Water productivity of irrigated crops in Sirsa district, India

Integration of remote sensing, crop and soil models and geographical information systems

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Abstract

Major issues with respect to water management in Sirsa district are waterlogging and salinization in areas with saline groundwater and over-exploitation of groundwater in areas with fresh groundwater. The present crop yield increase of the major crops in Sirsa district is marginal. Recent studies show that water is the main limiting factor to increase the crop yields. In order to identify the main water losses, an extensive WAter PROductivity study (WATPRO) has been performed in Sirsa district.

The WATPRO project focussed on (1) the integration and application of advanced research tools (remote sensing, detailed crop and soil models, and GIS), (2) the upscaling from local field scale to regional scale, (3) the application of recent concepts on water productivity at various scales, and (4) a survey of the most viable scenario's that improve water productivity in Sirsa district.

During the agricultural year 2001/02 extensive measurements were collected for the major crops wheat, cotton and rice at both experimental fields and at farmer fields with various soil, irrigation and management conditions. The water flow and salt transport model SWAP and the detailed crop growth model WOFOST were calibrated in order to reproduce the measurements at the experimental and farmer fields. The calibrated models have been used to analyse viable water management options at field level to improve *WP*.

High and low resolution satellite images have been used to derive the cropping pattern, and in conjunction with the remote sensing algorithm SEBAL to estimate evapotranspiration, biomass production and water productivity as distributed over Sirsa district. The main conclusion from the remote sensing analysis is that *WP* is good and rather uniform for wheat, and moderate for rice and cotton. The wider range in *WP* for rice suggests that by narrowing the variability and increasing the *WP* for rice, productivity if water resources in Sirsa can be improved substantially.

Available data sets of Sirsa district on meteorology, crops, soils, groundwater, canal and tubewell water and cultivable command areas, have been integrated into a GIS. The data were downscaled to a level of 30x30 m to allow comparison with remote sensing data. The followed stratification resulted in a final overlay with 2404 calculation units. For each unit the tuned SWAP/WOFOST combination was used to simulate crop growth and water and salt balances. The results of the current regional analysis are such that it can be used to compare regional scenario studies qualitatively. Improvement of both both instrument and data sets may enable a more quantitative approach.

A theoretical framework is presented to analyse *WP* at crop, field and regional scale for fresh and saline groundwater conditions. This methodology is applied to evaluate current proposals to increase and maintain water productivity in Sirsa district. By far the highest increase of *WP* can be expected from improved crop management (cultivation, fertilizer application, weed and pest control) and by replacing paddy rice with dry rice or corn.

Finally a field scale modeling approach and a regional modelling approach were used to explore the impact of different scenarios on yields, gross return and *WP*. Four scenarios have been explored indicating that (i) climate change will have a positive effect, (ii) increased salinity levels will have negative impacts on especially rice, (iii) proper irrigation scheduling is most important for wheat, and (iv) a further rise in groundwater levels will have a detrimental effect in some areas. Key recommendations for future water management in Sirsa, emerging from WATPRO, are the setup of an integrated agronomy-water management program to enhance crop yields and *WP*, the construction of a drainage system in waterlogged areas with saline groundwater, and enforced regulation of groundwater extraction.

The attached CD-ROM contains the collected data at experimental and farmer fields and of entire Sirsa district, the input files for the calibrated SWAP and WOFOST models, the LANDSAT and NOAA remote sensing images and the setup for the regional simulation.

Glossary

CCA	Cultivable Command Area; area suitable for agriculture with attached water rights
CCS HAU	Chaudhary Charan Singh Haryana Agricultural University
chak	the watercourse unit, in which 20-100 farmers share the irrigation water from one outlet
CI	confidence interval of optimized parameters
CV	coefficient of variation (ratio of standard deviation and arithmetic mean)
DM	weight of dry matter
DVS	crop development stage
EC	electrical conductivity
ET_a	actual evapotranspiration
ET_p	potential evapotranspiration
ET_{wl}	water limited evapotranspiration (optimal crop management, only water stress)
FM	weight of fresh plant material, which contains some moisture
GIS	geographical information system
HI	effective harvest index, ratio of fresh harvestable product and total dry matter production
HI_{dry}	dry harvest index, ratio of dry harvestable product and total dry matter production
HID	Haryana Irrigation Department
HSMITC	Haryana State Minor Irrigation and Tubewell Corporation
HYPRESS	European database of soil hydraulic functions, including pedotransfer functions
I	irrigation amount
IWMI	International Water Management Institute
kharif	summer crop season (April – October)
LAI	leaf area index
PTF	pedotransfer functions, which relate soil hydraulic functions with basic soil properties
rabi	winter crop season (October – April)
rostering	rotation of water supply among distributary canals
RMSE	root mean square error, measure for correspondence between observations and simulations
RS	remote sensing
SEBAL	the Surface Energy Balance Algorithm for Land
SIC	Sirsa Irrigation Circle
SO	weight of storage organ
STD	standard deviation
SWAP	Soil-Water-Atmosphere-Plant model
T_a	actual transpiration
T_p	potential transpiration
TDM	weight of total dry matter
TSUM	temperature sum, which determines the length of crop growth phases
warabandi	available canal water is spread to all farmers in proportion to their land holding
WMRI	water management response indicator
WOFOST	WOrld FOOd STudies, detailed plant growth model
WP_T	water productivity based on transpiration water only
WP_{ET}	water productivity based on evapotranspiration water only
WP_{Leach}	water productivity based on the sum of evapotranspiration and percolated water
WP_{Reg}	water productivity based on the sum of evapotranspiration, percolated water, distribution and conveyance losses
WP_{Irr}	water productivity based on total irrigation water supply
WP_{Supply}	water productivity based on sum of irrigation water supply and rainfall
WUR	Wageningen University and Research centre

1. Introduction

W. G.M. Bastiaanssen, J.C. van Dam and P. Droogers

1.1 Refocusing irrigation water management

The world population grows at a pace of 1.3 % per year. By 2025, global population will likely increase to 7.9 billion, more than 80 percent of whom will live in developing countries (*UN*, 1998). This growth in population combined with the expected increase in prosperity will put enormous pressure on water resources. As a matter of fact, 36% of the 2025 world population is projected to be living in China and India alone, so water management in India will rank high on the national and international political agenda. Although there is quite some uncertainty imbedded in these numbers, it is obvious that the current per capita water availability cannot be maintained. These developments put an enormous demand on the land and water resources and in particular on irrigated agriculture, that is responsible for 70% of the global fresh water withdrawals (*Seckler et al.*, 1998).

The available surface water resources are all exploited to meet the growing water demands, and most river basins are now at the edge of being developed to their maximum capacity. The risks are that basins retain all surface water resources in small and large reservoirs, and that the outflow diminishes to virtually nothing (‘closed basin’). This is far from being adequate for maintaining wetlands, estuaries, lagoons and other biodiversity-rich ecosystems that are traditionally found in the lower ends of basins. It has been estimated that during the 20th century, more than 50% of the wetlands are lost (*Bos and Bergkamp*, 2001).

Water demand exceeding water supply is – already – common for rural areas in the vicinity of fast expanding super metropolitans. Alluvial plains in the semi-arid and arid climates are the potential water conflict hazards because irrigation systems and urban water users have to share the space and resources. A fierce competition for water between the urban, industrial, agricultural and environmental users has began, and irrigated agriculture will – undoubtedly – have to develop new strategies based on water conservation. Although there is more demand for food to feed the expanding population, there is less water available for boosting the agricultural production. As a consequence, the irrigation sector has to utilize water resources more productively.

Several basins exploit groundwater for irrigation as a remedy to surface water resources scarcity, but this leads to unsustainable developments. Water policy makers have, therefore, to work out strategies for integrated water and environmental management, which rely on a proper knowledge of the basin hydrological and pollution conditions. Without strong governmental control on water rights and well permits, groundwater pumping can lead to unacceptable, fast declines of the groundwater table. Hence, irrigation with groundwater can only be a solution to overcome the shortage of surface water resources as long as the recharge rate is in balance with the extraction rate. Ideally, the groundwater system should function as a natural storage to overcome surface water shortage during dryer years, while additional recharge will take place during wetter years.

The often promoted solution to combat water scarcity is the improvement of irrigation efficiency, i.e. reducing water losses between the point of water diversion and the root zone soil moisture storage. This is, however, not a proper solution everywhere, because percolating water from fields that are irrigated is not necessarily bad (it is not always good either). When farmers are using groundwater or drainage water for irrigation, recycling of water resources will increase irrigation efficiencies that are substantially greater than the nominal field scale values. The ballpark figure for field scale irrigation efficiencies is 45%, and several studies have indicated that the irrigation efficiencies for deltas or river basins as a total system with recycling of percolation water can be as high as 80 to 100%. This implies that improvements in efficiency will be next to impossible, and is basically false hope. However, in shallow groundwater areas, irrigation efficiency is important to protect an area that is prone to water logging or soil salinization. When good quality irrigation water becomes deteriorated by saline groundwater, recycling is not longer an attractive management option, and managing canal water losses becomes a highly relevant issue.

Improving irrigation system efficiencies and reductions in irrigation water applications are no guarantee for successful water conservation. Reducing irrigation water supply will cut off the field scale percolation rates, but the impact on evapotranspiration (*ET*) can be minimal. The reduction in irrigation water supply by improved conveyance and application efficiencies may aggravate the declination of the groundwater table, or it deteriorates the water availability to downstream stakeholders. Despite many possible misconceptions about using irrigation efficiency terms are pointed out before (e.g. *Molden and Sakthivadivel*, 1999), it is still the standard building block of irrigation management planning, probably because alternative solutions are not well known.

One of the alternative solutions in water utilization is the framework of water accounting (*Molden*, 1997), which distinguishes different water use categories such as process depletion, non-process depletion, non-beneficial depletion, committed outflow and uncommitted outflow (Fig. 9.1). Others referred to these users as comprehensive *ET*, beneficial *ET*, non-beneficial *ET* and consumptive use. The framework of performance indicators describes the various aspects of water management such as production, utilization, environment and economy (e.g. *Bos et al.*, 1994; *Willardson et al.*, 1994; *Burt et al.*, 1997; *Kijne et al.*, 2003) and it needs to get more attention. The bottleneck is that tools are absent to make quick scans of the systems.

In summary, the major obstacles that prompt for a refocus on irrigation management are:

- The water flows and return flows in irrigation systems are generally poorly understood; it is uncertain what the irrigation efficiencies are at the various spatial scales;
- A higher or lower irrigation efficiency can be good or bad and does not lead to clear cut conclusions and management strategies;
- Water saving programs usually ignore the impact of the intervention on the hydrology of the surrounding environment;
- The tools for a more comprehensive irrigation performance framework are absent.

Hence, irrigation efficiency related management is not straightforward to implement, and a paradigm shift is required to describe the utilization of the water resources in irrigation systems in a simple manner. Agricultural production has traditionally been expressed in kg crop per ha of land, assuming that land resources are the limiting factor. In some cases land is indeed the limiting factor, but with the current water crisis, sufficiently available fresh water resources are becoming the binding constraint for food production, and limited water should be use more productively. It is therefore logic to express the agricultural performance in terms of kg crop produced per m^3 water used. From a plant physiological point of view this is already referred to for decades as water use efficiency (e.g. *de Wit*, 1958) or 'the amount of organic matter produced by a plant divided by the amount of water used by the plant in producing it'.

The terminology on water use efficiency is often confused with various versions of irrigation efficiency, thus describing losses or other forms of water that are not available for root water uptake. As an 'efficiency' is per definition related to comparing input with output during a given process, the same units for input and output should be applied (which does not hold true for water use efficiency). The classical concept of efficiency as used by engineers omits production values. The International Water Management Institute (IWMI) has started a strong lobby to change the nomenclature from water use efficiency into water productivity, which is now also followed by other Consultative Group on International Agricultural Research (CGIAR) institutes and the Food and Agricultural Organization of the United Nations (FAO). This provides also a better basis to concern with non-agricultural products that originate from water such as industries, bird habitats and tourism.

A key element in the discussion on Water Productivities (*WP*) is the nominal values and the ranges of *WP* for certain cropping systems. If the range is narrow, than there is only little scope to improve *WP*. There exists a general opinion that crop yield is a simple derivative of *ET*, assuming that the ratio of yield and *ET* is quasi-constant. In fact, *Doorenbos and Kassam* (1973) have demonstrated that yield and *ET* can be scaled between zero and a maximum value, and be related mutually by a single crop yield response factor K_y (Eq. 5.1). Although this is an interesting concept, the maximum yield for certain irrigation and drainage systems is not constant which makes yield over *ET* variable. *Bastiaanssen* (2000) showed the results of a literature review of wheat and corn, and he came to the conclusion that *WP* per unit depletion for wheat ranges between 0.4 to 1.6 kg/m^3 and that for corn the range was 0.3 to 2.7 kg/m^3. This implies that there is a factor 4 to 9 between the lowest and highest levels, and that an enormous scope for improving *WP* exists. An increase of *WP* by for instance 40% implies that the same food production can be maintained with 40% less crop water consumption. This is a great opportunity for the irrigation sector that needs to get more attention by water resources planners, agronomists and irrigation engineers. It needs to be emphasized that the saving should be related to *ET* ('wet saving') and not to water supply ('dry saving'). If we are able to increase the water productivity in irrigated agriculture, water can be allocated for other users in the river basin. In an extensive study towards world agriculture in 2015/2030, the FAO (2002) stresses the importance of higher water productivity in irrigated systems in order to meet the food demands of this century.

Traditional agronomical and hydrological knowledge need to be pooled together for addressing the following major problems with regard to *WP*:

- What are the benchmark *WP* values under practical conditions for various crops and what are the spatial variations occurring within and among irrigation schemes?
- How can we improve *WP* at the different spatial scales so that agricultural production can be maintained and fresh water resources come available for competing sectors or for expanding the irrigated area?

1.2 General background of water productivity

The water productivity concept is based on "more crop per drop" or "producing more food from the same water resources" or "producing the same amount of food from less water resources". In a broad sense, productivity of water is related to the value or benefit derived from the use of water. Definitions of water productivity are not uniform and change with the background of the researcher or stakeholder involved. For example, obtaining more kilograms dry matter production per unit of transpiration is a key issue for plant breeders. At a basin scale, economists wish to maximize the economical value from water used. There are several definitions of water productivity, so we have to ask ourselves *which crop* and *which drop* are we referring to (see Table 1.1).

Table 1.1 Some examples of stakeholders and definitions in the water productivity framework.

Stakeholder	Definition	Scale	Target
Plant physiologist	Dry matter / transpiration	Plant	Utilize light and water resources
Nutritionist	Calorie / transpiration	Field	Healthy food
Agronomist	Yield / evapotranspiration	Field	Sufficient food
Farmer	Yield / supply	Field	Maximize income
Irrigation engineer	Yield / irrigation supply	Irrigation scheme	Proper water allocation
Groundwater policy maker	$ / groundwater extraction	Aquifer	Sustainable extraction
Basin policy maker	$ / evapotranspiration	River Basin	Maximize profits

If we concentrate on the productivity than we can express this as total dry matter production or as actual yield as a harvestable product. Productivity expressed in kg is less useful if we want to compare different crops or different regions and under these circumstances, a definition based on economic value is more appropriate. These economic values can be based on simple gross value, so kg yield multiplied by market prices, but it can include also a complete economic evaluation to get the net benefits. Fluctuations in prices (per region and/or between years) can influence the *WP* substantially and it is therefore practical to use average world prices.

Water managers tend to be more concerned with the total water input. Rainfed farmers in arid areas, for example, are extremely concerned with capturing and doing the most with limited rainfall. Where an additional supply is available as supplemental irrigation, maximizing the output from a small amount of additional irrigation supply is normally highly productive. For irrigation farmers, and managers of irrigation systems, water supply is a managerial factor and they will evaluate their own *WP* on the basis of canal water supplies in relation to crop yield, rainfall, supplemental irrigation, or full irrigation supplies.

Water that has been evaporated through *ET* is not longer available for reuse in the basin to other stakeholders, so it should be used as productively as possible; opportunities for recycling are absent. It seems therefore an advantage of expressing *WP* per unit *ET*, but, as referred to earlier, this is a strong field and agronomical approach.

1.3 Summary of earlier work in Northwest India

The Sirsa Circle pilot area in Haryana state has been selected for a number of reasons. In the central and north-western region of Haryana, where the groundwater is brackish and no drainage outlets are available, canal irrigation has led to problems of water table rise, water logging and flooding, and secondary salinization. In the eastern region and other areas with fresh groundwater the water table is continuously declining. At the same time, Haryana together with Punjab – being the wheat belt of Asia - play an important role in the food production for the more than 1 billion inhabitants of India.

In the past decades, Haryana witnessed an impressive increase of crop yields. For instance average wheat grain yields in India rose from 1350 kg/ha in 1975 to 2450 kg/ha in 1998. Haryana participated in the Green Revolution, and current wheat grain yields in irrigated farmer fields fluctuate around 3900 kg/ha. In an extensive farming system analysis and planning study for sustainable food security in Haryana, *Aggarwal et al*. (2001) found that the availability of water is a major constraint to further food production increase in Haryana. These researchers stress the importance of more reliable data on water resources and water use in Haryana in order to improve its water management and crop production.

Indo-Dutch Operational Research Project on Hydrological Studies

One of the major studies undertaken to improve water management in Haryana State is the Indo-Dutch Operational Research Project on Hydrological Studies (*Agarwal and Roest*, 1996). This over ten-years intensive research, training and awareness creating project took place in Sirsa Irrigation Circle from 1989 to 1996. The main partners were Chaudhury Charan Singh Haryana Agricultural University, Hisar, India and Wageningen University and Research Centre, The Netherlands. The long term sustainability objectives of the project were dealt with by developing the following technologies:

- efficient on-farm water management;
- conjunctive use of fresh and saline water;
- development of drainage criteria;
- development of on-farm and regional integrated simulation models.

Based on the SWAP model linked to a GIS and a multi-objective optimization procedure, 6 major crop rotations in combination with 4 water management alternatives were explored (*Bastiaanssen et al*., 1996). Results indicate that sustainable water and salinity management is possible if drainage systems will be installed in 5 to 10% of Haryana and if canal water supply will be made variable, according to local soil physical needs and crop water requirements, incorporating contributions from shallow groundwater tables.

The regional water management analysis was also based on modeling approaches using SIWARE (*Boels et al*., 1996) for the canal and on-farm water management and SGMP for the regional groundwater flows (*Boonstra*, 1996). Two options were explored to solve the problems of rising groundwater tables in some areas and declining ones in other areas. The key to solve this would be to reduce on-farm irrigation applications, which was tested by two alternatives: water pricing and demand driven operations. Both options were concluded to be effective, but the demand driven option is difficult to implement since this would require a complete change in the infra-structure and would mean to abandon the *warabandi* system.

Jacobs and de Jong (1997) conducted an interesting field inquiry towards the perception of farmers and irrigation managers in the Adampur division near Hisar. The vision of these stakeholders was converted into water management rules, and the impact of these rules was evaluated through Water Management Response Indicators including relative evapotranspiration, salinity hazard index, salt concentration change, moisture storage change, and several groundwater related indicators (Box 4.1). The best solutions comprise drainage in shallow groundwater table areas, more tubewell use, lining of canals and watercourses, cropping pattern adjustments and bio-drainage through planting of eucalyptus trees.

Jhorar (2002) used the SIWARE model to reduce canal water supply by about 25% during the rainy season in the areas facing rising groundwater levels. In addition he increased the capacity of groundwater extraction by 60 mm y^{-1}. The models results revealed that groundwater of relatively poor quality can be used, and that the sustainability of the system depends on the rainfall distribution. Sirsa district appeared to be vulnerable to drought.

According to all these studies, one of the most important issues in solving Haryana's problem is to create a drainage outlet for the inland drainage basin area. Unfortunately, ten years after the Indo-Dutch study, the drain is not constructed due to high costs.

International Water Management Institute studies in Haryana

The International Water Management Institute has completed a set of studies concentrating on water productivity analysis during the last five years.

Sakthivadivel et al. (1999) integrated wheat yield from remote sensing with GIS data on soil type, water table depth, groundwater quality, district level discharge, rainfall and *ET*. The conclusion was that although *WP* is high, especially for Indian standards, rising water tables and salinity threats the sustainability of the irrigation system. In other words, equal emphasis should be given to the rising and falling trends of groundwater levels.

Bastiaanssen et al. (1999) linked the SIWARE output with crop yield assessed from the Indian Remote Sensing satellite (*Thiruvengadachari et al*., 1997) to estimate irrigation performance and *WP* for Sirsa irrigation district. One of their key findings is that the average *WP* of wheat is 0.88 kg m^{-3}, which was achieved at average crop yields of 3.76 t ha^{-1}. In terms of sustainability, average increase in groundwater storage is about 100 mm of water, which corresponds to a rise in groundwater level of about 80 cm y^{-1} if we use an average specific aquifer yield for Sirsa district of 0.12 (*Boonstra*, 1996).

A study based on intensive data collection over 216 farms in the Bhakra canal system was undertaken during the *rabi* season 2000-01 (*Hussain et al*, 2003). The study took place in the context of a major initiative, the Rice-Wheat Consortium for Indo-Gangetic Plains. This consortium strives to address the issues of productivity enhancement of rice and wheat in a sustainable fashion. Their study compared growing practices and production levels in the Punjab of Pakistan with these in Haryana, since the general assumption is that yields in Haryana would be almost double in comparison to the ones in Punjab, Pakistan. Some of their key findings with respect to wheat relevant for Haryana are:

- Average wheat yields are higher in India (4.48 t/ha) than in Pakistan (4.11 t/ha). However, the magnitude of yield difference is not as high as is generally perceived.
- There are significant differences in yields across farms and locations with yields ranging from 2.96 t/ha to 5.73 t/ha.
- Wheat yield differences are much higher across watercourses within a distributary than across distributaries.
- There is significant variation in total water (both surface and groundwater) applied. Per hectare water use varies from 746 m^3 to 4,322 m^3 averaging at 3,050 m^3 against crop water requirements of 3,300 m^3.
- Average productivity of consumed water is 1.36 kg m^{-3}. Average WP_{ET} is 1.47 kg m^{-3}.

Central Soil Salinity Research Institute studies

Various studies have been undertaken by the Central Soil Salinity Research Institute, Karnal, focusing on soil-water-plant interaction and salinity management options. A study on improving wheat productivity showed that improved crop varieties could indeed increase crop yields but would place a greater stress on soil and water management (*Tyagi and Sharma*, 2000). It was stated that the majority of research is still concentrating on farm irrigation scheduling, while the real problems are the inadequacies of the conveyance and distribution systems. Their results indicate also that the key option to increase wheat productivity lies in an improved drainage system to minimize water logging and secondary salinization.

A diagnosis and recommendation for improving water delivery performance in the Bhakra canal command area, to which Sirsa Irrigation Circle belongs, is given by *Tyagi* (1998). His analysis showed that canal water delivery, in terms of equity, timing and amount, was very poor. Three options were suggested for improvement:

- Improvement in water distribution equity and efficiency through the proper design of the unit command area size;
- Relaxing the rigidity of the delivery schedule;
- Improving reliability.

In fact, this would require substantial changes in the *warabandi* operational system and in the actual canal infrastructure.

Tyagi (2003) mentioned that irrigation with sodic water given after two turns of irrigation with fresh water, to rice as well as to wheat, helped in obtaining yields comparable to those with irrigation with fresh water. In the case of alternate irrigation with sodic and fresh water, crop yields were only marginally less than when fresh water alone was used.

A study by *Ambast et al*. (2002) on the rice-wheat crop rotation emphasized that canal water delivery is not a limiting factor during the *rabi* season (wheat) due to the low water requirement and high salt tolerance of the crop and the availability of groundwater. However, during *kharif* (rice) canal water is critical. From a series of scenarios they concluded that reducing the existing differences in canal water supply between head and tail farmers could increase average crop yields by 240 to 580 kg ha^{-1}.

Others

The option to use water pricing as a means to improve water productivity was explored by *Hellegers* (2003). The hypothesis tested was whether a mechanism of water pricing would be a feasible management tool to minimize seepage and percolation in saline, waterlogged areas and to minimize groundwater pumping in the declining groundwater areas. She concluded that since returns on water are on average about 100 times the price of delivery, a socio-political unacceptable increase in water price is required to achieve this. A solution proposed is to have reliable canal water supply in saline areas and, as a price, less reliable supply in fresh water areas.

Table 1.2 Water productivity values (kg m^{-3}) from Harayana (*ET* is evapotranspiration, *CW* is canal water supply)

Source	Scale	Crop and drop	Wheat	Rice	Cotton
Sharma et al. 1990	Field	Yield/*ET*	0.65	-	-
Bastiaanssen et al., 1996	Field	Yield/*ET*	1.27-1.43	-	0.46
Khepar et al. 1997	Field	Yield/*ET*	-	0.4 – 0.5	-
Bastiaanssen et al., 1999	Distributary	Yield/*ET*	0.83-1.18	-	-
Sakthivadivel et al., 1999	Distributary	Yield/*CW*	2.79	-	-
Bouman and Tuong, 2000	Field	Yield/ supply	-	0.2 – 0.4	-
Hussain et al., 2003	Field	Yield/*CW*	1.47	-	-
Hussain et al., 2003	Field	Yield/*ET*	1.36	-	-
Tyagi, 2003	Field	Yield / supply	1.2-1.8	0.36-0.67	-

1.4 The toolbox

An optimal water management planning relies on accurate knowledge of plant water consumption, water flows and salt transport throughout the growing season. This cannot be reconstructed from field measurements, so dynamic simulation models are deemed necessary to describe soil physical processes, the hydrology of the system and crop growth in order to extract *WP* values. As emphasized before, a thoroughly understanding of all the water flows enables the calculation of a set of *WP* values, each with its own comprehensions and usefulness.

In the past decades researchers devoted much effort to develop and calibrate field scale simulation models for water flow, salt transport and crop growth. In order to analyze crop water productivity, the different modules for simulation of vertical water flow, nutrient transport, salt transport, and crop growth were integrated in SWAP/WOFOST with close interaction between the processes. Clear and reliable calibration procedure were developed to extend the application of these integrated simulation models. Gradually these simulation models grew beyond the laboratory and plot scale and are now such mature that they can be very useful to analyze water productivity at farmer fields and, in combination with geographical information systems, at regional scale.

Over the last decade advances in remote sensing (RS) from satellites have resulted to practical applications of RS in water resources research and applications (*Schultz and Engman*, 2002). In the early days of RS, images were mainly used qualitative, but increase in accuracy of sensors, and especially a better understanding of processes, have evolved in the development of quantitative algorithms to convert raw data into useful information. Information on *ET*, yield and soil moisture helps water managers to adjust water allocation to ensure proper distribution between different users. These data are very useful to tune the simulation models on crop growth and soil transport processes. *Droogers and Bastiaanssen* (2002) have used a parameter optimization procedure to assess the planting dates and irrigation schedule of irrigated cotton in Turkey. *Ines and Droogers* (2002) have determined the irrigation water quality and irrigation schedule in Haryana. *Jhorar* (2002) found from inverse modeling techniques the hydraulic properties of irrigated soils as well as the groundwater extractions from the Ghaggar river belt.

After combining measured satellite data with crop growth and soil transport simulation models, a thorough analysis can be performed of current and future water productivities. The physically based integrated models are, once calibrated, perfectly suitable to study the effects of different water management options on *WP* and recommend the best scenarios for a productive and sustainable agricultural system that improves rural livelihoods.

1.5 WATPRO objectives

As one of the outcomes of the second World Water Forum in The Hague (2000), the Dutch ministry of Agriculture, Nature Management and Fisheries started the *Partners in Water for Food* action program. In the frame of this action program, various departments of Wageningen University and Research center, the International Water Management Institute and WaterWatch made plans to combine the operational knowledge in remote sensing and simulation of crop growth and soil transport processes to develop a general tool to assess regional water productivity in irrigated agriculture. The WATPRO project focussed on the following activities:

- integrate and apply advanced tools (remote sensing, improved simulation of crop growth, soil water flow and solute transport, geographical information systems);
- scale up from the local field scale to the regional scale;
- applying recent ideas from the international community on water productivity in river basins;
- survey future scenario's that improve water productivity in Sirsa district.

These 4 activities highlight the progress as compared to other studies conducted in the past and WATPRO. The innovative aspect is the diagnosis of the *current situation* by means of remote sensing technologies supported by field measurements, and of the *future situation* using simulation models that describe dynamic irrigation, drainage, salinity and crop growth processes simultaneously, in combination with geographic information systems.

The WATPRO project aimed at collecting the required water, crop and soil data at a large number of farmer and experimental fields and making them available in an accessible database These data were subsequently used to tune the simulation models for crop and soil water to current farmer practices.

Different organizations collaborated towards the successful implementation of the WATPRO project. The Water Resources Group of Wageningen University and Research centre (WUR) coordinated the project, and applied the generic water and salt transport model SWAP. Chaudhary Charan Singh Haryana Agricultural University (CCS HAU) implemented the project in Haryana, collected the data at experimental sites and farmer fields and developed the database. The Plant Production Systems Group of WUR analysed the crop experiments and applied the generic crop growth model WOFOST. Alterra Green World Research of WUR designed the regional data base and performed the regional water productivity analysis. WaterWatch analysed Landsat and NOAA satellite images for evapotranspiration and biomass production with the SEBAL model. The International Water Management Institute (IWMI) lead the discussion and analysis of water productivity. The WATPRO project has been financed by the Dutch ministry of Agriculture, Nature Management and Fisheries and lasted from January 2001 until November 2003.

In this report first a description is given of water management and crop production in Sirsa Irrigation Circle. The measurement program and database are described in detail in Chapter 3. The database is spread with the CD-ROM attached to this report. The water flow and salt transport at farmer fields is analysed with SWAP in Chapter 4. In Chapter 5 the model WOFOST is calibrated with the crop growth data at the experimental sites and applied to farmer fields in Sirsa Irrigation Circle. In Chapter 6 the remote sensing analysis of Landsat and NOAA images for evapotranspiration, biomass and water productivity is described. Chapter 7 contains the setup and results of the regional analysis with the SWAP-WOFOST combination. Chapter 8 shows the merit of combining disciplinary knowledge of crop growth, soil physics, hydrology, civil engineering, remote sensing, and computer science. This all comes together in Chapter 9 where the current water productivity in Sirsa Irrigation Circle at regional scale is discussed and viable options are given to use water in a more productive and sustainable way.

2. Water management and crop production in Sirsa Irrigation Circle

R.K. Jhorar, A.S. Dhindwal, Ranvir Kumar, B.S. Jhorar, M.S. Bhatto and Dharampal

2.1 Introduction

Irrigation Circle is an administrative unit within the management of Haryana Irrigation Department. Sirsa Irrigation Circle (SIC) is located in the extreme western part of Haryana State, India. It is situated between latitude 29.1° to 30.0° North and longitude 74.2° to 75.3° East, covering an area of 0.48 million ha. About 90 per cent of the total area under SIC belongs to Sirsa district and the rest to the adjacent Fatehabad district. The area is bounded by the State of Punjab in the north and north east, and by the State of Rajasthan in the west and south. Sirsa district was carved out of the Hisar district in 1975, hence, different statistical information before this period is part of Hisar district and is not available separately for Sirsa district. The Sirsa district is divided into seven administrative blocks i.e. Dabwali, Baragudha, Ellenabad, Rania, Sirsa, Odhan and Nathusari Chopta.

Water management in SIC, like any other arid and semi-arid region, is of very complex nature. Key factors related to water resource sector in SIC are: scarce and erratic rainfall, absence of any perennial river in and around the area, high evaporative (atmospheric) demand, marginal to poor quality of groundwater in most part, rising groundwater levels, occasional flooding and low water holding capacity of soils. Other factors affecting water use efficiency and crop production include: fluctuations in canal water supply, low irrigation application efficiency due to light textured soils, conveyance losses from the irrigation system and often delay and failure of monsoon rains.

