


Figure 6.2. Apple yield and area of apple plantation in the Kromme Rijn area from 1997 to 2011.

It is very interesting to see that even though the area of apple plantation in Kromme Rijn area is decreasing, but the apple yield per hectare is increasing (see figure 6.2). This is due to the application of new knowledge and innovation on new pesticide, irrigation scheme or new technology in agriculture.

Due to the limited available data on apple crop, a simple crop yield model is chosen for the SWAP model described here. With the simple model, SWAP could calculate the relative crop yield. This is realized by taking the ratio between the actual transpiration (T_a) and the potential transpiration (T_p) (see equation 5.11.), i.e. relative crop yield (Y_a/Y_p) = (T_a/T_p). To obtain the average relative yield for the entire area of Kromme Rijn, the average relative crop yield for all the point of interests is taken (see table 6.3). To be able to compare the yield response of the SWAP model and the data obtained from CBS, the data of apple yield (ton/ha) in Kromme Rijn area is normalized to the value of apple yield in 2011 because this year is the highest apple production in the presented years (see table 6.3, figure 6.3., see appendix B for the detail data of individual points).

Year	SWAP Model [Average Relative Yield]	CBS Data [Yield normalised to 2011]
1997	0.80	0.60
1998	0.60	0.64
1999	0.88	0.77
2000	0.76	0.69
2001	0.76	0.69
2002	0.82	0.62
2003	0.94	0.69
2004	0.78	0.85
2005	0.83	0.75
2006	0.83	0.74
2007	0.69	0.80
2008	0.78	0.81
2009	0.90	0.88
2010	0.86	0.80
2011	0.80	1.00

Table 6.3. Calculation of average relative crop yield (see appendix B for detail results).

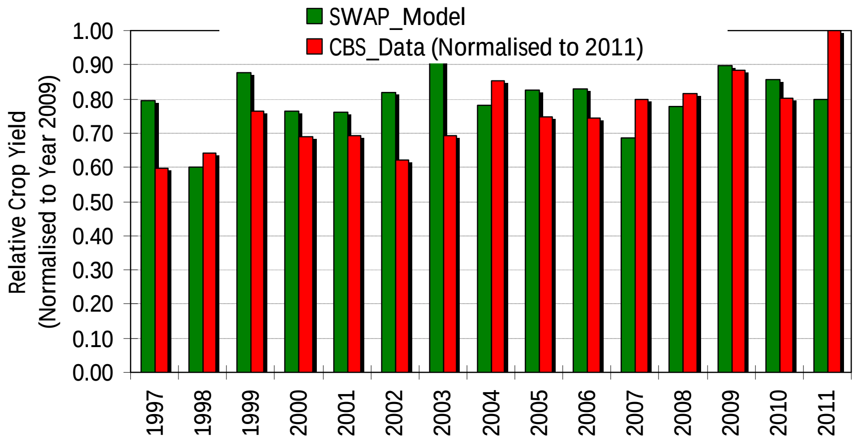


Figure 6.3. Calculation of average relative crop yield (see appendix B for detail of the calculation

Despite all the simplification used in the SWAP model, it still could capture some trends of the relative apple yield in the Kromme Rijn area. However, there are some years where the SWAP model overestimates the actual relative crop yield. This is mainly due to the fact for the simple model was chosen here. The limitation of this model in predicting the relative crop yield is discussed further in chapter 8.

6.4 Remote sensing data

Since 2011, HDSR also collected biomass information in the area of Kromme Rijn using remote sensing data. Assuming that crop yield has a linear correlation with measured biomass, HDSR could then indirectly monitor the development of crop in Kromme Rijn area. The SWAP model for each measurement points is calculated and gives the relative crop yield information in 2011. Adopting the assumption that accumulated biomass has a linear correlation with crop yield, the comparison of relative crop yield and relative accumulated biomass could be derived. This comparison could be used to test the capability of the model to predict the spatial difference of relative crop yield at the area of interest.

To enable the comparison of the biomass estimation using remote sensing technique the accumulated measured biomass is taken as the parameter to normalized the measured accumulative biomass for each point of interest. The maximum measured accumulated biomass for each point of interest is then normalized to the highest accumulated total biomass. This normalized biomass value is then compared to the relative crop yield calculated by SWAP. The detail of remote sensing data is shown in appendix C and the results of normalized biomass are shown in table 6.4. As can be seen in figure 6.4, the model can reasonable depict the different measured biomass depending on the location. However, for the location of 314 and 556, SWAP underestimates the relative biomass calculation. It should be noted that measurement of biomass carried out using the remote sensing technique also includes all the vegetation in the area of interest, i.e. not only apple crops but also grass and other vegetations.

	Total Biomass (Kg/ha)	Relative Biomass	SWAP relative yield
Point 219	52101	0.85	0.81
Point 176	52643	0.86	0.79
Point 280	48865	0.80	0.78
Point 314	61089	1.00	0.80
Point 350	49466	0.81	0.95
Point 556	57685	0.94	0.70
Point 270	51776	0.85	0.78
Point 187	50479	0.83	0.81

Table 6.4. Relative biomass measured by remote sensing technique.

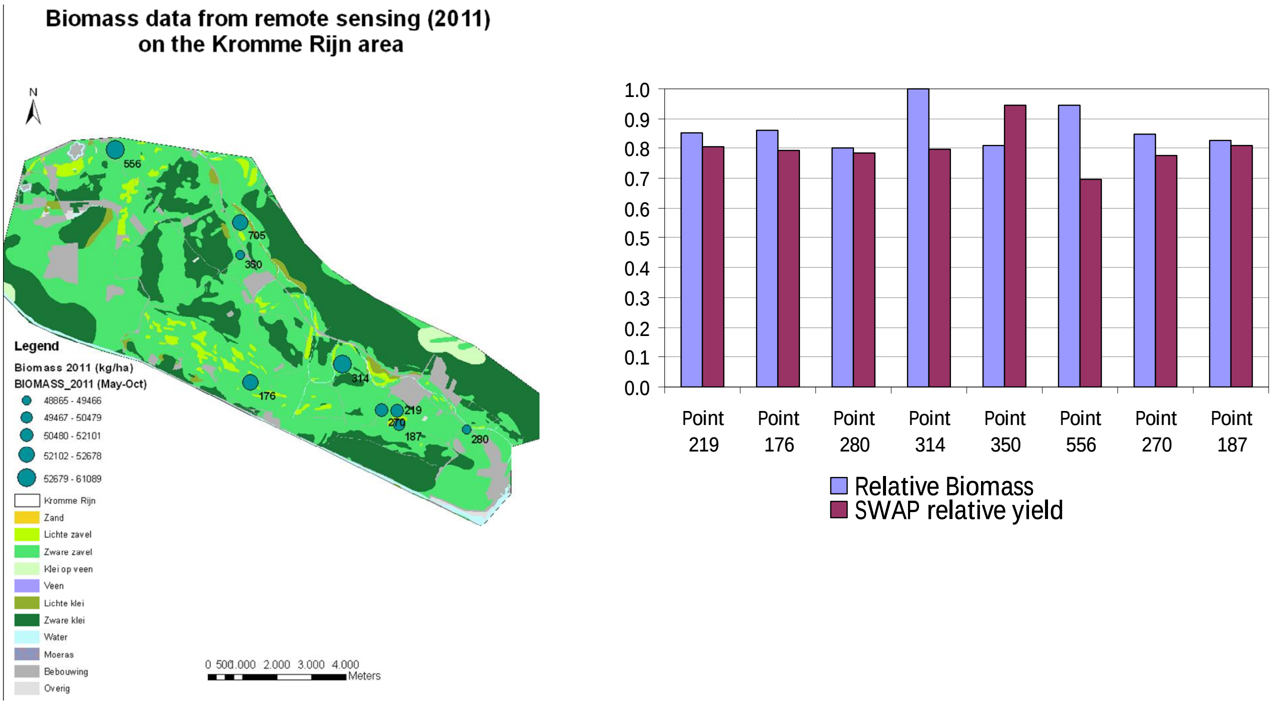


Table 6.4. Relative biomass measured by remote sensing technique compared to relative crop yield obtained from SWAP model described here for the year 2011.

6.5. Outlook

The input parameters used to utilize SWAP program to calculate ground water level shows good fit with the measured ground available ground water level data. In addition, despite the many assumption and the simplification in the model, the calculation of relative crop yield using SWAP model agree (with some exception) qualitatively with relative apple yield in recorded by CBS and relative accumulated biomass (assuming that relative biomass is linearly proportional to relative crop yield) measured by HDSR. Therefore, it is useful to utilize the model to predict the impact of climate change on crop yield and water demand in the area of Kromme Rijn.

Chapter 7
Results and analysis – Impact of Future Climate Scenario on GWL and Water Demand

7.1. Introduction

Climate Change is reported to affect many aspects in environment, e.g. ground water level, water demand and crop yield (Beersma 2004, Tallaksen 2004, Kroes 2011, Van Walsum 2011;2012). There are many models that present the prediction of future temperature, for example SIMGRO, MetaSWAP and SWAP. In this thesis, future climate scenario (W+) presented by KNMI is used to predict future water demand. Future climate scenario is beneficial to study and explore the impacts of climate change on various aspects so that possible strategies could be formulated to any predicted eliminate/minimize negative impacts.

The W+ scenario is the worst case scenario for The Netherlands described by van de Hurk (2006). It is predicted that in the future (2050) the temperature will be raised to 2^{o}C, extreme weather in the winter, and less rainfall in the summer, resulting higher evapotranspiration and raising of the sea level.

As described in chapter 6, the SWAP model for apple crop plantation in Kromme Rijn has been validated using the available data. Therefore, this model can be further utilized to predict ground water level and water demand in the future (i.e. 2046-2055) in order to maintain optimum apple crop yield. This can be realized by providing the predicted future meteorological data into the SWAP model with the input parameters that has been validated model. The results of impact of future climate changes on water demand in Kromme Rijn area are presented in this chapter and are compared with the reference year (1986-1995). This chapter will be concluded with the estimation of water demand in the future which is useful information for HDSR in order to ensure sufficient water supply to Kromme Rijn area.

7.2. Future Climate Scenario

The future climate scenario used here is obtained from KNMI. The future climate scenario provided by KNMI gives information on the characteristics of the average weather and the chance of weather extremes.

As described in chapter 5, meteorological data, i.e. daily minimum and maximum temperature, precipitation, humidity, wind speed and solar radiation, is needed to enable as input for SWAP model to calculate potential evapotranspiration. The KNMI provided future daily mean temperature and rainfall. However, HDSR does not provide the prediction of humidity in the future. Here, a prediction of future humidity is presented.

Humidity has a strong correlation with average daily temperature, therefore, based on the average daily temperature provided by KNMI can be used to predict humidity in the future. Further, it is assumed that the wind speed and the radiation are assumed to be the same as the reference year (van Walsum, 2011, 2012). The estimation of these input meteorological parameters is explained in the following section.

7.2.1. Temperature

The future climate scenario W+ predicts that the temperature will increase by 2 degrees in 2050 compare to that in 1990. This means, for example, the temperature in 2046 is about 2 degrees higher compared to that in 1986 (reference time). This could be illustrated in the following figures. The time series of future temperature prediction available from KNMI website is used here.

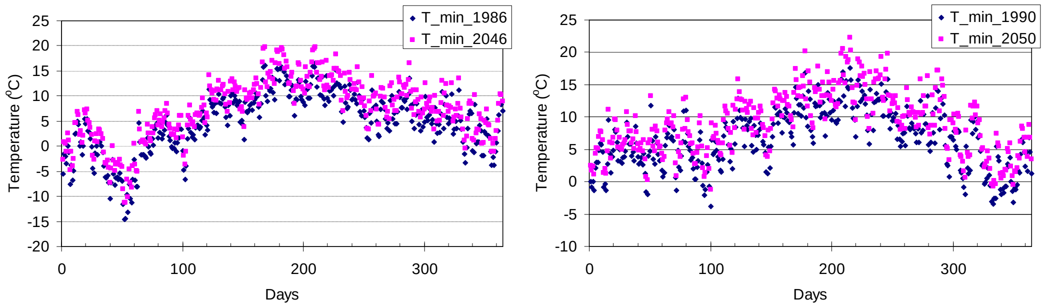


Figure 7.1 Minimum temperature measured in 1986 and 1990 compared to the predicted minimum in future climate, i.e. 2046 and 2050.