2.2 Climate and rainfall

The climate of the area is characterised by its dryness, extremes of temperature and scanty rainfall. The mean daily maximum temperature during May and June, which is the hottest period, varies from 41 to 46 °C . On individual days, during the hot period, it may rise up to about 49 °C. Hot winds, with low relative humidity, often causes dust storms during the hot season. January is generally the coldest month with a mean daily maximum temperature of 21 °C and a minimum 5 °C. During the months of December and January, occasional fogs reside in the area. An agricultural year may be divided into four distinct seasons: the hot dry season from March to June, hot rainy (monsoon) season from July to September, post-monsoon season from October to November and cold season from December to February.

The reference evapotranspiration in SIC is 4 to 5 times as large as the amount of rainfall. On an average SIC receives 300-550 mm of rainfall. This amount is not only insufficient but is highly erratic both in quantity and distribution. Successful crop production without supplemental irrigation is hardly possible even in the rainy season. About 80 % of the annual normal rainfall occurs during the monsoon months of July to September. On an average, the area has 20 rainy days (i.e. days with rainfall of 2.5 mm or more) in a year. Sometimes a large amount of the total rainfall is sometimes received in a few heavy storms, causing temporary ponding of fields of crops, particularly in the low lying areas. In the past, when farmers used to rely mainly on rainfall, it was a common practice to store and conserve as much of the rainfall as possible. However, with the development and operation of the canal irrigation system, the practice of in situ conservation of rain water receives less and less attention.

2.3 Topography and soil types

The general topography of the SIC is almost plain with some isolated steep contours in the vicinity of the Ghaggar river which flows through the central part. Ground surface elevations vary from 192 to 207 m above mean sea level. The terrain can be classified into three major types: old alluvial plains, recent alluvial plains and aeolian plains with sand dunes. The old alluvial plain is a vast surface of flat to rolling terrain and extends from the northern boundary of SIC towards the south. The southern most part of SIC is covered by aeolian plains with sand dunes. A narrow belt along the Ghaggar river, between the old alluvial plains and the aeolian plains, is covered by recent alluvial plains. The soil texture generally varies from loamy sand to sandy loam, with some sandy soils occurring in patches. The soil texture in the belt along Ghaggar river varies from silt loam to silty clay loam. Invariably, all the soils have low organic carbon content and under natural conditions light soil cover.

2.4 Canal Irrigation

2.4.1 Canal Irrigation System

Sirsa Irrigation Circle is part of the Bhakra Irrigation Project and has an extensive canal network (Fig. 2.1). The irrigation system consists of a large network of main canals, branch canals, distributaries, minors and watercourses. The irrigation water originates from the Gobind Sagar Storage Reservoir located across the river Sutlej in the State of Himachal Pradesh. SIC is served by three main canals. Bhakra Main Line enters in the north, Sukhchain distributary in the central part, and Fatehabad branch in the south. Tails of these canals supply water to the adjoining areas of Rajasthan. The seasonal river Ghaggar, which originates from the Siwalik hills on the outer Himalayan ranges, flows from the eastern to the western direction through the central part of the SIC. During monsoon, water from the Ghaggar river is partly diverted for irrigation. A recently constructed dam in the Ghaggar river near Sirsa will increase the amount and reliability of irrigation water from the river.

The Bhakra project was designed to distribute a limited supply of water to a maximum number of farmers. Because of the limited available water supply, irrigation water is not continuously available to the different parts of an irrigation command. Water supply is rotated among a group of canals following a procedure known as *rostering*. The period of *rostering* is 24 days. Typically an irrigation command area has three distributaries in a group, say A, B and C. During the first 8 days of a rotation, distributary A has first priority and receives fully supply of water. Distributary B has second priority and receives water depending on the availability. Distributary C has the lowest priority and will receive water only when the regional water supply is excessive. During the next 8 days of rotation, distributary C moves to first priority, distributary A to second and distributary B to third. During the last 8 days of rotation, the priority order moves on again

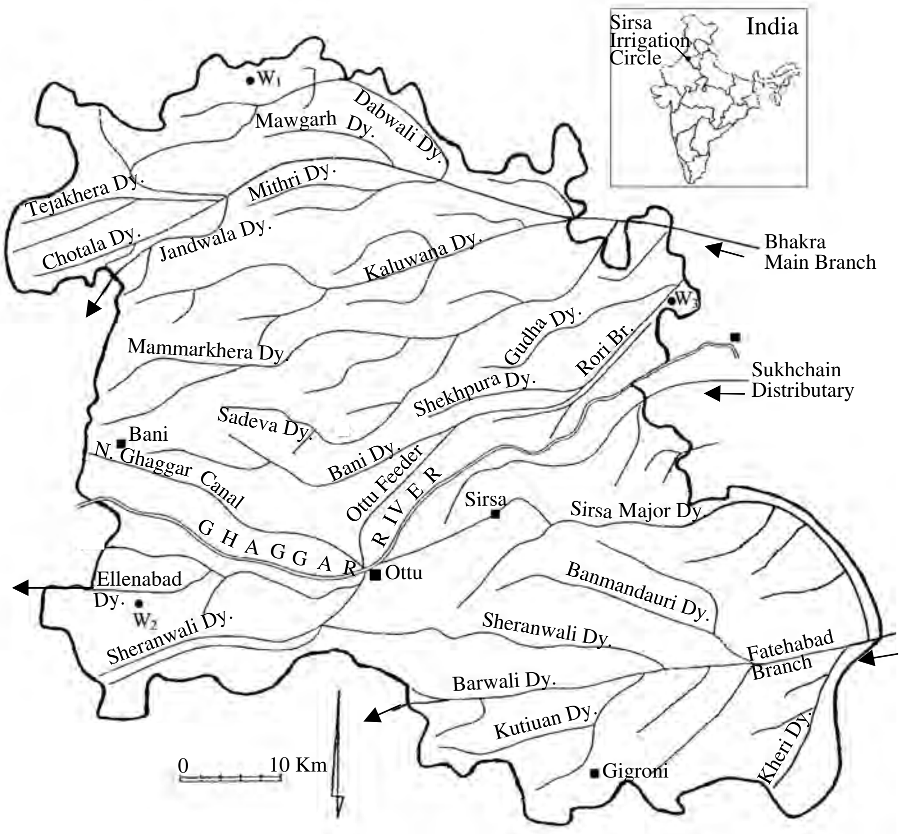

Figure 2.1 Location of the Sirsa Irrigation Circle showing the canal network.

The distribution of water among the farmers is at the watercourse level. The allocation is based on a rotational system during one week called *warabandi*. Water from a watercourse is allocated to the individual farmer for a specified period in proportion to his land holding. In this way, every farmers is ensured of a fixed irrigation time per unit land per week. This system of water distribution has the advantage of ease in operation and minor management problems. The disadvantage is that the farmer's entitlement of water is irrespective of soil type and crop water requirements. Moreover, there is no compensation for seepage losses that occur from head to tail within the *chak*. During their turn, the farmers distribute the water on their fields. The amount of water applied to each field is decided by the farmer. Commonly, farmers use the surface flooding method to irrigate their fields. Irrigation water charges to farmers are fixed and based on type of crop and area actually irrigated with surface water. They are irrespective of the amount of water applied to each field during a crop season. This means the farmers have to pay less if they irrigate less area with the same amount. It may appear that this could lead to over irrigation and wasteful use of water (*Agarwal and Roest*, 1996). However, prevailing water charges are very low and, as such, they have no influence on farmers' management decisions (*Navalawala*, 1999; *Hellegers*, 2003).

2.4.2 Canal Irrigation system performance

Considering the availability of irrigation facilities, Sirsa district has a relatively favourable condition. Currently, about 90 % of the net area sown is irrigated against the State average of about 81 % and national average of about 40 %. Of the total net area irrigated in the district, about 80 % receives supply from the canal irrigation system whereas only about 50 % of the net area sown at the State level is provided with canal irrigation facilities. Although SIC has an extensive network of canal systems, the supply from the upstream is often not sufficient to provide sufficient water at all the time. Moreover, the irrigation water, whenever available, is supplied to the farmers at fixed rotations. It is well recognized that sufficient water availability and flexible water delivery are key requirements that will allow farmers to adopt new technologies for improving water use efficiency.

Adequate water supply to irrigate crops is the primary concern of a water supply system. *Tyagi* (1996) studied the performance of irrigation system (Fatehabad Branch) at farm as well as watercourse level. The average relative water supply RWS (ratio of water supply and water demand over a period of time) was observed to be 0.72 in summer and 0.65 in winter at the head reach and 0.58 in summer and 0.50 in winter at the tail reach of watercourses. This clearly indicates the insufficiency of the available canal water supply to meet the demands. The significant reduction in RWS towards the tail end is due to seepage losses occurring in the watercourses. The observed value of discharge in two watercourses (one lined and one unlined) is given in Table 2.1.

Table 2.1 Observed discharge in head, middle and tail reaches of watercourses (*Tyagi,* 1996).

Distributary	Watercourse name	Lined/unlined	Location	Discharge (l/s)
Kutiuan	780L	Lined	Head	39.5
			Middle	32.7
			Tail	26.4
Sheronwali	2000R	Unlined	Head	30.5
			Middle	20.7
			Tail	15.8

The decrease in discharge from head reach to tail end indicates that considerable seepage losses occur in the watercourses. This clearly shows the need for proper management of the watercourses to avoid seepage losses. This also means that the current *warabandi* system, which allocates water to different farmers based on land holding irrespective of their location along the watercourse, results in inequitable water distribution among the farmers, thereby affecting the productivity of canal water use.

Over the years, the water requirements of the irrigated areal in SIC has increased, while the available canal water amounts kept the same. This means that during the initial years of SIC the available canal water has been used less efficiently. The main reasons for this low efficiency are: lack of experience with the water application, uneven fields, unlined water conveyance system and complacency of the farmers due to the high yields compared to previously rain fed fields. During the sixties of the previous century, when the extensive canal irrigation system was introduced in SIC, most of the watercourses were unlined. Currently, most of the watercourses are lined. However, most of the field channels supplying water to individual fields are still unlined.

2.5 Groundwater

The groundwater situation in Sirsa district is highly variable both in quality and depth. Besides aquifer permeability and thickness, the quality and depth of groundwater are main factors affecting its utilization. A network of observation wells is maintained by the Groundwater Cell of the Agriculture Department for periodic monitoring of the groundwater levels and the groundwater quality.

2.5.1. Groundwater quality

Groundwater quality is a major issue in the utilization of groundwater in the area. Keeping in mind the potential salinity hazard of irrigation water, the groundwater has been classified into three broad categories: good (EC_{gw} < 2 dS m^{-1}), marginal (EC_{gw} 2-6 dS m^{-1}) and poor (EC_{gw} > 6 dS m^{-1}), where EC_{gw} is the electrical conductivity of groundwater. Sometimes, the marginal quality groundwater is further referred to as sub-marginal (EC_{gw} 2-4 dS m^{-1}) or marginal (EC_{gw} 4-6 dS m^{-1}) quality water. The groundwater quality on both sides of the Ghaggar river was generally good, resulting in the installation of numerous tubewells in the belt along the river. The deep groundwater quality in the northern and extreme southern part of the SIC was quite poor. However, over the years, a relatively better quality water layer has developed over the saline groundwater. This prompted farmers in these areas to install shallow tubewells. Generally speaking, the shallow groundwater has a better quality than the deep groundwater. According to a 2001 groundwater quality map of Haryana, prepared by Haryana State Minor Irrigation and Tubewells Corporation (HSMITC), the shallow groundwater quality was good in about 28 %, marginal in 64 % and poor in 8 % of the Sirsa district. On the other hand deep groundwater quality was good in 20 %, marginal in 16 % and poor in 64 % of the area. In some cases, high residual sodium carbonate (RSC > 2.5 meq/l) is also observed in the groundwater. Use of this water requires the application of gypsum to prevent sodification of fine-textured soils.

2.5.2. Groundwater depths

Over the years, major portion of the Sirsa district has experienced rise in groundwater levels. The average groundwater level in the Sirsa district has risen from 18 m below the ground surface in 1974 to about 10 m in June 2000. However, certain areas, particularly along the river Ghaggar have experienced a declining trend in the groundwater levels. In general, the rising trend in groundwater levels was observed in the areas underlain with the poor to marginal quality groundwater and the declining trend in the areas underlain with good quality groundwater. The rising groundwater levels are mainly caused by lack of extraction of groundwater with marginal quality, seepage from the canal irrigation system, occasional heavy rainfall events and insufficient natural drainage. The declining groundwater levels are mainly due to over exploitation of good quality groundwater for the wheat-rice crop rotation. The long term groundwater level trends shows that the average rate of groundwater rise slows down. Between 1974 and 1984 the average rise in Sirsa district amounted 0.63 m y^{-1}, while between 1990 and 2000 the average rise amounted 0.09 m y^{-1} only. In June 2000, prior to the monsoon period, the groundwater levels in Sirsa district ranged from less than 3 to more than 25 m below soil surface (Fig. 7.3).

2.5.3. Groundwater use

Groundwater use is implemented in two ways. The State Government operates deep direct irrigation and augmentation tubewells and farmers operate shallow tubewells. The augmentation tubewells supply water to canals. A major portion of groundwater use takes place through farmers owned shallow tubewells. The number of tubewells increased from 8,217 in the year 1976 to about 32,000 in the year 2000. This shows the farmers interest to use groundwater for irrigation. However, the increase in the intensity of tubewells is mainly concentrated in the regions where groundwater is of relatively better quality. The number of tubewells per km^2 varies from as low as 2 in the Dabwali block to 5-10 in the Sirsa, Rania, Baragudha and Elenabad block.

In India, groundwater development is classified into three categories (white, grey and dark) depending on the extent of groundwater exploitation. In category white the level of exploitation is below 65% of the annual utilizable groundwater potential. In category grey this precentage ranges from 65% to 85%. In category dark the percentage of exploitation exceeds 85%. In Sirsa district, the level of groundwater exploitation varies from about 14 % in the Dabwali block to more than 154 % in the Ellenabad block. Accordingly to the level of groundwater exploitation, the Ellenabad block belongs to the ‘dark’ category and needs either to decrease the groundwater pumping or increase the groundwater recharge. The Rania block belongs to the ‘grey’ category. On the other hand, all the other blocks (Dabwali, Nathusari Chopta, Baragudha, Odhan and Sirsa) belong to the ‘white’ category. These blocks require more attention to arrest the rising groundwater levels.

2.6 Crop production

Two distinct crop growing season can be identified in the area: the winter growing season from October to April, called *rabi*, and the summer growing season from April to October, called *kharif*. In Sirsa district about 95 % area is suitable for cultivation with net sown area of about 87 % in the year 1999-2000. Out of the net sown area, about 66 % is cultivated both during the *rabi* and *kharif* season.

2.6.1 Cropping pattern

Before canal irrigation was introduced in SIC during the sixties, the crops were mainly grown with rain water and conserved soil moisture. Gram (chickpea) in the *rabi* season and Bajra (pearl millet) in the *kharif* season used to be the major crops grown. Due to the development of the canal irrigation system and increased groundwater exploitation during the last thirty years, there is a continuous shift in the cropping pattern towards more water demanding crops (Table 2.2). During the period from 1975-76 to 2000-01, the area under rice increased by more than 200%, wheat by about 190% and cotton by 170%. On the other hand the area under pearl millet and chickpea decreased by about 95%. At present, wheat in the *rabi* season and cotton and rice in the *kharif* season are the main crops. Other important crops are oil seeds, gram (chickpea) and fodder. Cotton-wheat and rice-wheat are the most dominant crop rotations. Although presently sugarcane is not an important crop, its area is likely to increase due to the construction of a sugar mill in the region.

Table 2.2 Area (10^3 ha) of major crops in Sirsa District.

Crop	1975-1976	1984-1985	1999-2000	2000-2001
Rice	13	25	45	40
Bajra	62	18	3	3
Wheat	84	130	236	244
Gram	147	125	13	8
Barley	11	3	5	9
Cotton	74	85	205	200
Oilseeds	19	40	42	37
Total	410	426	549	541

2.6.2 Crop yields

The crop productivity in the area is generally at the same level as the average of Haryana state and is substantially higher than the average in India. The increase in crop yields over the years (Fig. 2.2) was mainly the result of more irrigation facilities, improved crop varieties and increased fertilizer use. However, at present in SIC the crop yield increase is only marginal or even stagnates.

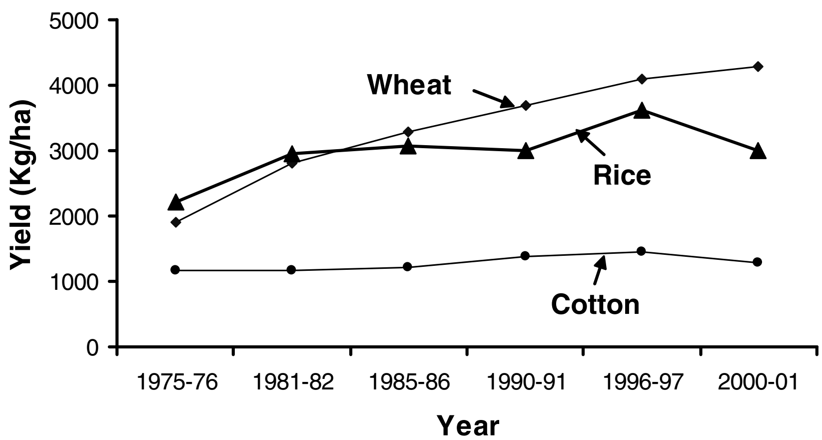

Figure 2.4 Average yields of wheat, cotton and rice in Sirsa district.

2.7 Major issues related to water management and crop production

The major issues related to water management in SIC are:

- rising groundwater levels in areas underlain with marginal to poor quality groundwater due to water losses from the irrigation system;
- declining groundwater level in the good quality groundwater zones due to over exploitation;
- waterlogging risks (groundwater depth < 3.0 m) in a few pockets, associated with secondary soil salinization;
- inflexible canal water supply and shortage of water to irrigate all agricultural crops.

It is vital to exploit the full potential of conjunctive use of surface and groundwater as a solution to the problem of inflexible canal water supply, water logging and soil salinization. Sincere efforts are also required to resolve the issue of stagnating crop production. Sharp increase in wheat and rice yield was the main contributing factor to the green revolution that India witnessed in the past. In order to meet India's future demands for food, fibre and oil, it is very important to increase the crop productivity. This is even more urgent as the area under cultivation is likely to decrease. Equally important is to enhance the water productivity because less and less water will be available for agriculture in future. These challenges can be met to a large extent by manipulation of agronomic practices (e.g. sowing time and method, irrigation methods, diversification including low water demanding crops), in situ rain water conservation, artificial groundwater recharge and safe use of marginal quality groundwater.

3. Measurement program and description data base

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3.1 Introduction

The objectives of WATPRO are to analyse the current water productivity of wheat, cotton and rice in Sirsa district, and to explore the options to improve water productivity. For this purpose the simulation model SWAP 2.0 is used. The model needs a large number of input parameters, therefore an elaborate measurement program on crop growth, soil water flow and salt movement was executed.

Experimental fields at research stations as well as farmer fields were used. The experiments were needed to calibrate the detailed crop module WOFOST for wheat, rice and cotton (see Chapter 5). For these crops several cultivars and different levels of moisture availability were included in the experiments at the regional research stations, Sirsa and Karnal. The farmer fields were used to calibrate SWAP for different soil types, and to obtain information about the actual situation and the variation within the region. The selection of the farmer fields was based on their location within the irrigation system (head, middle, tail), the crop rotation (wheat-cotton or wheat-rice) and the presence of salinity and/or waterlogging problems. Figure 3.1 shows the location of the farmer fields in Sirsa district.

In the next paragraphs the selection of the farmer fields (Par. 3.2), the set up of the experiments (Par. 3.3) , the methods used for the various measurements (Par. 3.2-3.3), and the regional data that were collected (Par. 3.4) will be treated. All collected data are available on the enclosed CD-ROM. The contents and structure of the CD-ROM are described in Appendix A.

3.2 Farmer fields

In Sirsa district at 6 sites 4 farmer fields (in total 24) were monitored from November 2001 until November 2002. At each site one field was intensively monitored in terms of irrigation supply, crop growth, soil moisture and salinity profiles. The other 3 fields at each site were monitored more extensively and served for additional verification of the analysis. The sites were selected to have different combinations of crop, water, soil and groundwater conditions. Out of the 16 fields with wheat-cotton rotation, 12 fields represented normal and 4 fields represented waterlogged and saline conditions. The wheat-cotton fields were all supplied with canal water from distributaries and minors of the Fatehabad branch of the Bhakhra Canal System (Fig. 3.1). The wheat-rice fields were fed through the Northern Ghaggar canal at the downstream of Ottu weir. In the wheat-rice fields most irrigation water came from the tubewells. In most wheat-cotton fields canal water was the main source of irrigation water.

The textures at the farmer fields range from clay loam to loamy sand (Fig. 4.4). Wheat-rice fields (sites S1 and S2) are situated on heavy soils in a relatively small area. Wheat-cotton in Sirsa district is cultivated predominantly on light soils. The groundwater quality of the wheat-rice region is very good (< 2 $dS.m^{-1}$). This is caused by recharge from the seasonally flowing

Ghaggar river. In wheat-cotton regions, the groundwater quality varies from good (< 2 $dS.m^{-1}$, sites S4 and S5) to poor (>6 $dS.m^{-1}$, site S6 with shallow groundwater (< 1.5 m)).

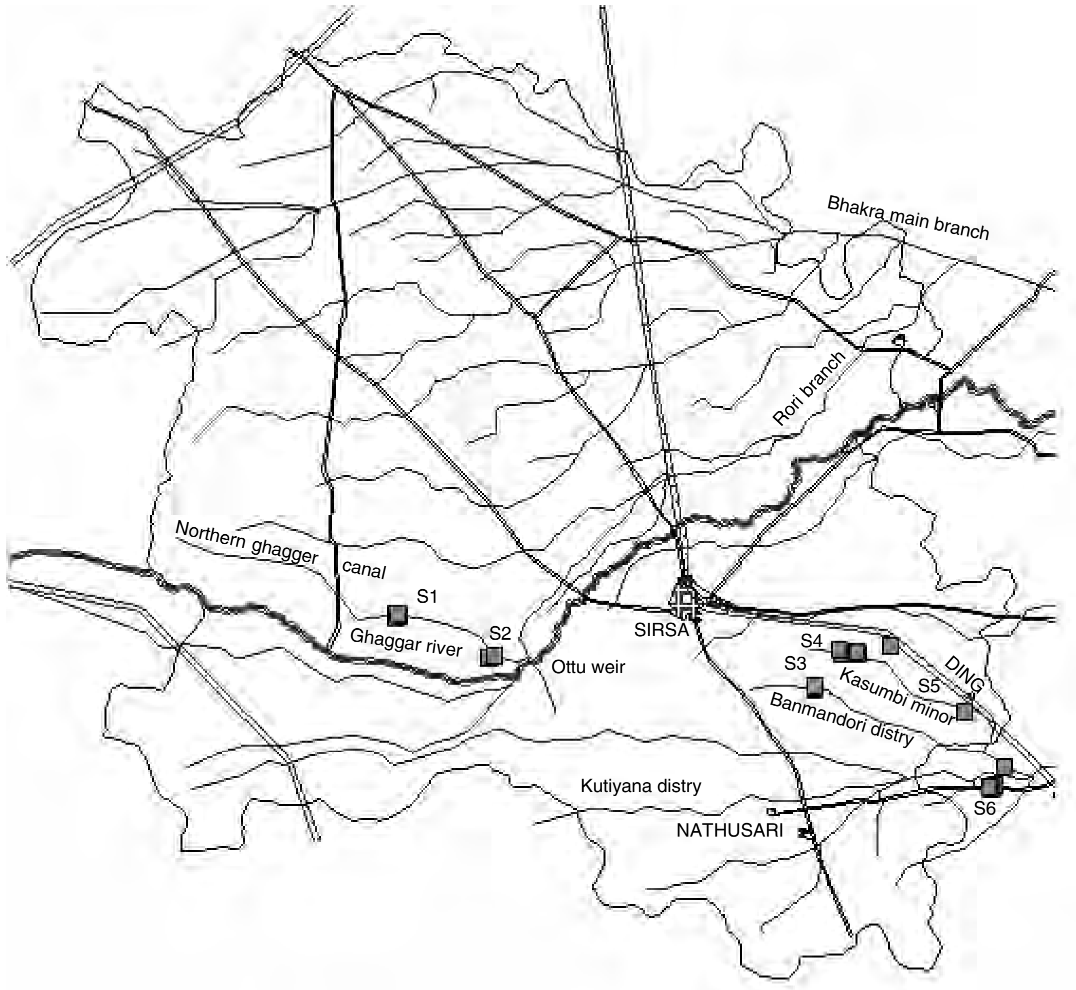

Figure 3.1 Location of the farmer fields at 6 sites in Sirsa district.

3.2.1 Soil measurements

At each farmer field soil samples were taken at sowing from 0-15, 15-30, 30-60, 60-90 and 90-120 cm depth. The samples were analyzed for basic physico-chemical properties: texture, bulk density, hydraulic conductivity, infiltration rate, field capacity, maximum water holding capacity, *pH*, electrical conductivity (*EC*), organic carbon, mineral nitrogen (N), available phosphorous and potash, DTPA-extractable Zn, Cu and Mn. The methodology is described briefly below.

Texture: Particle size of the soils was determined with the International Pipette Method (*Piper*, 1966). The soils were classified based on the percentages of the various particle sizes. The soil texture in wheat-cotton fields was generally sandy loam, while in wheat-rice fields sandy-clay loam to clay loam texture was found (Fig. 4.4).

Bulk density: The bulk density was determined in the field with the Core Method, using a root auger of 7.5 cm diameter and 15 cm height. The bulk density is calculated as the dry weight of the soil per unit volume. It ranged from 1.29 to 1.43 in wheat-rice fields, and from 1.48 to 1.70 $g.cm^{-3}$ in wheat-cotton fields.

Hydraulic conductivity: The saturated hydraulic conductivity (K_{sat}) of the core soil samples was determined in the laboratory with the Constant Water Head Method (*Klute and Dirksen*, 1986). The hydraulic conductivity in wheat-cotton fields ranged from 0.23 to 2.15 $m.d^{-1}$, while in wheat-rice fields, K_{sat} was less than 0.5 $m.d^{-1}$.

Infiltration rate: The basic infiltration rate was determined with a closed top infiltrometer according to *Malik et al.* (1990).

Soil moisture content: The soil moisture content on weight basis was determined with the gravimetric method using a post hole auger at sowing, before and after each irrigation, and at harvest. It was converted into the soil moisture content on volume basis by considering the bulk density of the respective soil layers. The same soil samples were analysed for *EC* and *pH*.

Saturation percentage: The saturation percentage of the disturbed soil samples at sowing was determined with the saturation paste method. Its value ranged from 46.1 to 59.8% for wheat-rice fields, and from 30.8 to 35.8% for wheat-cotton systems.

Field capacity: The field capacity was determined in the field by covering the fully saturated soil surface with a polythene sheet and measuring the moisture content after 24-72 hours depending on soil type. The field capacity ranged from 24.9 to 40.0% in wheat-rice fields, and from 19.7 to 32.2% in wheat-cotton fields.

Chemical analysis: Soil samples taken at sowing were analyzed for *pH*, electrical conductivity (*EC*), organic carbon (OC), mineral nitrogen (N), available phosphorus (P), available potassium (K), DTPA-extractable Zn, Cu, and Mn, and Calcium carbonate ($CaCO_3$). The methods used are described briefly in Table 3.1.

Table 3.1 Methods used for the chemical soil analysis.

Properties	Method adopted
pH	In soil-water suspension of 1:2 by *pH* meter
EC	In soil-water suspension of 1:2 was measured by conductivity meter
OC	Wet digestion method of *Walkley and Black* (1934) as described by *Jackson* (1973)
Mineral NH_4 and NO_3 - N)	Steam distillation method (*Keeney and Nelson*, 1982)
Available phosphorus	Olsen's method. The soil was extracted with 0.5 M $NaHCO_3$, *pH* 8.5 in the presence of Darco G-60. and determined colorimetrically.
Available potassium	Flamephotometerically (*Piper*, 1966)
DTPA-extractable Zn, Cu and Mn	Extracted with DTPA reagent (0.005M DTPA *pH* 7.3) developed by *Lindsay and Norvell* (1978) and estimated on atomic absorption spectrophotometer
$CaCO_3$	Rapid titration method as described by *Puri* (1949)

In general, the soils of the farmer fields are low in organic carbon and available N, medium in available P and high in available K. The available Zn, Mn and Cu varies from 0.14 to 4.86, from 4.98 to 21.80 and from 0.31 to 1.01 $kg.ha^{-1}$, respectively. Most of the soils are sodic with a *pH* ranging from 8.0 to 9.0. Some of the soils in the wheat-cotton fields with shallow groundwater are saline sodic.

3.2.2 Irrigation water measurements

With respect to irrigation water, we recorded the timing, source (canal or tubewell), amount, and quality of each irrigation gift. At the 8 farmer fields in the wheat-rice area hardly any canal water was used (<1%). However, in general in this area, canal water supplements tubewell water in the *kharif* season, depending upon the rainfall in the catchment and subsequent release in Northern Ghaggar Canal. At the 16 wheat-cotton fields the percentage of canal water ranged from 30% (site S3) to 90% at site S6 with shallow groundwater and poor groundwater quality.

Depth of applied irrigation water: To compute the depth of applied irrigation water, the discharge from the field watercourses and tubewells was measured.

Discharge measured with the current meter method: The velocity of the water flowing in the watercourses was measured with a current meter and the discharge was estimated by multiplying the water velocity with the appropriate cross-sectional area.

Discharge measured with the coordinate method: The coordinate method was used for measuring discharge from fully flowing tube wells (*Michael,* 1992). In this method the horizontal distance and vertical distance are measured from the center of the end of pipe to the center of the jet. This method can only be applied to horizontal, full flowing pipes.

Discharge measured with the volumetric method: The discharge from partially flowing tube well pipes was estimated with the volumetric method. The time to fill a container with known volume was measured.

3.2.3 Crop measurements

For wheat, rice and cotton the dates of the main phenological stages were recorded. In addition the plant density, number of tillers, height, dry matter (*DM*) in different plant organs, leaf area, photosynthetically active radiation (*PAR*) were recorded at different stages (3 to 8 times), depending upon the duration of the crop growth period. The table below gives an overview of the measurement timing. All these observations were performed for randomly selected plants/locations scattered over the entire field.

Table 3.2 Timing of crop measurements (DAS = days after sowing; DAT = days after transplanting).

Wheat	Cotton	Rice
emergence panicle initiation (38-42 DAS) anthesis (80-90 DAS) maturity (120-135 DAS)	emergence 40-45 days from sowing squaring(70-80 DAS) flowering (85-100 DAS) boll development (120-140 DAS) picking (150-170 DAS).	transplanting(30 DAS) panicle initiation (40-45 DAT) anthesis (60-65 DAT) maturity (110-120 DAT)

Plant density and tillers: The number of plants and tillers were counted from one meter row length for wheat and 1 m^2 for rice, whereas for cotton 10 m row length was taken, each at five locations. These values were converted into numbers per m^2 or per hectare.

Plant height: The plant height was measured from the soil surface to the top of the straightened shoot/leaf of 25 randomly tagged plants.

Dry matter: Above ground plant parts were cut at the soil surface from one meter row length for wheat, 10 plants (hills) for rice, and 5 plants for cotton, each at three locations. These samples were divided into leaves (living and dead leaf blade), stems and fruiting/storage organs, and weighed after oven drying at 65 $^{\circ}$C.

Leaf area: At five locations in each field, the area of fresh (green) leaves from 0.25 m row length for wheat, one hill for rice, and one plant for cotton was measured with a laser leaf area meter (CI-310). These measurements were converted into leaf area index (*LAI*; m^2 leaf per m^2 soil).

Photosynthetically active radiation (PAR): *PAR* was measured with a Sunscan canopy analysis system type SS1 at anthesis and milk stage in wheat; at panicle initiation, anthesis and at grain development stages in rice; at 45 days from planting, squaring, flowering and boll development stages in cotton. The various components of *PAR*, i.e. total and diffuse beam fraction, incident and transmitted radiation, as well as the *LAI* were measured at the soil surface, at 50% crop height, and above the canopy.

Rooting depth: Rooting depth was recorded at panicle initiation, anthesis and grain development stages in wheat and rice, and at 45 days from sowing, squaring, flowering and boll development stages in cotton. A root auger of 7.5 cm diameter and 15 cm height was used to extract the roots. The roots were washed and the living roots were separated .

Final yield: For wheat and rice the number of effective tillers, spike weight, grains per spike, and test weight (1000 grains) were recorded at harvest from the harvested and sun dried samples of 1 m^2 at 5 locations in each field. After manual threshing, the grain and straw yields were recorded and converted into kg per hectare. The harvest index was calculated as the ratio of sun dried grain yield to that of total sun dried biological (grain + straw) yield. In cotton, the number of bolls from 10 plants were counted. After sun drying, the boll weight and seed-cotton yield was recorded. After final picking, the complete above ground plants were harvested to determine stalk yield. The harvest index was calculated as the ratio of sun dried seed cotton yield to that of total sun dried biological (seed-cotton + stalk) yield. These seed-cotton samples were ginned to separate cotton seeds from lint and to obtain an estimate of lint yield. Ginning percentage was calculated as the ratio of lint to that of seed-cotton.

Nutrient contents: percentages of N, P, and K were determined. Grounded samples of 0.5 g for stems and leaf and 0.2 g for grain were digested in diacid mixture of 4:1 (H_2SO_4:$HClO_4$). A known volume was prepared, and the aliquot was stored in plastic bottles for analysis of N, P and P, with the methods described in Table 3.3.

Table 3.3 Methods used for the chemical plant analysis.

Properties	Method adopted
Nitrogen	Colorimetric (Nessler's reagent) method of *Lindner* (1944)
Phosphorus	Vanadomolybdo-phosphoric acid yellow colour method
Potassium	Flamephotometerically (*Piper*, 1966)

3.2.4. Management practices

Besides above measurements, we recorded general management practices such as (details on attached CD-ROM):

- crop rotation in recent years;
- sowing date, rate, method, cultivar, and row spacing;
- fertilizer application: timing, amounts, method, type of fertilizer;
- pesticide application: timing, amounts, method, type of pesticide;
- harvesting date and method;
- presence of problems such as severe weed infestation, dying of seedlings.

3.3 Field experiments at Research Stations

To obtain the data required for the calibration of WOFOST (Chapter 5) crop experiments were conducted at the Cotton Research Station (CRS) in Sirsa for wheat-cotton rotations and at the Regional Research Station (RRS) in Karnal for wheat-rice rotation during *kharif* season 2001 for rice, during *rabi* season 2001-02 for wheat, and during *kharif* season 2002 for cotton. For all three crops different cultivars were included and different moisture availability levels. A short description of the experiments is given in Table 3.4. The details on soil properties, crop growth parameters, irrigation timing and amounts are given on the attached CD-ROM. The methodologies used for the various observations were the same as those used for the farmers fields (Par. 3.2).

Table 3.4 Short description of the crop experiments in Sirsa and Karnal.

Crop	Experiment	Location	Cultivars	Treatments	Emergence
Wheat	Moisture	Sirsa	PBW343	1. $I / ET_a = 0.9$ after CRI[1] 2. $I / ET_a = 0.7$ after CRI 3. $I / ET_a = 0.5$ after CRI	Dec. 13, 2001
Wheat	Cultivar	Sirsa	PBW343, PBW373, HD2329, HD2687, WH711, WH147, Raj3765	Optimum irrigation water supply	Dec. 13-15, 2001
Wheat	Moisture	Karnal	Early: PBW343 Late: PBW373	1. $I / ET_a = 0.9$ after CRI 2. $I / ET_a = 0.7$ after CRI 3. $I / ET_a = 0.5$ after CRI	Early: Dec. 5, 2001 Late: Dec. 16, 2001
Wheat	Cultivar	Karnal	Early: PBW343, HD2687, UP2338 Late: PBW373, Raj3765, UP2425	Early and late sowing Optimum irrigation water supply	Early: Nov. 28, 2001 Late: Dec. 19, 2001
Rice	Moisture+ Cultivar+ Puddling	Karnal	HKR46 HKR126	1. continuous flooding, 2 puddlings 2. continuous flooding, 4 puddlings 3. irrigation1-2 days after disappearance water[2], 2 puddlings 4. irrigation 1-2 days after disappearance water, 4 puddlings 5. irrigation 4-5 days after disappearance water, 2 puddlings 6. irrigation 4-5 days after disappearance water, 4 puddlings	May 30, 2001 Transplanting: July 4, 2001
Cotton	Moisture+ Cultivar	Sirsa	H1098 LHH144	1. optimum moisture (4 post-sown irrigation) 2. medium moisture (3 post-sown irrigation) 3. low moisture (2 post-sown irrigation)	May 21, 2002

[1] I = irrigation water; ET_a = crop evapotranspiration; CRI = crown root initiation;
[2] disappearance of ponded water on field.

3.4 Regional data

3.4.1 Meteorological data

An extensive data set with daily values measured over the period 1990 – 2002 was available from the meteorological station at CRS in Sirsa. These data include minimum and maximum temperature, relative humidity, vapour pressure in the morning and evening, sunshine hours, wind speed and rainfall. The latitude of the meteorological station of Sirsa is 29.33^0. Rainfall measurements from five extra rainfall stations spread over the area, namely Ottu, Abubsher, M.Khera, Panjuwana and Kalanwali, were available for the period 1977 –2000. The monitored farmers fields were in a range of 20-35 kms from the meteorological station.

The meteorological data obtained from CRS Sirsa contained some missing data and errors. Therefore, a comparison with data from the meteorological station at CCS HAU, Hisar (about 90 km from Sirsa) was made. Missing data were estimated with the help of the relations between the data from Sirsa and Hisar. In the case of wind speed the data from Hisar were used. Radiation values were derived from sunshine hours using the Angstrom formula with coefficients $a = 0.29$ and $b = 0.41$ (*Roelevink*, 2003). Figure 3.2 shows the temperature, radiation, rainfall and vapour pressure during *rabi* and *kharif* of 2001/02.

The climate of the region is characterized by its dryness and extremes of temperature and scanty rainfall. Hot periods with maximum day temperature > 45 °C occur from May to October. The average annual rainfall over the period 1990-2002 is 367 mm, but from November 2001 until November 2002 only 190 mm rainfall was measured. The region can be classified as sub-tropical, semi-arid and continental. The period from June to September constitutes the South-West monsoon. However, rainfall is highly erratic both in quantity and in distribution (Table 3.5).

Tabel 3.5 Monthly rainfall (mm) in Sirsa during the years 1990 – 2002.

	Month												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1990	0	68	12	6	38	9	164	92	136	0	16	0	541
1991	0	30	7	47	11	73	19	30	0	23	0	0	239
1992	17	15	0	3	5	21	115	85	90	0	0	0	352
1993	0	10	0	0	13	44	37	0	69	0	0	0	173
1994	10	7	0	2	7	77	128	17	96	0	0	0	343
1995	38	25	15	0	0	82	117	134	30	0	0	0	441
1996	14	28	16	11	0	83	63	143	46	51	0	2	457
1997	15	1	13	50	61	41	138	255	31	47	16	13	680
1998	2	45	7	4	0	0	157	31	62	99	5	0	411
1999	36	0	0	0	25	64	94	68	0	0	0	0	286
2000	15	18	0	0	0	13	209	0	0	0	0	0	255
2001	7	0	0	14	149	83	127	2	6	3	0	0	392
2002	0	10	1	0	87	20	11	23	36	0	0	10	198

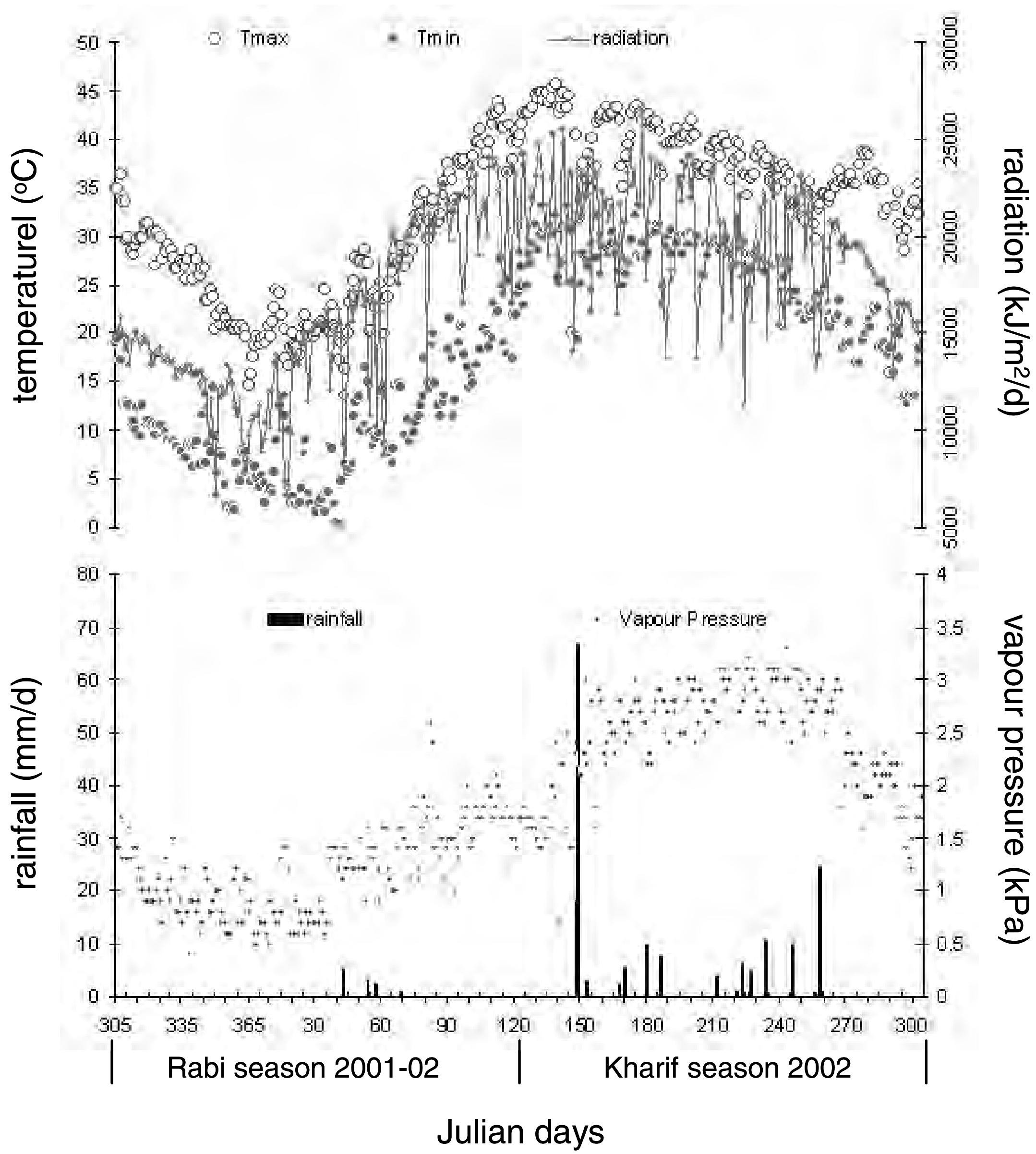

Figure 3.2 Climatic conditions in Sirsa Irrigation Circle during the year 2001-02.

3.4.2 Land use

For the years 1976-77, 1980-81, 1982-83, 1984-85 and 1989-90 data on crop areas in *rabi* (wheat, gram(irr.), gram(rainfed), oilseed (irr.), oilseed (rainfed), berseem, and fallow) and in *kharif* (paddy rice, pearlmillet (irr.), pearlmillet (rainfed), cotton, sorghum, fodder (irr.), fodder (rainfed), and fallow) were procured from the Department of Agriculture in Haryana for all the 364 villages. The Cultivable Command Area (*CCA*) is the area around an outlet on which the amount of canal water supply is based. Data on *CCA* were obtained per village, and the *CCA* varies little between years.

Cropped areas in *rabi* 2001-02 and *kharif* 2002 were derived from remote sensing images (Landsat-7 images of March 18 and September 10, 2002; Chapter 6). Field campaigns resulted in a data base with 249 and 77 ground truth points of known land cover for *rabi* and *kharif* respectively.

3.4.3 Soil information

Soil type: The soil map of Sirsa (*Ahuja et al.,* 2001) was digitized into 10 soil series. For each soil profile a vertical schematization in soil horizons was based on *Ahuja et al.* (2001). For more details see Chapter 7.

Salinity: For each soil serie, measurements were available of the soil salinity. Soil salinity was measured as electric conductivity (*EC*) in a soil-water mixture ($EC_{1:2}$ expressed in dS.m^{-1}). $EC_{1:2}$ was transformed into salinity in the liquid phase (mg.cm^{-3}) using the relations mentioned in *Agarwal and Roest* (1996) and *Kumar et al.* (1996):

$$EC_{\mathrm{e}} = 5.2 EC_{1:2} \tag{3.1}$$

$$EC_{\mathrm{FC}} = 1.75\, EC_{\mathrm{e}} \tag{3.2}$$

$$C_{\mathrm{FC}} = 0.707\, EC_{\mathrm{FC}} \tag{3.3}$$

where EC_{e} is the *EC* of the saturated soil paste, $EC_{1:2}$ is the *EC* of one part soil mixed with two parts distilled water (dS m^{-1}), EC_{FC} is the soil electrical conductivity at field capacity (dS m^{-1}) and C_{FC} is the soil salinity concentration at field capacity (mg cm^{-3}) as derived for Hisar conditions.

Water table depth: Historical water table depth data (June and October, before and after monsoon) were procured from Haryana State Minor Irrigation and Tubewell Corporation (HSMITC) for 164 observation points for the period 1984 – 2000. Interpolation between the observation points was achieved by Arc View's Spatial Analyst, using the method of Inverse Distance Weighted. The groundwater depth of June 2000 is given in Figure 7.3. Figure 7.4 shows the rise and decline of groundwater of Sirsa district in the period 1990-2000.

Groundwater quality: For several tubewells the quality of groundwater was measured over the period 1982-1995 at three times a year (June, October and January). The data on water quality in dS.m^{-1} were divided by 0.653 to get the quality in mg.cm^{-3}, according to *Kumar et al.* (1996). In Sirsa district the groundwater quality varies from 0.8 to 10.1 mg/cm^3 and shows small changes over the last 10 years.

Tubewells: All farmers use tubewells and mix the groundwater with canal water. In Sirsa district three types of tubewells can be distinguished:

- shallow tubewell, installed by farmers;
- direct irrigation tubewells, installed by HSMITC;
- augmentation tubewells, installed by HSMITC.

Data on the number of tubewell for each type per village were collected. For estimations of total discharge, see Chapter 7.

3.4.3 Canal irrigation water

A description of the canal irrigation system is given in Par. 2.3. Sirsa district is divided in four divisions as shown in Fig. 7.7. Within a division, inflow and outflow of the main distributaries were measured twice a day. Each division exists of three subdivisions. It was not possible to analyse the water availability on the more detailed level of subdivision, because most of discharges of the minor canals were measured in gauge readings. The quality of canal water is good and constant throughout the year.

Ghaggar river discharges: Data on river discharges at Ottu Weir during July-October (4 month monsoon) for the period 1979–1992 were procured from the Department of Irrigation, Haryana.

Canal irrigation: Daily data on the canal water availability for the period 1977-2001 were collected from Department of Irrigation, Haryana, for all entry and exit points (Fig. 2.1). The 3 entry points are Bhakra main branch (RD100), Sukhchain distributary (RD54) and Fatehabad branch (RD100). The 3 exit points are Southern Ghaggar canal (tail SGC), Jandewal (tail Jandewala), and Baruwali (tail Barwali).

Data of the period 1993-2002 has been digitized and is available on the accompanying CD-ROM (see appendix A).

4. Water and salt balances at farmer fields

R. Singh, J.C. van Dam and R.K. Jhorar

Abstract

Experiments in combination with deterministic simulation models offer the opportunity to gain detailed insights into the system behaviour in space and time. In this chapter the agrohydrological model SWAP is used to analyse the water flow and salt transport at the measured farmer fields. The soil textures range from clay loam to loamy sand. The percentages of canal water with respect to total amount of irrigation water range from 30 to 90%. Most of the information required to apply SWAP could be measured directly in the field or laboratory. The main unknowns were the soil hydraulic functions which are valid at field scale level. These functions were determined by automatic calibration with PEST using measured soil moisture and salinity profiles before and after irrigations. The calibrated SWAP model was used to derive the water and salt balances. In case of the wheat-cotton rotation, the relative transpiration of wheat was in general ≈0.68, which means moderate water stress. An exception were fields in saline groundwater areas which showed more stress (≈0.35). The cotton crops at all fields showed a relative transpiration ≈0.60, which is caused by irrigation water shortage and low rainfall in the monsoon of 2002. In case of the wheat-rice rotation, the relative transpiration of both wheat and rice are close to potential levels. This is attributed to the availability of sufficient tube well water with good quality. Pedotransfer functions based on the soil database HYPRESS were used to derive soil hydraulic functions for the farmer fields and next simulate the water and salt balance. In comparison with the results of the calibrated SWAP, soil hydraulic fucntions based on pedotransfer functions resulted in almost similar relative transpirations. This means that pedotransfer functions might be used in the regional analysis to derive soil hydraulic functions for water productivity analysis.

4.1 Introduction

Climate, soil, and regional groundwater flow are natural factors which affect local and regional soil water flow and salt transport. Besides these natural factors, there are certain man-made factors like cropping pattern, irrigation and groundwater exploitation. Unfortunately, the combination of these natural and man-made factors in Sirsa Irrigation Circle (SIC) have resulted in unfavourable environmental conditions. For instance during October 1998 about 13% of the SIC area experienced waterlogging (groundwater depth < 3 m) and salinization (*Singh*, 2000a). At the same time with present irrigation efficiencies there is not enough rain and canal water available to meet the crop water demands (*Dhindwal and Kumar*, 2000). Since it is hardly possible to withdraw more water from natural resources, future irrigation developments should focus on improvement of water use efficiency at both field and regional scale. Measures which may improve the water productivity concern e.g. the irrigation schedulling, the cropping pattern, or conjunctive use of good quality canal water and bad quality groundwater. The key to evaluate different options lies in the assessment of the resulting water and salt balances (*Bastiaanssen et al.,* 1996).

Field experiments yield site-specific information and are very expensive and time consuming to conduct for all crop growth conditions, especially if they should be representative for a sequence of years. However experiments in combination with deterministic simulation models offer the opportunity to gain detailed insights into the system behaviour in space and time (*Perreira et al.*, 1992; *Roest et al.*, 1993). Deterministic soil and water balance models like SWAP quantify all water and salt balance components and their interactions in the Soil-Water-Plant- Atmosphere continuum during the whole year. The accuracy of these predictive models depends upon proper identification of the required model input parameters. Before application of these models in a certain situation, a profound analysis of its input parameters and their influence on the predicted results is necessary. Some of the model input parameters can be measured directly in the field, but others remain uncertain. Inverse modeling can be used to determine indirectly the remaining unknown input parameters. In order to apply inverse modeling, accurate field observations are needed which characterize the system behaviour and the uncertain parameters should be sufficiently sensitive to the field observations.

The main objective of this chapter is to evaluate the present agricultural practices with respect to the field scale water and salt balance. In order to do so Water Management Response Indicators (WMRI) are defined which relate different water and salt balance components (*Bastiaanssen et al.*, 1996). The agrohydrological model SWAP was calibrated using measurements at farmer fields for various combinations of soil, crop, irrigation amount, water quality and groundwater level. Subsequently the calibrated model was used to analyse the effect of viable options for efficient and sustainable water management.

4.2 SWAP model description

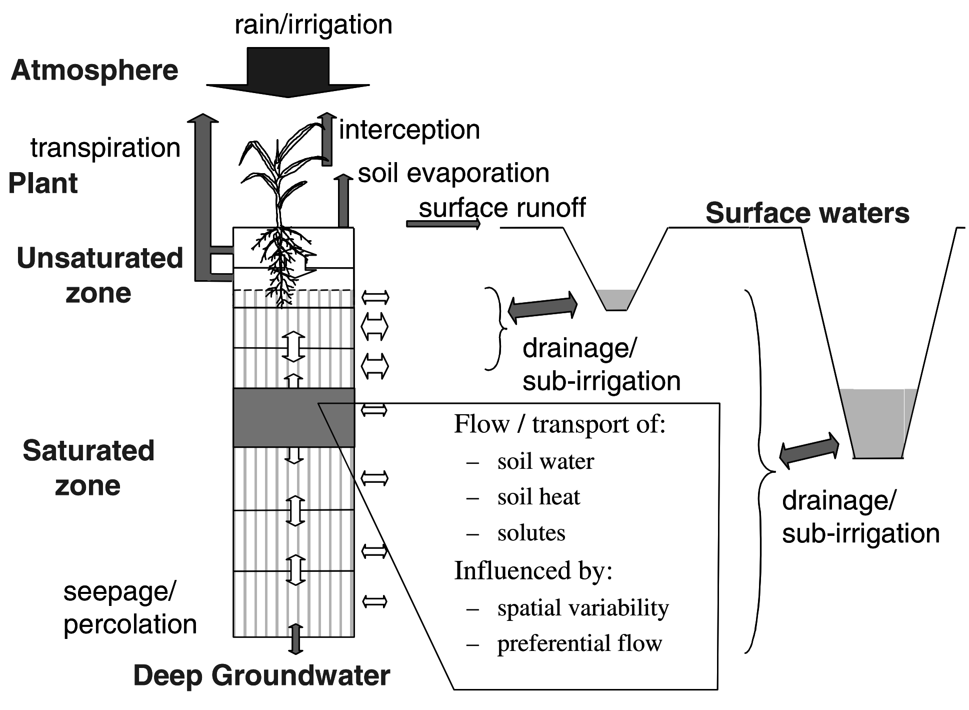

Figure 4.1 Schematization of hydrological processes incorporated in SWAP.

SWAP (*Van Dam et al.,* 1997; *Kroes et al.*, 1999) is an agrohydrological model (Soil-Water-Atmosphere-Plant) which calculates water and salt balances of cropped soil columns. Using deterministic, physical laws, SWAP simulates variably saturated water flow, solute transport and heat flow in top soils in relation to crop development (Fig. 4.1). SWAP offers a wide range of possibilities to address practical questions in the field of agricultural water management and environmental protection. Options exist for irrigation scheduling, drainage design, salinity management, leaching of solutes and pesticides, and crop growth.

SWAP may simulate up to three crops in a year and contains a detailed (Chapter 5) and simple crop model. For calibration of water flow and salt transport at farmer fields, the simple crop model was used. In this model the leaf area index, crop height and rooting depth are prescribed as function of crop development stage, which is either controlled by the temperature sum or linear in time. These measured data are sufficient to determine rainfall interception, potential soil evaporation and crop transpiration at the top boundary. When the simple crop model is used, the effect of water and salt stress on crop production might be quantified with yield response factors as function of crop development stage (*Doorenbos and Kassam*, 1979; *Smith*, 1992):

$$1-\frac{Y_{\mathrm{a},k}}{Y_{\mathrm{p},k}}=K_{\mathrm{y},k}\left(1-\frac{T_{\mathrm{a},k}}{T_{\mathrm{p},k}}\right) \tag{4.1}$$

where $Y_{\mathrm{a},k}$ and $Y_{\mathrm{p},k}$ (ML^{-3}) are the actual and potential crop yield during growing stage k, $T_{\mathrm{a},k}$ and $T_{\mathrm{p},k}$ (L) are the actual and potential transpiration during growing stage k, and $K_{\mathrm{y},k}$ (-) is the yield response factor. For semi-arid and arid regions, a simplified linear relationship between relative yield, Y_a / Y_p and relative transpiration, T_a / T_p might be applied (*de Wit*, 1958; *Hanks*, 1974, 1983; *Stewart et al.*, 1977; *Feddes*, 1985):

$$\frac{Y_\mathrm{a}}{Y_\mathrm{p}}=\frac{T_\mathrm{a}}{T_\mathrm{p}} \tag{4.2}$$

4.2.1 Water and salt balance

The water balance (cm) of a vertical soil column with vegetation during a certain period can be written as:

$$\Delta W = P + I - R - P_\mathrm{i} - T_\mathrm{a} - E_\mathrm{a} - E_\mathrm{w} + Q_\mathrm{bot} \tag{4.3}$$

where ΔW is the change in soil water storage, P is precipitation, I is irrigation, R is surface runoff, P_i is interception by vegetation, T_a is actual transpiration, E_a is actual soil evaporation, E_w is evaporation of ponding water and Q_bot is water percolation at the soil column bottom (+ upward).

The salt balance of this soil column over a certain time interval can be written as:

$$\Delta C = PC_\mathrm{p} + IC_\mathrm{i} + Q_\mathrm{bot}C_\mathrm{bot} \tag{4.4}$$

where ΔC is the change in salt storage (g cm^{-2}), C is solute concentration (g cm^{-3}), and subscripts *p*, *i*, and *bot* refer to precipitation, irrigation and bottom flux, respectively.

4.2.2 Soil water flow

Soil water movement is governed by the gradient of the hydraulic head, H (cm) which be written as:

$$H = h + z \tag{4.5}$$

where h is the soil water pressure head (cm) and z is the vertical coordinate (+upward). In unsaturated soils water flow is predominantly vertical. Using Darcy's law, the water flux density q (cm d^{-1}) can be expressed as (+ upward):

$$q = -K(h)\left[\frac{\partial h}{\partial z}+1\right] \tag{4.6}$$

where K is the unsaturated hydraulic conductivity (cm d^{-1}) as function of soil water pressure head. The law of mass conservation of a soil column with root water extraction S_a (d^{-1}) gives:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S_a(z) \tag{4.7}$$

where θ is the volumetric soil water content ($cm^3\ cm^{-3}$) and t is time (d). Combination of Eqs. 4.6 and 4.7 yield the general soil water flow equation, which is known as Richards' equation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_\text{a}(z) \tag{4.8}$$

where $C(h) = \partial\theta/\partial h$ is differential water capacity (cm^{-1}).

SWAP solves the Richards' equation numerically for specified boundary conditions and with know relations between the soil variables θ, h and K. The relation between θ and h (retention function) might be described with the analytical equation proposed by *Van Genuchten* (1980):

$$\theta(h) = \theta_\text{res} + \frac{\theta_\text{sat} - \theta_\text{res}}{\left[1+|\alpha h|^n\right]^{\frac{n-1}{n}}} \tag{4.9}$$

where θ_{res} is residual water content ($cm^3\ cm^{-3}$), θ_{sat} is saturated water content ($cm^3\ cm^{-3}$), and α (cm^{-1}) and n (-) are empirical shape factors. Equation 5.9 in combination with the theory of *Mualem* (1976) provides a versatile relation between θ and K:

$$K(\theta) = K_\text{sat} S_\text{e}^{\lambda}\left[1-\left(1-S_\text{e}^{\,n/n-1}\right)^{\frac{n-1}{n}}\right]^2 \tag{4.10}$$

where K_{sat} is the saturated hydraulic conductivity (cm d^{-1}), λ is an empirical coefficient (-), and S_e is the relative saturation $(\theta - \theta_{res}) / (\theta_{sat} - \theta_{res})$.

4.2.3 Top boundary condition

The top boundary condition is determined by the potential evapotranspiration, irrigation and precipitation fluxes. The potential evapotranspiration can be estimated by the Penman-Monteith equation (*Monteith*, 1965, 1981; *Smith*, 1992; *Allen et al.*, 1998):

$$ET_\text{p} = \frac{\dfrac{\Delta_\text{v}}{\lambda_\text{w}}\left(R_\text{n} - G\right) + \dfrac{p_1\rho_\text{air}C_\text{air}}{\lambda_\text{w}}\dfrac{e_\text{sat}-e_\text{a}}{r_\text{air}}}{\Delta_\text{v} + \gamma_\text{air}\left(1+\dfrac{r_\text{crop}}{r_\text{air}}\right)} \tag{4.11}$$

where ET_p is the potential transpiration rate of the canopy (mm d^{-1}), Δ_v is the slope of the vapour pressure curve (kPa K^{-1}), λ_w is the latent heat of vaporization (J kg^{-1}), R_n is the net radiation flux density above the canopy (J $m^{-2}\ d^{-1}$), G is the soil heat flux density (J $m^{-2}\ d^{-1}$), P_1 accounts for unit conversion (= 86400 s d^{-1}), ρ_{air} is the air density (kg m^{-3}), C_{air} is the heat capacity of moist air (J $kg^{-1}\ K^{-1}$), e_{sat} is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), r_{air} is the aerodynamic resistance (s m^{-1}), γ_{air} is the psychrometric constant (kPa K^{-1}), and r_{crop} is the crop resistance (s m^{-1}). In order to solve Eq. 4.11 the weather variables solar radiation, air humidity, wind speed and air temperature are required. In addition the crop characteristics minimum resistance, reflectance (albedo), and height are needed (*Allen et al.*, 1998).

At a crop which partly covers the soil, ET_p is split into potential soil evaporation E_p (cm d^{-1}) and potential transpiration T_p (cm d^{-1}). This partitioning is achieved by crop leaf area index, *LAI* (-), which is a function of crop development stage (*Goudriaan*, 1977; *Belmans*, 1983):

$$E_p = ET_p e^{-k_{gr} LAI} \qquad (4.12)$$

where K_{gr} (-) is the extinction coefficient for global solar radiation. In wet soil conditions, the actual soil evaporation rate E_a (cm d^{-1}) will be equal to E_p. In dry soils conditions, E_a is governed by maximum soil water flux, E_{max} (cm d^{-1}) in top soils, which can be determined by Darcy's law as:

$$E_{\max} = k_{½} \left(\frac{h_{\text{atm}} - h_1 - z_1}{z_1} \right) \qquad (4.13)$$

where $k_{½}$ (LT^{-1}) is mean hydraulic conductivity between the soil surface and first node, h_{atm} (cm) is soil water pressure head in equilibrium with the air humidity, h_1 (cm) is the soil water pressure head of first node, and z_1 (cm) is the soil depth of the first node. In our experience the Darcy flux of Eq. 4.13 overestimates the actual soil evaporation flux. Therefore in addition to Eq. 4.13 we used the empirical function of *Black et al.* (1969) to limit the soil evaporation flux to E_{emp}. In our analysis SWAP determined actual evaporation rate by taking the minimum value of E_p, E_{max} and E_{emp}.

The potential transpiration rate, T_p (LT^{-1}), follows from the balance:

$$T_p = \left(1 - \frac{P_i}{ET_{p0}} \right) ET_p - E_p \qquad (4.14)$$

where P_i (cm d^{-1}) is the water intercepted by vegetation and ET_{p0} is the potential evapotranspiration of a wet crop, which can be estimated by the Penman-Monteith equation assuming zero crop resistance. The ratio P_i / ET_{p0} denotes the day fraction during which interception water evaporates and transpiration is negligable.

For practical reasons we adopted an homogenous root distribution over the rooting depth. The maximum root water extraction rate S_{max} (d^{-1}) was calculated as:

$$S_{\max} = \frac{T_p}{z_{\text{root}}} \qquad (4.15)$$

with z_{root} the rooting depth (cm). Under non-optimal conditions i.e. either too dry, too wet or too saline, S_{max} is reduced. For water stress *Feddes et al.* (1978) proposed a reduction function as depicted in Fig. 4.2. The critical pressure head h_3 for too dry conditions depends on T_p. The values of the input variables h_1, h_2, h_{3h}, h_{3l}, and h_4 (cm) are assumed to be crop specific and can be found in literature (*Taylor and Ashcroft*, 1972; *Doorenbos and Kassam*, 1979; *Wesseling et al.*, 1991; *Smith*, 1992).

The reduction in crop yields due to salinity stress is linearly related to the soil water electrical conductivity *EC* (*Maas and Hoffman*, 1977). Assuming a one to one relationship between relative yield and relative transpiration (Eq. 4.2), they proposed the reduction function depicted in Fig. 4.3.

In case of simultaneous water and salt stress, the actual root water extraction rate S_a (z) is calculated as the product of the reduction coefficients (*Cardon and Letey*, 1992):

$$S_a(z) = \alpha_{rw}\alpha_{rs}S_{max}(z) \tag{4.16}$$

where α_{rw} and α_{rs} are reduction coefficients (-) for water and salinity stress. The actual transpiration rate T_a follows from the integration of $S_a(z)$ over the rooting depth.