7.2.2 Rainfall

KNMI predicts the future rainfall throughout the year, and it is predicted that more extreme rainfall in the winter and less rainfall in the summer. The time series of rainfall data obtained from KNMI website will be used as input in the model. An example of rainfall measured in 1990 and the predicted rainfall is shown in the following figure.

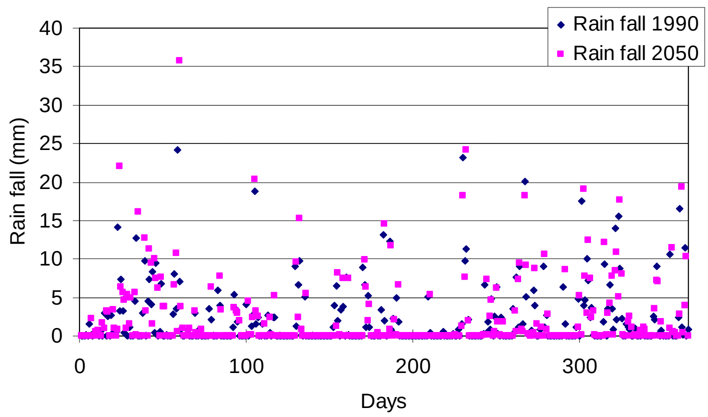


Figure 7.2 Rainfall measured in 1990 and the rainfall in the future (2050) predicted by KNMI.

7.2.3 Air Humidity

Air humidity is a term that describes the amount of water vapor in the air and can be expressed in several ways. In agro meteorology, there are some common expressions to indicate air humidity such as vapor pressure, dew point temperature, and relative humidity. Humidity values indicate the likelihood of precipitation and dew. High humidity reduces the rate of evaporation. Relative humidity in air depends very much on the average temperature in the area of interest and the environment. The relation between of humidity with average temperature is unique for every location (Allen et al, 1998) The relative humidity expressed in kPa increases with increasing daily average temperature (see figure 7.3.). Therefore, to enable the prediction of humidity in the future, a correlation between daily mean temperature for all point of interest with recorded humidity for the reference year (1986 -1995) is first need to be made. An example of the correlation between daily average temperatures with relative humidity is shown in figure 7.3. The correlation between daily average temperature and humidity could be fit with second order polynomial equation (with good correlation, R^2 better than 0.8) within the range of average temperature of interest. With the fitting equation obtained from the correlation between average temperatures with humidity in every location of interest, prediction for the humidity in the future can be done by inserting the prediction of average daily temperature given by KNMI in the fitting equation. This method is used to obtain the humidity data for future climate prediction.

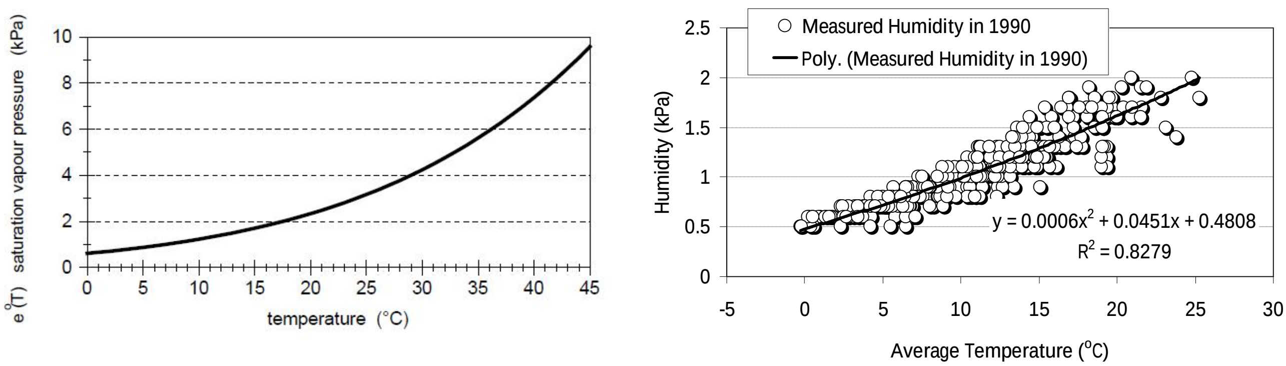


Figure 7.3 The correlation between the humidity and average temperature, FAO report (Allen et al, 1998)(left) and De Bilt station in 1990 (right).

7.2.4 Radiation and Wind Speed

The prediction of future radiation and wind speed is not available. This is very difficult since there are so many factors influencing these parameters. However, van Walsum stated (2011) that it is realistic to use the radiation and wind speed data of the reference time as data for future meteorological data. In this thesis, the radiation and wind speed data are assumed to be the same to the reference time (i.e wind speed and radiation in 1986 is the same as that in 2046, data in 1990 is the same as that in 2050, and so on).

7.3. Results of the SWAP Model

Based on the meteorological data for future climate as described above, prediction of ground water level, crop yield and water demand could be carried out by taking the other input parameters the same as described in chapter 5.

As described earlier, this thesis aims to calculate water demand in the Kromme Rijn area in response to climate change in the future in order to maintain maximum apple crop yield. In the calculation with SWAP model, the model is set to simulate the amount of irrigation in order to obtain relative crop yield larger than 0.95 as suggested in the SWAP manual. This is realized by activating the subroutine of scheduled irrigation in the irrigation input menu. Activating this subroutine means that the SWAP model will apply automatically a certain amount of irrigation to reach the relative crop yield of at least 0.95.

7.3.1. Ground Water Level

The comparison of ground water level in the reference time (1986 – 1995) and future time (2046 - 2055) is shown in the following figures. As can be seen from figure 7.4 the ground water level in the future (2046-2055) is lower than that in the reference year (1986-1995). In general, ground water level in the summer 2046-2055 is about 10 to 50 cm annually lower than that in 1986-1995

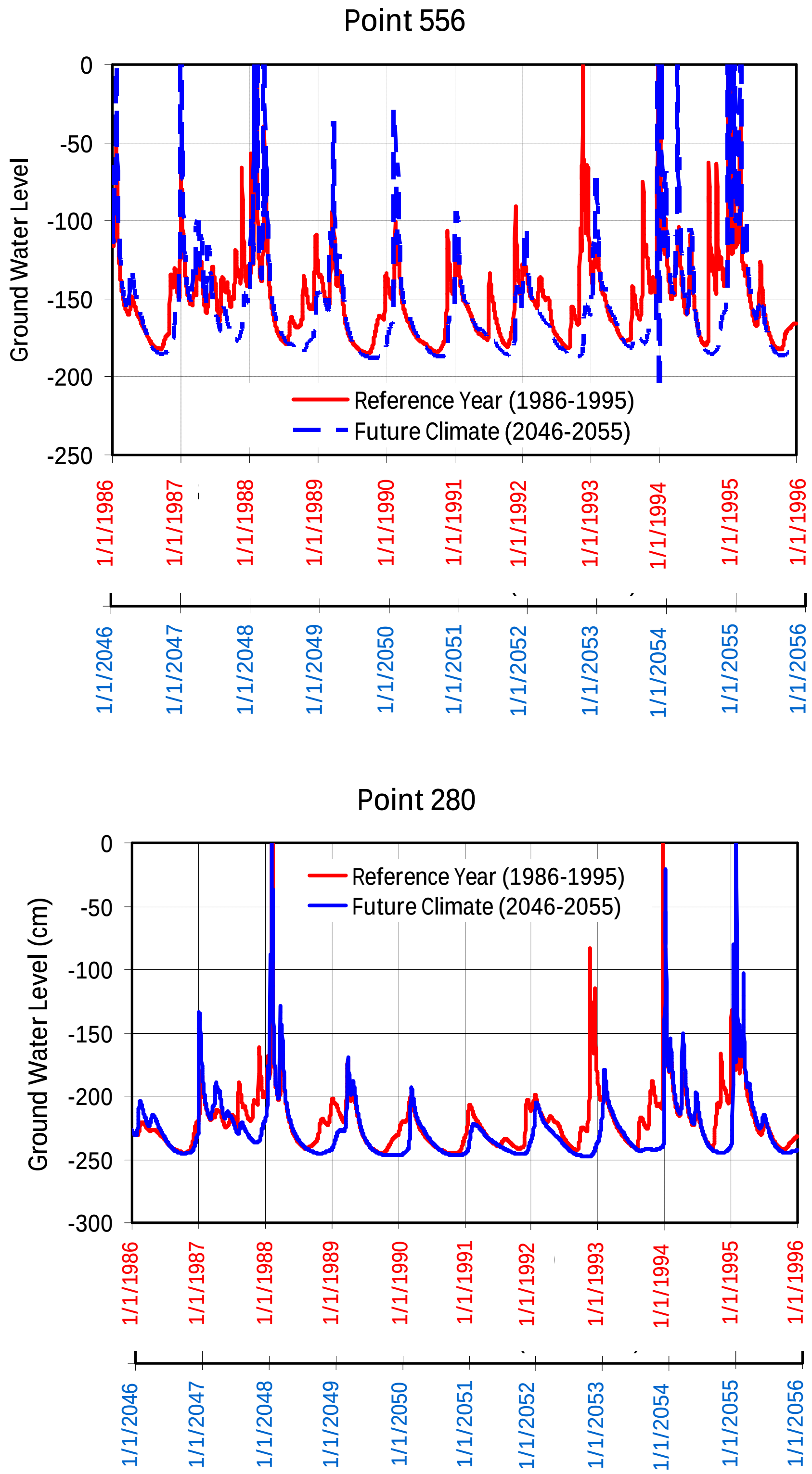
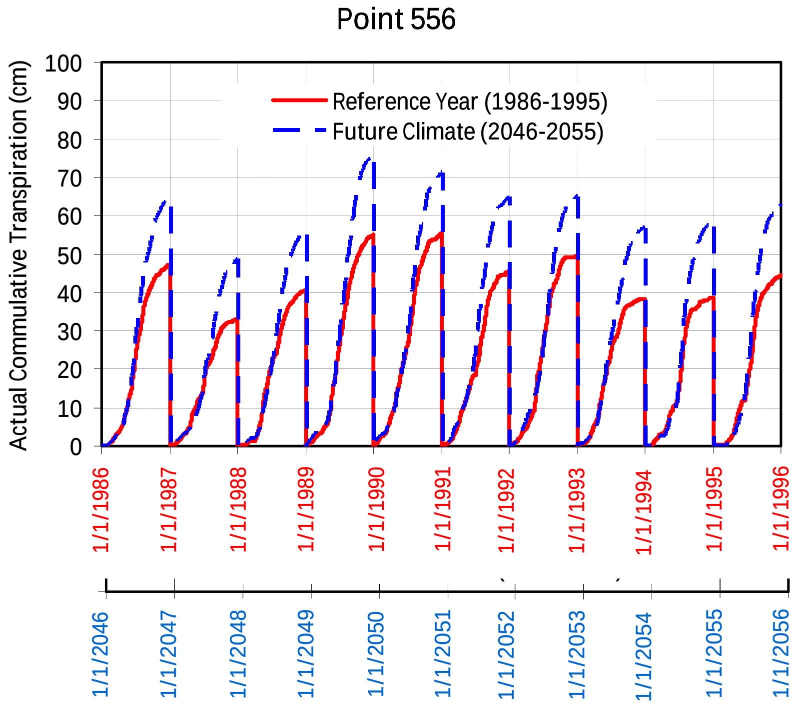


Figure 7.4 Groundwater in the reference time and in the future.

7.3.2 Actual Transpiration and Evaporation

The following figure sshows the calculated actual transpiration and evaporation for the reference time (1986 -1995) and the figure climate (2046-2055). Figures 7.5 and 7.6 clearly show that actual transpiration and evaporation will increase in the future. This is expected as the temperature in the future climate is predicted to be higher which therefore increase transpiration and evaporation. In average, for the future climate transpiration will increase by 15 to 25 cm annually higher than that in the reference year. Further, for the future climate, evaporation will increase 2 to 4 cm/year.