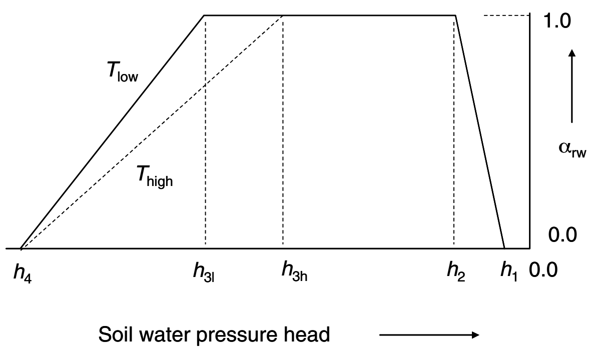

Figure 4.2 Reduction coefficient α_{rw} as function of soil water pressure head h and potential transpiration rate T_p (*Feddes et al.*, 1978).

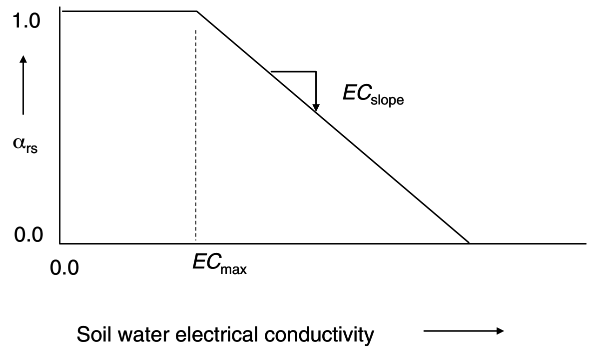

Figure 4.3 Reduction coefficient α_{rs} as function of soil water electrical conductivity EC (*Maas and Hoffman*, 1977).

4.2.4 Bottom boundary condition

In case of deep groundwater levels (< 3 m below soil surface) we will assume free drainage conditions. In that case the percolation flux at the bottom of the soil column will be calculated from:

$$q = -K(h)\left(\frac{\partial h}{\partial z} + 1\right) = -k(h)(0+1) = -k(h) \tag{4.17}$$

In case of shallow groundwater levels (within 3 m of soil surface) the measured groundwater levels were specified as bottom boundary condtion.

4.2.5 Solute transport

The movement of salts in a soil column is governed by convection, diffusion and dispersion. Convection is the bulk movement of salts along with the soil water, diffusion is the net transport of dissolved molecules due to concentration differences, and dispersion is the salt spreading due to different soil water velocities in the soil matrix. In irrigated field soils we may neglect diffusion, as this process is much slower than dispersion. Therefore we described the total salt flux density, J (g cm^{-2} d^{-1}), with:

$$J = J_{con} + J_{dis} \tag{4.18}$$

where J_{con} is the convection flux density (g cm^{-2} d^{-1}) and J_{dis} is the dispersion flux density (g cm^{-2} d^{-1}). The convection flux follows straight from the soil water flux density q:

$$J_{con} = qC \tag{4.19}$$

At laminair flux conditions, the dispersion flux density is proportional to the salt concentration gradient and water flux density (*Bear*, 1972):

$$J_{dis} = -q\,L_{dis}\frac{\partial C}{\partial z} \tag{4.20}$$

where L_{dis} (cm) is the so-called dispersion length.

The principle of salt mass conservation gives for an elementary soil volume:

$$\frac{\partial \theta C}{\partial t} = -\frac{\partial J}{\partial z} \tag{4.21}$$

In Eq. 4.21 decomposition and root uptake of salts are neglected as we are dealing with long term effects in saline soils. Combination of Eqs. 4.18 – 4.21 results in the much applied convection-dispersion equation:

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial z}\left[q\, L_{\text{dis}} \frac{\partial C}{\partial z} \right] - \frac{\partial q C}{\partial z} \tag{4.22}$$

Equation 4.22 is valid for dynamic, one-dimensional, convective-dispersive salt transport and permits the simulation of root water uptake reduction due to salt stress in the unsaturated/saturated soils (*Jury et al.*, 1991). SWAP solves this transport equation numerically, using specified initial concentrations and concentrations in irrigation and groundwater.

4.3 Materials and methods

4.3.1 Monitoring of farmer fields

Farmer fields were monitored at 6 sites (4 farmer fields at each site) from november 2001 until november 2002. At each site one field was intensively monitored in terms of irrigation supply, crop growth, soil moisture and salinity profiles. The other 3 fields at each site were monitored more extensively and allowed for additional verification. The sites were selected by CCS HAU to have different combinations of crop, water, soil and groundwater conditions. Chapter 3 describes in more detail the sites and measurements program.

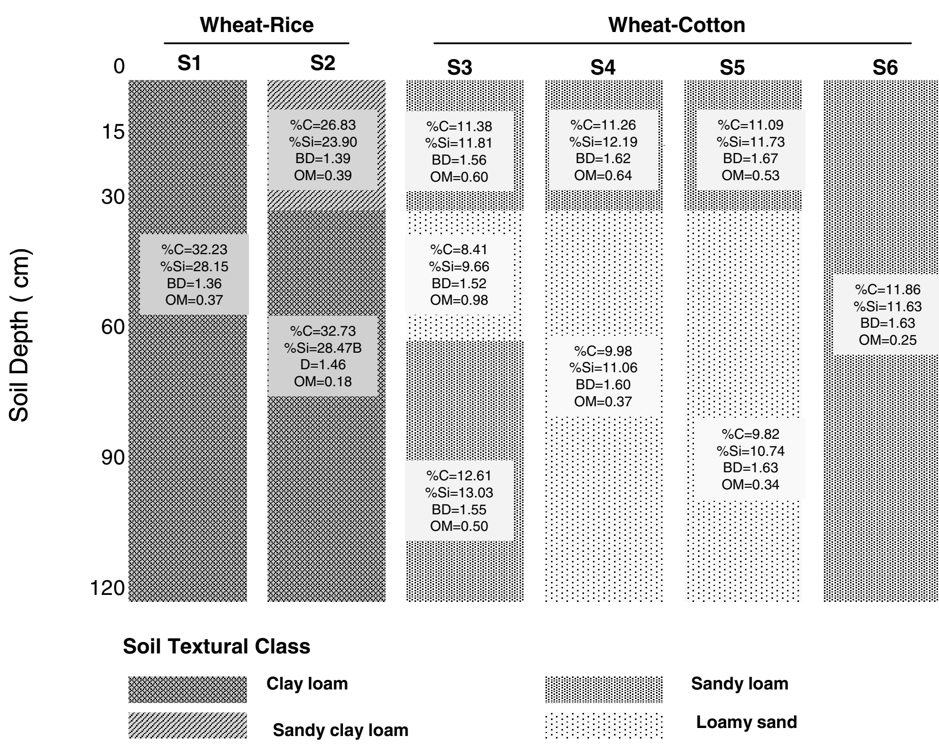

Figure 4.4 Soil texture data at farmer's fields. C = clay, Si = silt, BD = bulk density (g/cm^3) and OM = soil organic matter.

Figure 4.4 shows the soil textures at the 6 sites. The textures range from clay loam to loamy sand. Wheat-rice (sites S1 and S2) is cultivated on heavy soils in a relatively small area. Wheat-cotton, which is predominant in SIC, is mainly cultivated on relatively light soils. The groundwater quality of the wheat-rice region is very good (< 2 dS/m). This is caused by recharge from the seasonally flowing Ghaggar river. In wheat-cotton regions, the groundwater quality varies from good (< 2 dS/m, sites S4 and S5) to marginal (2-4 dS/m, site S3). Site S6 with a wheat-cotton rotation has a small groundwater depth (< 1.5 m) and poor groundwater quality (> 6 dS/m).

The meteorological data of year 2001-02, including minimum and maximum temperature, relative humidity, vapour pressure in the morning and evening, sunshine hours, wind speed and rainfall were collected from a meteorological station installed at ICAR-Cotton Research Institute in Sirsa. The monitored farmers fields were in a range of 20-35 kms from the meteorological station. Plant height, leaf area index, rooting depth, and amounts of dry matter, grain and straw, were recorded during crop development and at the harvest. With respect to irrigation water, the source (canal or tubewell), amount and quality of each irrigation gift were recorded. At the 8 farmer fields in the wheat-rice area hardly canal water was used (<1%). At the 16 wheat-cotton fields the percentage of canal water ranged from 30 % (site S3) to 60 % (S5), with a maximum (90 %) at site S6 with poor groundwater quality.

4.3.2 Input parameters of SWAP

The SWAP input parameters might be categorized into atmosphere, crop, water and soil. Most of the information required for the application of SWAP could be measured directly in the fields or laboratory. Note that in this chapter the crop development (*LAI*, rooting depth) is prescribed according to the measurement data.

The upper boundary was defined by the potential evapotranspiration and amounts of rainfall and irrigation. For this study, potential evapotranspiration was estimated by the Penman-Monteith equation (Eq 5.11) using recorded meteorological data. Most of the parameters used by Eq. 4.11 can be calculated from standard meteorological data and crop parameters measured at fields (Allen et al., 1998). The meteorological data obtained from ICAR-Cotton Research Institute, Sirsa were not accurate enough. Therefore, a comparison with data from a metorological station of HAU at Hisar (about 90 km from Sirsa) was made, and if needed corrections were made (see attached CD-ROM).

The observed leaf area index was used for partitioning of potential evapotranspiration into potential soil evaporation and potential transpiration. In addition to the maximum Darcy flux, the empirical equation of *Black et al.* (1969) was used to restrict actual soil evaporation. The plant height, leaf area index, and rooting depth were prescribed according to the measurements as function of crop development stage. The critical pressure head values for root water uptake were derived from literature. For salt transport the dispersion length L_{dis} was set to 5 cm (*Nielsen et al.*, 1986). The various input parameters are summarized in Table 4.1.

Table 4.1 **Input parameters as used in SWAP at the farmer fields.**

Parameter	Wheat	Rice	Cotton
Evaporation			
Evaporation coefficient of Black (cm $d^{-½}$)	0.35	-	0.35
Crop			
Minimum canopy resistance, r_{crop} (s m^{-1})	70	70	70
Critical pressure heads, h (cm)			
h_1	-1.0	100.0	-1.0
h_2	-22.9	55.0	-22.9
h_{3l}	-1000	-160	-1200
h_{3h}	-2200	-250	-7500
h_4	-16000	-16000	-16000
Light extinction coefficient, K_{gr}	0.375	0.300	0.450
Salinity			
Critical level, EC_{max} (dS/m)	6.0	3.0	7.7
Decline per unit EC, EC_{slope} $(dS/m)^{-1}$	7.1	11.1	5.4
Dispersion length, L_{dis} (cm)	5.0	5.0	5.0

The initial soil moisture was not measured at all fields; therefore, the initial moisture profile was generated by running SWAP one year in advance and using the final pressure heads as initial condition. The initial salinity profile was derived from the field measurements.

4.3.3 Inverse modeling of soil hydraulic functions

Water flow and salt transport is very sensitive to the soil hydraulic functions $\theta(h)$ and $K(\theta)$. The parameters describing these functions (Eqs. 4.9 and 4.10) were based on the measured texture and so-called PedoTransfer Functions (PTF) which relate soil texture with $\theta(h)$ and $K(\theta)$. However the accuracy of PTF is limited for site specific water flow and salt transport. Therefore the soil hydraulic parameters had be calibrated either manually or automatically. We used automatic calibration, which is also called inverse modeling.

At each site the measured soil moisture and salinity profiles before and after irrigation in *rabi* were used for the calibration of the soil hydraulic functions. A non-linear parameter estimation program, PEST (*Doherthy et al.*, 1995) was linked with SWAP (Fig. 4.5). An objective function quantifies the differences between model results and observations. If the observation error follow a multivariate normal distribution with zero mean, no correlation, and constant variance for each measurement type, maximization of the probability of reproducing the observed data leads to the weighted least squares objective function $O(\mathbf{b})$:

$$O(\mathbf{b}) = \sum_{i=1}^{N}\left[\left\{w_\theta\left(\theta_m\left(t_i\right)-\theta\left(\mathbf{b},t_i\right)\right)\right\}^2+\left\{w_{EC}\left(EC_m\left(t_i\right)-EC\left(\mathbf{b},t_i\right)\right)\right\}^2\right] \quad (4.23)$$

where $\theta_m(t_i)$ and $EC_m(t_i)$ are the observed soil moisture and soil salinity at time t_i, N is the number of measurements, $\theta(\boldsymbol{b},t_i)$ and $EC(\boldsymbol{b},t_i)$ are the simulated values of θ and EC using an array with parameter values $\boldsymbol{b}$, and w_θ and w_{EC} are weighting factors. In case of random observation errors only, according to maximum likelihood the weighting factor for a particular observation should be equal to the inverse of the standard deviation of the observation error of that particular observation type. *Gribb* (1996) weighted each different data type by the inverse of the mean values. We used w_θ = 1 and w_{EC} = 10% of average measured water content divided by average measured salinity concentration. In this way we accounted for measurement unit differences of θ and *EC* and at the same time gave relatively more weight to the water content measurents.

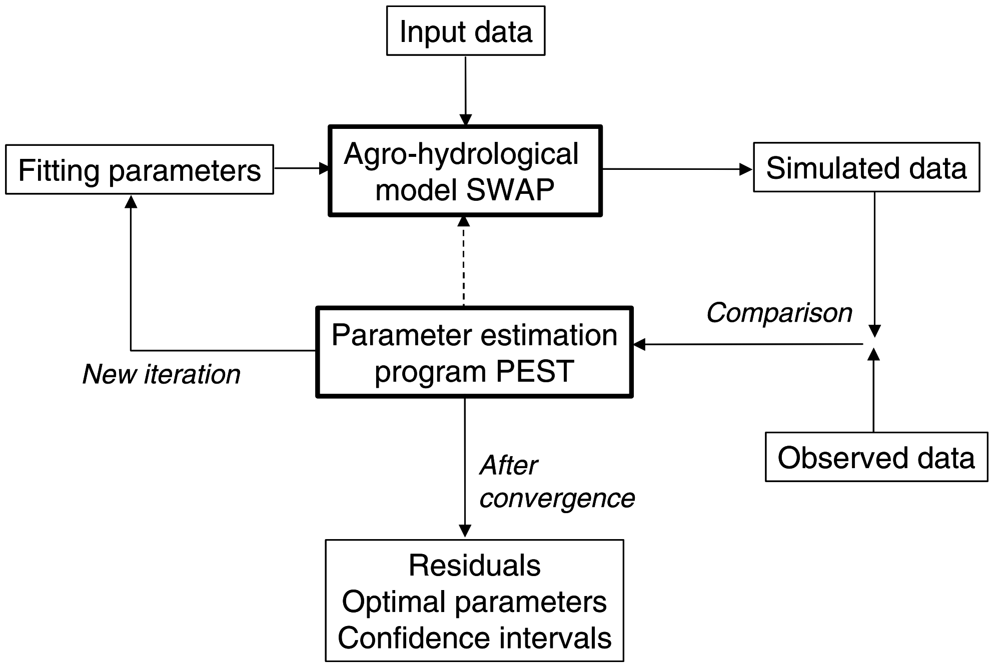

Figure 4.5 Communication between simulation model SWAP and parameter estimation program PEST.

A standard inverse method must be well-posed in order to achieve unique and stable parameter estimates. A well-posed inverse problem can be realized by reducing the number of fitting parameters (*Kool and Parker,* 1988). Of the parameters describing the soil hydraulic functions (Eqs. 4.9 and 4.10) the saturated soil moisture content, θ_s (cm^3cm^{-3}) and saturated hydraulic conductivity, K_{sat} (cm/day) have a clear physical meaning, and can be measured easily. So the values of these parameters were taken from the measurements at various fields. The residual water content θ_r (cm^3cm^{-3}) and the shape parameter λ show low sensitivity and were derived from pedotransfer functions (*Russo*, 1988). Two soil hydraulic parameters remained uncertain: α (cm^{-1}) and *n*. Most of the fields considered in this study have two or three soil layers (Fig. 4.4), the total number of fitting parameters therefore amounted 4-6. In case of regular measurements at ordinary field conditions, 4-8 hydrological parameters could be estimated uniquely with a low coefficient of correlation and variation (*van Dam*, 2000). Pedotransfer functions were used to derive initial estimates of the fitting parameters.

4.3.4 Water Management Response Indicators

High crop yields indicate the success or failure of irrigation and drainage, but they provide no information on the environmental sustainability or the difference between intended and actual water deliveries of an irrigation system (*Molden and Gates*, 1990). The goals of efficient water management are to achieve maximum crop yields with a minimum amount of water along with sustainability ensuring control of waterlogging, salinization and environmental degradation. Water Management Response Indicators (WMRI) quantify the realization of these goals (*Bastiaanssen* et al., 1996).

We used the WMRI's as listed in Box 4.1. Relative transpiration gives actual crop water use and is directly related to the crop yield (Eq. 4.2). This ratio indicates the intensity of water and salt stress on the crop. The contribution of different water resources to actual evapotranspiration is quantified by the rainfall and irrigation contribution index. The percolation index indicates the leaching fraction and therefore the salinization or waterlogging risk. The salt storage index expresses the salt build up in the root zone. For a sustainable system, the salt storage change must be near zero or negative over a long period.

Box 4.1 Definiton of Water Management Response Indicators (Bastiaanssen et al., 1996)

Relative transpiration $= \dfrac{T_a}{T_p}$

Rainfall contribution $= \dfrac{P}{ET_a}$

Irrigation contribution $= \dfrac{I}{ET_a}$

Percolation index $= \dfrac{Q_{bot}}{I}$

Salt storage index $= \dfrac{\Delta C}{C}$

with T_a and T_p the actual and potential transpiration (mm), ET_a is the actual evapotranspiration (mm), P and I are rainfall and irrigation water amounts (mm), Q_{bot} is deep percolation (mm, + upward), and C and ΔC (g cm^{-3}) are the initial and change in salt storage in the soil profile.

4.4 Results and discussion

4.4.1 Soil hydraulic functions

Soil moisture and salinity profiles were measured during the entire crop growing period (January-April). The calibration process was performed with the first part of the observations, and the second part of the observations was used for validation. The soil hydraulic parameters α and n of the different soil layers of the stratified soil profile were optimized simultaneously. Table 4.2 shows the optimized parameter values together with the other soil hydraulic parameter.

Table 4.2 Derived soil hydraulic parameters at the 6 measurement sites. Parameters α and n are optimized.

Field	Soil Layer (cm)	Texture	Soil hydraulic parameters					
			θ_r (cm^{3}cm^{-3})	θ_s (cm^{3}cm^{-3})	K_{sat} (cm d^{-1})	α (cm^{-1})	λ (-)	n (-)
			Wheat-Rice combination					
S1F1	>0	CL	0.01	0.57	1.57	0.005	-2.57	1.93
S2F5	0-30	SiCL	0.01	0.50	2.63	0.010	-2.53	1.40
	>30	CL	0.01	0.58	1.87	0.005	-2.37	1.77
			Wheat-Cotton combination					
S3F11	0-30	SL	0.01	0.34	61.82	0.011	-1.55	1.42
	30-60	LS	0.01	0.33	73.81	0.052	-1.35	1.19
	>60	SL	0.01	0.38	60.58	0.005	-1.58	1.58
S4F16	0-30	SL	0.01	0.31	101.71	0.014	-1.67	1.29
	>30	LS	0.01	0.32	120.87	0.036	-0.87	1.19
S5F20	0-30	SL	0.01	0.34	138.69	0.041	-1.56	1.21
	>30	LS	0.01	0.31	141.62	0.024	-0.80	1.16
S6F24	>0	SL	0.01	0.36	132.82	0.080	-0.91	1.19

Repetition of the optimisation process with different initial parameter values resulted in the same results which showed the uniqueness of the solution. Table 4.3 lists the coefficient of variation (ratio of standard deviation and mean) and the correlation between the parameters. The coefficient of variation was relatively low for the parameter *n* compared to the parameter α. This is attributed to the higher sensitivity of parameter *n* to soil moisture flow (*Ritter et al.*, 2003). For proper calibration also the correlation coefficients of the estimated parameters should be small. As Table 4.3 shows, the correlation coeffcients were acceptably small.

Table 4.3 Coefficients of variation and correlation matrix of optimized parameters for two typical examples: fields S1F5 and S5F20.

Soil layer (cm)	Parameter	Optimized value	Coefficient of variation	Correlation coefficient			
				α_1	n_1	α_2	n_2
		Field S2F5 (Wheat-Rice combination)					
30	α_1	0.010	0.271	1.000			
	n_1	1.40	0.064	0.153	1.000		
>30	α_2	0.005	0.504	0.594	0.864	1.000	
	n_2	1.77	0.021	0.255	0.380	0.425	1.000
		Field S5F20 (Wheat-Cotton combination)					
30	α_1	0.041	1.474	1.000			
	n_1	1.20	0.100	-0.771	1.000		
>30	α_2	0.024	1.182	0.530	0.122	1.000	
	n_2	1.16	0.010	0.228	-0.093	0.256	1.000

As a typical example Fig. 4.6 shows the observed and simulated water contents and salinity concentrations of field S5F20. The average *RMSE* of θ and *EC* of this field were 0.022 (cm^3cm^{-3}) and 0.08 (dS/m) in the wheat season, showing that soil water flow and salt transport were well simulated by SWAP. A slightly higher *RMSE* value (0.051 cm^3cm^{-3}) of θ during the cotton crop was caused by some overestimation of soil moisture, particularly at deeper soil depths (Fig. 4.6). This might be caused by the spatial variation of rainfall during the monsoon season.

Table 4.4 Numer of observations *N* and *RMSE* of soil moisture and salinity for both the calibration period (first part wheat season) and validation period (second part wheat season).

Field No.	Calibration				Validation			
	θ (cm^3cm^{-3})		*EC* (dS/m)		θ (cm^3cm^{-3})		*EC* (dS/m)	
	N	*RMSE*	*N*	*RMSE*	*N*	*RMSE*	*N*	*RMSE*
S1F1	15	0.032	10	0.179	13	0.023	15	0.195
S2F5	15	0.016	15	0.201	15	0.027	15	0.247
S3F11	20	0.025	20	0.254	20	0.033	20	0.308
S4F16	25	0.022	25	0.147	20	0.026	20	0.102
S5F20	30	0.022	25	0.094	30	0.022	25	0.067
S6F24	18	0.037	15	1.289	20	0.039	15	1.839

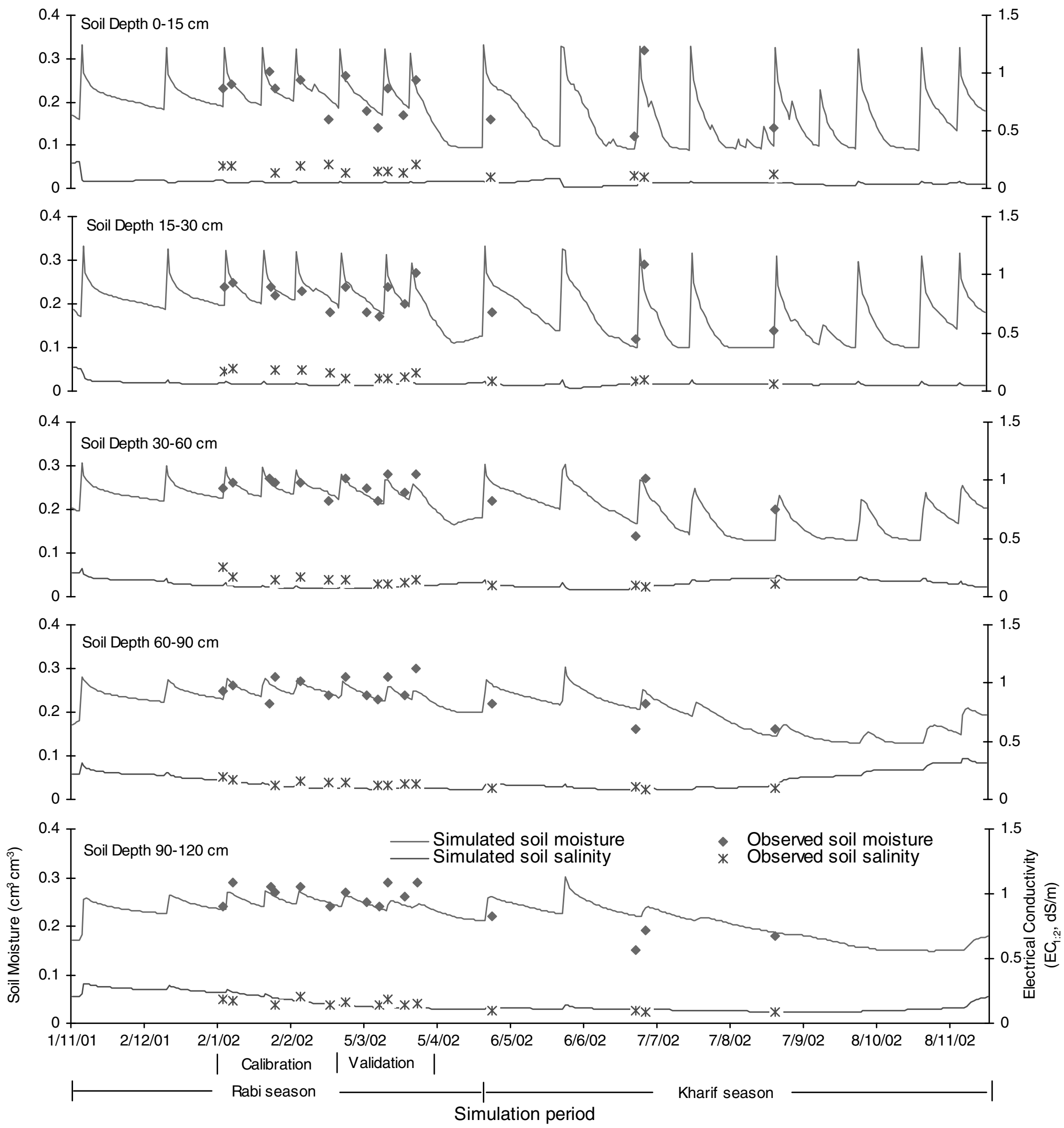

Figure 4.6 Typical example (field S5F20 with wheat-cotton rotation) of observed and simulated soil moisture and salinity concentrations. Calibration was performed for the first half of the *rabi* season.

The Root Mean Square Error (*RMSE*) is useful to quantify the differences between observed data and simulated data with the optimized parameters:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[M_i - S_i(\mathbf{b})\right]^2} \tag{4.24}$$

where M_i and $S_i(\boldsymbol{b})$ are measured and simulated values for an output variable. Table 4.4 lists the *RMSE* values in case of θ and *EC* values in the soil profile. The *RMSE* of θ (cm^3cm^{-3}) ranges from 0.016 to 0.039. These small values reveal a good to acceptable calibration and validation of the model at all fields. The simulation of *EC* was also in good agreement with observations at all fields, except at field S6F24 (*RMSE* = 1.839 dS/m) which has a shallow water table with poor groundwater quality. As no systematic under- or overestimation of θ and *EC* was observed, the differences in simulated and observed θ and *EC* are contributed to spatial variation and observation errors which are inevitable at field conditions.

4.4.2 Water and salt balances

Wheat-cotton and wheat-rice are the most prominent crop rotations in SIC. Wheat is the main crop during the *rabi* season and cotton/rice during the *kharif* season. Early sowing (in October) of wheat is practised in wheat-rice regions, while late sowing (in November) is practised in wheat-cotton regions. In 2002 the sowing of *kharif* crops was delayed 15-20 days due to a late start of the monsoon. The late sowing of *kharif* crops resulted in late harvesting. The period 1 Nov 2001 – 31 Oct 2002 was comparatively dry with a total rainfall amount of 190 mm as compared to 370 mm in an average year. The calibrated soil hydraulic parameters (Table 4.2) along with other inputs (Table 4.1) were used to simulate the water and salt balances of the farmer fields at the 6 investigated sites.

Wheat-Cotton combination

The water and salt balances for *rabi* (1 Nov 2001 – 30 Apr 2002) and *kharif* (1 May 2002 – 20 Nov 2002) for wheat-cotton are presented in Table 4.5. The average annual ET_p for the wheat-cotton combination according to the Penman-Monteith equation (Eq 4.11) was as high as 2097 mm. A relative transpiration T_a / T_p = 0.75 is acceptable for Haryana conditions (*Boumans et al.*, 1988). The relative transpiration was sufficiently high (> 0.75) for wheat crop at all fields, except at S6F24 where a very high salt stress was observed (T_a / T_p = 0.66). We also simulated field S6F24 without salt stress. In that case T_a / T_p would rise from 0.66 to 0.96 for wheat and from 0.37 to 0.55 for cotton. This shows the relative impacts of salt stress and water stress in both seasons. The average ET_p during *kharif* season (≈1500 mm) was 2.5 times higher than *rabi* season (≈ 580 mm), while the relative irrigation supplies were more during *rabi* season (Table 4.5). The cotton crop at all fields was under water stress showing a lower value (≈ 0.60) of relative transpiration. Main causes are irrigation water shortage and the low rainfall (≈ 180 mm) in the monsoon of 2002.

Table 4.5 Computed seasonal water and salt balance components for the wheat-cotton rotation.

Field	Crop season	Water balance components (mm)							
		P	I	T_p	T_a	E_p	E_a	Q_{bot}	ΔW
S3F11	*Rabi* (wheat)	11	430	275	244	313	94	-77	23
	Kharif (cotton)	177	301	438	277	899	151	-86	-37
S4F16	*Rabi* (wheat)	11	391	299	253	303	99	-6	42
	Kharif (cotton)	177	554	909	582	617	164	-25	-44
S5F20	*Rabi* (wheat)	11	568	253	245	305	111	-171	52
	Kharif (cotton)	177	737	1054	685	623	142	-132	-51
S6F24	*Rabi* (wheat)	11	336	192	126	387	81	-151	-11
	Kharif (cotton)	177	285	922	339	604	102	-19	-6
		Salt balance components (mg cm^{-2})$^{(1)}$							
			IC_i					$Q_{bot}C_{bot}$	ΔC
S3F11	*Rabi* (wheat)		102					-19	83
	Kharif (cotton)		33					-22	11
S4F16	*Rabi* (wheat)		25					-3	22
	Kharif (cotton)		36					-11	24
S5F20	*Rabi* (wheat)		20					-49	-30
	Kharif (cotton)		26					-38	-12
S6F24	*Rabi* (wheat)		13					-412	-400
	Kharif (cotton)		5					-276	-270

(1) Height soil column considered is 300 cm.

Potential transpiration for wheat ranged from 192 mm at field S6F24 (Table 4.5) in saline and waterlogged area to 364 mm at field S1F1 (Table 4.7) in the well-productive wheat-rice region. Similarly, for cotton T_p ranged from 438 to 1054 mm (Table 4.5). The actual annual evapotranspiration, ET_a for wheat-cotton estimated by SWAP ranged from 648 mm in shallow watertable and saline (field S6F24) region to 1182 mm in the well-productive (S5F20) areas. The comparative crop performance on different fields was evaluated by the relative transpiration. As T_p we used the potential transpiration of the best developed crops (in case of wheat 364 mm at field S1F1 and in case of cotton 1054 mm at field S5F20). Table 4.6. shows that the actual crop yields are ≈68 and 60% of potential yields for wheat and cotton, respectively, in fresh groundwater areas, while only ≈ 35% (S6F24) in saline and waterlogged areas.

Table 4.6 Computed annual water management response indicators (Box 4.1) for the wheat-cotton rotation.

Field	Water Management Response Indicators						
	Relative transpiration		Rainfall contribution	Irrigation contribution		Percolation index	Salt storage index
	Wheat	Cotton		Canal	Tubewell		
S3F11	0.67	0.26	0.24	0.28	0.68	-0.22	1.32
S4F16	0.69	0.55	0.17	0.00	0.86	-0.03	0.21
S5F20	0.67	0.65	0.16	0.00	1.10	-0.23	-0.26
S6F24	0.35	0.32	0.29	0.78	0.18	-0.27	-0.25

Table 4.6 shows the WMRI for the wheat-cotton rotation. The annual percolation index was < -0.20 for most of the fields, except at field S4F16. In this field the perolation index of -0.03 indicates salt buildup in the soil profile, which is also clear from the salt storage index. The salt storage index was also relatively high for field S3F11 despite a percolation index of -0.22. This is caused by the poor groundwater quality (3.73 dS/m) at this field.