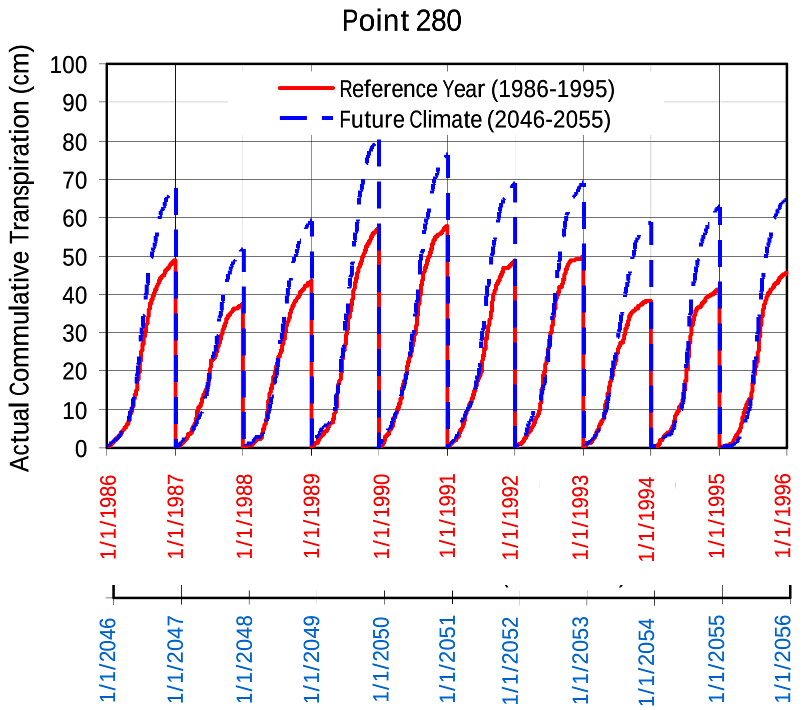
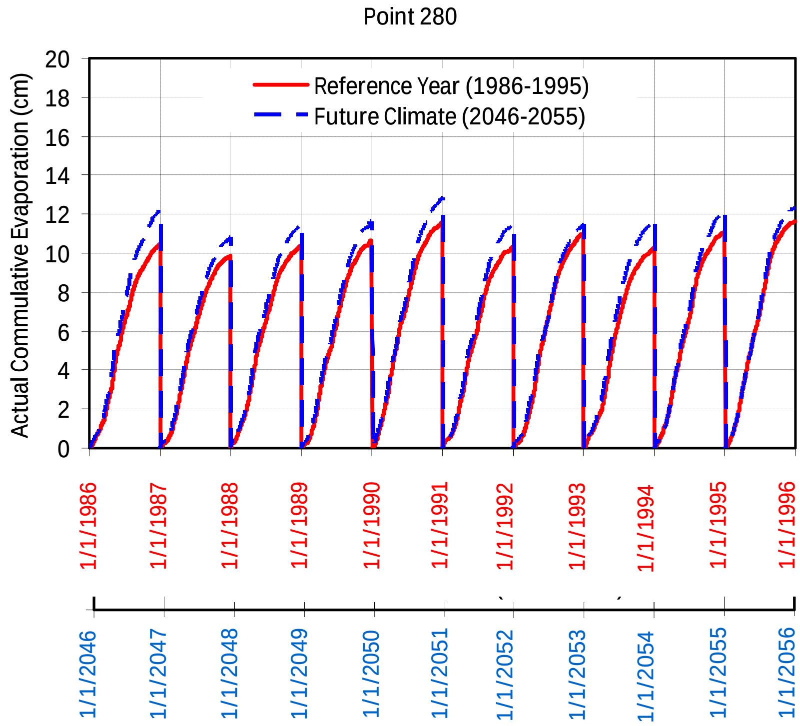


Figure 7.5 Calculated transpiration for the reference time (1986 – 1995) and future time (2046 – 2055).



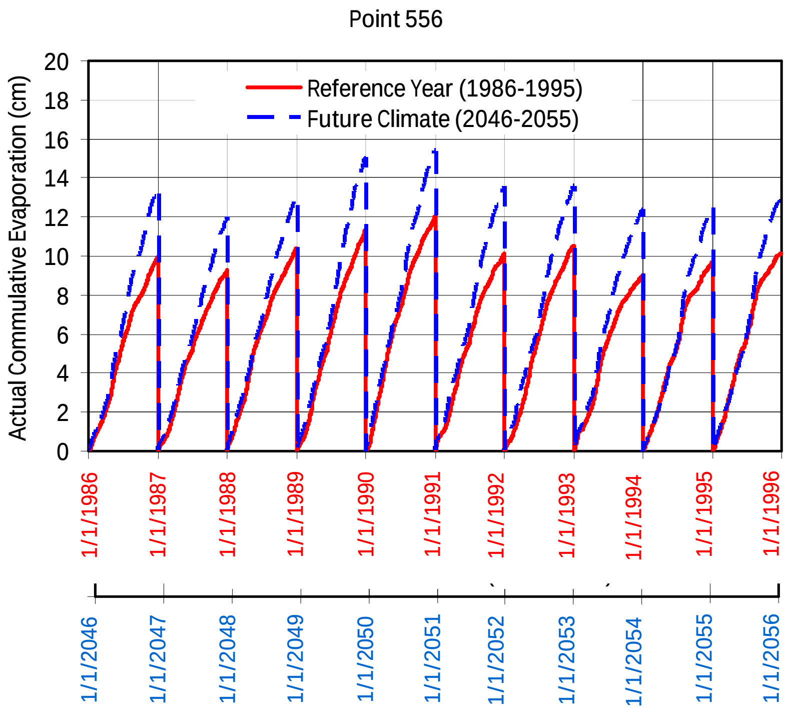


Figure 7.6 Calculated evaporation for the reference time (1986 – 1995) and future time (2046 – 2055).

7.3.3. Irrigation

In order to maintain the crop yield, the water demand should be supplied. In the model, the SWAP program calculates the need for irrigation to achieve optimum relative crop yield in the year. In this way the SWAP software can calculate the amount of irrigation needed to maintain high crop yield. The results are shown in the following figure.

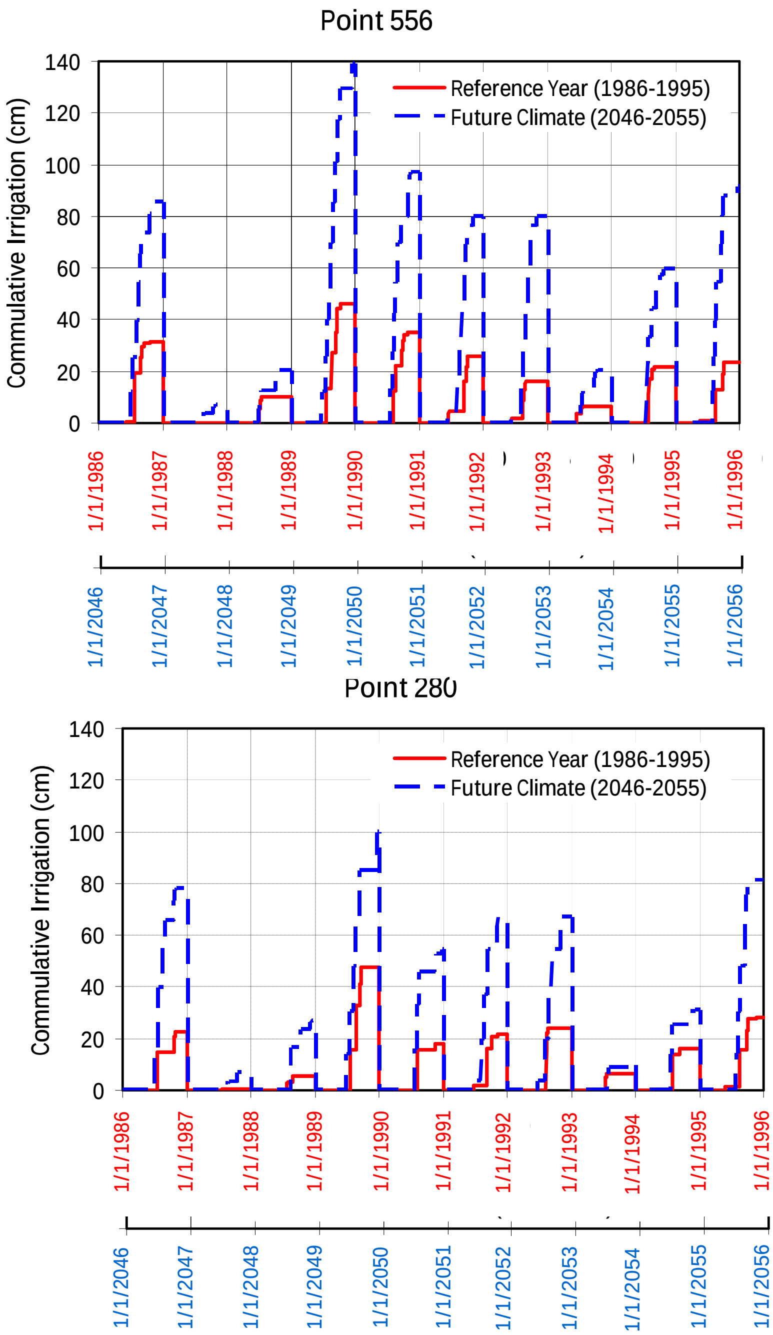


Figure 7.6 Net cumulative irrigation needed to maintain crop yield ≈ 1 for the reference time (1986 – 1995) and future time (2045 -2055).

The results shows that the irrigation need is between 0.05 to 1.5 mm per day (1.8 – 55 cm/year) in 1986 – 1995 while in 2046 – 1955 the irrigation is expected to be 0.5 to 4 mm per day (18 – 150 cm/year) depending meteorological conditions. This clearly shows the need for more water demand in the future in order to maintain the crop yield due to climate change (see figure 7.6).

Water demand (irrigation + infiltration) for the area of Kromme Rijn will be increased in the future (2046-2055) by a factor of 2 compared to the reference time (see figure 7.7).

7.3.4. Water Demand

As described in chapter 5, the irrigation in Kromme Rijn is done by surface irrigation and sub irrigation through the ditches. The total water demand, i.e. irrigation plus infiltration from the ditches, is summarized in table 7.1. Assuming that the depth and the surface water levels in the ditches are the same as that described in chapter 5, the prediction of the SWAP model described here reveals the fact that the total water demand in the future is higher than that in the reference year (see table 7.1). The results is expected because in the future the temperature will increase and therefore evaporation and transpiration will increase (see the previous section), thereby the demand for water will be increased.

	Water Demand		
Year	(cm/year)	m^3/year	m^3/sec
1986	38.9	3.16E+06	0.10
1987	3.7	2.98E+05	0.01
1988	14.4	1.17E+06	0.04
1989	66.2	5.39E+06	0.17
1990	36.3	2.95E+06	0.09
1991	36.2	2.94E+06	0.09
1992	38.0	3.09E+06	0.10
1993	13.8	1.12E+06	0.04
1994	29.8	2.42E+06	0.08
1995	40.0	3.25E+06	0.10

	Water Demand		
Year	(cm/year)	m^3/year	m^3/sec
2046	166.5	1.35E+07	0.43
2047	16.7	1.36E+06	0.04
2048	58.7	4.78E+06	0.15
2049	231.2	1.88E+07	0.60
2050	153.7	1.25E+07	0.40
2051	137.0	1.11E+07	0.35
2052	220.4	1.79E+07	0.57
2053	42.9	3.49E+06	0.11
2054	106.2	8.63E+06	0.27
2055	158.0	1.28E+07	0.41

Table 7.1. Water demand predicted by SWAP model in the future.

7.4. Water demand in the future

The prediction of future climate on the increase of temperature results in higher evaporation, transpiration and therefore increasing water demand to ensure optimum crop yield in the apple plantation in the Kromme Rijn area. The following figure shows the results of water demand in the future compared to the reference year. In the future, the total water demand will increased (up to 230 cm/year; 0.6 m^3/sec, assuming that the total agricultural area in the future remain 813 ha, see figure .7.7).