The rainfall contribution to crop evapotranspiration was mainly during *kharif* (cotton), and very low (≈190 mm) as compared to irrigation supplies to the fields. The tubewell water amounts compared to canal irrigation amounts were very high at most of the fields, except field S6F24. The low canal water supplies are attributed to the low rainfall and drought conditions throughout the agricultural year 2001-02. The high canal water contribution in the saline region (S6F24) must be due to restriction on groundwater use. The use of more canal water in saline region is beneficial in leaching of salt (salt storage index = -0.25), but also contributes to more recharge (percolation index = -0.27), which may increase waterlogging and secondary salinization in the future.

Wheat-Rice combination

For optimal growing conditions of rice, farmers maintain water ponding on the soil surface during the rice season. In order to reduce the seepage losses, the soil is puddled before rice transplantation. In the simulation of soil water flow during rice crop, therefore the saturated hydraulic conductivity of the upper 30 cm soil depth was reduced to 20 % in order to capture the effect of soil puddling.

The water and salt balance for *rabi* (1 Oct 2001 - 30 April 2002) and *kharif* (1 May 2002 – 15 Oct 2002) for wheat-rice is presented in Table 4.7. The simulated annual ET_p for wheat-rice was 1963 and 2021 mm at field S1F1 and S2F5, respectively. The actual evapotranspiration, ET_a for individual wheat and rice crops was 411 and 880 mm, respectively. This gives an annual ET_a of 1291 mm in case of the wheat-rice rotation, while ET_a amounted 1349 mm in case of the wheat-cotton rotation. The high value of average E_a (415 mm) during the rice season as compared to 94 mm during the wheat season were due to water ponding on the soil surface in the rice crop.

Table 4.7 Computed seasonal water and salt balance components for the wheat-rice crop rotation.

Field	Crop season	Water balance components (mm)							
		P	I	T_p	T_a	E_p	E_a	Q_{bot}	ΔW
S1F1	*Rabi* (wheat)	13	343	364	364	353	88	-329	-43
	Kharif (rice)	177	1250	475	457	772	405	-121	44
S2F5	*Rabi* (wheat)	13	424	330	326	381	99	-195	-19
	Kharif (rice)	177	1062	565	536	744	425	-98	18
		Salt balance components (mg cm^{-2})(1)							
			IC_i					$Q_{bot}C_{bot}$	ΔC
S1F1	*Rabi* (wheat)		20					-31	-11
	Kharif (rice)		74					-11	63
S2F5	*Rabi* (wheat)		24					-75	-51
	Kharif (rice)		61					-41	20

(1) Height soil column considered is 300 cm.

The soil water storage decreased during the wheat crop and increased during the rice crop. The higher percolation (-329 and -195 mm) during wheat season is attributed to the saturated soil profile left after rice crop and heavy irrigations of ≈ 200 mm in the early stage (Oct-Nov) of the wheat crop. However, large irrigations (≈1150 mm) during *kharif* season produces less percolation because the creation of a puddled soil layer (low saturated hydraulic conductivity) before rice transplantation results in water ponding. The table shows the leaching of salt during the wheat season (ΔC = negative), and salt accumulation in the rice season (ΔC = positive).

Table 4.8 lists the WMRI of the wheat-rice rotation. The relative transpiration was relatively high (> 0.75) due to high irrigation (≈ 1540 mm) supplies. The relative transpiration showed that actual yields for wheat and rice are very close to the potential yields. The average observed yields of 6.5 and 7.7 t/ha for wheat and rice at fields S1F1 and S2F5 confirmed a very good crop growth in the wheat-rice regions which has a good groundwater quality. The annual salt storage index at field S1F1 showed salt build up in soil profile having a high value of percolation index (-0.28), while at field S2F5 leaching of salts was observed with a low value of percolation index (-0.20). The positive salt storage index at field S1F1 was caused by very low initial salt concentrations.

Table 4.8 Computed annual water management response indicators (Box 4.1) for the wheat-rice rotation.

Field	Water Management Response Indicators						
	Relative transpiration		Rainfall contribution	Irrigation contribution		Percolation index	Salt storage index
	Wheat	Rice		Canal	Tubewell		
S1F1	1.00	0.81	0.15	0.00	1.21	-0.28	0.44
S2F5	0.90	0.95	0.14	0.00	1.07	-0.20	-0.10

4.5 Soil hydraulic parameters for regional scale

A large region as Sirsa Irrigation Circle might be divided into homogeneous units with respect to soil, landuse, groundwater, etc. The SWAP-WOFOST combination might be applied to each of these units, to derive regional *WP* values (Chapter 7 and 9). In order to do so, for each soil unit the soil hydraulic properties are required. Pedotransfer functions (PTF) might be used to estimate the soil hydraulic properties using soil texture information which is available on regional scale. Nemes et al. (2003) showed the potential of using of internationally developed PTF as an alternative to laboratory measurements. However, they stressed the importance of the testing PTF with the specific model for the specific research goal.

The PTF based on a European soil database (HYPRESS: *Wösten et al*., 1998) was tested at different farmer fields for their suitability to derive *WP* in Sirsa Irrigation Circle. The input soil information (percent clay, silt, organic matter and bulk density) required by HYPRESS to derive the soil hydraulic parameters was extracted from a soil survey in Sirsa by *Ahuja et al*. (2001). Table 4.9 lists the resulting parameters.

Table 4.9 Soil hydraulic parameters derived by pedotransfer functions based on HYPRESS.

Soil texture	Soil layer (cm)	Soil hydraulic parameters					
		θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	K_s ($cm\ d^{-1}$)	α (cm^{-1})	λ (-)	n (-)
Sandy loam	0-30	0.01	0.36	51.98	0.059	-1.58	1.28
	>30	0.01	0.36	25.16	0.067	-1.43	1.26
Loamy sand	0-30	0.01	0.34	74.93	0.066	-0.63	1.39
	>30	0.01	0.35	36.12	0.088	0.23	1.41

The performance of PTF was compared with the calibrated soil hydraulic parameters at fields in the wheat-cotton region. The initial moisture profile generated during the calibration process was considered as measured. The same initial soil moisture profiles were used for the simulation based on parameters derived by PTF. Table 4.10 shows that in case of PTF the discrepancies in simulated and observed soil moisture were higher, particularly at field S3F11, while salt concentrations were simulated as good as at simulations based on the calibrated soil hydraulic parameters.

Table 4.10 *RMSE* of measured and simulated water contents and *EC* concentrations using calibrated and HYPRESS soil hydraulic parameters.

Field	Calibrated		Pedotransfer function	
	θ (cm^3cm^{-3})	*EC* (dS/m)	θ (cm^3cm^{-3})	*EC* (dS/m)
S3F11	0.029	0.284	0.075	0.193
S4F16	0.025	0.142	0.038	0.131
S5F20	0.022	0.080	0.043	0.079

Table 4.11 Water Management Response Indicators (Box 4.1) as simulated by SWAP using calibrated and HYPRESS soil hydraulic parameters.

Field	Relative transpiration				Percolation index		Salt storage index		Change in water storage (mm)	
	Calibrated		PTF		Calibrated	PTF	Calibrated	PTF	Calibrated	PTF
	Wheat	Cotton	Wheat	Cotton						
S3F11	0.67	0.26	0.73	0.29	-0.22	0.0	1.32	1.89	-14	121
S4F16	0.69	0.55	0.74	0.54	-0.03	-0.13	0.21	0.02	-2	-82
S5F20	0.67	0.65	0.67	0.62	-0.23	-0.33	-0.26	-0.47	-1	-110

The actual evapotranspiration by PTF was found to be fairly close to that estimated by calibrated soil hydraulic parameters (Table 4.11) at all 3 fields. The percolation index and salt storage index were deviating in comparison to those estimated by calibrated soil hydraulic parameters which is mainly caused by the invoked initial conditions. However, the good correspondence for relative transpiration (Table 4.11) shows the potential to use PTF from databases as HYPRESS to derive soil hydraulic parameters for regional water productivity analysis in Sirsa district.

4.6 Conclusions

The good agreement between simulated and observed soil moisture (RMSE ≈ 0.016 to 0.039 cm^3cm^{-3}) and salinity (RMSE ≈ 0.094 to 1.839 dS/m) provides confidence to use the calibrated and validated SWAP model to derive water and salt balances at the different sites for current and optional water management. The inverse methodology was found to be efficient in the calibration of the soil hydraulic parameters using observed soil moisture and salinity before and after irrigation events. The water and salt balance analysis at different fields showed a very high exploitation of groundwater in wheat-rice regions (field S1F1 and S1F5). The use of poor groundwater quality was found to be resulting in high salt buildup ($\Delta C / C_i$ = 1.32 at field S3F11). The water stress was observed more on *kharif* crops i.e. cotton ($T_a / T_p \approx 0.60$) as compared to wheat crop ($T_a / T_p > 0.75$). The crop performance as indicated by relative transpiration was almost potential (≈ 0.90) in wheat-rice regions, while it was very poor (≈ 0.30) in waterlogged and saline conditions (field S6F24).

5. Analysis of crop growth

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Summary

SWAP/WOFOST was used for a balanced estimation of yield and *ET*, and to include interactions between soil-water and solute transport and crop development. This way *WP*, defined as yield divided by *T* or *ET*, can be estimated accurately for a wide range of field conditions and management options. The model was calibrated for wheat, rice and cotton in Sirsa. In 2002 the simulated water-limited productions for rice and cotton are close to the actual productions at the farmer fields. However, for wheat the yield gap was considerable. Part of the yield gap could be explained with a statistical analysis. With better nutrient, pest and disease management the yield gap of wheat can be bridged, which will lead to higher water productivity. Transpiration and assimilation are affected proportionally by water stress. Consequently, in general deficit irrigation will have a minor effect on WP_T and WP_{ET}. However, the timing of water stress does affect the ratio between grain yield and T, and the WP_T. Considerable differences in *WP*'s between years can be observed, due to differences in evaporative demand between years. Soil type does not affect WP_T, but it does affect the optimum timing of irrigations and the total *E* during the growing season. With early sowing of wheat higher *WP*'s can be obtained, because higher grain yields can be obtained. The water need does not decrease with earlier sowing, it increases slightly. The large differences in WP_T and WP_{ET} between crops are due to the contribution of *E* to *ET*, the harvest index and the chemical composition.

5.1 Introduction

5.1.1 Water productivity and simulation models

Often used definitions for water productivity (*WP*) are the yield divided by the (evapo)transpiration (*E*)*T* or irrigation. Irrigation amounts are based on crop needs for *ET*. In order to derive options for improvement of *WP*, simultaneously good estimates of crop production and (*E*)*T*, and their interactions are needed. Simulation models can be of great help in estimating crop production and *ET* in a wide range of situations.

WOFOST is a dynamic, explanatory model for crop growth with descriptive elements, but with a relatively simple soil module ('tipping bucket'*; Boogaard et al.*, 1998*; Supit et al.,* 1994). Early versions of SWAP, a dynamic explanatory model with descriptive elements, only had forcing functions to describe soil cover, and rooting depth ("simple crop module"). There was no interaction between water availability and e.g. leaf development (*van Dam et al.*, 1997*; Kroes et al.*, 1999). The combination of SWAP with WOFOST in SWAP version 2.0, hereafter called SWAP/WOFOST, gives a more balanced description and quantification of the various physical and physiological processes underlying crop growth, soil moisture flow and solute transport and their interactions (*van Ittersum et al.*, 2003).

In this chapter SWAP/WOFOST will be used to study the effect of various management practices and changes in environmental factors. It may enhance awareness of the effect of different management practices and help in decision making at field scale.

5.1.2 Research objectives

This chapter will explore the options to improve water productivity at field scale by focusing on the following objectives:
1. Further development of crop growth models for conditions in Sirsa Irrigation Circle (SIC);
2. Quantifying the maximum increase in water productivity by changes in crop management.

The crop growth analysis performed for this chapter consists of 3 steps:
1. Analysis of crop data from experiments and farmer fields and calibration of SWAP/WOFOST for wheat, cotton and rice;
2. Comparison of actual and simulated crop production and *ET* at farmer fields;
3. Analysis of some management options and their effect on water productivity.

5.2 Calibration of SWAP/WOFOST for wheat, rice and cotton

5.2.1 The detailed crop module in SWAP

SWAP 2.0 contains three crop growth routines: a simple module, a detailed module, and the detailed module attuned to simulate grass growth. Independent of external stress factors, the simple model prescribes the length of the crop growth phases, leaf area, rooting depth and height development. The detailed crop module is based on WOFOST 6.0 (*Supit et al.,* 1994; *Spitters et al.,* 1989).

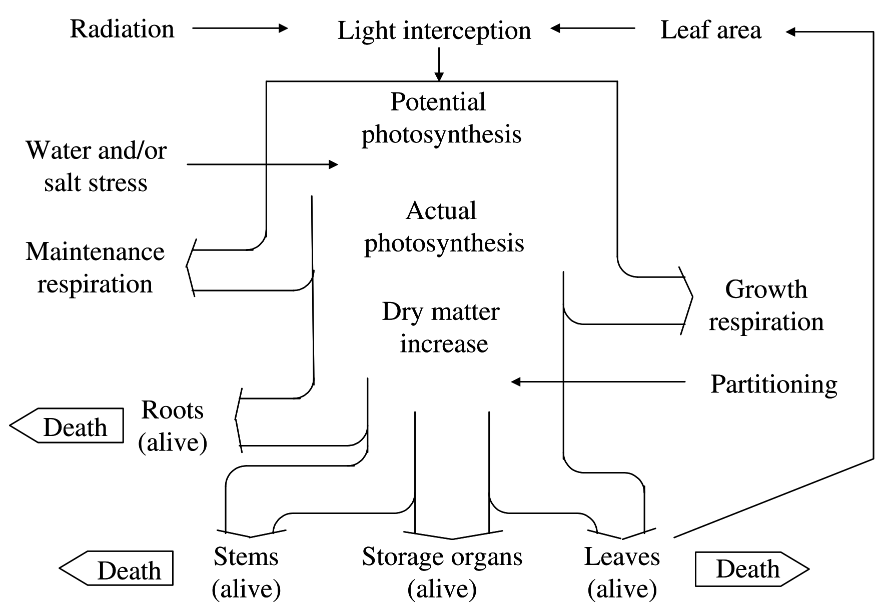

Figure 5.1 Overview of the main crop growth processes and interactions as included in WOFOST.

Figure 5.1 shows the main processes and relations included in the detailed crop module. The intercepted radiation energy is a function of the incoming radiation and the leaf area index (*LAI*). WOFOST computes at three selected moments of the day incoming photosynthetically active radiation just above the canopy. Using this radiation and the photosynthetic characteristics of the crop, the potential gross assimilation is computed at three selected depths in the canopy (*Spitters et al.,* 1989). Gaussian integration of these values results in the daily rate of potential gross CO_2 assimilation (kg $CO_2.ha^{-1}.d^{-1}$). This potential can be reduced due to water and/or salinity stress. The ratio of actual *T* and potential *T*, T_a/T_p, is used as reduction coefficient.

Part of the assimilates produced are used to provide energy for the maintenance, depending on the amount of dry matter (*DM*) in the various living plant organs, the relative maintenance rate per organ and the temperature. The remaining assimilates are partitioned among roots, leaves, stems and storage organs (*SO*), depending on the phenological development stage (*DVS*) of the crop (*Spitters et al.,* 1989). Than conversion into structural *DM* takes place, and part of the assimilates is lost as growth respiration.

The net increase in leaf structural *DM* and the specific leaf area ($ha.kg^{-1}$) determine leaf area development, and hence the dynamics of light interception, except for the initial stage when the rate of leaf appearance and final leaf size are constrained by temperature, rather than by the supply of assimilates. The dry weights of the plant organs are obtained by integrating their growth and death rates over time. The death rate of stems and roots is considered to be a function of *DVS*. Leaf senescence occurs due to water stress, shading (high *LAI*), and also due to life span exceedance.

Some simulated crop growth processes are influenced by temperature, such as the maximum rate of photosynthesis and the maintenance respiration. Other processes, such as the partitioning of assimilates or decay of crop tissue, are steered by the *DVS*. Development rates before anthesis are controlled by day length and/or temperature. After anthesis only temperature will affect development rate. The ratio of the accumulated daily effective temperatures, a function of daily average temperature, after emergence (or transplanting in rice) divided by the temperature sum (*TSUM*) from emergence to anthesis, determines the phenological development stage. A similar approach is used for the reproductive growth stage (*van Dam et al.,* 1997).

Water uptake of the crop is determined by the rooting depth, root density distribution, soil water pressure head, and critical pressure heads for wet and dry conditions (Fig. 4.2). When the soil water electrical conductivity becomes higher than the crop specific critical salinity levels, *T* is reduced as illustrated in Fig. 4.3.

5.2.2 Methodology

To calibrate SWAP/WOFOST for wheat, cotton and rice, data are needed from experiments where potential and/or water-limited production levels are obtained (Chapter 3). Potential production is the production level defined by CO_2-concentration in the air, radiation, temperature and intrinsic plant characteristics. Water-limited production is the production level when the growth rate is limited only by water shortage during at least a part of the growing season. Before calibrating the crop module in SWAP/WOFOST, the best soil and water parameters were determined in a calibration procedure using SWAP with the simple crop module (prescribing crop characteristics, based on field measurements; see Chapter 4).

A crop data file for a similar cultivar and similar climatic conditions is used as a "start" file. Part of the crop parameters can be adjusted and determined on the basis of the experimental data or literature. For the parameters that cannot be fixed, a range of realistic values is determined, based on experimental data and literature. During the calibration the latter parameters are adjusted by running the model with various combinations of values within these realistic ranges (Table 5.1). With the help of automated calibration (PEST*; Doherty et al.,* 1995) the smallest possible deviation from the observed data was obtained. As observed data the leaf *DM*, storage organs *DM*, total above ground *DM* (*TDM*) and *LAI* were used. In this project a good simulation of the *LAI*, and consequently of the *ET*, is very important. Therefore, the sum of squared differences for the *LAI* had a relatively higher weight than for *DM*. This had hardly any effect on the simulation of *DM* (<0.5% difference).

Table 5.1 Overview of crop parameters that were based on measurements, and those adjusted, within realistic values, during calibration. Parameters not mentioned are based on literature.

Parameters based on measurements	Parameters adjusted during calibration
Initial *DM*, *LAI* and growth rate *LAI*	Initial *DM* and growth rate *LAI*(1)
Specific leaf area	Life span leaves(1), (2)
Life span leaves	Specific leaf area(1)
Effect temperature on assimilation	Effect temperature on assimilation(1)
DM-partitioning	*DM*-partitioning(1), (2)
Conversion coefficients	Extinction coefficient diffuse light(2)
Rooting depth increase	Initial light use efficiency(2)
Maximum rooting depth	Maximum assimilation rate(2)
Crop height	Death rate leaves due to water stress
Length growth phases	Critical pressure heads for water uptake
Day length sensitivity	Root density distribution(2)
	Critical salt level and reduction factor
	Relative root distribution

(1) Only small changes of values, based on measurements, within possible measurement errors; for *DM*-partitioning also some adjustments due to absence of reallocation in model;
(2) Most important crop parameters adjusted during calibration.

After calibration, SWAP/WOFOST was validated. A completely independent validation was not possible, since for the determination of crop parameters some data from the other treatments in the experiments were used (mainly specific leaf area and *DM*-partitioning) and also some data from the farmer fields (to determine daylength sensitivity). However, comparison of the simulated crop growth with the measured crop growth for the treatments or farmer fields that were not used as reference for calibration (but without nutrient stress and with good control of pests and diseases) gives an indication of the validity of the crop files.

5.2.3 Calibration for wheat

For the calibration, data from the moisture experiment with wheat cultivar PBW-343 were used. Treatments "0.7" and "0.5" (irrigation water/ET_p=0.7 or 0.5 after crown root initiation were used as reference (Chapter 3). In Figures 5.2-5.3 measured *DM* and *LAI* is compared with the fitted *DM* and *LAI*, obtained with SWAP/WOFOST. The estimation of the *TDM* and the final yield is good (Fig. 5.2 and 5.3). The *LAI* is estimated reasonably, although in the beginning of the growing season it is underestimated and at the end overestimated. Comparison of the estimated *ET* obtained with SWAP/WOFOST and the simple crop module (using measured *LAI*) shows that the difference in total *ET* from emergence to maturity is only 1.5% higher with the measured *LAI*. In the simple crop module linear interpolation between measured *LAI*'s takes place. This results in some overestimation of *LAI*, and thus of transpiration in the beginning of the growing season.

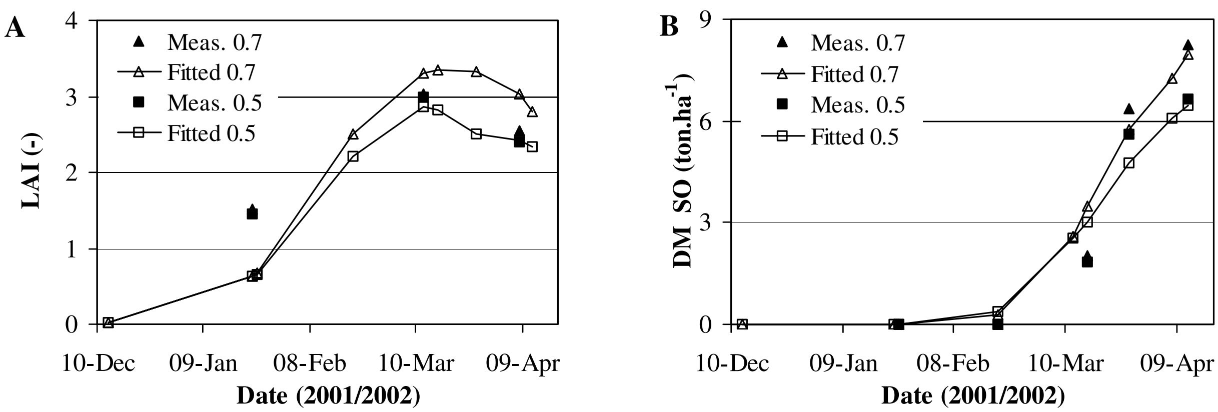

Figure 5.2 Measured and fitted *LAI* (A) and *DM* in storage organs (B) for wheat cultivar PBW-343 (moisture experiment Sirsa; "0.7" means irrigation water/ET_p = 0.7 after crown root initiation; calibrated model with measured plant height, length growth phases and rooting depth; 80% grain in storage organs).

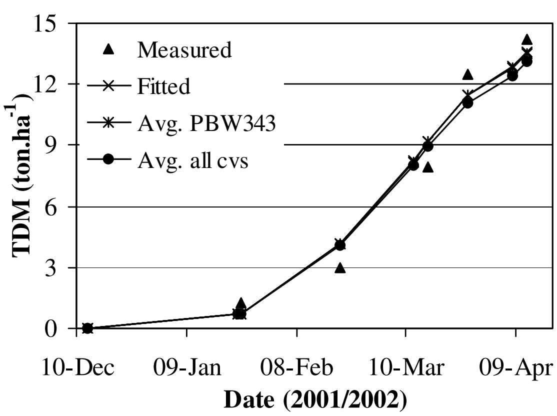

Figure 5.3 Measured and fitted total above ground *DM* for wheat cultivar PBW-343 (Sirsa 2001-02; "0.7" means irrigation water/ET_p = 0.7 after crown root initiation; calibrated model; "avg." is with average length growth phases, plant height and rooting depth).

The wheat cultivars used in the experiments and at the farmer fields appeared to be sensitive to daylength during the vegetative and generative stage. Since this cannot be included in SWAP/WOFOST (Par. 5.2.1), four crop files for different sowing dates were prepared (different lengths of growth phases, represented by the *TSUM*s). The difference between wheat cultivar PBW-343 and the other cultivars seems small. There is no clear difference in *DM* partitioning in relation to development stage between cultivars and between sowing dates. The length of the growing season for PBW-343 is almost the same as the length of the growing season of the other cultivars. Only the relative length of the vegetative phase is slightly longer for PBW-343. Therefore, the calibrated crop module for PBW-343 was used also for other cultivars, with the exception of the length of the growth phases.

A sensitivity analysis was performed where all crop parameters were increased or decreased with 10%. The model is considered relatively sensitive when a change of 10% results in more than 10% change in e.g. *DM* or *ET* (Table 5.2). The analysis showed that, for mild and severe water stress, SWAP/WOFOST is relatively sensitive to the specific leaf area, the conversion coefficients for assimilates to structural biomass, the length of the vegetative growth phase, and the maximum daily increase in rooting depth. Under mild water stress the model is also relatively sensitive to changes in the maximum assimilation rate and the initial light use efficiency. When there is clear water stress the model becomes relatively sensitive to the extinction coefficient. Correct estimation of these parameters is essential. Most of the above mentioned parameters are based directly on the measurements in the experiments, and therefore contain limited uncertainty. The maximum assimilation rate and initial light use efficiency are estimated indirectly during calibration. Similar results were obtained for cotton and rice.

Table 5.2 Overview(1) of SWAP/WOFOST sensitivity to changes in parameters under mild water stress (irrigation schedule "0.7") and severe water stress (no irrigation) (soil experimental station Sirsa, initial conditions of wheat moisture experiment).

		Mild water stress			Severe water stress		
	Change	*DM* Storage Organs	Total above ground *DM*	Trans-piration	*DM* Storage Organs	Total above ground *DM*	Trans-Piration
Specific leaf area	+10%	109	114	110	89	107	102
	-10%	84	81	87	110	90	98
Temperature sum vegetative phase	+10%	95	107	111	70	102	103
	-10%	93	87	83	134	95	94
Max. assimilation rate	+10%	109	110	104	100	107	101
	-10%	89	88	95	99	91	99
Extinction coef-ficient diffuse light	+10%	98	100	104	90	97	101
	-10%	102	100	95	113	104	99
Initial light use efficiency	+10%	110	112	105	101	108	101
	-10%	88	87	95	99	91	99
Conversion coefficients	+10%	113	118	108	95	113	101
	-10%	83	80	90	103	86	98

(1) Results of 10% change in parameter values that did not result in more than 10% change in *SO*, *TDM*, *T* are not shown; relative change shown: 100=same as reference situation without change of crop parameters.

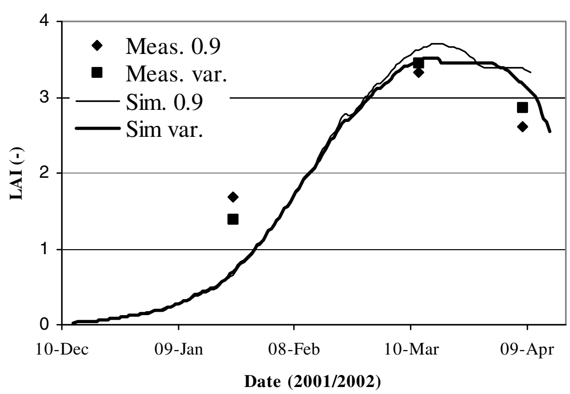

Figure 5.4 Measured and simulated *LAI* for wheat cultivar PBW-343 (wheat experiments; "0.9" means irrigation water/ET_p = 0.9 after crown root initiation; "var." is variety experiment; simulated with average length growth phases, plant height and rooting depth for PBW-343).

Validation was performed with treatment "0.9" from the moisture experiment and for cultivar PBW343 in the variety experiment (Chapter 3). Simulation of *DM* development and *LAI* was good during the main part of the growing period. Figure 5.4 shows the *LAI* development for both treatments. Some underestimation of the *LAI* in the first part of the growing season is observed.

5.2.4 Calibration for rice

For rice, fields 6 and 2 with cultivar PR-106 were used for calibration of SWAP/WOFOST, since calibration of the soil-water module in SWAP for the rice experiment in Karnal could not be performed due to missing data. The yield in field 6 was that high, that we assumed that hardly any (water) stress occurred. For field 2 we assumed that the lower yield was due to only water stress. Rice growth is simulated from transplanting to maturity. Figures 5.5 and 5.6 show some results for field 6. *LAI* development in the early season could be fitted well, but later on in the growing season *LAI* is overestimated. This overestimation takes place in the period with almost complete soil cover, and therefore, it hardly results in overestimation of the *T* (< 0.5% lower *T* compared with the simulation with measured *LAI* for field 6).

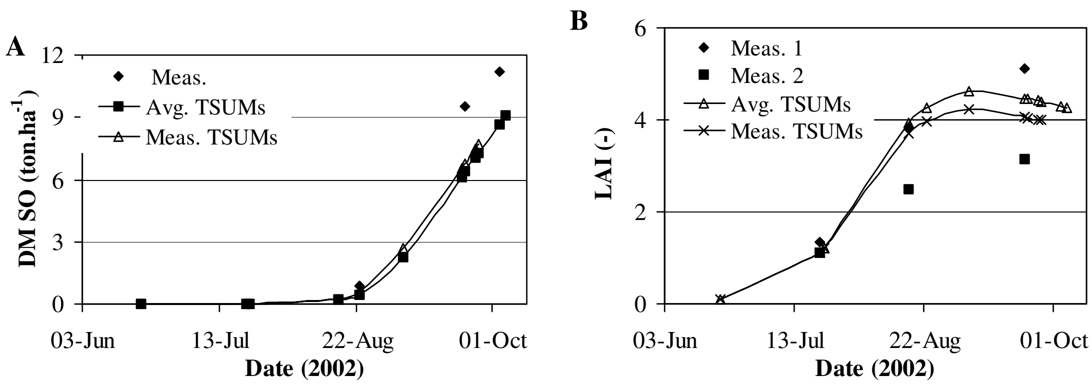

Figure 5.5 Measured and fitted *DM* in storage organs (A; 81% grain) and LAI (B) for rice cultivar PR-106 in field 6 (Meas. 1 = measured with PAR-meter; Meas. 2 = measured with leaf area meter; meas./avg. TSUMs = measured/average length growth phases).

The *DM* in the *SO* (Fig. 5.5A) and the *TDM* is somewhat underestimated. However, higher crop productions could not be obtained with realistic values for the crop parameters. Besides, the samples taken at harvest (larger samples and 5 replicates) give a lower estimate of final yield than the samples taken for *DM*-partitioning (shown in figures; 3 replicates; 81% of *SO* is grain; see also Par. 5.3). With average *TSUM*s, the final *DM* in *SO* at maturity is clearly higher than with the observed *TSUM*s ($9.1 \cdot 10^3$ kg *DM*.ha^{-1} compared with $7.7 \cdot 10^3$ kg *DM*.ha^{-1}). However, this amount of biomass is reached 8 days later. The longer simulated growing season results in higher *T* (532 mm compared with 491 mm).

In all farmer fields cultivar PR-106 was used. The farmers transplant the rice from 28 to 58 days after emergence (avg. 38 days; June 12 to July 1). The length of the growth phases between transplanting and maturity, measured in °C·d, was almost constant, independent of the transplanting date (transplanting to anthesis: 81 ± 4 days; anthesis to maturity: 26 ± 4 days).

Validation of the crop files was performed with the other farmer fields (fields 1, 4 and 5; production close to potential; Par. 5.3). The largest deviation found was 17% when average lengths of the growth phases were used.

5.2.5 Calibration for cotton

For cotton the data from the moisture experiment with cultivars LHH-144 and H-1098 were used to determine the best crop parameters (Chapter 3). Figures 5.6 and 5.7 show some results. *LAI* development in the early season is overestimated, but later on it is underestimated. This underestimation takes place in the period with almost complete soil cover, and fitted *LAI* remains mostly above 3. Therefore, it hardly results in underestimation of *T* (<0.5% difference with measured *LAI*).