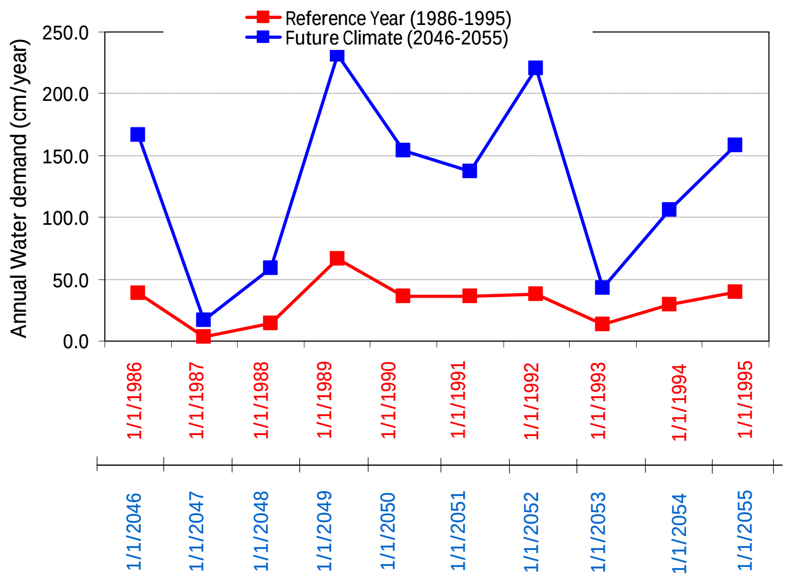


Figure 7.7 Water demand calculated by SWAP model for reference time (1986 -1995) and future time (2046 – 2055).

Chapter 8
Discussions

8.1 Model calibration (Groundwater level, Crop yield and Biomass data)

As described in chapter 4, the SWAP model presented here requires many parameters as input, i.e. meteorological data, irrigation parameters, crop parameters, soil properties, drainage parameters, and bottom boundary conditions. The meteorological data that were used in the SWAP model presented here are available from the KNMI website and are readily available. For fixed irrigation input data, data from HDSR was used, which defined the agreement between HDSR and the farmers in the Kromme Rijn area about the supply of irrigation water for the agriculture sector (0.15 mm/day - 0.60 mm/day). However, iteration is needed to determine the values of drainage resistance (within reasonable range) to fit the available ground water level data. Here, a sensitivity analysis of drainage resistance values on the calculation of bottom flux, infiltration and crop yield is presented. Further, the quality of the relative crop yield obtained from the SWAP model is discussed.

8.1.1 Drainage resistance

In the area of Kromme Rijn, based on the data of ground water level and type of oils, it is estimated that the drainage resistance in Kromme Rijn area is higher than 700 days (Bot, 2011, Gerretsen, 1993). After the iteration to fit the ground water level, it was found that the drainage resistance (γ_d) values were between 700-1000 days and infiltration resistance (γ_i) values were between 1000-1500 days (see chapter 5). These values were in the similar range as reported in literature (van Hardeveld, 2005; Gerretsen, 1993). In accordance to the SWAP manual, it is common to differ the infiltration resistance from the drainage resistance. Here, $\gamma_i \approx 3/2\ \gamma_d$ (van Dam, 1997) is used (as suggested by SWAP manual). Here, the SWAP model calibration shows that heavy loamy soil has a higher drainage resistance compared to light loamy soil (see table 5.3).

The values of drainage resistance significantly influence water balance calculation. Here, a sensitivity analysis has been carried out to study the influence of drainage resistance on crop yield, bottom flux and infiltration. By keeping all the other input parameters constant, the values of drainage resistance simulated are between 400 and 1500 days. The values of bottom boundary parameters were adjusted to fit the measured groundwater level. The results are presented in figure 8.1.

According to HDSR data, bottom flux in the Kromme Rijn area, depending on the location, is between 1 to 2 mm/day (36 – 73 cm/year). As can be seen from figure 8.1c, for drainage resistance (γ_d) of 400 days the calculated bottom flux is significantly higher than the maximum value of expected bottom flux in the Kromme Rijn area (i.e. 2 mm/day ≈ 73 cm/year) (see figure 3.13 in chapter 3). Bottom flux calculation shows decreasing value for increasing drainage resistance. However, there is a marginal difference on the results of bottom flux calculation for γ_d between 1000 and 1500 days.

The values of γ_d = 1500 days means that water from soil surface would take about 5 years to drain. This seems to be a very long time for an agricultural soil. Therefore, based on the above mentioned arguments, the plausible value of γ_d is between 700 to 1000 days, which is found in this thesis. For the values of γ_d between 700 to 1000 days the calculated bottom fluxes are well bellow the expected bottom flux in the area of Kromme Rijn area (i.e. lower than 73 cm/year).

Even though the drainage resistance has a significant influence on bottom flux and infiltration calculation, but it has marginal influence on relative crop yield calculation (note that the simple apple crop yield model is used here). This suggest that the relative crop yield calculated with SWAP with the simple model is strongly influenced by the meteorological condition that represents a green canopy that intercepts precipitation, transpires and shade the ground (van Dam, 1997). Further discussion on crop yield is presented in the following section.

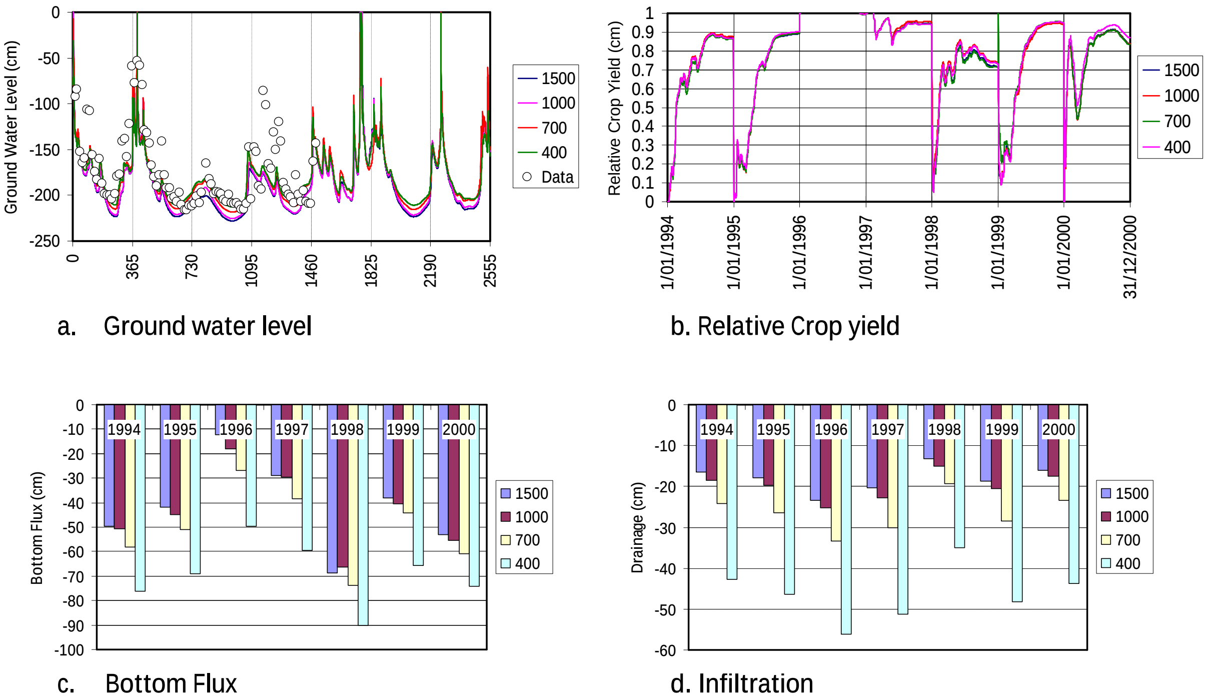


Figure 8.1. Sensitivitiy analysis: the influence of drainage resistance parameters on crop yield, bottom flux and infiltration.

8.1.2. Apple crop parameters and Crop yield

8.1.2.1 Apple crop parameters.

There is no available data in the literature that describe the input parameters to model apple crop yield in SWAP model. Most of the study has been done on seasonal crops, e.g. grass, potatoes, maize, sugar cane. Apple crop parameters used here were obtained from the Nationaal Hydrologisch Instrumentarium (NHI) report that suggests users to use the parameters for oak (eik) trees. The results presented here show that with these input parameters, SWAP model built here could capture the measured ground water levels in the study area. However, as will be discussed further, in the next sections, the prediction of apple crop yield is less good. In order to better improve the model, measurements of crop parameters for apple crop are necessary in the future. With these measurements, a detailed model of apple crop could be implemented in the SWAP model, therefore the prediction of crop yield can be carry out more accurately.

8.1.2.2 Crop Yield

According to CBS data the area of apple plantation in Central Netherland is decreasing over the years, but the apple crop yield per hectare in the area is increasing, especially since 2002 (see figure

8.2). Further, based on the data obtained from CBS, not only apple yield, but also potatoes and pear productions have been increasing over the years (see figure 8.2).

CBS reported that 2011 is remembered as a record harvesting production for apple. This is mainly due to the fact that the cultivation of fruits is more innovative and professional resulting in high production. The farmers, for instance, can choose new high yielding and better storable varieties. The new varieties of apple; Junami, Kanzi, and Ruben for instance rose to 13 percent of the total apple fruit plantation area in The Netherland. Furthermore, the management of plant density in the cultivation and investment in 'drip' irrigation and cooling system for the fruit led to significant higher yields per hectare. At this moment, apple production per hectare is about 5 times higher compared to the apple yield in 1947 and four times for pear production (www.cbs.nl).

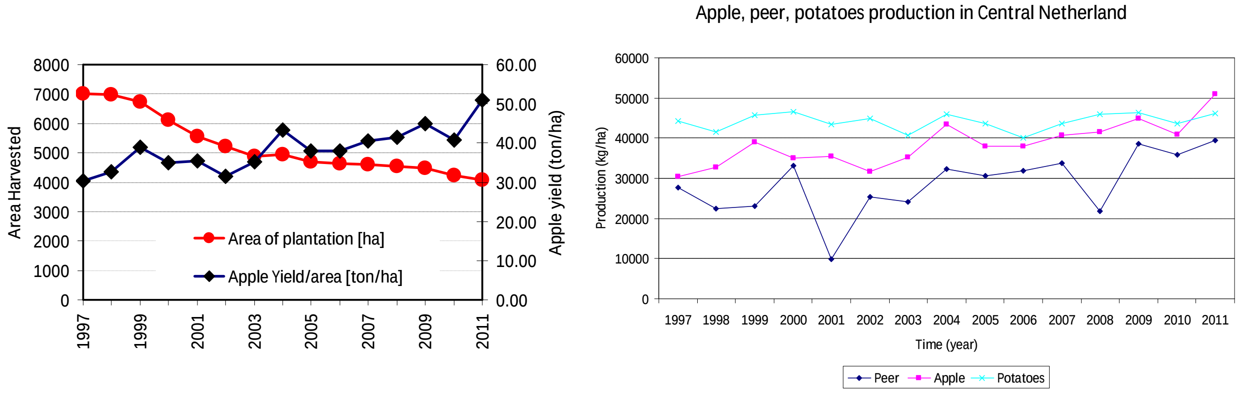


Figure 8.2. Data obtained from CBS: (left) Apple crop yield in the area central part of the Netherlands (right) Production of pear, apple and potatoes in the Netherlands.

For each growing stage *k* the actual yield $Y_{a,k}$ (kg/ha) relative to the potential yield $Y_{p,k}$ (kg/ha) is calculated in SWAP model using the following equation:

$$1 - \frac{Y_{a,k}}{Y_{p,k}} = K_{y,k}\left(1 - \frac{T_{a,k}}{T_{p,k}}\right) \tag{8.1}$$

Where $K_{y,k}$ is the yield response factor of growing stage *k*, and $T_{p,k}$ (cm) and $T_{a,k}$ (cm) are the potential and the actual transpiration respectively, during growing stage *k*. For the SWAP model defined here, a simple crop yield model is used. The value of potential and actual transpiration can be calculated by using SWAP model. However, the value of crop yield response factor (K_y) should be given (input data) in the model. Crop yield response is a function of the age of the apple plants, the type of the species, irrigation method and management and the growth stage due to the changes in meteorological data (van Dam, 1997).

In the SWAP model for apple crop presented here, a simple model is chosen. This is because mostly parameters needed to apply detailed crop model are unknown. In the crop simple model, the yield response factor of the whole growing stage is assumed to be equal to 1 (as suggested by van Dam, 1997). By using the simple model for crop yield, the relative crop yield for each point of interest in the Kromme Rijn area could be calculated (chapter 6). For the year 1997 to 2011 the results are compared with apple yield data for central part of the Netherlands obtained from CBS (see figure 8.3.). The majority of apple yield in central Netherlands is coming from the area of Kromme Rijn area. Therefore this data could be used as representative data for Kromme Rijn area. In order to make a qualitative comparison between the relative crop yields with CBS data, recorded apple yield for each year is normalized to the apple crop yield in 2011 since the apple crop yield in 2011 is the maximum apple yield ever recorded.

As can be seen from figure 8.3., the results of simple crop yield model defined in SWAP could only partially follow the trend of recorded apple crop yield. It is important to mention here that the exact amount of irrigation applied in the field is not also known. The amount of irrigation applied in the model is based on the general rule in HDSR. In addition the effect of fertilizers is not modeled here.

The main discrepancy between the calculated relative crop yield and the recorded crop yield is in 2003 and in 2011. The year 2003 is recorded as dry year and apple yield recorded by CBS shows low relative yield (≈ 0.6). However, the simple crop yield model defined in SWAP predicts relative crop yield higher than 0.9. This is mainly due to the fact that in the simple SWAP model the crop yield response factor is set to 1. Because of this assumption, the crop yield response due to the dynamics of meteorological data throughout the year condition could not be captured. Furthermore, the actual irrigation amount and irrigation schedule that were applied to the Kromme Rijn area were unknown during this year. In addition, in the field of course, there are different types of irrigation management and usage of fertilizers. These factors are not modeled here. However, despite the simplicity of the model, the trend of relative crop yield between 2004 and 2010 could be capture pretty well with the model.

In the case of very high apple production in 2011, the better agricultural management and irrigation also could be the reason. In addition, due to the 'perfect' weather for apple growth which is warm during the flowering stage (in the spring). Research also showed that warm temperatures early in the season stimulate fruit growth and increase ultimate size resulting higher crop yield (Ferree and Warrington et al., 1999).

It seems that the chosen simple crop model presented here could only capture the relative crop yield during normal year, but fail to predict relative crop yield in extreme dry year. Therefore, caution is needed when choosing the simple model option in SWAP for extreme dry year.

In order to enable better apple crop yield prediction, it is recommended to use the detailed crop yield model available in SWAP, however this requires effort to measure all the parameters needed to determine crop yield response factor (K_y). This is not a straight forward task and will require significant effort.

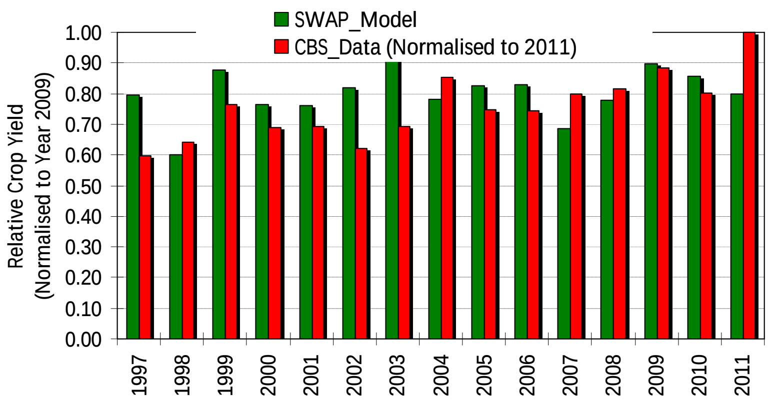


Figure 8.3. Relative crop yield calculated from SWAP model and recorded apple crop yield obtained from CBS.

8.1.3 Biomass from remote sensing data

To further test the capability of the model predict spatial difference of crop yield, comparison of the calculated crop yield using SWAP model is compared with biomass measurement obtained from remote sensing technique carried out by HDSR.

Assuming that crop yield has a linear correlation with measured biomass, HDSR could then indirectly monitor the development of crop in Kromme Rijn area by recording biomass in the Kromme Rijn area by using remote sensing data. HDSR has been using this method since 2011. Figure 8.4 shows the measured biomass in the study area. Adopting the assumption that biomass has a linear correlation with crop yield, the normalized crop yield and biomass could be derived (see figure 8.4). For points 219, 176, 280, 270 and 187 the predicted relative yield is comparable with the relative measured biomass. However, for points 314, 350 and 556, some difference between the relative measured biomass and the calculated relative yield is observed. This could be due to the fact that the measured biomass using remote sensing method takes into account the other vegetation in the area of interest. Therefore, more detail study on the correlation between measured biomass using remote sensing and crop yield potential for apple is necessary.

Overall, accepting the fact that the measured biomass in Kromme Rijn area is not only contain apple crop yield biomass but also other vegetation in the area and knowing all simplification of crop yield model made here, the model could still reasonably predict the spatial differences in relative crop yield response.

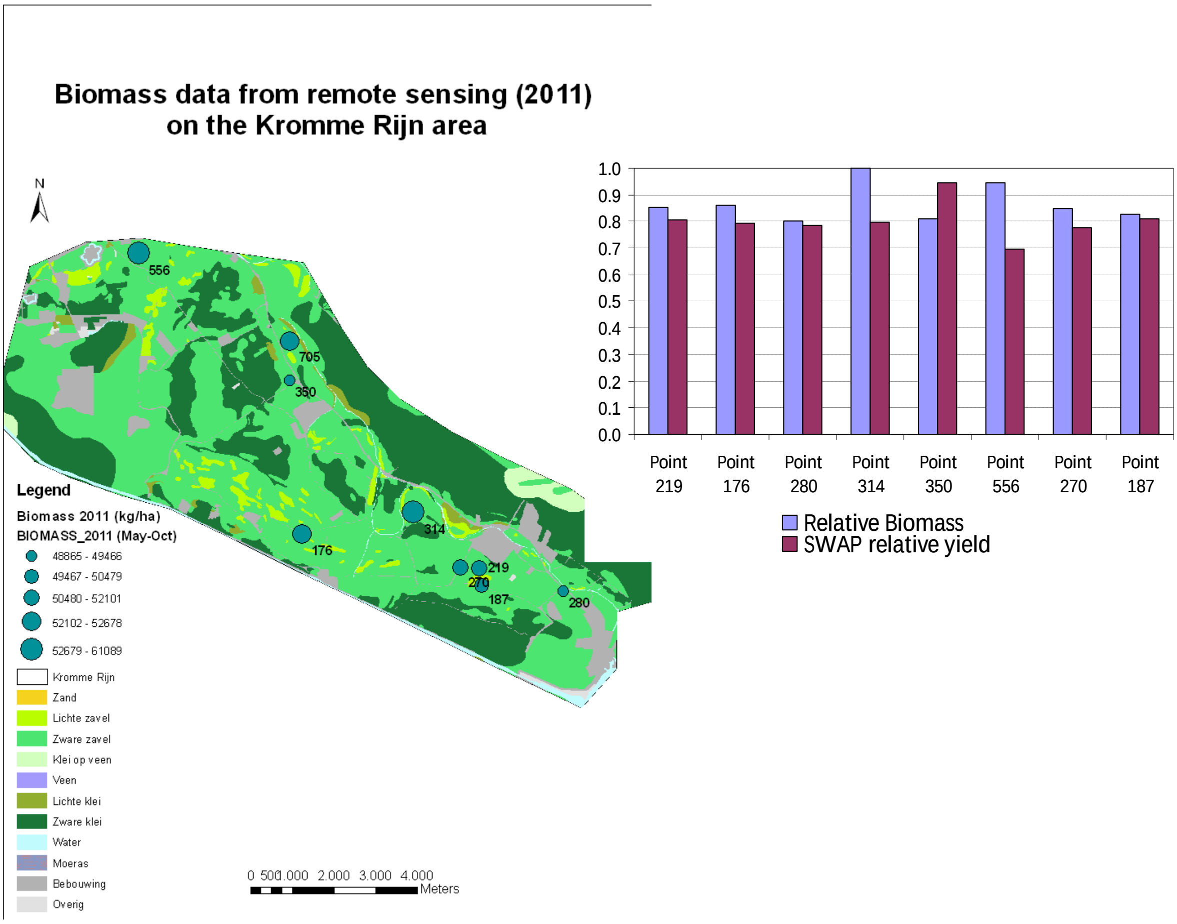


Figure 8.4. Spatial difference of biomass in 2011 in Kromme Rijn.

8.3 Influence of drought on ground water level and water demand

It is known from the literature that drought will influence ground water level and water demand. In this section, the SWAP model developed here is checked whether it could capture general knowledge on the impact of drought on ground water level, water demand and crop yield.

Several years were selected to be analyzed as a normal year, wet year and dry year. Based on the recorded rainfall and evapotranspiration during spring summer, the year 2003 (438 mm rainfall and 227 mm rainfall shortage), 1996 (412 mm rainfall and 199 rainfall shortage) and 1986 (435 mm rain and 207 rainfall shortage) are identified as a dry year while the year 2000 (930 mm rainfall) as typical normal year and the year 1998 (1040 mm rainfall) is a wet year (see chapter 2). Water demand is depending on the balance between water adsorbed into the ground (rain, irrigation, bottom flux) and water leaving the ground (runoff, transpiration, soil evaporation, and drainage).

The water demand needed to maintain good soil moisture and yield optimum apple yield is summarized in figure 8.5. One can see that in year 1998, which is the wet year, the water demand is a little less than that in normal year 2000. For the dry year, i.e. 1998, 1986 and 2003, the water demand is higher than that in the normal year 2000. The extreme water demand in 2003 is due to the fact that the average maximum temperature in summer is higher than that in 1986, 2000, 1996 and 1998. The SWAP model described here showed, as expected, that water demand is higher as the amount of water from rain is less.

Year (Apr-Sept)	Rain (mm)	Water Demand irrigation+infiltration (cm)	Remark
1998	1040	15,42	Wet year
2000	658	16,88	Normal year
1996	412	18,71	Dry Year
1986	435	17,74	Dry Year
2003	438	26,38	Dry Year

Table 8.1 Water demand calculated using SWAP model.

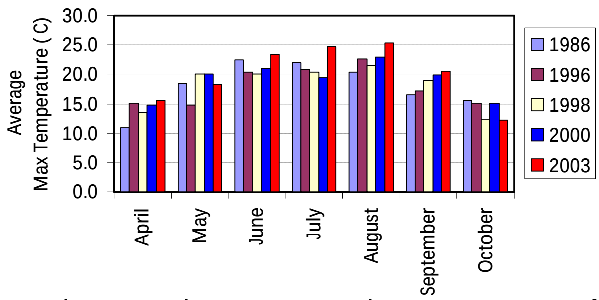


Figure 8.5 the average maximum temperature from April to September for the wet year (1998), dry year (1986, 1996 and 2003) and normal year (2000).

In the wet year in 1998, the ground water level was shallower compared to the normal year in 2000. As expected, during the dry year in 1986, 1996 and 2003 the ground water level were deeper than the normal year 2000 (see figure 8.6). This is plausible since during the wet year, water flux into the soil is high and therefore decreasing the depth of the ground water level and in the contrary, the ground water level will get deeper due to the lack of rain provided that the surface water levels in the ditches are kept constant (see figure 8.6). This results shows that the SWAP model presented here could capture the general knowledge on the impact of drought on ground water level and water demand.

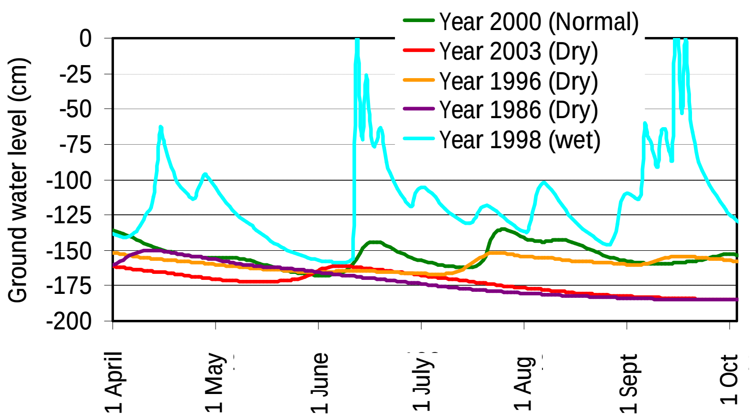


Figure 8.6. Ground water level during wet year (1998), dry years (1986, 1996 and 2003) and normal year 2000.