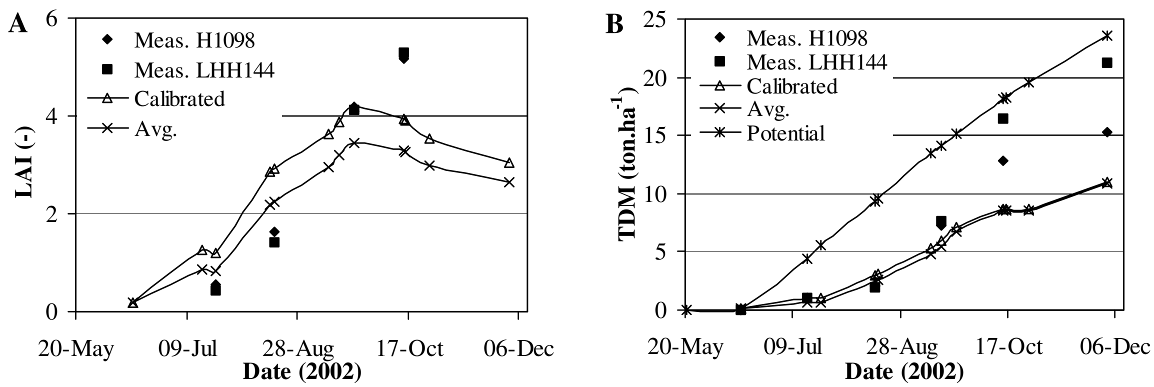

Figure 5.6 Measured and fitted *LAI* (A) and total above ground *DM* (B) for cotton cultivars H-1098 and LHH-144 with "optimum" moisture (moisture experiment; Fitted/avg. = measured/average length growth phases and rooting depth).

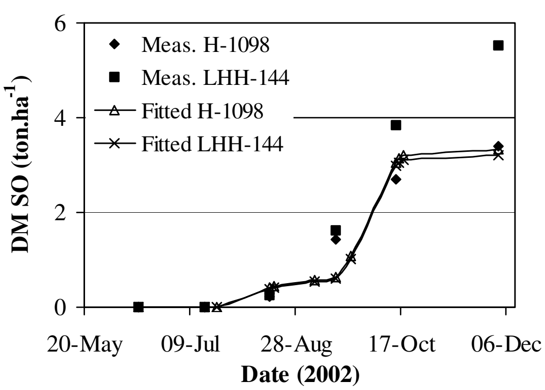

Figure 5.7. Measured and fitted *DM* in storage organs (44% seed cotton) for cotton cultivars H-1098 and LHH-144 with "low" moisture (moisture experiment; length growth phases and rooting depth as measured).

Most obvious in Figure 5.6 is the underestimation of water-limited *DM* production. However, the calculated final potential *DM*-production is only slightly higher than the measured *TDM* for LHH-144, indicating that the calculated moisture stress is the main reason for the underestimation of the water-limited production. Water-limited *DM* production in the first part of the growing season could be fitted well. During this period on purpose light to medium water-stress was created to avoid excessive vegetative growth. From the second part of September on severe water stress is simulated, whereas in practice apparently hardly any stress occurred. The calculated amount of soil water from 30-120 cm depth is severely underestimated. The soil-water module of SWAP was calibrated using data from the *rabi* season. Maybe these soil water parameters do not represent accurately the situation in the *kharif* season. The calculated *E* (avg. 0.5 mm.day^{-1}) and percolation (13 mm) were not the reason for this underestimation. The calculated T_p of about 800 mm in 196 days in the *kharif* season seems realistic. The amount of water applied (with irrigation and rain about 460 mm) is very low compared to the calculated T_p. With the values for the crop parameters within realistic ranges, it was impossible to come close to the measured productions under "optimum" moisture. The reason for the large differences between the measured and calculated *DM*-productions is not clear. Possibly the rooting depth was underestimated (88 cm measured), or there might have been some upward movement of water from soil layers below 120 cm. There is some uncertainty about the value for the canopy resistance (70 $s.m^{-1}$), but the range of uncertainty (60-80 $s.m^{-1}$) can not explain more than 10% of the difference between measured and calculated *TDM*. For the maximum assimilation rate and the initial light use efficiency the maximum values found in literature were used. Maybe the maintenance respiration has to be lowered. However, no data are available to do this, except for *SO*.

For "low" moisture availability the fitted *DM* production was close to the measured production for H1098, but *DM* production for LHH-144 was still clearly underestimated (Figure 5.7). The water content in the soil layers up to 120 cm depth was estimated better than for "optimum moisture". No clear underestimation of soil water content was observed.

The cultivars used in the experiment were not cultivated on the selected farmer fields, although these two cultivars are cultivated in the region. The cotton cultivars used at the farmer fields appeared to be sensitive to daylength during the vegetative and generative stage. Since this cannot be included in SWAP/WOFOST (Par. 5.2.1), three crop files for different sowing dates were prepared. The *DM* partitioning in relation to *DVS* did not differ clearly between early and late sowing.

The year 2002 was a relatively dry year. Water was probably the most limiting element during the growing season. Therefore, the comparison between the measured and simulated productions at the farmer fields could serve as a kind of validation. The results in Par. 5.3 show that the average level of production was simulated reasonably. However, for 5 out of the 10 fields large differences between the simulated water-limited yield and the actual yields were obtained.

5.3 Comparison of actual and simulated crop production and evapotranspiration

5.3.1 Methodology

With SWAP/WOFOST potential and water-limited production can be simulated (Par. 5.2.2). By definition, water-limited production can only be reached when the crop is amply supplied with nutrients and when it is free of weeds, pests and diseases (for potential production also ample supply of water is needed). In the farmer fields, generally, further reduction of the water-limited production takes place by effects of nutrient shortage, weeds, pests, diseases and/or pollutants, which lead to the so-called actual production. This means that a translation of simulated water-limited to actual production and (*E*)*T* is needed. For this purpose a "management" factor might be used which reduces the simulated yield. However next a better approach is described.

DM-production
In order to translate the simulated water-limited production to the actual production, the measured actual yields and the simulated water-limited productions were compared for each farmer field. Measured productions at harvest (5 replicates) were used for the comparison, and not with those for *DM*-partitioning (3 replicates), since the latter are considered less accurate (fewer and smaller replicates). For rice and cotton too few comparisons were available to analyse the difference statistically. For wheat 17 comparisons could be made. For the remaining 7 fields no calibration of the soil-water module was possible. The simulation model includes already most aspects of crop production, such as sowing date, amount, timing and quality of water supply. However, some aspects are not included, e.g. nutrient stress, competition with weeds, or unfavourable pH. Besides this, calibration was performed for PBW-343 and for emergence date December 13. Simulation for other cultivars and emergence dates may be less accurate. With the help of the available information from the farmer fields, the explaining value of several variables for the yield gap between actual and simulated water-limited production was studied.

Evapotranspiration
Also translation of simulated water-limited *ET* (hereafter called ET_{wl}) obtained with SWAP/WOFOST to actual *ET* (hereafter called ET_a) is needed. ET_a was not measured, however with the help of the simple crop module (and using measured *LAI* values) reasonable estimates of ET_a can be made. Several researchers established relations between yield and T, *ET* or vapour deficit (*Tanner & Sinclair*, 1983). The constants in the relations are often not given for the 3 crops and conditions in our study. However, in our case we have limited data available to determine the constants ourselves. *Doorenbos & Kassam* (1979) presented the relation:

$$\left(1-\frac{Y_a}{Y_p}\right)=K_y\left(1-\frac{ET_a}{ET_p}\right) \quad (5.1)$$

where Y_a is the actual yield component (e.g. total above ground biomass or grain), Y_p is the potential yield, ET_a is cumulative actual evapotranspiration, ET_p is the cumulative potential evapotranspiration and K_y is a constant dependent on yield component and plant species. The relation was assumed valid for water deficits up to 50%. The K_y values given by *Doorenbos & Kassam* (1979) are based on an analysis of experimental data covering a wide range of growing conditions and represent high-producing crop varieties, well-adapted to the growing environment and grown under a high level of crop management.

5.3.2 Comparison for wheat

Dry matter production
As expected the water-limited yields are higher than the actual yields at the farmer fields, since SWAP/WOFOST does not include the effects of nutrient stress and pests and diseases. Only for fields 22 and 24 the water-limited yields were lower than the actual yields. This can be due to several things: the cultivars on these fields can be less sensitive to salt stress, salt transport is not simulated well, or water content is underestimated. Simulation with a less sensitive cultivar (20% higher critical salt level) resulted in an increase of 53% of the yield in field 24 and less in field 22, but the simulated yields still remained clearly below the measured yield. Some fields have very high water-limited productions, e.g. fields 1 and 2.

These productions were all simulated with early sowing and are higher than the potentials mentioned by *Aggarwal et al.* (2000). On the other hand, these simulated yields are close to the highest measured yields with late sowing in the variety experiment (Chapter 3).

The relation found between the measured actual and simulated water-limited wheat yields is weak (R^2: 0.25-0.33 for *TDM*), but positive. Simulation with average *TSUM*s for all cultivars (Table 5.3) gives more or less the same relation as simulation with measured *TSUM*s (similar R^2). The average water-limited *TDM* is 41-43% higher than the measured *TDM* (5 replicates; Table 5.3). The average water-limited grain yield (kg *FM*.ha^{-1}; assuming 80% grain in *SO*, 14 % moisture (fresh material)) is 87-89% higher than the measured actual grain yield (5 replicates). When using the final *DM* estimates based on the samples for *DM*-partitioning (3 replicates; Chapter 3) the water-limited *TDM* is only 2% higher than the measured actual *TDM*, and water-limited grain yield is 30-31% higher than the measured actual grain yield. Apparently, it was difficult to get representative samples. The measurements with 3 replicates are considered less accurate due to the lower number of replicates and the smaller sample size.

For simulation at regional scale and over several years no measured *TSUM*s can be used, because they are not available at these scales. In the case of wheat the difference between measured and average *TSUM*s never resulted in differences larger than 0.7 ton fresh grain per ha and 2.3 ton total above ground fresh biomass per ha.

Table 5.3 Measured actual and simulated water-limited wheat production (10^3 kg.ha^{-1}) at farmer fields (various cultivars; calibration of soil-water module per field).

	Measured (5 replicates)		Simulated (meas. TSUMs)		Simulated (avg. TSUMs all cultivars)		Simulated (avg. TSUMs PBW-343)	
Field	Grain *FM*(1)	Total *FM*(1)	*FM* grain	Total *FM*	*FM* grain	Total *FM*	*FM* grain	Total *FM*
1	7.0	16.1	11.6	20.5	10.9	18.2	-	-
2	4.7	9.5	10.6	17.5	11.1	18.9	-	-
4	6.4	14.7	9.9	16.9	9.9	16.9	-	-
5	5.9	15.4	9.9	16.6	10.4	17.8	-	-
6	6.1	14.0	10.2	17.1	10.7	18.6	-	-
7	5.2	14.3	8.9	14.7	9.6	16.4	-	-
9	2.5	6.2	5.1	11.1	5.1	11.0	5.0	11.3
10	4.4	10.3	9.6	18.4	9.7	17.5	9.7	18.2
11	4.4	11.3	9.4	18.3	9.6	17.6	9.5	18.1
13	4.3	10.7	6.5	11.9	5.9	10.3	5.9	10.3
15	5.0	12.1	10.4	19.1	10.2	18.4	10.3	19.2
16	5.2	11.4	9.1	18.5	9.5	17.7	9.4	18.2
18	3.3	8.0	9.3	17.2	9.2	17.3	-	-
19	2.3	5.7	7.9	16.6	8.2	15.7	8.2	15.7
20	4.3	9.2	9.9	17.9	9.9	17.9	-	-
22(2)	3.0	7.9	0.0	0.0	0.0	0.0	-	-
24(2)	1.8	4.2	1.0	2.0	1.2	2.4	-	-
Avg.	4.6	11.0	8.6	15.8	8.8	15.6	8.3	15.8

(1) 14% and 12% moisture in grain and straw (fresh material, *FM*), 0.8 grain in *SO* (avg. farmer fields+experiments)

(2) salt stress simulated, see text

Multiple linear regression has been applied to analyse the difference between the water-limited *TDM* production and the actual *TDM* production. The following variables were taken into account:

- Cultivar (for calibration PBW-343 used);
- Emergence date (for calibration emergence at Dec. 13 used, potential production increases with earlier sowing);
- Time between maturity and harvest (measured *DM* was determined during harvest, whereas the simulated *DM* is at maturity);
- Use of herbicides (competition with weeds may result in yield reduction);
- pH in top 30 cm (pH influences the availability of nutrients);
- Available Zn in top 30 cm (Zn deficiency occurs regularly in the region);
- N applied (as a measure of N availability);
- P applied (as a measure of P availability);
- Rotation (rotation with rice may have effects on soil properties not included in the model);
- Discharge (irrigation times were not provided on a very exact basis. The higher the discharge, the higher the possible error in irrigation amounts used in the simulations).

This list of variables was based on the information available at the farmer fields. Since the aim is to "translate" the simulated water-limited productions to actual productions at regional level, the selection of variables was also based on available information at village or regional level (*Aggarwal et al.,* 2001). Fields 22 and 24 were left out the comparison, due to doubt about the simulated water-limited yields, and because these two fields change the significance of certain variables dramatically. After determining the explaining value of each individual variable, variables were added until the best explaining model (highest R_{adj}^2 and/or highest significance) was obtained. This procedure was repeated for the difference between the simulated water-limited and actual *SO* production.

Table 5.4 Best models obtained with the statistical analysis of the difference between the simulated water-limited (WL) production and the measured actual (A) production (5 replicates) for wheat on the farmer fields (see text for explanation).

Explaining variables		Simulated with measured *TSUM*s		Simulated with avg. *TSUM*s (all cultivars)	
		TDM_{WL}-TDM_A	SO_{WL}-SO_A	TDM_{WL}-TDM_A	SO_{WL}-SO_A
Cultivar	PBW-343=0, other =1	4748	2336	4259	1553
Maturity to harvest	d	458	274	-	-
Herbicide use	Yes=1, no=0	-1752	-	-	-
Avail. Zn 0-30 cm	$kg.ha^{-1}$	-1591	-	-1751	-
N applied	$kg.ha^{-1}$	44.4	-	48.8	-
Rotation with	Rice=1, cotton=0	-10195	-1874	-8460	-1269
Constant		-1178	2659	-687	4618
R_{adj}^2		0.54	0.20	0.34	-0.005
Significance		0.045	0.148	0.087	0.408

(1) *SO* = *DM* storage organs, *TDM* = total above ground *DM*; assumed: 80% grain in *SO*, 14% moisture in air-dried grains, 12% moisture in air-dried straw.

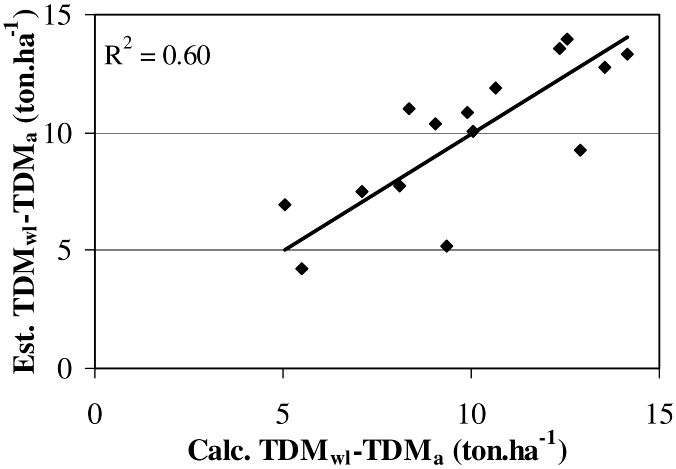

Figure 5.8 Relation between calculated and estimated water-limited and actual *TDM* (water-limited production of wheat simulated with average *TSUM*s; estimated difference calculated with statistical model from Table 5.4).

The statistical analysis shows that the difference between the simulated water-limited production and the measured production most often can be explained partly by the cultivar used and the rotation. At maximum 54% of the difference is explained with the included variables. When using average *TSUM*s during the simulation, as will be done during the regional analysis, a much lower percentage of the difference between the water-limited production and the actual yield is explained and the significance of the models decreases. Fig. 5.8 shows how well the statistical model for *TDM* (avg. *TSUM*s) reproduces the difference between the water-limited and actual *TDM*. The models for *SO* are never significant at the 0.10 probability level, but the harvest index (HI) for grain (on *DM* basis) as observed in the farmer fields does not show a trend with *TDM* production level and is rather stable (average 0.42, std. 0.03). This value can be used to estimate the grain yield from the *TDM* production.

The statistical models are based on data from one year and a limited number of farmer fields, that were not distributed evenly over the region. For reliable "translation" of the water-limited yields to actual yields more data and especially data from more years are needed, since the effect of e.g. pests and diseases can differ considerably between years.

Evapotranspiration

Doorenbos & Kassam (1979) mention a range of *ET* for wheat of 450-650 mm, assuming a growing period of 180-250 days for winter wheat. *Bastiaanssen et al.* (1996) mention a lower range of 400 mm for crop water requirements. The simulated ET_p for the farmer fields is in the range of 419-607 mm (avg. 526 mm), but the estimated ET_a is 224-440 mm (avg. 353 mm) and the simulated ET_{wl} is 139-393 mm (avg. 316 mm). This is very similar to the ET_a values from Bastiaanssen et al. (1996). However, the growing season in the farmer fields is on average 138 days. Figure 5.9 shows the relation between the relative *TDM* and *SO* production and the relative *ET*. The K_y value from literature is 1.0 for winter wheat and 1.15 for spring wheat (*Doorenbos & Kassam*, 1979). Here higher values are obtained (1.24 for *TDM*, 1.64 for *SO*). However, the data used are limited and contain some uncertainty. The ET_a is estimated using linear interpolation between the measured *LAI*'s, resulting in a slight overestimation of the *LAI* and transpiration in the beginning of the growing season. Thus, in reality ($1-ET_a/ET_p$) might have been higher. If TDM_p is overestimated, than ($1-TDM_a/TDM_p$) is overestimated as well. Besides, water was not the only limiting factor for actual production as can be seen in Table 5.3. The K_y of *Doorenbos & Kassam* (1979) was established for high management levels, suggesting that water was the main limiting factor.

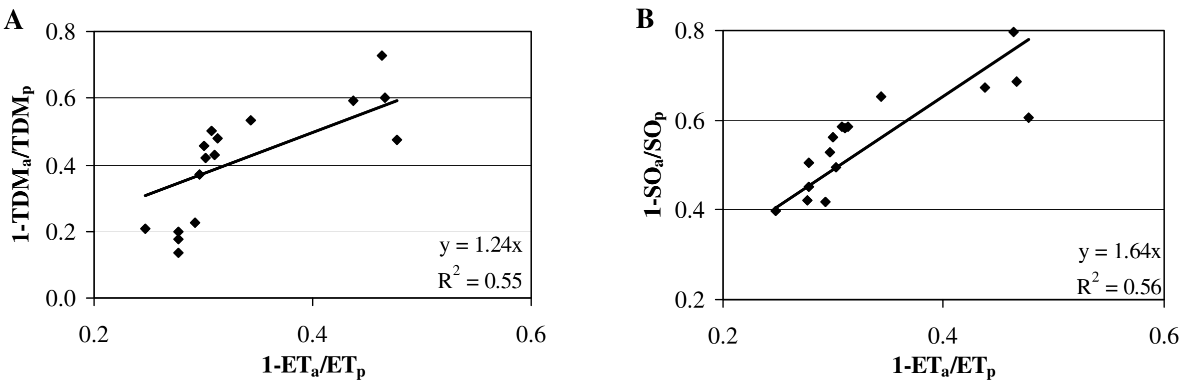

Figure 5.9 Relation between the ratio of actual *TDM* to simulated potential *TDM* (A) or the ratio of the actual *SO* to the simulated potential *SO* (B) and the ratio of estimated actual *ET* and simulated potential *ET* for farmer fields with wheat (Sirsa 2001/02; average lengths of growth phases).

5.3.3 Comparison for rice

Dry matter production

The relation found between the measured actual and simulated water-limited rice yields is weak ($R^2 < 0.35$; only 5 fields) and slightly negative. However, the average simulated *TDM* of rice is only 1-3% higher than the average measured *TDM* (Table 5.5). The average simulated grain yield is less than 4% higher than the average measured grain yield. All yields were close to the simulated potential yield. Apparently, the actual yield was hardly limited or reduced by nutrients, water and/or pests and diseases. *Aggarwal et al.* (2000) mention potential rice productions of 10.8 10^3 $kg.ha^{-1}$ for Sirsa. However, 2002 was a year with relatively high temperatures and a shorter growing season, resulting in relatively low productions.

Table 5.5. Measured actual and simulated water-limited rice production (10^3 $kg.ha^{-1}$) at farmer fields (cultivar PR-106; calibration of soil-water module per field).

	Measured (5 replicates)		Simulated (measured *TSUM*s)		Simulated (avg. *TSUM*s)	
Field	grain *FM* (1)	total biomass *FM* (1)	grain *FM* (1)	total biomass *FM* (1)	grain *FM* (1)	Total biomass *FM* (1)
1	8.1	18.0	7.5	15.6	8.8	19.4
2	7.4	16.0	8.8	20.3	8.2	17.6
4	8.0	18.7	8.9	20.2	8.7	19.1
5	9.0	19.0	8.0	16.3	7.5	15.7
6	8.0	16.5	7.2	16.6	8.8	19.3
Avg.	8.1	17.6	8.1	17.8	8.4	18.2

(1) air dry samples (fresh material, *FM*) about 16% moisture; 0.81 grain in *SO* (avg. farmer fields);

Evapotranspiration

Doorenbos & Kassam (1979) mention a range of *ET* for rice of 450-700 mm. *Tuong* (1999) mentions an *ET* for rice in Punjab of 770-530 mm for transplanting dates ranging from May 1 to July 16, respectively. *Bastiaanssen et al.* (1996) mention water requirements up to 1500 mm. The simulated ET_p for the farmer fields is in the range of 816-943 mm (avg. 888 mm), estimated ET_a is 796-920 mm (avg. 872 mm) and the simulated ET_{wl} is 795-928 mm (avg. 873 mm). In the *Kharif* season temperatures are high and vapour pressure was low in 2002. Consequently, evaporative demand was high. 50-56% of *ET* is T.

The K_y value from literature is >1.15 (*Doorenbos & Kassam*, 1979). For rice only 5 comparisons for actual and potential *DM* and *ET* and a very narrow range of relative *TDM* and *ET* are available. This is not sufficient to determine a K_y. In this case we will have to use the K_y value from literature to estimated *ET* for production levels below potential.

5.3.4 Comparison for cotton

Dry matter production

The relation between the measured actual and simulated water-limited cotton yields is weak (R^2: 0.08-0.38), but positive. The average water-limited *TDM* is 4-6% lower than the average actual *TDM* (5 replicates; 15% moisture in air-dry seed cotton, 18% in straw). The average simulated seed cotton yield (kg $FM.ha^{-1}$; assuming 44% seed cotton in *SO*, and same moisture contents) is 27-32% higher than the average actual seed cotton yield.

Table 5.6 Measured actual and simulated water-limited cotton production (10^3 $kg.ha^{-1}$) at farmer fields (various cultivars; calibration of soil-water module per field).

	Measured (5 replicates)		Simulated (measured *TSUMs*)		Simulated (average *TSUMs*)	
Field	Seed cotton *FM* (1)	Total *FM* (1)	Seed cotton *FM* (1)	Total *FM* (1)	Seed cotton *FM* (1)	Total *FM* (1)
10	1.8	7.3	3.7	17.0	4.4	18.2
11	0.4	1.3	1.0	6.2	1.4	7.3
13	2.2	16.8	3.2	12.3	3.3	12.9
15	1.9	9.0	2.0	10.2	1.9	9.9
16	2.3	12.9	3.8	17.3	3.6	17.4
18	3.6	22.8	3.4	14.2	3.0	12.6
19	2.8	14.2	3.2	14.7	3.1	14.4
20	2.3	14.1	4.0	17.1	4.2	17.6
22	0.0	0.2	0.4	2.9	0.5	2.9
24	3.3	29.2	1.6	8.8	1.9	9.0
Average	2.1	12.8	2.6	12.1	2.7	12.2

(1) 15% and 18% moisture in seed cotton and straw (fresh material, *FM*); 0.44 seed cotton in *SO* (avg. farmer fields+experiments).

Evapotranspiration

Doorenbos & Kassam (1979) mention an ET_a range for cotton of 700-1300 mm for a growing season of 150-180 days. The simulated ET_p for the farmer fields is in the range of 1340-1675 mm (avg. 1527 mm), but for an average growing season of 192 days. The estimated ET_a is 263-777 mm (avg. 553 mm) and the simulated ET_{wl} is 274-795 mm (avg. 559 mm). The high ET_p is probably due to the climate in Sirsa with high temperatures and low vapour pressure. The simulated ET_a is lower due to the water stress that is simulated in all fields. Transpiration composes 62-84% of the *ET*.

The K_y value from literature for cotton is 0.85 (*Doorenbos & Kassam*, 1979). This value could not be reproduced in our study. However, the simulated water stress was in all cases more than 50% (ET_a/ET_p<0.5). The K_y value is assumed valid for water stress of less than 50%. The number of comparisons between actual and potential yield and *ET* is not sufficient for determining a K_y value, especially not when taking into account the uncertainty in ET_a estimates and simulated productions (Par. 5.3.2). Using only the averages of all fields, a K_y of 0.86 is obtained for seed cotton, and a K_y of 0.84 for *TDM*. This is very close to the value mentioned above.

5.4 Management options and water productivity

5.4.1 Definitions of water productivity

As will be discussed in Chapters 8 and 9 the relevant definition of water productivity (*WP*) can change with the spatial and temporal scale one is working on. In this paragraph we will discuss the effect of some management options and climate on yield and *WP* at field scale. Only transpired water is used in a productive way. This means that definitions such as kg *TDM* or economic yield per unit transpiration are logical to use. Evaporation, water used for field preparation, leaching of salts, etc. does not directly result in crop production, although some water is needed for e.g. field preparation, and evaporation cannot be avoided completely. The water need of a crop depends also on management practices. When a rice field is prepared long before transplanting, more water will be lost due to evaporation, compared with preparation and ponding shortly before transplanting. In literature *WP* is often given (implicitly) as yield per unit water supplied through e.g. irrigation. This water use is, however, not the same as the water need of a crop on a certain field, since over- or under irrigation may occur. For a fair comparison between fields, one should focus on water needs, and management practices should be kept the same, or minimum amounts of water needed for these practices should be defined. To avoid arbitrary choices, we will focus on *T* and *ET* from emergence to maturity. To understand where and when water can be saved, distinction between water needs for T, E, leaching of salts, etc. is needed. In this chapter we focus mainly on water needs for *T* and E. Some data on production per unit water supplied by irrigation will be presented for the farmer fields. The effect of management options and climate is demonstrated mainly for wheat, but for rice and cotton similar effects are observed.

5.4.2 Levels of water productivity

In Table 5.7 the simulated *WP* for different irrigation schedules is presented. Various definitions are used to give an idea of the effect of the definition on the level of *WP*.

Wheat

Open Universiteit (1992) and *Lövenstein et al*. (2000) mention as indicative values for wheat 1.5-2.5 kg grain *DM*.m^{-3} *T*. With a harvest index *HI* of 0.40-0.50 this results in a *WP* of 3-6.25 kg *TDM*.m^{-3} *T*. In Table 5.7 a maximum *DM* production of 5.8 kg.m^{-3} *T* is presented and a grain yield of 2.56-2.76 kg *DM*.m^{-3} *T*. This is close to or within the range presented above. From this we can conclude that the simulated T_{wl} is in the correct order of magnitude. In *Doorenbos & Kassam* (1979) a *WP* of 0.8-1.0 kg grain.m^{-3} *ET* for wheat is mentioned (12-15% moisture in grain; yield level 4-6 ton grain.ha^{-1}). *Tuong* (1999) mentions in his overview of some literature a range of 0.65-1.5 kg fresh grain.m^{-3} *ET*. *Hussian et al.* (2003) give *WP*'s of 1.25-1.38 kg.m^{-3} water consumed in India, and an average of 1.27-1.71 kg.m^{-3} water diverted. The difference between the WP_{ET} in Table 5.7 and the values from literature is mainly due to the yield level, and to the time before emergence and after maturity taken into account in the other studies (here *ET* from emergence to maturity). The estimated *WP*'s in the farmer fields (Table 5.8; lower yields) are lower than those in Table 5.7, but close to the values from literature and the *WP*'s obtained with remote sensing (Chapter 6). The WP_T and WP_{ET} in Table 5.7 can be considered the maximum that could be obtained in 2001/02 with emergence at Dec. 13.

Table 5.7 Simulated *WP*'s of wheat, rice and cotton (kg.m^{-3}) for season 2001/02, Sirsa.

Definition *WP*$^{(2)}$	Wheat: irrigation schedule$^{(1)}$		Rice: farmer fields		Cotton: irrigation schedule$^{(1)}$	
	1	2	2	6	O	L
Yield DM/T_{wl}	2.76	2.56	1.29	1.27	0.60	0.44
Yield DM/ET_{wl}	2.22	2.10	0.80	0.75	0.49	0.35
Yield DM/I	1.64	1.78	0.49	0.41	0.90	0.87
Yield FM/T_{wl}	3.21	2.97	1.47	1.44	0.70	0.51
Yield FM/ET_{wl}	2.58	2.44	0.91	0.85	0.58	0.41
Yield FM/I	1.91	2.06	0.56	0.46	1.06	1.02
TDM/T_{wl}	5.76	5.65	2.99	2.89	2.55	1.94
TDM/ET_{wl}	4.63	4.64	1.85	1.70	2.10	1.56
TDM/I	3.43	3.92	1.14	0.92	3.83	3.86
Yield$^{(2)}$ *DM* (10^3 kg.ha^{-1})	6378	5526	7369	6247	2539	1432
TDM (10^3 kg.ha^{-1})	13300	12218	17027	14186	10851	6377
T (mm)	231	216	569	491	426	328
ET (mm)	287	263	928	833	517	409
I (mm)	388	311	1489	1537	283	165

(1) wheat: schedule 1 and 2 are "0.7" and "0.5" in moisture experiment; Cotton: Schedule O and L are "optimum moisture" and "low moisture" in moisture experiment (Chapter 3); Rice: irrigation water from transplanting to maturity.

(2) wheat: 80% grain in *SO*, 14% moisture in grain; rice: 81% grain in *SO*, 12% moisture in grain: cotton: 44% seed cotton in *SO*, 15% moisture in seed cotton; T_{wl}/ ET_{wl}: from emergence/transplanting to maturity.

Rice

In *Doorenbos & Kassam* (1979) a productivity of 0.7-1.1 kg grain.m^{-3} *ET* is mentioned (15-20% moisture in grain; yield level 4-8 ton grain.ha^{-1}). *Tuong* (1999) found a range of 0.40-1.61 kg fresh grain.m^{-3} *ET*. The WP_{ET} in the farmer fields is mostly within this range. The average WP_{ET} obtained with remote sensing (Chapter 6) is slightly lower than the average for the farmer fields. *Bouman & Tuong* (2000) give WP_I of 0.2-0.4 kg grain.m^{-3} in India. *Aslam & Prathapar* (2001) mention WP_I of up to 1.0 kg wheat grain.m^{-3} in Pakistan. Our data are within this range. *Lu et al.* (2002) mention a WP_I of up to 16 kg grain.m^{-3}, but in these cases rainfall covers a much larger fraction of water needs. The low WP_I of rice compared with wheat and cotton is due to the high percolation and seepage losses. *Bouman & Tuong* (2000) mention percolation losses of up to 50-80%. Theoretically, 150-250 mm of water is needed to saturate the top soil and establish a water layer, but in practice water evaporates, recharges groundwater and there is flow out of the field during field preparation (*Tuong,* 1999). The same author mentions a range of 350-1500 mm needed for land preparation. In pot experiments, without seepage and percolation, *WP*'s of up to 1.9 kg grain.m^{-3} water inputs could be reached (*Bouman & Tuong*, 2000).

Table 5.8 Estimated *WP* values of wheat, rice and cotton (kg.m^{-3}) on the farmer fields (2001/02, Sirsa).