8.4 Water demand for future climate and implication for HDSR

As described in chapter 7, the calibrated model (described in chapter 6) is used to predict the future water demand in the area of Kromme Rijn. Here, the water demand for the future is calculated using the climate scenario W+. The results of water demand for the future is shown in table 8.2 below based on the total fruit plantation are in the Kromme Rijn (i.e. 813 ha)

As can be seen in table 8.2, the maximal water demand in the future will be about 0.60 m^3/sec (assuming that the total agricultural area in the future remain 813 Ha). This is within the same range as reported in other studies. The study carried by Van Tuinen and Witjes (2012) predicts that the water demand in the future will be about 0.64 m^3/sec. Today, the HDSR supplies up to 0.3 m^3/sec. This means that the HDSR need to double the amount for irrigation with a factor of 2 in the future.

At present, depending on the location of the inlet water, HDSR can supply water between 0.7 m^3/sec up to 10 m^3/sec (inlet capacity). This is just above the water demand in the future predicted by the SWAP model presented here. If the amount of water supplied to Kromme Rijn could be maintained in the similar level as it is today, based on the calculation presented here, then in the future the capability of HDSR to satisfy water demand is just enough. However, taking into account all the simplification and the uncertainties in the model, it is safer for HDSR to increase the water supply capability in the future, particularly at the location where the inlet water capacity is low, in order to cope with the increasing water demand in the future.

	Water Demand				Water Demand		
Year	(cm/year)	m^3/year	m^3/sec	Year	(cm/year)	m^3/year	m^3/sec
1986	38.9	3.16E+06	0.10	2046	166.5	1.35E+07	0.43
1987	3.7	2.98E+05	0.01	2047	16.7	1.36E+06	0.04
1988	14.4	1.17E+06	0.04	2048	58.7	4.78E+06	0.15
1989	66.2	5.39E+06	0.17	2049	231.2	1.88E+07	0.60
1990	36.3	2.95E+06	0.09	2050	153.7	1.25E+07	0.40
1991	36.2	2.94E+06	0.09	2051	137.0	1.11E+07	0.35
1992	38.0	3.09E+06	0.10	2052	220.4	1.79E+07	0.57
1993	13.8	1.12E+06	0.04	2053	42.9	3.49E+06	0.11
1994	29.8	2.42E+06	0.08	2054	106.2	8.63E+06	0.27
1995	40.0	3.25E+06	0.10	2055	158.0	1.28E+07	0.41

Table 8.2 Water demand for the future to maintain optimum crop yield.

Chapter 9
Conclusions and Recommendations

9.1 Conclusion

The aims of this study were to assess the impact of drought and predict drought in the future (KNMI climate scenario) on groundwater fluctuation, apple crop yield and water demand in the area of Kromme Rijn. Based on the work presented in this thesis, the following conclusions can be drawn:

- SWAP model for apple crop plantation is presented and calibrated. The model presented here is able to show the impact of drought on decreasing ground water level and increasing water demand in order to maintain optimum apple crop yield for the past 30 years.
- Based on the future climate scenario, the predicted temperature rise will increase evapotranspiration, reduces water storage and therefore increases the demand on water (for irrigation and infiltration). The water demand in the future predicted by the SWAP model is between 0.05 to 0.60 m^3/sec. This implies that compared to water supply applied today (0.3 m^3/sec), the HDSR need to double the amount for irrigation with a factor of 2 in the future.
- Today, HDSR can supply water between 0.7 m^3/sec up to 10 m^3/sec (inlet capacity). This is just above the water demand in the future predicted by the SWAP model. If the amount of water supplied to Kromme Rijn could be maintained in the similar level as it is today, then in the future water demand would be just enough. However, due to the simplification and the some degree of uncertainty in the model, it is safer for HDSR to increase the minimum supply water capability to be prepared for the future, particularly in the area where the inlet water capacity is low.

9.2 Recommendations

- As described in chapter 8, the main limitation of the SWAP model presented here is the crop yield response factor. In this study the crop yield response factor (K_y) is assumed to be 1 for the whole growing period. To enable better prediction of crop yield potential a study (and field work) needs to be carried out in order to accurately determine the crop yield response factor and to fulfil all other data needed to simulate detailed crop model for apple crop.
- Due to temperature increase predicted (based on climate change scenario), the water demand in the Kromme Rijn area will be increasing as well. This will imply that the potential water shortage will increase. Further innovation of growing apple/fruit crop with less water demand such as deficit irrigation (Vazifedoust et al, 2008; Kirda C, 2000), optimum amount of apple plants per hectare by reducing apple plantation area to ensure enough water supply for other crops and gain higher water productivity (Vazifedoust et al, 2008), new optimum irrigation schedule (amount and timing) and water distribution system, etc.
- If the correlation between remote sensing data and the crop yield could be established, then the remote sensing method to calculate biomass and predict potential crop yield can be used to regulate the right amount of irrigation (water demand) in the Kromme Rijn area.
- To get better estimation of irrigation demand for agricultural purposes, it is important to have irrigation monitoring of how much actual irrigation water applied in the Kromme Rijn area. With this observed data a better prediction of potential and actual crop yield and irrigation schedule could be simulated by the SWAP model.

Reference

Allen, R.G, Pereira, L.S., Raes, D., and Smith, M., 1998, Crop evapotranspiration: guidelines for computing crop water requirements, *FAO irrigation and drainage paper No. 56*, Rome 300 pp

Arnold G., van Baaren E., Berger H., van Ek R., van Kempen C., Oosterberg W., Roosjen R., Stuurman R., van Weert F., 2011, Droge Kost, innoveren op droogte en watertekort, Deltares The Netherlands.

Beersma J.J., Adri Buishand, T., Buiteveld, H., 2004, Droog, Drooger, Droogst, KNMI/RIZA-bijdrage aan de tweede fase van de Droogtestudie Nederland, KNMI -publicatie; 199-I I.

Boland A.M, Ziehrl, A., Beaumont J., 2002, Orchard crops, Guide to Best Practice in Water Management, ISBN 174106 313 2

Bot, B., 2011, Grondwater-zakboekje, Bot Raadgevend Ingenieur, Rotterdam.

Bruins, H.J., and Berliner, P.R.: 1998, Bioclimatic aridity, climatic variability, drought and desertification: definitions and management options. *The arid frontier-interactive management of environment and development* (H.J. Bruins and H. Lithwick, eds.). Kluwer Academic Publishers. Dordrecht, The Netherlands.

Bresser, A.H.M, Berk, M.M, van den Born, G.J, van Bree, L., van Gaalen, F.W., Ligtvoet, W., van Minnen, J.G. , Witmer, M.C.H., 2005, The effects of climate change in the Netherlands, Netherlands Environment Assessment Agency, MNP report number: 773001037

De Vries, J.J., 1974, Groundwater flow systems and stream nets in the Netherlands, PhD. Thesis, Vrije Universiteit, Amsterdam, 226 pp.

Droogers, P.; Immerzeel, W.W.; Lorite, I.J.; 2010, Estimating actual irrigation application by remotely sensed evapotranspiration observations, *Agricultural Water Management*, Volume: 97 (2010), pp. 1351-1359.

Feddes, R.A, Kowalik, P.J and Zaradny, H., 1978, Simulation of field water use and crop yield, Simulation Monographs, Pudoc, Wageninegen, 1989 pp.

Ferre, D.C, and Warrington, I.J, 2003, Apples; Botany, production, and uses, CABI Publishing.

Gerretsen, M., 1993, Hydrologisch onderzoek Kromme Rijn, Deelreport I en II, Femsats, Rapport Buro Kwantitatief Grondwaterbeheer no. 6A.

Glantz, M.H., 1994, Drought, desertification and food production. *Drought follows the plow* (Glantz H.H. Ed). Cambridge University Press. Cambridge: 6-22.

Groten, S.M.E and Ocatre, R, 2002, Monitoring the length of the growing season , with NOAA, International of Arid Environments 41, 401-410.

Hanson, P.J and Weltzin, J.F, 2000, Drought disturbance from climate change: response of United States forests, The Science of the Total Environment 262, 205-220

Huygen, J., van Dam J.C., and Kroes, J.G., 2000, SWAP graphical user interface, User manual, Alterra, Research Institute, Wageningen, The Netherlands

IPCC, 2007. Climate Change 2007: Synthesis Report. The final part of the IPCC's Fourth Assessment Report (AR4). Retrieved from: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

Karl, T.R., and Koscielny, A.J.: 1982, Drought in the United States: 1895-1981. *Journal of Climatology* 2, 313-329.

Kroes, J.G. and Supit, I., 2011, Impact analysis of drought, water excess and salinity on grass production in The Netherlands using historical and future climate data, *Agriculture, Ecosystem and Environment* 144, pp 370-381.

Kroes, J.G., J.C. van Dam, P. Groenendijk, R.F.A. Hendriks and C.M.J. Jacobs, 2008. SWAP version 3.2. Theory description and user manual. *Alterra-report 1649*, 262 pp, Alterra, Research Institute, Wageningen, The Netherlands.

Kroes, J.G., J.C. van Dam, Huygen, J., Vervoort, R.W, 1999, User's guide of SWAP version 2.0, Technical Document 53, DLO Winand Staring Centre, Wageningen, The Netherlands.

Kroes, J.G., J.C. van Dam, Huygen, J., 2000, SWAP, Graphical User Interface user manual, DLO Winand Staring Centre, Wageningen, The Netherlands.

Koenraadt, R., Menkveld A., Stark, M., Koomen, A., 2008, Watergebiedsplan tussen Kromme Rijn and Amsterdam-Rijnkanaal, Hoogheemraadschap De Stichtse Rijn landen, Sector Strategie en Plannen, Houten, The Netherlands.

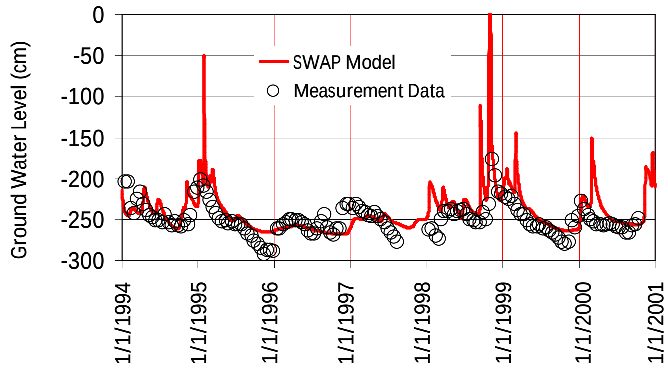
Ma Y., Feng, S., Huo, Z., Song, X., 2011, Application of the SWAP model to simulate the field water cycle under deficit irrigation in Beijing, China, *Mathematical and Computer Modelling* 54, pp 1044-1052.

Olesen JE, Bindi M (2004) Agricultural impacts and adaptations to climate change in Europe. *Farm Policy* J 1:36–46

Oosterbaan L., 2004, Netherland drought study, Final report Phase 2, Institute for Inland Water Management and Wastewater (RIZA), Lelystad.
Panu, U. S., and T. C. Sharma (2002), Challenges in drought research: some perspectives and future directions, *Hydrology Science Journal., 47(S),* S19–S30.
Peters, E. (2003), Propagation of drought through groundwater systems- illustrated in the Pang (UK) and Upper-Guadiana (ES) catchments, PhD. Thesis, Wageningen University, The Netherlands, 203 pp.
Quiring, S.M., and Papakryiakou, T.N.: 2003, An evaluation of agricultural drought indices for the Canadian praires. *Agricultural and Forest Meteorology* 118, 49-62.
Querner, E.P, 2000, The effects of Human Intervention in the Water Regime, *Groundwater*, Vol. 38 No. 2, pp. 167-171
Schlesinger, W.H. *et al*.: 1990, Biological feedbacks in global desertification. *Science* 247: 1043-1048.
Supit, I., 1997. Predicting national wheat yields using a crop simulation and trend models. *Agricultural and Forest Meteorology* 88, 199–214.
Tallaksen, L.M. and van Lanen, H.A.J, 2004, Hydrological Drought-processes and estimation methods for streamflow and groundwater, developments in water science, 48, Elsevier.
Van Dam, J.C., Huygen, J., Wesseling J.G., Feddes, R.A., Kabat, P., van Walsum P.E.V, Groenendijk, P., and van Diepen C.A., 1997, Theory of SWAP version 2.0 simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment, Landbouw universiteit Wageningen & DLO Winand Staring Centrum, *Technisch document 45*.
Van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G., 2008. Advances of modelling water flow in variably saturated soils with SWAP. *Vadose Zone Journal 7 (2)*, 640–653.
Van den Hurk, B.J.J.M., Klein Tank, A.M.G., Lenderink, G., van Ulden, A.P., van Oldenborg, G.J., Katsman, C.A., van den Brink, H.W., Keller, F., Bessembinder, J.J.F., Burgers, G., Komen, G.J., Hazeleger, W., Drijfhout, S.S., 2006, KNMI Climate Change Scenarios 2006 for the Netherlands, KNMI, De Bilt, Netherlands, *KNMI Publication* WR-2006-01.
Van der Wateren, B., Gonggrijp, A., van der Brand, L., Zeeman, W., Wolters, H., Kroon, T., van de Heijdt B., 2003, Netherlands Drought Study, Final report Phase 1, Institute for Inland Water Management and Wastewater (RIZA), Lelystad.
Van Tuinen, E.S.J. and Witjes, Th.G.J., 2012, Knelpuntenanalyse 2.0; Zoet water HDSR; Deel 1 &2, Wiitteveen and Bos, Deventer, The Netherlands.
Van Walsum, 2011, Influence of feedbacks from simulated crop growth on integrated regional hydrologic simulations under climate scenarios, Hidrology and Earth system sciences discussions, 8, 10151-10193.
Van Walsum and Supit, I., 2012, Influence of ecohydrologic feedbacks from simulated crop growth on integrated regional hydrologic simulations under climate scenarios, Hidrology and Earth system sciences discussions, 16, 1577-1593.
Vicento-Serrano, S.M, 2007, Evaluating the impact of drought using remote sensing in a Mediterranean, semi-arid region, *Natural Hazards* 40 (1), pp. 173-208.
Vazifedoust, M., 2007, Development of an agricultural drought assessment system: Integration of agrohydrological modelling, remote sensing and geographical information, Disertation, Wageningen University, The Netherlands.
Vazifedoust, M., van Dam, J.C., Feddes, R.A., Feizi, M., 2008, Increasing water productivity of irrigated crops under limited water supply at field scale, *Agricultural water management* 95, pp 89 – 102.
Wilhite D.A., and Glantz, M.H.: 1985, Understanding the drought phenomenon: the role of definitions. *Water International* 10, 111-120.
Wilhite, D.A., and M.D. Svoboda (2000), Drought early warning systems in the context of drought preparedness and mitigation, in *Early Warning Systems for Drought Preparedness and Drought Management*, edited by A.
Wilhite, M.V.K. Sivakumar, and D.A. Wood, pp. 1–16, *Proc.* of an Expert Group Meeting, Lisbon, Portugal, September 5–7, 2000.
Wu, H and Wilhite, D.A., 2004, An Operational Agricultural Drought Risk Assessment Model for Nebraska, USA, *Drought Mitigation Center Faculty Publications.* Paper 7.
Wösten, J.H.M., A. Lilly, A. Nemes, and C. Le Bas (1998), Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning, report 156, DLO Winand Staring Centre, the Netherlands.
Yano, T., Aydin, M., Haraguchi T., 2007, Impact of Climate Change on Irrigation Demand and Crop Growth in a Mediterranean Environment of Turkey, *Sensors* 7, 2297-2315

Appendix A
Results of SWAP model Calibration

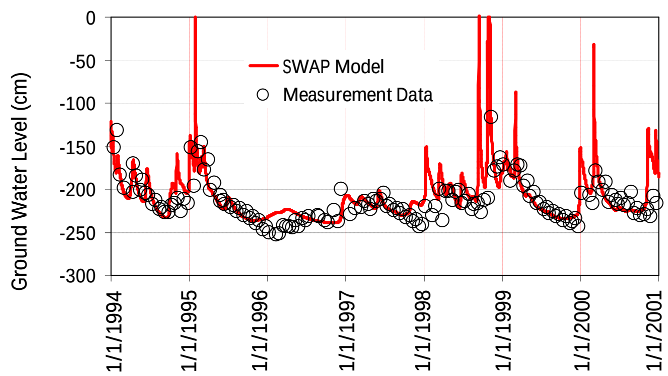
Ground Water Level (Point 176)



	Point 176								
	Water in (cm)			Water Out (cm)					
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-71.11	4.59	8.94	42.06	11.17	-35.63
1995	72.95	8.7	-69.59	3.94	1.96	45.75	11.47	-35.88
1996	57.57	8.68	-38.04	3.49	0.45	44.93	9.77	-41.35
1997	74.35	7.3	-49.34	3.99	15.14	46.34	11.12	-39.31
1998	123.96	4.69	-95.52	5.45	9.93	28.22	10.5	-31.26
1999	90.15	7.35	-68.75	4.8	1.49	47.2	11.23	-36.03
2000	93.24	5.96	-78.77	5.12	0.11	39.12	10.88	-34.47

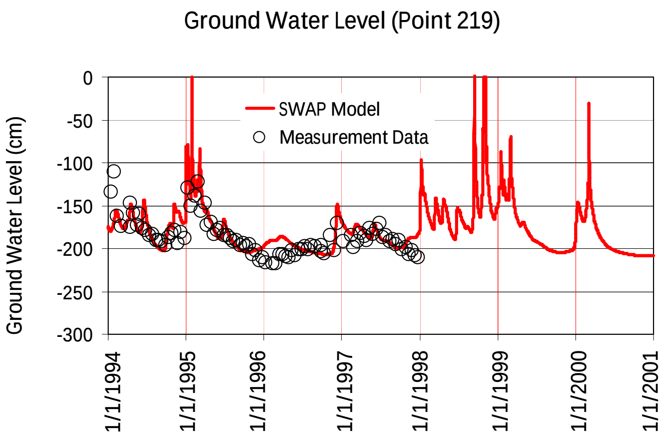
Figure A1. Ground water level calibrations and calculated water balance at site 176.

Ground Water Level (Point 187)



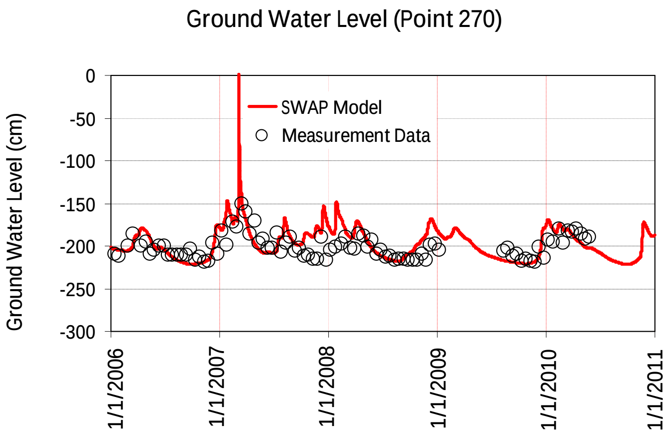
	Point 187								
	Water in (cm)			Water Out (cm)					
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-76.86	4.59	6.12	41.58	9.65	-29.12
1995	72.95	8.7	-58.62	3.94	13.15	48.23	9.98	-32.18
1996	57.57	8.68	-29.88	3.49	0.97	46.39	8.83	-37.17
1997	74.35	7.3	-42.86	3.99	14.75	47.95	9.62	-34.86
1998	123.96	4.7	-93.07	5.45	11.52	28.85	8.64	-26.08
1999	21.87	7.35	-61.48	4.8	3.42	48.99	9.98	-31.71
2000	93.24	5.96	-74.27	5.12	0.15	40.68	9.63	-29.67

Figure A2. Ground water level calibrations and calculated water balance at site 187.



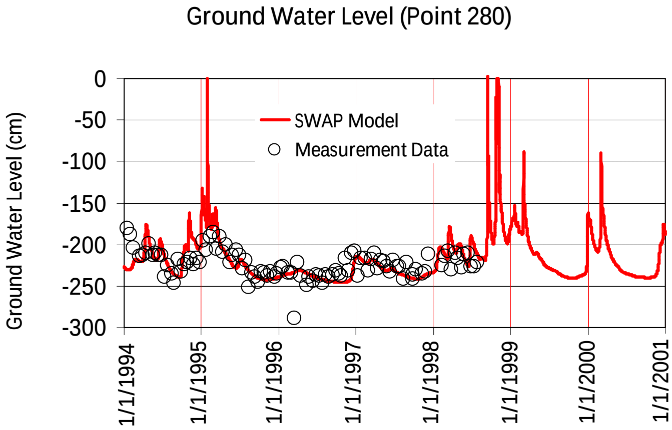
	Point 219							
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-39.99	4.59	22.9	46.93	5.22	-18.32
1995	72.95	8.7	-42.51	3.94	8.35	49.47	5.5	-17.64
1996	57.57	8.69	-20.36	3.49	4.65	50.77	4.98	-22.8
1997	74.35	7.3	-29.04	3.99	12.2	49.51	5.05	-20.77
1998	123.96	4.69	-61.53	5.45	35.26	34.14	4.4	-12.95
1999	90.15	7.35	-35.87	4.8	17.43	53.18	5.38	-19.23
2000	93.24	5.96	-51.78	5.12	9.54	42.75	5.15	-15.55

Figure A3. Ground water level calibrations and calculated water balance at site 219.



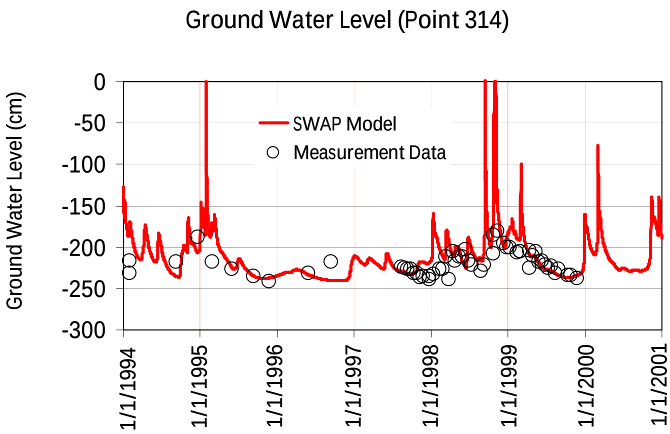
	Point 270							
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
2006	80.71	5.96	-38.47	4.03	8.21	54.35	10.79	-35.36
2007	95.11	5.96	-64.83	4.58	13.2	38.72	10.59	-29.74
2008	88.05	7.31	-52.05	4.64	12.73	48.03	11.23	-32.6
2009	77.69	4.56	-39.96	3.99	5.32	52.43	11.7	-35.05
2010	82.53	7.31	-45.66	4.14	14.15	51.91	11.03	-33.83

Figure A4. Ground water level calibrations and calculated water balance at site 270.



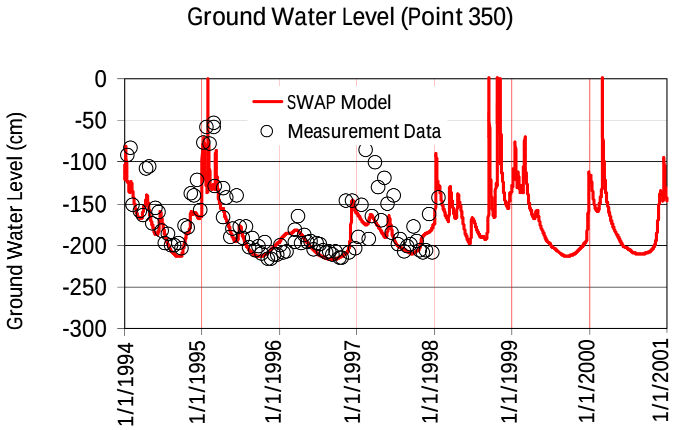
	Point 280							
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-57.99	4.59	6.38	41.84	11.17	-26.83
1995	72.95	8.7	-57.88	3.94	5.11	45.86	11.47	-26.79
1996	57.57	8.68	-31.29	3.49	0.95	44.84	9.77	-33.69
1997	74.35	7.3	-48.71	3.99	1.06	43.62	11.12	-29.18
1998	123.96	4.69	-89.02	5.45	12.46	27.48	10.5	-18.34
1999	90.15	7.35	-58.45	4.8	1.5	47.01	11.23	-26.68
2000	93.24	5.96	-55.1	5.12	16.79	41.52	10.88	-27.63

Figure A5. Ground water level calibrations and calculated water balance at site 280.