Definition WP[2]	Wheat		Rice		Cotton	
	Avg.	Range	Avg.	Range	Avg.	Range
yield $FM^{(1)}/T_a$	1.73	0.80-2.06	1.87	1.56-2.65	0.41	0.02-0.71
yield $FM^{(1)}/ET_a$	1.28	0.26-1.60	1.13	0.82-2.10	0.33	0.01-0.58
yield *FM*/irr	1.32	0.35-2.93	0.63	0.50-0.84	0.59	0.05-1.65
TDM/T_a	3.61	1.75-4.28	3.40	2.83-4.72	2.13	0.11-3.71
TDM/ET_a	2.66	1.37-3.29	2.09	1.66-3.75	2.08	0.08-3.66
TDM/irr	2.73	0.77-5.85	1.15	0.90-1.51	3.02	0.32-6.86

[1] Wheat: 14% moisture in grain, rice: 16% moisture in grain; cotton: 15% moisture in seed cotton;
[2] Grain *FM* = measured grain fresh material (*FM*); *TDM* = measured total above ground dry matter; T_a/ET_a: from emergence/transplanting to maturity with measured *LAI*.

Cotton

For cotton little information is available, but *Doorenbos & Kassam* (1979) mention a seed cotton production of 0.4 to 0.6 kg.m^{-3} *ET* (10% moisture in seed cotton; yield level 3-4.6 ton seed cotton.ha^{-1}). *Droogers & Kite* (2001) mention *WP*'s of 0.21 to 0.54 kg seed cotton.m^{-3} *T* for basin to field level, and of 0.16 to 0.39 kg seed cotton.m^{-3} *ET*, also for basin to field level. The *WP*'s in Table 5.7 are somewhat above or in this range, but on the farmer fields lower *WP*'s are obtained. The average WP_{ET} obtained with remote sensing (Chapter 6) is very similar to the average WP_{ET} form the farmer fields in Table 5.8. The yield levels in SIC are clearly lower than the productions used by *Doorenbos & Kassam* (1979). There is a strong relation between the *WP* obtained and the *TDM* on the farmer fields (R^2=0.9).

The differences in WP_T between the three crops are due to the differences in chemical composition and harvest index (*Tanner & Sinclair*, 1983). For WP_{ET} also the fraction of *E* in *ET* is important. In the cases shown in Table 5.7 the fraction *E* in *ET* was about 0.20 for wheat and cotton, however, for rice it was around 0.40. In the farmer fields the fraction *E* in *ET* ranges from 0.22-0.34 for wheat, 0.43-0.49 for rice, and 0.16-0.38 for cotton. Irrigation need is strongly related to the *ET* of a crop. In SIC the rainfall is low, therefore a large part of the *ET* should be covered by irrigation. Extra water may also be needed for soil preparation. For wheat the farmers used 45-224 mm to prepare the field before sowing (average 116 mm). For rice the farmers used 104-157 mm to submerge the field shortly before transplanting.

The *WP* values in Table 5.7 are in most cases higher than the *WP* values found in literature. This is partly due to the fact that only T_{wl} or ET_{wl} from emergence/transplanting to maturity were used in the calculations in this chapter. To give an idea of the effect of a longer period, the ET_{wl} from sowing to harvest for wheat was calculated, assuming that sowing took place a week before emergence, and harvest took place a week after maturity. This resulted in 2.31 kg wheat grain *FM*.m^{-3} ET_{wl} for irrigation schedules 1 and 2 in Table 5.8 (compare with 2.44-2.58). Especially the transpiration after maturity caused this decrease in *WP*. Secondly, the simulated potential and water-limited *WP*'s will normally be higher than the *WP*'s obtained on farmer fields, since the farmers experience yield reductions due to pests and diseases, nutrient limitations, etc. The effect of pests and diseases can vary enormously. A pest or disease that reduces leaf area from the beginning of de growing season, will reduce transpiration and final grain yield proportionally. In that case the WP_T may still be close to the maximum. However, a pest or disease that reduces grain yield, but not the leaf area (thus *T*), will result in clearly lower yield per unit *T*. According to *Tanner & Sinclair* (1983) and *Van Keulen & Wolf* (1986) there are no strong indications for large differences in the *T* to assimilation ratio under different nutritional conditions. However, *Ritchie* (1983) and *Tuong* (1999) presents results that show an increased yield per unit *ET* with increased nitrate availability. These seemingly contradictory results may be due to the different definitions used: the first per unit *DM* produced, and the second per unit grain. The timing of nutrient shortage is important: nutrient shortage during grain filling results in lower assimilation rates and lower grain production, whereas the production of leaves and stems may not be affected much. *Ritchie* (1983) argues that the maximum *ET* is reached at a lower *LAI* than the maximum *DM* production. Thus, any nutrient application that increases *LAI* above the *LAI* for maximum *ET* up to the *LAI* for maximum *DM* production, will result in increased *WP*.

5.4.3 Deficit irrigation

When water supply is not sufficient to keep the actual or water-limited *T* (T_a or T_{wl}) of a crop equal to T_p, the stomata in the leaves will partially close and *DM* production will decrease. When using "deficit" irrigation, not enough irrigation water is applied to keep T_a equal to T_p. Generally, in SIC the available canal irrigation water is insufficient to cover crop needs completely.

Table 5.9 shows *WP* values for irrigation schedules varying in the level of deficit and the timing of the deficit. The WP_T and WP_{ET} remain more or less stable, irrespective of the irrigation schedule, as expected (except for "opt.-20% beginning season" and T_{wl}/T_p=0.8). The small differences are due to differences in *HI* (0.47-0.49). It appears that assimilation and *T* are affected approximately to the same extent (*Tanner & Sinclair*, 1983; *Van Keulen & Wolf*, 1986; *Penning de Vries et al.,* 1989). Consequently, the amount of *DM* produced per unit *T* remains more or less constant. The fraction *E* is relatively small and rather stable (0.18-0.21 of ET_{wl}), therefore, WP_{ET} also hardly changes.

Table 5.9 Simulated *WP* of wheat (kg.m^{-3}) and grain yield (10^3 kg.ha^{-1}) for 2 irrigation schedules (2001/02, soil experimental station Sirsa, emergence date 13/12).

	Grain FM/T_{wl} (2)		Grain FM/ET_{wl} (2)		Grain *FM*/ *I*		Grain kg *FM*	
Irrigation schedule	T_{wl}/T_p >0.95 (1)	T_{wl}/T_p >0.8	T_{wl}/T_p >0.95	T_{wl}/T_p >0.8	T_{wl}/T_p >0.95	T_{wl}/T_p >0.8	T_{wl}/T_p >0.95	T_{wl}/T_p >0.8
optimum schedule	3.22	3.18	2.54	2.62	2.62	2.87	7.9	6.9
opt. -20% all irr	3.13	3.09	2.46	2.53	3.00	3.31	7.2	6.3
opt. -20% beginning season	3.14	2.62	2.49	2.07	2.81	2.46	6.8	4.8 (3)
opt. -20% end season	3.22	3.17	2.54	2.61	3.28	3.55	7.9	6.9

(1) irrigation back to field capacity when T_{wl}/T_p = 0.95 or 0.80;

(2) 80% grain in *SO*, 14% moisture in grain; T_{wl} / ET_{wl}: from emergence to maturity;

(3) *HI* = 0.42, compared with 0.48 for other treatments.

The yield level, however, does change with the irrigation schedule and the timing of water stress. *Hussain et al.* (2003) also observed this. Consequently, the WP_I does change with the irrigation schedule. When less irrigation water is applied, the rainfall covers a larger fraction of the (*E*)*T*. Consequently, WP_I increases with decreasing irrigation amounts. How much WP_I increases depends on the timing of the water stress. Light water stress at the end of the growing season results in less yield depression, compared with a constant mild water stress during the whole growing season. Many crops are less sensitive to water stress during the ripening stage. The low *WP* values for the runs with water stress at the beginning of the growing season are due to the poor *LAI* development and, consequently, lower yield.

5.4.4 Variation between years

For the same crop and cultivar, different *WP*'s can be obtained in different years and environments. This is mainly due to the difference in water vapour concentration between the atmosphere and inside the stomata. When the relative humidity of the atmosphere is lower, and the leaf temperature is higher, more water will be lost (*Tanner & Sinclair*, 1983), and *WP* will be lower.

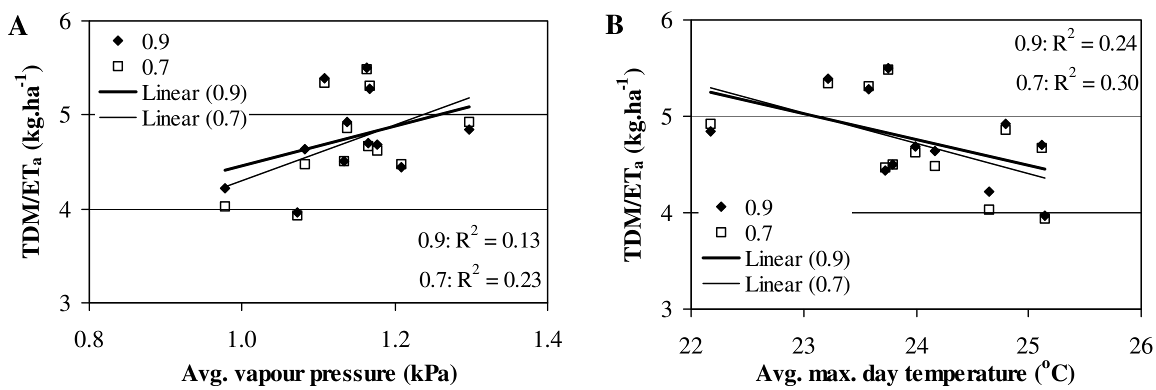

Figure 5.10 Relation between WP_{ET} and the average vapour pressure (A) or average maximum day temperature (B) during the growing season (emergence date 17/11, "optimum" irrigation schedule for $T_{wl}/T_p > 0.9$ or 0.7).

Table 5.10 shows the *WP* values for 2 irrigation schedules. The difference within years is small (Par. 5.4.2). However, there is considerable variation in *WP* values between years. No clear relations were found between the individual climatic input data and the *WP* values. However, some weak relations exist between the *WP* and the average vapour pressure and average maximum day temperature during the growing season (Fig. 5.10). When the average maximum day temperature is higher, the *WP* is generally lower. When the average vapour pressure is higher, higher *WP*'s can be obtained. Low vapour pressure often coincided with low rainfall (R^2=0.24) and especially with high avg. maximum day temperatures (R^2=0.72). Consequently, in the years with the lowest rainfall, the evaporative demand is highest.

Table 5.10 Simulated water productivity of wheat (kg.m^{-3}) and grain yield (10^3 kg.ha^{-1}) for 2 irrigation schedules and several years (soil experimental station Sirsa, emergence date 17/11).

Year	Grain FM/T_{wl} (2)		Grain FM/ET_{wl} (2)		Grain FM/I		Grain FM	
	T_{wl}/T_p >0.9 (1)	T_{wl}/T_p >0.7	T_{wl}/T_p >0.9	T_{wl}/T_p >0.7	T_{wl}/T_p >0.9	T_{wl}/T_p >0.7	T_{wl}/T_p >0.9	T_{wl}/T_p >0.7
1991	4.31	4.26	3.32	3.26	5.16	3.89	11.6	10.4
1992	3.81	3.59	2.95	2.83	3.62	4.63	10.5	8.5
1993	3.63	3.36	2.83	2.67	3.07	3.17	10.3	8.3
1994	3.30	3.15	2.60	2.52	3.07	3.08	9.3	8.2
1995	4.80	4.69	3.59	3.51	5.00	5.36	11.3	10.5
1996	3.88	3.73	2.98	2.90	4.37	5.02	10.4	9.2
1997	3.97	3.93	3.11	3.13	4.10	6.10	11.7	10.7
1998	3.99	3.96	3.02	3.04	4.55	5.75	10.7	9.9
1999	3.42	3.34	2.68	2.63	3.00	3.13	9.9	9.1
2000	3.65	3.52	2.87	2.82	3.56	3.17	10.5	9.1
2001	3.41	3.29	2.79	2.70	3.61	3.46	10.6	9.3
2002	3.74	3.66	2.95	2.91	3.29	3.22	9.4	8.2
Average	3.83	3.71	2.98	2.91	3.87	4.17	10.5	9.3

(1) irrigation back to field capacity when T_{wl} / T_p = 0.90 or 0.70;

(2) 80% grain in *SO*, 14% moisture in grain; T_{wl} / ET_{wl}: from emergence to maturity.

In years with a lower average day temperature, the growing season was a little longer (crop development is determined by temperature, *TSUM*s). This longer growing season resulted in a higher *DM* production. As a result of climate change temperatures are expected to increase (Chapter 9). From the above analysis, we can conclude that this will probably result in lower maximum WP_T and WP_{ET} (when the vapour pressure remains the same).

5.4.5 Sowing date

Table 5.11 Simulated *WP* of wheat (kg.m^{-3}) for different sowing dates (2001/02, soil of experimental station Sirsa; optimum schedule with $T_{wl} / T_p > 0.9$(1)).

Definition *WP*	Sowing date (2001)			
	Nov. 10	Nov. 20	Nov. 30	Dec. 10
Grain FM/T_{wl} (2)	3.75	3.55	3.36	3.12
Grain FM/ET_{wl} (2)	2.95	2.79	2.64	2.45
Grain FM/I (1)	3.35	3.21	3.05	2.78
TDM/T_{wl}	5.96	5.82	5.75	5.49
TDM/ET_{wl}	4.69	4.57	4.53	4.31
TDM/I	5.33	5.26	5.22	4.89
Grain *FM* (10^3 kg.ha^{-1})	9.4	9.0	8.3	7.4
TDM (10^3 kg.ha^{-1})	15.0	14.7	14.3	13.0
T (mm)	251	253	248	237
ET (mm)	319	322	315	302
I (mm)	281	280	273	266
Days E-M	142	135	126	118

(1) irrigation back to field capacity when T_{wl} / T_p = 0.90; *I* = opt. irrigation amount calculated by SWAP;

(2) 80% grain in *SO*, 14% moisture in grain; T_{wl} / ET_{wl}: from emergence to maturity.

Sowing date can have an effect on *WP*, since the conditions during the growing season may change with the sowing date (Table 5.11). With later sowing the yield decreases. *Aggarwal et* *al.* (2000) and *Hussain et al.* (2003) also mentioned that early sowing results in higher yields. Also *WP* decreases when wheat is sown later. The decrease in grain *FM* per unit water consumed or applied is partly due to the relatively shorter period between flowering and maturity with later sowing. This results in lower harvest indices with late sowing (54% grain for Nov. 10; 49% grain for Dec. 10), and consequently lower grain production per unit (*E*)*T*. Besides this, the yield decreases relatively faster than the (*E*)*T* or the irrigation need. When the same level of water stress is applied, early sowing results in higher *WP* and higher yields, but also in higher absolute amounts of irrigation water applied.

5.4.6 Soil type

Table 5.12 shows some results of a comparison of *WP*'s for two soils. As initial conditions complete saturation 10 days before emergence was used.

Table 5.12 Simulated *WP* of wheat ($kg.m^{-3}$) on 2 soils. Simulated with emergence on November 23, 2001, and with completely saturated soil 10 days before emergence.

	Field 5		Field 16	
	T_{wl}/T_p >0.9[(1)]	T_{wl}/T_p >0.7	T_{wl}/T_p >0.9	T_{wl}/T_p >0.7
Grain FM/T_{wl}[(2)]	3.72	3.68	3.69	3.58
Grain FM/ET_{wl}[(2)]	3.15	3.18	2.90	2.84
Grain FM/I[(1)]	4.10		3.93	4.92
Grain *FM* ([(1)]10^3 $kg.ha^{-1}$)	9.5	9.5	9.5	8.7
TDM ([(1)]10^3 $kg.ha^{-1}$)	15.3	15.4	15.1	14.0
T (mm)	254	259	257	242
ET (mm)	300	300	327	305
I (mm)	231	0	241	176
Texture	Loam-Clay loam		Sandy loam-Loamy sand	
AWC[(3)] 0-30 cm	0.33		0.18	
AWC 30-120 cm	0.49		0.14	
θ_{sat} 0-30 cm	0.50		0.31	
θ_{sat} 30-120 cm	0.58		0.32	
K_{sat} 0-30 cm (cm.d-1)	2.63		101.7	
K_{sat} 30-120 cm (cm.d-1)	1.87		120.9	

[(1)] irrigation back to field capacity when T_{wl}/T_p = 0.90 or 0.70; *I*=opt. irrigation amount calculated by SWAP;
[(2)] 80% grain in *SO*, 14% moisture in fresh grain; T_{wl} / ET_{wl}: from emergence to maturity;
[(3)] *AWC* defined as the fraction water between pF2.0 and pF4.2.

As expected, the soil type has no or hardly any effect on the WP_T (Par. 5.4.2). However, soil type may affect E, since in some soils the top soil dries out faster than in others. In the simulations in Table 5.12, the fraction *E* of ET_{wl} was lower for field 5 (0.15) than for field 16 (0.21). The soil in field 5 has a much higher water holding capacity. Therefore, less frequent irrigations are needed, affecting the number of days with wet soil surface. *Gupta et al.* (2002) observed some variation in the percentage *ET* of total water requirements. It was lowest for a sandy loam (33%) and highest for (sandy) clay loam (44%). When infiltration rates are high (as in field 16), irrigation water does not remain long on the soil surface. However, when overirrigating takes place, the extra amount percolates fast. In field 16 more frequent and smaller irrigations are needed than in field 5. Under these conditions it may be more difficult to avoid underirrigation or overirrigation. Not included here are the possible differences in minimum amounts of water needed for soil preparation.

5.4.7 Irrigation water quality

The equation of Maas and Hoffman to express the tolerance of crops to salt, as used in SWAP/WOFOST, assumes that crops respond primarily to the osmotic potential of the soil solution. Other chemical effects of the presence of salts, such as nutritional disorders and toxic effects, are generally secondary in importance (*Tanji,* 1990) and not considered here. The hypothesis that seems to fit observations best asserts that excess salt reduces plant growth, primarily because it increases the energy that the plant must expend to acquire water from the soil and make the biochemical adjustments necessary to survive (*Tanji,* 1990; *Penning de Vries,* 1975; *Yeo,* 1983). The response to salinity varies with many factors, including climate, soil conditions, agronomic practices, irrigation management, crop variety, stage of growth, and salt composition (*Tanji,* 1990).

Long term simulations were performed with different irrigation water qualities (not shown here). As expected WP_T and WP_{ET} are hardly affected by the salt levels in the irrigation water, since the effect of salt is the same as that of water stress.

5.5 Discussion and conclusions

5.5.1 Methodology and recommendations for further research

WOFOST includes many aspects of crop growth, however some are not included such as redistribution of carbohydrates, nutrient stress and pest and disease effects. The combination of SWAP/WOFOST has a clear advantage over the simple crop growth module that may also be used in SWAP, since the interactions between soil water and solute transport and crop development and feedback through *LAI* and *ET* are included. Once calibrated, the crop files can be used for varying levels of water and salt stress, sowing dates, etc. Hence, SWAP/WOFOST is a useful tool to study the effect of various conditions and management options on water productivity. This is not possible with the simple crop module. A disadvantage is the larger volume of data needed for calibration. However, after calibration and validation it can be used in a wide range of situations.

A translation of the water/salt-limited productions simulated with SWAP/WOFOST is needed to get estimates of actual productions, due to nutrient stress and/or yield reductions by pests and diseases. A statistical analysis as used here can be useful to analyse the yield gap, but more data from more years are needed. The selected farmers fields were not distributed homogeneously over the whole region and the number of comparisons (farmer fields) was too limited to derive relations that are valid for entire SIC and for several years. Apparently it was difficult the include the variation in the fields during the field measurements (see difference between *DM*-partitioning samples (3-replicates) and final sampling (5 replicates). This further complicated the comparison between the water-limited yields and the actual yields of the farmer fields.

Although a large amount of data was collected, calibration of the crop files was regularly complicated by limited information. Insufficient information was available to calibrate for salt stress, although salt stress is a potential problem in a large part of the region. Since the crop cultivars were not known to be very sensitive or insensitive to salt stress, general data were used to simulate salt stress. Correct estimation of *T* and *E* is essential to get reliable *WP* estimates. However, no reliable A-pan measurements or lysimeter data are available to check the estimates of ET_a obtained with the simulation model and remote sensing. The ET_a values are in the correct order of magnitude, but there might be some over- or under-estimation.

5.5.2 Management options, water productivity and yield level

The level of deficit irrigation hardly affects the WP_T and WP_{ET}, but it does affect yield level. Depending on the timing of irrigations and thus water stress, with the same amount of irrigation water available, a considerable variation in water-limited yield can be obtained. As a consequence, WP_{Irr} can vary, and investments in measures that allow adjusting the timing of irrigations may be profitable. Many farmers in the region have access to groundwater. If this groundwater is of sufficient quality it gives the farmers the possibility to irrigate when needed. This access to groundwater also increases the reliability of water supply, and may reduce overirrigation.

WP values can vary considerably over the years. In years with below average rainfall often the evaporative demand is above average. Hence, the demand for irrigation in these years is increased due to the low rainfall, but also due to the higher crop needs. The *WP*'s in these years are relatively low. For good management of the crop and to avoid severe water stress in the most sensitive crop stages, the farmers need good estimates of the potential *ET*. In other words, reliable and local weather data are needed on the short term, e.g. on a weekly basis. The weather data from the experimental station in Sirsa contained a lot of missing data and some data were unreliable. It is not possible to provide one fixed irrigation scheme that is valid for all years. For optimum use of water, constant adjustment to the climatic conditions at that moment is needed.

Early sowing results in higher potential wheat yields and *WP* values. However, the absolute amounts of water needed also increase with earlier sowing. With earlier sowing only less water per unit production is needed.

The soil type does not affect the WP_T, but it does affect the level of WP_{ET} and WP_I. On coarser soils generally lower WP_{ET} and WP_I will be obtained due to the higher fraction of *E* in *ET*, the higher risk of percolation, and the higher number of irrigations needed.

There are large differences in *WP* values between crops due to the contribution of *E* to *ET*, the harvest index and the chemical composition. The maximum WP_T for rice and wheat does not differ too much (similar chemical composition and HI), but the maximum WP_{ET} for irrigated rice will always be much lower than for wheat, due to the large *E* losses from the ponding water in rice.

Management options, such as earlier sowing, and good nutrient and pest and disease management can increase water productivities, especially in wheat. These management options will increase production, but will not decrease water use. Only irrigation scheduling based on more detailed information about evaporative demand may result in some reduction of water use, as compared to the current situation.

At present, there is still a yield gap between the actual yields obtained by the farmers and the water/salt-limited yield. This gap may be bridged by better nutrient management and better control of pests and diseases (*Dhindwal et al*., 2002). As a result the WP_T and WP_{ET} may increase. However, when the actual yields are close to the water-limited yields, as was observed for rice and cotton in the farmer fields, increased productions (up to potential productions) can only be obtained with the same or higher absolute amounts of water, and WP_T and WP_{ET} will not increase further. This was concluded also by *Bouman et al.* (2002). In this last case, making more water available for nature, industry and domestic users will result in lower agricultural production, and a choice has to be made between the need for more food production and the amount of water available for other than agricultural uses.

6. Remote sensing analysis

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Summary

High and low resolution satellite images have been used in conjunction with the remote sensing algorithm SEBAL to obtain spatially discrete values of crop water productivity for wheat, rice and cotton. A multi-spectral crop classification has been carried out in addition for making a crop wise evaluation feasible. The overall accuracy of the classification is low due to insufficient ground truth collection, but also due to poor crop stand of cotton, with a resulting interference of soil background reflectance as a result. The accuracy of wheat and rice classification is acceptable, but for cotton it is not. Without any calibration, the wheat yield predictions by SEBAL were slightly overestimated (6%). The rice yields matched also very well the data (2 % deviation). The cotton yields needed to be calibrated by modifying the harvest index, because default values for cotton were inappropriate. Improvements in the remote sensing model can be made by refining the harvest index into a variable value that is a function of the total above ground dry matter production. The ET and crop yield derived for wheat, rice and cotton have been used to compute the spatial variability of crop water productivity. The ranges are larger for rice (*CV*=26%) than for cotton (*CV*=13%) and wheat (*CV*=6%). The overall conclusion is that the water productivity is good and rather uniform for wheat, and are moderate for rice and cotton. The wider range in water productivity for rice suggest that by narrowing the variability and increasing the absolute value for rice, productivity of water resources in Sirsa can be improved. Chances for rice have more potential than for cotton, because cotton needs a sub-surface drainage system for reclaiming the saline soils.

6.1 Introduction

This chapter describes the results of the remote sensing component of estimating crop water productivity. A description of the Surface Energy Balance Algorithm for Land (SEBAL) methodology is provided in Appendix B. The applied remote sensing methodology consists of three steps: first, a land cover classification was made for the 2001-02 *rabi* and 2002 *kharif* season. Secondly, SEBAL was applied to calculate dry matter production and actual evapotranspiration. For this purpose satellite images of the *Landsat Enhanced Thematic Mapper* (Landsat ETM) and the *Advanced Very High Resolution Radiometer* of the *National Oceanic and Atmospheric Administration* (NOAA-AVHHR) were acquired and processed. The third and final step is to integrate the monthly SEBAL results of NOAA with the daily Landsat results and fuse them together into spatially discrete values of water productivity.

6.2 Satellite images used

For the project, a total of 12 NOAA images and 5 Landsat scenes were acquired and processed. The number of cloud free Landsat images was – unfortunately - limited and below the average for the climatic conditions in India. The characteristics of the NOAA and Landsat TM sensor are outlined in Table 6.1, while in Tables 6.2 and 6.3 details on the acquired and processed images are given. Finally in Fig. 6.1, an example of both types of images is presented. Two elder ortho-rectified Landsat TM5 images were used to geometrically correct all other raw NOAA and Landsat images to UTM.

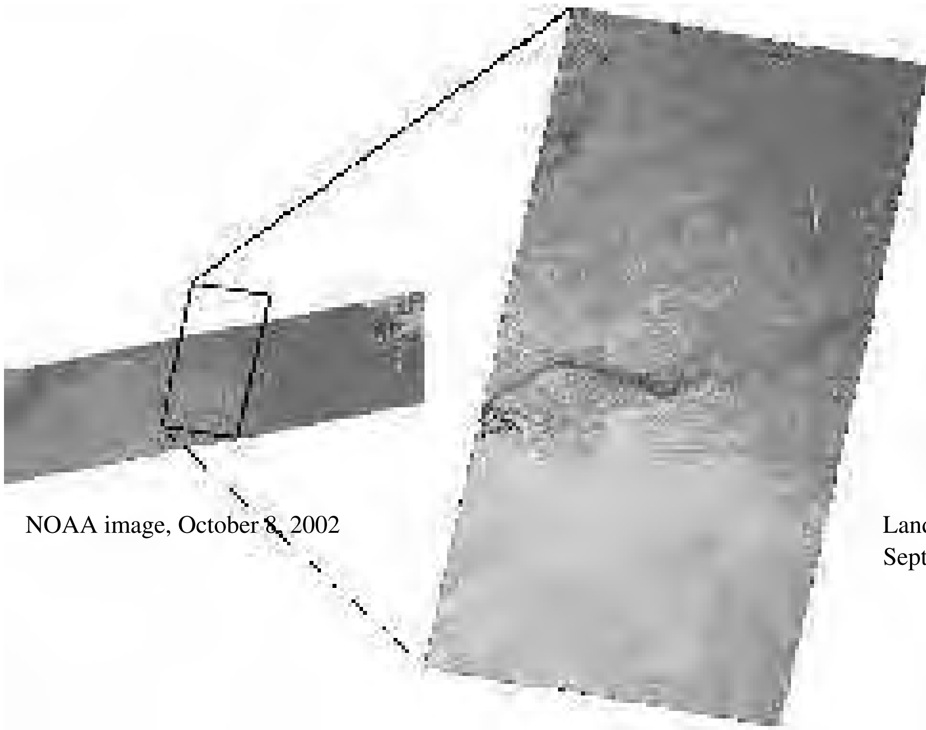


Figure 6.1 Example of a NOAA and Landsat multi-spectral image.

Table 6.1 Main NOAA and ETM Landsat characteristics.

	Landsat ETM	NOAA
number of bands	7	5
spatial resolution	30 m (thermal band 60 m)	1100 m
spatial coverage	185x185 km	2800 km
temporal resolution	16 days	daily
operational since	1984 (Landsat TM5)	1994 (NOAA-14)
	1999 (Landsat ETM7)	1998 (NOAA-15)
		2000 (NOAA-16)
cost	€ 600-1500	free of charge

Table 6.2 Acquired and processed Landsat ETM images

Track/frame	Sensor	Date	Purpose
148 / 39	TM5	September 14, 1989	geometric correction
148 / 40	TM5	September 14, 1989	geometric correction
148 / 39.5	TM7	March 18, 2002	SEBAL rabi
148 / 39	TM7	September 10, 2002	SEBAL kharif
148 / 40	TM7	September 10, 2002	SEBAL kharif

Table 6.3 Processed NOAA-16 images

rabi 2001-02	kharif 2002
November 26, 2001	May 5, 2002
December 24, 2001	June 11, 2002
January 21, 2002	July 10, 2002
February 18, 2002	August 18, 2002
March 26, 2002	September 20, 2002
April 25, 2002	October 8, 2002

6.3 Land cover classification

A land cover classification has been performed for both the *rabi* and *kharif* season. The land cover classification will be used as input for the yield and water productivity calculations.

***Rabi* season 2001-02**

A Landsat-7 image of March 18, 2002 was used to assess the land cover in the *rabi* season. The land cover classification was performed using a series of consecutive unsupervised classification steps. The unsupervised classification has been carried out on the basis of the ISODATA clustering algorithm. The ISODATA algorithm assigns pixels to the nearest cluster, based on the spectral distance. The algorithm is iterative in that it repeatedly performs an entire classification and afterwards recalculates the new statistics of the clusters. The re-calculated means of every cluster are the basis for a new iteration, in which all pixels are assigned again to the nearest cluster. The process ends when a certain number of pixels are not assigned to a different cluster. A default value of 95% has been used in this exercise. The number of clusters has to be fixed beforehand.

Three ISODATA clustering attempts have been performed, using respectively 5, 10 and 20 clusters. The ISODATA clustering with 5 classes has been used to separate bare soil, water and vegetation. The ISODATA results with a larger number of clusters have been used to separate the different vegetation classes. A field campaign conducted by the Haryana Agricultural University resulted in a database with 249 records of land cover. This database has been used to assign the ISODATA clustering results to land cover classes. The result of the classification is presented in Fig 6.2. The major crop grown during the *rabi* season is wheat, with the other crops representing a much smaller fraction of the total cropped area (see Table 6.4).

The spectral signatures for wheat were not identical, and this distinction could be related to sowing date (early vs. late wheat depending whether cotton or paddy was the preceding crop), the wheat variety or other management factors. To indicate these differences, Table 6.4 contains two classes of wheat (wheat I and wheat II). Oil seed occupies 7 % of the total cropped area. The spectral features of other crops identified in the field campaign were not distinctive enough to be separated by the ISODATA algorithm, so a class with 'other crops' was generated.