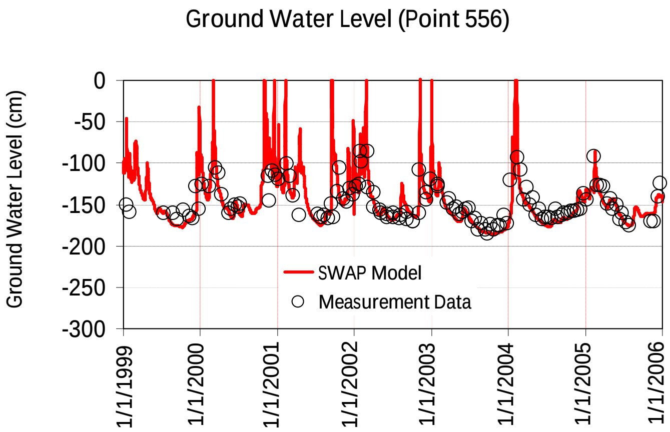
	Point 314							
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-70.21	4.59	8.82	41.71	9.65	-23.69
1995	72.95	8.7	-56.69	3.94	1.73	47.11	9.98	-26.49
1996	57.57	8.68	-31.47	3.49	0.95	46.3	8.83	-31.97
1997	74.35	7.31	-48.32	3.99	0.75	44.8	9.62	-28.31
1998	123.96	4.7	-91.31	5.45	11.63	28.51	8.64	-18.65
1999	90.15	7.35	-57.63	4.8	1.31	48.79	9.98	-26.31
2000	93.24	5.95	-69.35	5.12	0.15	40.6	9.63	-23.93

Figure A6. Ground water level calibrations and calculated water balance at site 314.



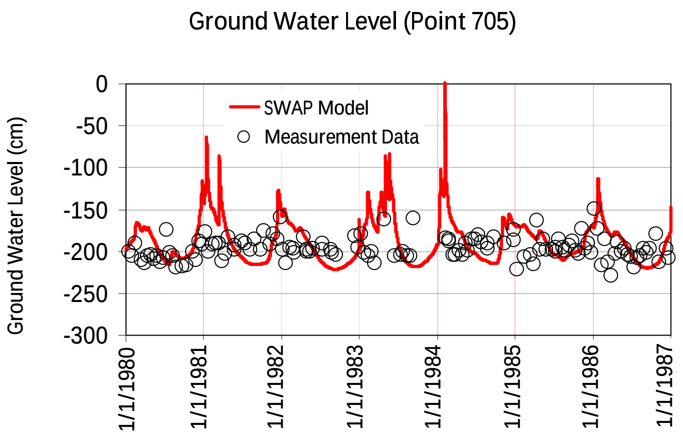
	Point 350							
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1994	102.52	7.31	-54.61	4.59	21.29	41.25	9.65	-22.97
1995	72.95	8.7	-49.41	3.94	8.38	45.4	9.98	-23.97
1996	57.57	8.68	-26.16	3.49	5.15	45.8	8.83	-28.8
1997	74.35	7.3	-37.09	3.99	10.66	44.33	9.62	-26.51
1998	123.96	4.69	-77.89	5.45	25.71	27.32	8.64	-17.95
1999	90.15	7.35	-48.89	4.8	10.21	47.05	9.98	-24.12
2000	93.24	5.95	-47.37	5.12	22	41.67	9.63	-24.5

Figure A7. Ground water level calibrations and calculated water balance at site 350.



	Point 556							
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1999	90.15	7.31	-40.18	4.8	8.87	44.89	9.98	-12.14
2000	93.24	8.7	-56.22	5.12	6.12	33.79	9.63	-8.18
2001	103.89	7.31	-55.29	5.07	12.5	35.71	9.77	-8.42
2002	92.4	7.3	-42.84	4.3	14.65	39.2	10.22	-11.47
2003	61.27	8.68	-15.96	3.43	7.3	55.37	10.74	-17.7
2004	85.94	7.35	-31.15	4.45	12.38	45.75	10.66	-14.23
2005	87.29	5.96	-30.59	4.44	16.28	46.4	10.42	-14.51

Figure A8. Ground water level calibrations and calculated water balance at site 556.



Point 705								
	Water in (cm)			Water Out (cm)				
Year	Rain	Irrigation	Bottom Flux	Interception	Runoff	Transpiration	Soil evaporation	Drainage
1980	86.18	5.95	-27.06	5.02	11.95	45.96	10.52	-17.76
1981	99.3	5.96	-46.82	5	15.46	41.45	9.93	-13.49
1982	60.07	5.96	-18.8	3.9	4.32	53.76	10.71	-19.43
1983	82.79	7.3	-37.37	4.03	9.04	43.24	10.22	-15.63
1984	81.93	5.96	-39.3	4.24	8.89	40.12	9.32	-15.23
1985	70.05	5.96	-29.08	4.26	11.1	40.6	8.25	-17.35
1986	71.61	10	-25.51	3.61	8.09	48.81	10.23	-18.07

Figure A9. Ground water level calibrations and calculated water balance at site 705.

Appendix B
Results of Relative Yield Calculation

Location	Year	SWAP Model		
		Transpiration (cm)		Relative Crop Yield
		Potential	Actual	
176	1997	19.82	15.67	0.79
	1998	15.87	10.22	0.64
	1999	21.05	19.02	0.90
	2000	18.42	14.72	0.80
	2001	19.68	15.84	0.80
	2002	18.74	15.45	0.82
	2003	23.26	22.76	0.98
	2004	20.54	16.44	0.80
	2005	20.6	17.84	0.87
	2006	23.48	19.96	0.85
	2007	18.98	13.27	0.70
	2008	20.3	14.9	0.73
	2009	22.48	20.83	0.93
	2010	21.56	18.73	0.87
	2011	20.67	16.39	0.79
187	1997	26.19	19.9	0.76
	1998	21.76	13.44	0.62
	1999	27.4	24.08	0.88
	2000	24.67	18.99	0.77
	2001	25.74	18.96	0.74
	2002	25.29	22.82	0.90
	2003	29.62	28.78	0.97
	2004	26.59	20.51	0.77
	2005	26.51	22.65	0.85
	2006	29.6	24.43	0.83
	2007	25.67	17.33	0.68
	2008	26.88	24.08	0.90
	2009	28.99	26.7	0.92
	2010	27.8	23.71	0.85
	2011	27.23	22.01	0.81
219	1997	28.98	22.77	0.79
	1998	24.25	13.51	0.56
	1999	30.3	24.65	0.81
	2000	27.51	18.91	0.69
	2001	28.48	19.16	0.67
	2002	28.12	22.56	0.80
	2003	32.74	29.33	0.90
	2004	29.49	22.35	0.76
	2005	29.36	21.85	0.74
	2006	32.76	26.37	0.80
	2007	28.72	18.92	0.66
	2008	29.92	21.56	0.72
	2009	32.12	27.61	0.86
	2010	30.76	26.08	0.85
	2011	30.36	24.48	0.81

Location	Year	SWAP Model		
		Transpiration (cm)		Relative Crop Yield
		Potential	Actual	
270	1997	19.82	15.96	0.81
	1998	15.87	9.43	0.59
	1999	21.05	18.64	0.89
	2000	18.42	13.42	0.73
	2001	19.68	14.52	0.74
	2002	18.74	15.37	0.82
	2003	23.26	21.93	0.94
	2004	20.54	15.69	0.76
	2005	20.6	16.98	0.82
	2006	23.48	19.9	0.85
	2007	18.98	12.88	0.68
	2008	20.3	14.51	0.71
	2009	22.48	19.7	0.88
	2010	21.56	18.19	0.84
	2011	20.67	16.02	0.78
280	1997	19.82	18.77	0.95
	1998	15.87	9.95	0.63
	1999	21.05	18.97	0.90
	2000	18.42	14.5	0.79
	2001	19.68	15.19	0.77
	2002	18.74	15.17	0.81
	2003	23.26	22.67	0.97
	2004	20.54	15.87	0.77
	2005	20.6	17.75	0.86
	2006	23.48	19.77	0.84
	2007	18.98	12.86	0.68
	2008	20.3	14.91	0.73
	2009	22.48	20.6	0.92
	2010	21.56	18.51	0.86
	2011	20.67	16.19	0.78
314	1997	26.19	19.86	0.76
	1998	21.76	13.44	0.62
	1999	27.4	23.98	0.88
	2000	24.67	18.91	0.77
	2001	25.74	18.92	0.74
	2002	25.29	22.7	0.90
	2003	29.62	28.75	0.97
	2004	26.59	20.22	0.76
	2005	26.51	22.96	0.87
	2006	29.6	24.32	0.82
	2007	25.67	17.21	0.67
	2008	26.88	24.01	0.89
	2009	28.99	26.61	0.92
	2010	27.8	23.57	0.85
	2011	27.23	21.77	0.80

Location	Year	SWAP Model		
		Transpiration (cm)		Relative Crop Yield
		Potential	Actual	
350	1997	47.09	43.18	0.92
	1998	39.73	27.44	0.69
	1999	50.49	47.86	0.95
	2000	45.29	38.17	0.84
	2001	47.66	44.96	0.94
	2002	46.31	40.85	0.88
	2003	56.7	54.05	0.95
	2004	49.85	47.36	0.95
	2005	49.73	47.93	0.96
	2006	57.49	52.38	0.91
	2007	48.17	37.95	0.79
	2008	51.69	47.11	0.91
	2009	53.99	52.58	0.97
	2010	53.08	51.4	0.97
	2011	52.07	49.25	0.95
556	1997	26.19	16.92	0.65
	1998	21.76	10.73	0.49
	1999	27.4	21.03	0.77
	2000	24.67	14.78	0.60
	2001	25.74	15.9	0.62
	2002	25.29	16.68	0.66
	2003	29.62	24.99	0.84
	2004	26.59	17.79	0.67
	2005	26.51	17.7	0.67
	2006	29.6	22.32	0.75
	2007	25.67	13.75	0.54
	2008	26.88	16.71	0.62
	2009	28.99	23.18	0.80
	2010	27.8	21.48	0.77
	2011	27.23	18.93	0.70
705	1997	26.19	19.63	0.75
	1998	21.76	12.3	0.57
	1999	27.4	25	0.91
	2000	24.67	21.85	0.89
	2001	25.74	21.39	0.83
	2002	25.29	19.83	0.78
	2003	29.62	26.75	0.90
	2004	26.59	20.66	0.78
	2005	26.51	20.65	0.78
	2006	29.6	24.21	0.82
	2007	25.67	20.26	0.79
	2008	26.88	20.74	0.77
	2009	28.99	25.58	0.88
	2010	27.8	23.96	0.86
	2011	27.23	21.5	0.79

Appendix C
Results of Relative Biomass Calculation

	Biomass (Kg/ha)							
Measurement Date	Point 219	Point 176	Point 280	Point 314	Point 350	Point 556	Point 270	Point 187
01-May	2926	2632	2293	2779	2865	3181	2533	2293
10-May	2792	2720	2358	2843	2901	3212	2561	2320
20-May	2703	2881	2374	2945	2852	3221	2604	2391
01-Jun	2601	3212	2457	3010	2728	3186	2633	2457
10-Jun	2510	3349	2550	3348	3025	3348	2853	2642
20-Jun	2708	3449	2629	3881	3140	3447	3102	2842
01-Jul	2781	4089	3035	4184	3242	3628	3331	3035
10-Jul	2895	3639	2880	4290	3335	3709	3395	3114
20-Jul	3103	3597	2993	4306	3331	3696	3383	3218
01-Aug	3428	3973	3339	4338	3251	3668	3424	3339
10-Aug	3503	3144	3214	4161	3078	3610	3366	3252
20-Aug	3651	2851	3210	3957	2830	3565	3259	3277
01-Sep	3956	3183	3376	3810	2803	3496	3158	3376
10-Sep	3453	2432	3080	3343	2626	3108	2936	3938
20-Sep	2846	1988	2621	2923	2285	2791	2659	2667
01-Oct	2692	2517	2409	2630	1961	2635	2465	2409
10-Oct	1582	1223	1844	1976	1451	1855	1846	1823
20-Oct	1053	804	1305	1416	972	1343	1318	1188
01-Nov	918	960	898	949	790	986	950	898
Total Biomass	52101	52643	48865	61089	49466	57685	51776	50479
Relative Biomass	0.9	0.9	0.8	1.0	0.8	0.9	0.8	0.8
SWAP relative yield	0.8	0.8	0.8	0.8	0.9	0.7	0.8	0.8