The accuracy of the classification depends on several factors, such as the spectral separability of the land cover classes, heterogeneity of the land surface, and the extent of field truth. The accuracy of the current classification is aggravated by the fact that the agricultural plots have

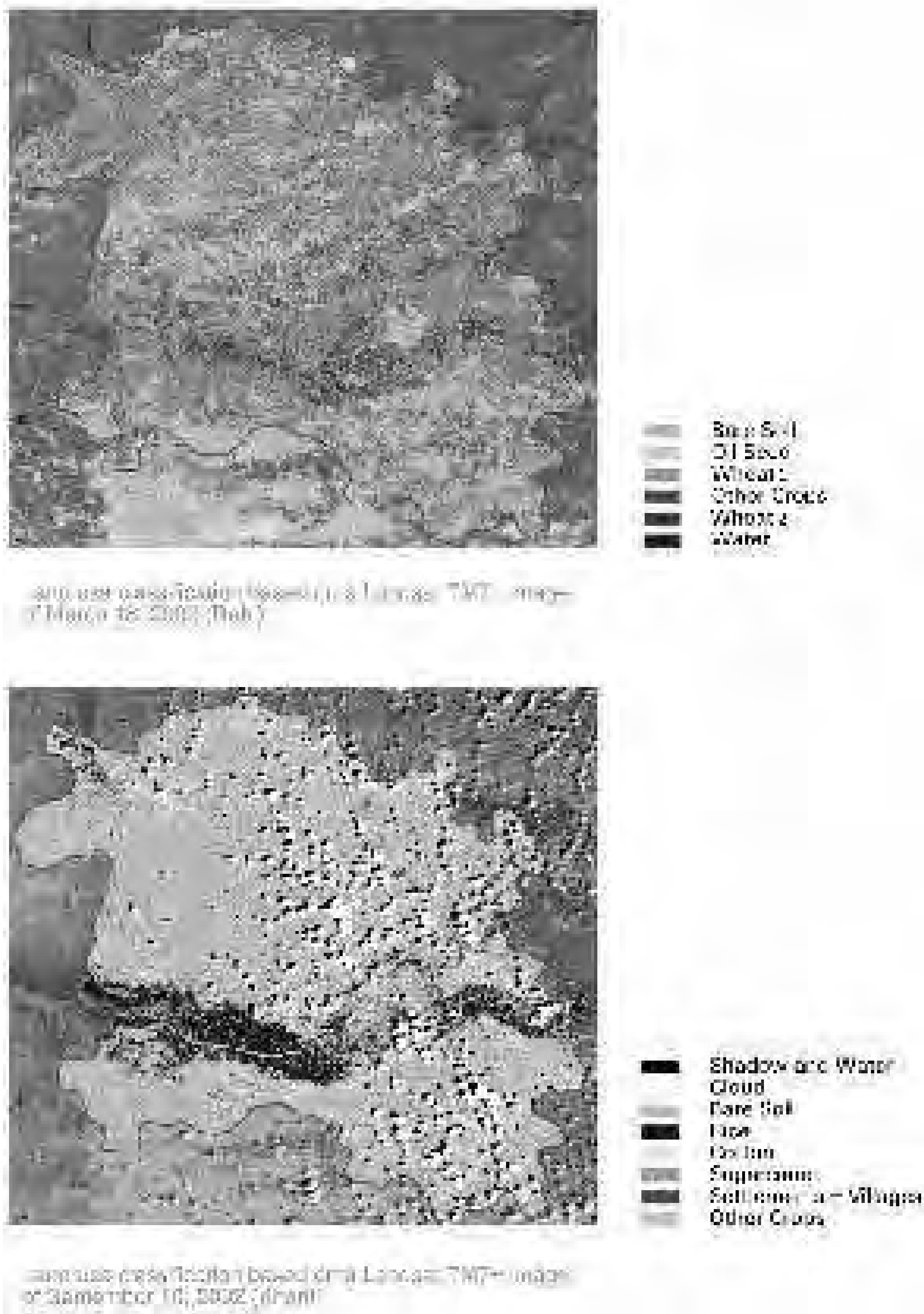


Figure 6.2 Land cover classification for the 2001-02 *rabi* and 2002 *kharif* season.

a small size and that most ground truth samples originate from a limited area. More ground points will improve the accuracy of the classification. The total area under wheat has been classified as being 1766 km^2, and this is 8% more than an earlier classification carried out by *Thiruvengadachari et al.* (1997), who report upon a wheat area of 1630 km^2 in Sirsa Circle during the rabi 1995-96 season. Their classification accuracy was 97% for wheat, which is extremely high due to a very large sample set they had collected from the field. The 8% difference in acreage can be both an error in the current classification, and an increase in the wheat acreage.

Sirsa has a large fraction of bare soil and fallow land prone to waterlogging and salinization. The tail end location of the Bhakra system will provide less canal water which reduces the water availability at the farm gate.

Table 6.4 Results of the land cover classification for the 2001-02 *rabi*-season for entire Sirsa Circle

Land cover	km^2	%
Wheat-I	477	12
Wheat-II	1,289	31
Oil Seed	303	7
Other Crops	528	13
Bare Soil	1,238	30
Settlement and villages	218	5
Water	51	1
Unclassified	0	0
Total	4,104	99

Kharif season 2002

The Landsat-7 image of September 10, 2002 has been used to perform a land cover classification of the *kharif* season. Part of the Landsat scene was clouded so for these pixels no land-use could be detected. Both shadows and clouds are present on the final results of the land cover classification. Water could not be spectrally separated from shadow and appears therefore as 'water and shadow' in the classification results.

The same ISODATA clustering methodology as applied for the *rabi* season, has been used for the *kharif* season. A field research has been conducted in the Sirsa region, which resulted in a database of 77 ground truth points of known land cover. Despite that such dataset is not sufficient to cover a range of field conditions, the database has been used for the interpretation of the ISODATA results. The accuracy could for this study not be assessed. In general, a crop classification has an accuracy of 85% if the ground truth data collection is complete, so in this case it is expected to be lower.

The final result of the land cover classification is presented in Fig. 6.2. The two major crops in the *kharif* season are rice and cotton (Table 6.5) and they are approximately equally present. Also a small amount of sugarcane is grown during the *kharif* season. Other crops (pearl millet and sorghum) could not be identified separately due to small spectral differences between these crops and the limited ground truth data available. Public domain data on crop acreages (http://sirsa.nic.in/htfiles/25agriculture.html) in Sirsa suggest an area of 370 km^2 for rice 2001-02, which deviates 24% from the 459 km^2 estimated in this classification. It should be mentioned that the same database report for the 1999-00 season an acreage of 450 km^2, which is almost identical (98% accuracy) with results obtained in this study.

The large percentage of other crops in Table 6.5 is likely to be cotton, because the statistical data shows that there is approximately 4 times more area irrigated by cotton than by rice. The lesson learned here is that extensive field work on crop identification is a necessity for proper crop classifications.

The total cropped area in *rabi* is 2597 km^2 and this shrinks to 2236 km^2 during *kharif*. The exact reasons for that are not known, but it may be related to the higher consumptive use during the summer season, among others, because kharif crops consume twice the water amount of rabi crops, or more. The average portion of bare soil is with 1119 km^2 on average (27%) rather large, and likely related to the (i) limited surface water resources available at the end of the Bhakra irrigation system and (ii) the soil salinity that makes agriculture as a business investment no longer feasible. *Bastiaanssen et al.* (1999) indicated that tubewell extractions above 6.1 dS/m (4000 ppm) do hardly occur in Sirsa Circle and that most farmers draft groundwater when the quality of the groundwater is less than 2.3 dS/m (1500 ppm). The presence of saline groundwater refrains farmers from crop cultivation. The alluvial flood plain of the Ghaggar river is finer textured than those in surrounding areas, and the water quality underneath the main river system is generally good due to seepage losses from the river bed. The groundwater quality outside the river corridor is poor, and crop cultivation has to rely on canal water.

Table 6.5 Results of the land cover classification for the kharif season

Land cover	km^2	%
Rice	459	11
Cotton	435	11
Sugarcane	316	8
Other Crops	1,026	25
Cloud	395	10
Bare soil	999	24
Settlements + Villages	218	5
Water and shadow	173	4
Unclassified	84	2
Total	4,105	100

6.4 The Surface Energy Balance Algorithm for Land (SEBAL)

The Surface Energy Balance Algorithm for Land (SEBAL) is an image-processing model comprised of 25 computational steps that calculates the actual (ET_{act}) and potential evapotranspiration rates (ET_{pot}), as well as other energy exchanges between land and atmosphere. The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum (Fig. 6.3). SEBAL computes a complete radiation and energy balance along with the resistances for momentum, heat and water vapour transport for every individual pixel. The resistances are a function of state conditions such as soil water potential (and thus soil moisture and soil salinity), wind speed and air temperature and change from day-to-day.

Satellite radiances will be converted first into land surface characteristics such as surface albedo, leaf area index, vegetation index and surface temperature (see Fig 6.3). These land surface characteristics can be derived from different types of satellites. First, an instantaneous evapotranspiration is computed, that is subsequently scaled up to 24 hours and longer periods.

In addition to satellite images, the SEBAL model requires daily averaged routine weather data on wind speed, humidity, solar radiation and air temperature. In this study, daily routine weather data has been obtained from the stations at Hisar (for the *kharif* season) and Sirsa (for the *rabi* season). There is no data on land cover, soil type or hydrological conditions required to apply SEBAL.

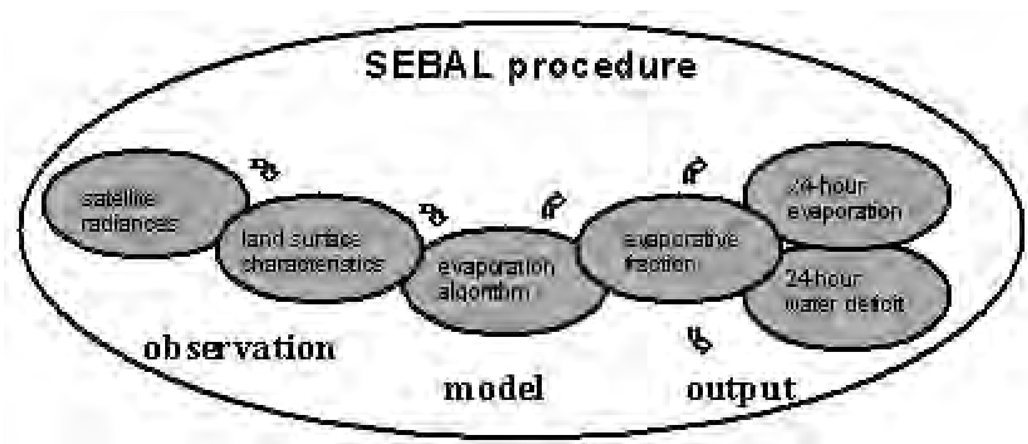


Figure 6.3 Flow chart of the principal steps in SEBAL to derive instantaneous 24-hour ET_{act} and ET_{pot} values.

6.5 SEBAL results *rabi*-season 2001-02

In order to derive physical yield from dry matter production, one should know the length and starting date of the growing period and the harvest index for each crop. These data are derived from literature indications of the cropping calendar. *Boels et al.* (1996) show a growing season for *rabi* crops that runs from approximately November 15 until April 15 (150 days). *Bastiaanssen et al.* (1996) gives similar patterns: December 1 - April 15 (135 days). *Singh and Sharma* (1993) mention a total length of the growing season for wheat of 135 to 145 days. Figure 6.4 is based on satellite measurements and demonstrates a low dry matter production in November, while from December dry matter production increases steadily until March and this confirms that wheat is emerging in December. The peak growth occurs during March, and ripening is reflected by a lower dry matter production in April. Based on this, a growing period of 135 days will be applied for the determination of wheat yield starting on December 1, 2001 and lasting until April 15, 2002.

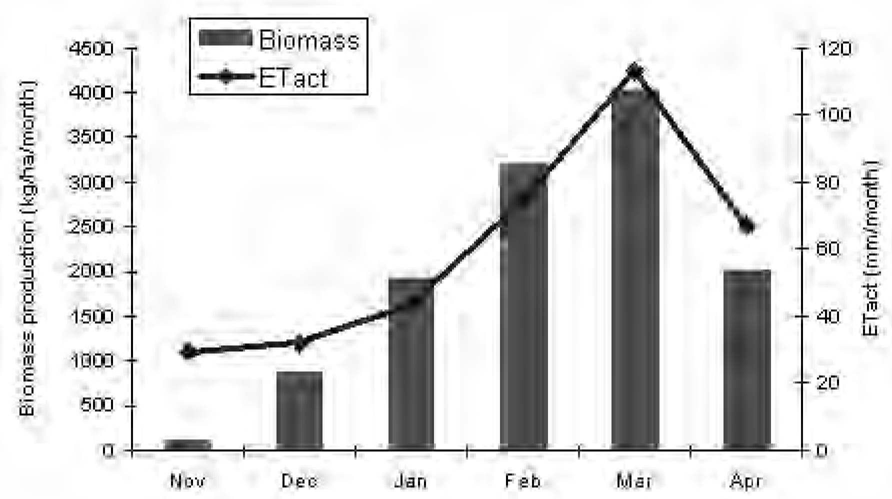


Figure 6.4 Average monthly dry matter production and ET_{act} for five NOAA-AVHRR pixels dominated by wheat in Rabi 2001-02.

The effective harvest index, *HI* (-), is defined in this study as the ratio between total fresh harvestable product (which includes some moisture) and total dry matter production. From a previous wheat yield study in the Indus Basin (Pakistan), *Bastiaanssen and Ali* (2003) found *HI* = 0.39. When the fresh matter contains 11% moisture, this is equivalent to a harvest index for dry matter grain production HI_{dry} of 0.35. An effective value of 0.39 was also used by *Suthakar* (2002) to compute the wheat yield in Haryana for the rabi 1995-96 season with NOAA-AVHRR images and the SEBAL model. He compared the resulting SEBAL wheat yield data with the well calibrated spatial wheat yield maps of *Thiruvengadachari et al* (1997), and found an average deviation of 83 kg/ha without any adjustment of the harvest index. This implies that – although based on Pakistan - a fixed value of 0.39 is very reasonable for the conditions encountered in Haryana.

During the rabi 2001-02 field campaigns conducted by CCS HAU in the Sirsa region, yield samples on 24 trial fields were collected to measure *HI* locally. The average measured value of HI_{dry} is 0.42 with a standard deviation of 0.03. At a moisture content of 10%, this means *HI* = 0.46. The comparison between the yields obtained from SEBAL with 0.39 and the crop cutting experiments suggest that *HI* = 0.43 provides a better fit because the dry matter production is slightly overestimated by SEBAL. Fig. 6.5 displays the yield collected by CCS HAU and the remote sensing estimates of wheat yield. The black dot at the center of the graph represents the average of the 24 fields for both methods.

Figure 6.5 shows a remarkable result: the variation of the field cuttings is considerably larger (1800 to 7100 kg/ha) than the variation in the remote sensing estimation (1800 to 5200 kg/ha). The SEBAL yields are based on 30m x 30m pixels, whereas the field cuts are based on a much smaller surface area (0.5m x 0.2m). The standard deviation within the 24 sample fields have been computed and added as bars. It appears that the standard deviation is higher for plots with a lower yield, which implies that fields with a poor production exhibit also more heterogeneity. Highly productive fields indicate a small standard deviation and they thus have a homogeneous crop stand.

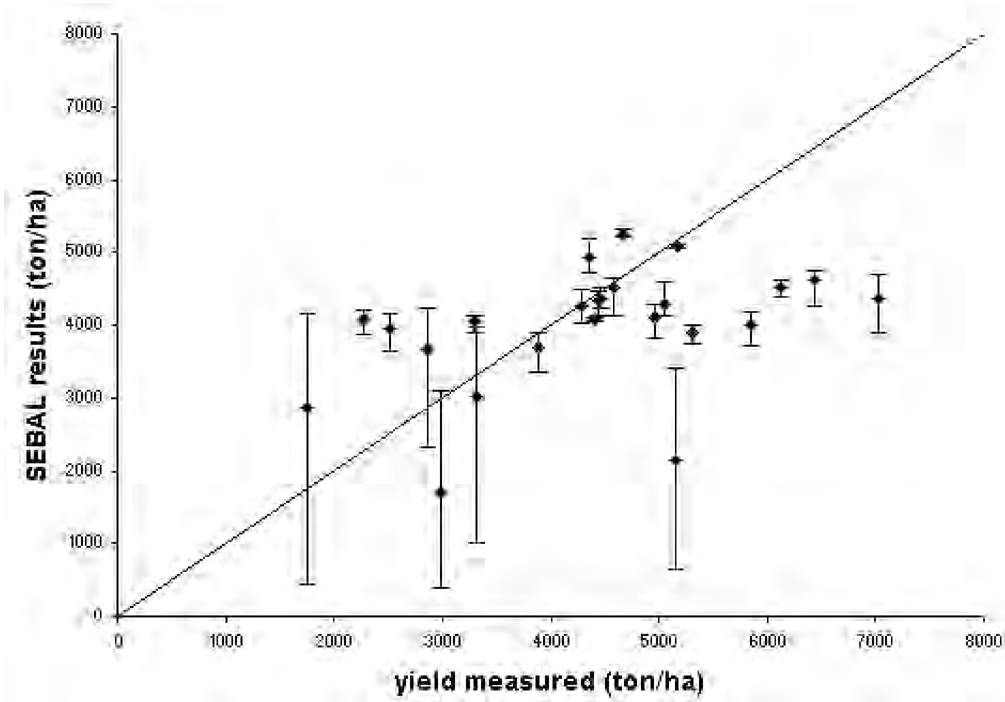


Figure 6.5 Relationship between wheat yield from SEBAL and from in situ measurements. An effective harvest index of 0.39 has been used in the SEBAL-based yield predictions. The vertical bars reveal the standard deviations of Landsat pixels within a given sample field.

Table 6.6 Average wheat yield for 24 field sites.

Source	Year	Wheat yield (kg/ha)
SEBAL (*HI* = 0.39)	2001-02	3932
SEBAL (*HI* = 0.43)	2001-02	4335
SEBAL (*HI* = 0.46)	2001-02	4637
Crop cutting – this WATPRO project	2001-02	4382
Farm interview – this WATPRO project	2001-02	4250
Thiruvengadachari et al. (1997) – Sirsa	1995-96	3760
World Bank – Haryana	1995-98	3750
Department of Agriculture – Sirsa	1975-76	1899
Department of Agriculture – Sirsa	1999-00	4283
Department of Agriculture – Sirsa	2000-01	4616
Indian Bureau of Statistics	2000-01	4161

The wheat yield results have been further verified against published secondary data (see Table 6.6). It seems that statistical data published by the World Bank for the period 1995-98 is with 3750 kg/ha somewhat lower than what is found during the field campaigns. This can be related to the difference in years, but it is also related to the difference in spatial scale between the experimental field sites and the state wise survey conducted in Haryana. A recent study of the Indian Bureau of Statistics revealed for rabi 2000-01 in the Sirsa Circle an average wheat yield of 4161 kg/ha, which is in close agreement with the 4382 kg/ha harvested from the experimental plots. Since the effective harvest index of 0.39 better fits the statistical data that the harvest index obtained from experimental fields, a constant value of *HI* = 0.39 has been used throughout the further analysis.

The crop consumptive use or actual evapotranspiration (ET_a) has been computed with SEBAL and the resulting map for all pixels – independent of land cover – is demonstrated in Fig. 6.7. The ET_a of well-irrigated crops is 350 to 400 mm per season. These are the groundwater irrigated areas with a high density of tubewells in the Ghaggar corridor. Farmers who depend on surface water resources have a lower ET_a, i.e. in the order of 250 to 350 mm. The bare soils have a very low ET_a, which depends on the depth to the groundwater table. The soil evaporation at the southern fringes of Sirsa Circle and the desert surfaces of Rajasthan exhibit an evaporation of approximately 50 mm, which corresponds to the winter rainfall (a shower of 25 mm was measured on February 12, 2002 in Hisar).

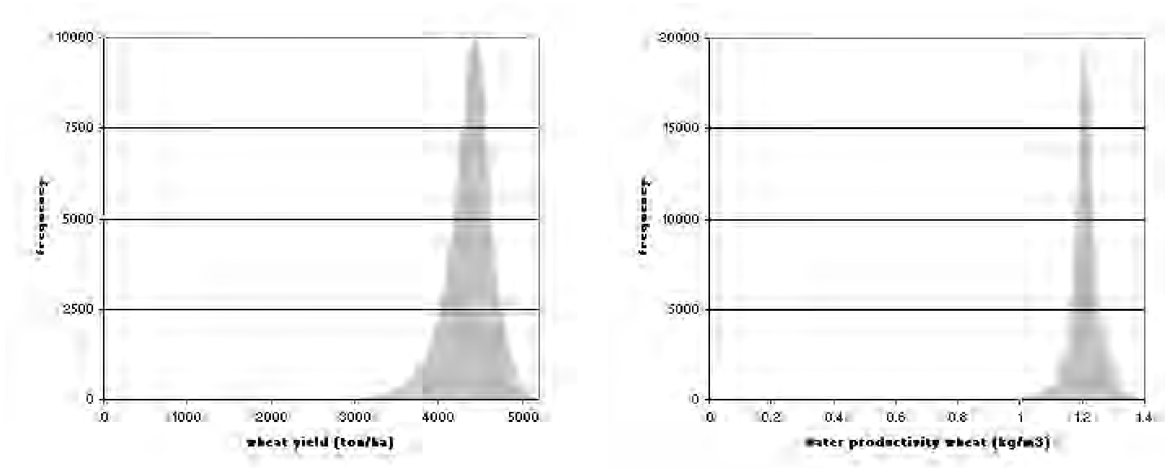
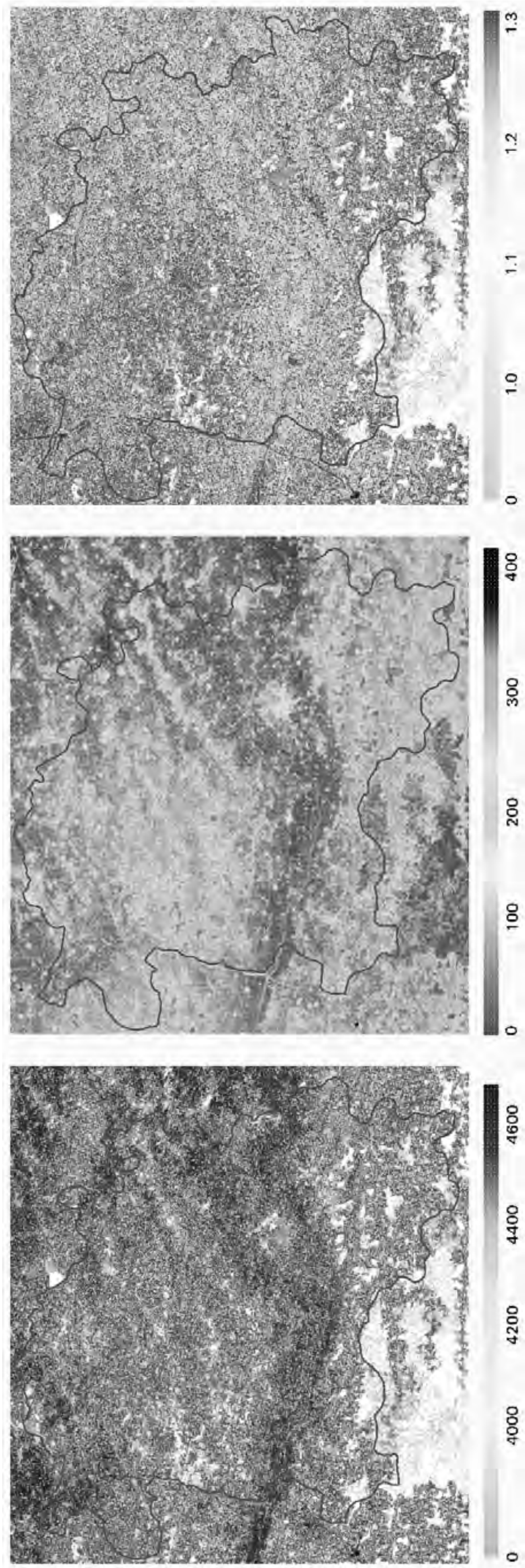


Figure 6.6 Frequency distribution of fresh wheat yield based on an effective harvest index of 0.39 and water productivity per unit depletion.

Measurements of actual evapotranspiration are not very common in South-Asia. One known exception to the authors, is an evapotranspiration study conducted in the Pakistan Punjab (*Ahmed et al*., 2002), who report a total ET_a of 327 mm for the period between December 6, 2000, to April 30, 2001, for a 145 days period. A SEBAL based study on wheat evapotranspiration in Pakistan gave values ranging between 300 to 400 mm per season (*Bastiaanssen et al*., 2002). The simulated wheat evapotranspiration with the SWAP model as part of the previously executed Indo-Dutch project showed ET_a to lay in the range between 286 (1993) to 319 mm (1992) for non-irrigated wheat, and 320 mm (1991) to 359 mm (1992) for irrigated wheat (*Bastiaanssen et al.,* 1996). These values agree well with the data presented in Fig. 6.7.

The water productivity, WP_{ET} (kg/m^3) is calculated as the ratio of crop yield and actual evapotranspiration. The values of WP_{ET} vary between 1.0 to 1.4 kg/m^3 per unit of water consumed (see Fig. 6.6). At the farmer fields the ratio of measured crop yields and simulated



a: yield of wheat (ton/ha)   b: total actual evapotranspiration   c: water productivity WP_{ET}

Figure 6.7 Yield, actual evapotranspiration and water productivity of wheat actual evaporation with SWAP yielded WP_{ET} values in the range of 0.84-1.86 with an average of 1.32 (Table 8.1). *Molden et al.* (2000) compared the water productivity of irrigated wheat systems in Pakistan and India. They found a value of 1.1 kg/m^3 as an average for the Bhakra system. According to Fig. 6.6, the average water productivity for wheat is 1.22 kg/m^3, the mode is 1.21 kg/m^3, and the distribution follows the typical bell shape for a standard normal distribution. The standard deviation is 0.07 kg/m^3. Hence, there is a large group of farmers that have 0.07/1.22*100% is 6% more water productivity than colleague farmers. This implies that there is only limited scope to improve the water productivity of wheat. The class with the highest water productive wheat systems are located outside the Sirsa Circle in the Punjab and in Rajasthan (see Fig. 6.7). The highest productivity found is 1.61 kg/m^3.

6.6 SEBAL results *kharif* season 2002

Rice

Singh et al. (2001) provide transplanting dates for rice: June 26 in 1996, and June 11 in 1997. Field preparation normally starts approximately one week before the transplanting and therefore the start of the *ET* calculations can be set at June 4 and June 19 for these two cases. *Boels et al.* (1996) report on starting dates for rice in Haryana of approximately June 15. *Singh and Sharma* (1993) give a total length of the growing season between 110-130 days for rice. The growing period for rice is set to June 15 to October 15 (120 days), which agrees with the seasonal dry matter production series demonstrated in Fig. 6.8, part A. June and July shows a value of 500 kg/ha/month which is low and probably caused by non-rice crops being present in rice dominant NOAA pixels. Rapid growth of rice is visible in August and September. Senescence commences in October with a lower production than in the preceding month.

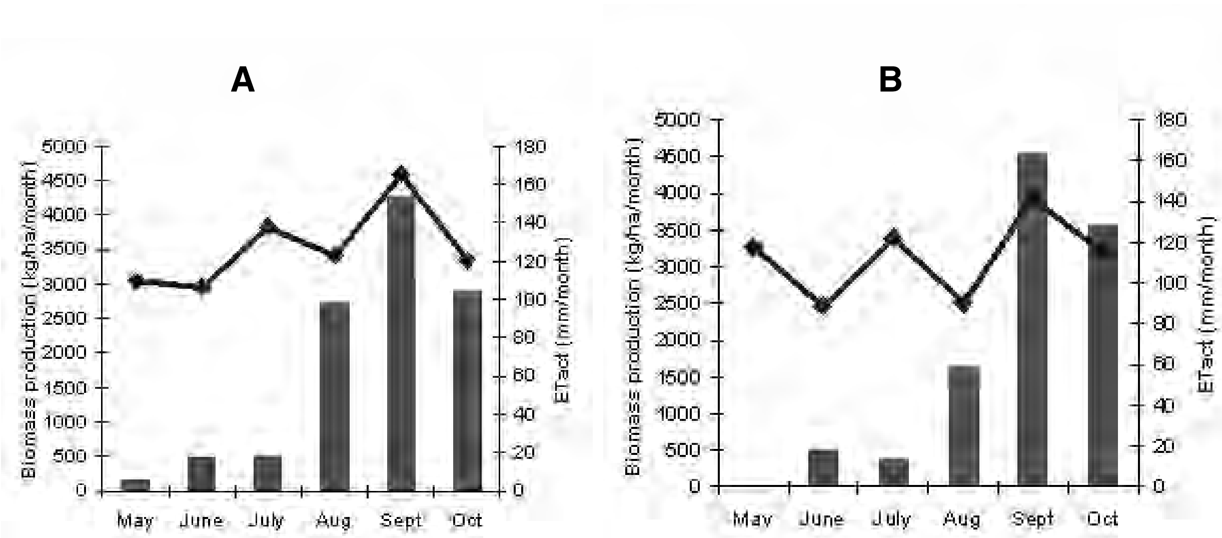


Figure 6.8 Average monthly dry matter production and ET_{act} for five pixels dominated by rice (part A) and cotton (part B).

Bastiaanssen and Ali (2003) used for Pakistan *HI* = 0.28, which is associated to a moisture content of 10%. This low value is caused by the cultivation of traditional aromatic *basmatic* rice varieties in Pakistan. India, however, has introduced at a large scale high yielding rice varieties during and after the green revolution. In comparison to Pakistan, *HI* in India is therefore likely to be substantially higher.

Doorenbos and Kassam (1979) mention a harvest index for rice in the range 0.40-0.50. Field measurements of the harvest index (*N*=19) showed values based on dry matter in a range of 0.41 to 0.48. The average harvest index was 0.46, which will yield at a grain moisture content of 16% *HI* = 0.53. It should be mentioned that the same experimental fields showed a production of 7 to 8 ton/ha and more, which flags the results because this is feasible only for the most superiour fields (one field yielded 8.9 ton/ha which is about double the average yield in the region). It is therefore probable, that *HI* from the experimental fields is systematically overestimated. The field data on harvest index showed the following relationship:

$$HI_{\text{dry}} = 0.378 + 0.01\,TDM \qquad (6.1)$$

where *TDM* (ton ha^{-1}) is the total dry matter production of the season. Since the relationship between HI_{dry} and *TDM* is not statistically significant ($R^2 = 0.23$) and measured *HI* values are very high, *HI* = 0.45 is used in the results for rice presented hereafter. This is equivalent to $HI_{\text{dry}} = 0.39$ at 16% moisture.

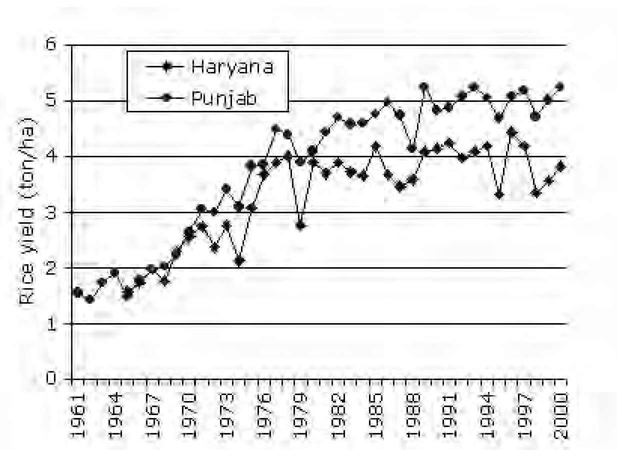


Figure 6.9 Fourty years of rice yield progression in Haryana and Punjab (source Agriculture Centre for Monitoring Indian Economy & India Directorate of Economics and Statistics).

Rice yields in Sirsa Circle exhibit a large range between less than 1000 to 5488 kg/ha. The mode is 4490 kg/ha and the average is 3733 kg/ha. The standard deviation is 1060 kg/ha. The World Rice Statistics, which is published periodically by IRRI, presents comprehensive time series information related to rice yield. For Harayana, an average yield of 3580 kg/ha for 1999 and a value of 3830 kg/ha for 2000 is given. The India Directorate of Economics and Statistics and the Agriculture Centre for Monitoring Indian Economy have published rice yield data for Harayana and Punjab for the last 40 years. Fig. 6.9 shows that the average rice yield over the last 5 years in Haryana is approximately 3800 kg/ha. These values are in a good agreement with our estimation of 3733 kg/ha and the IRRI value of 3830 kg/ha (2% deviation).

According to Fig. 6.10, the top rice yield region is located in the Ghaggar plain, some 20 km West of Sirsa town. If the peak harvest index of 0.48 would have been used for these top-level producing fields at a moisture content of 16%, the fresh yield would have been 6790 kg/ha which is near to the field measurements. This demonstrates that the inclusion of a variable harvest index is advisable for future remote sensing studies and that it enhances the spatial variability of yield.

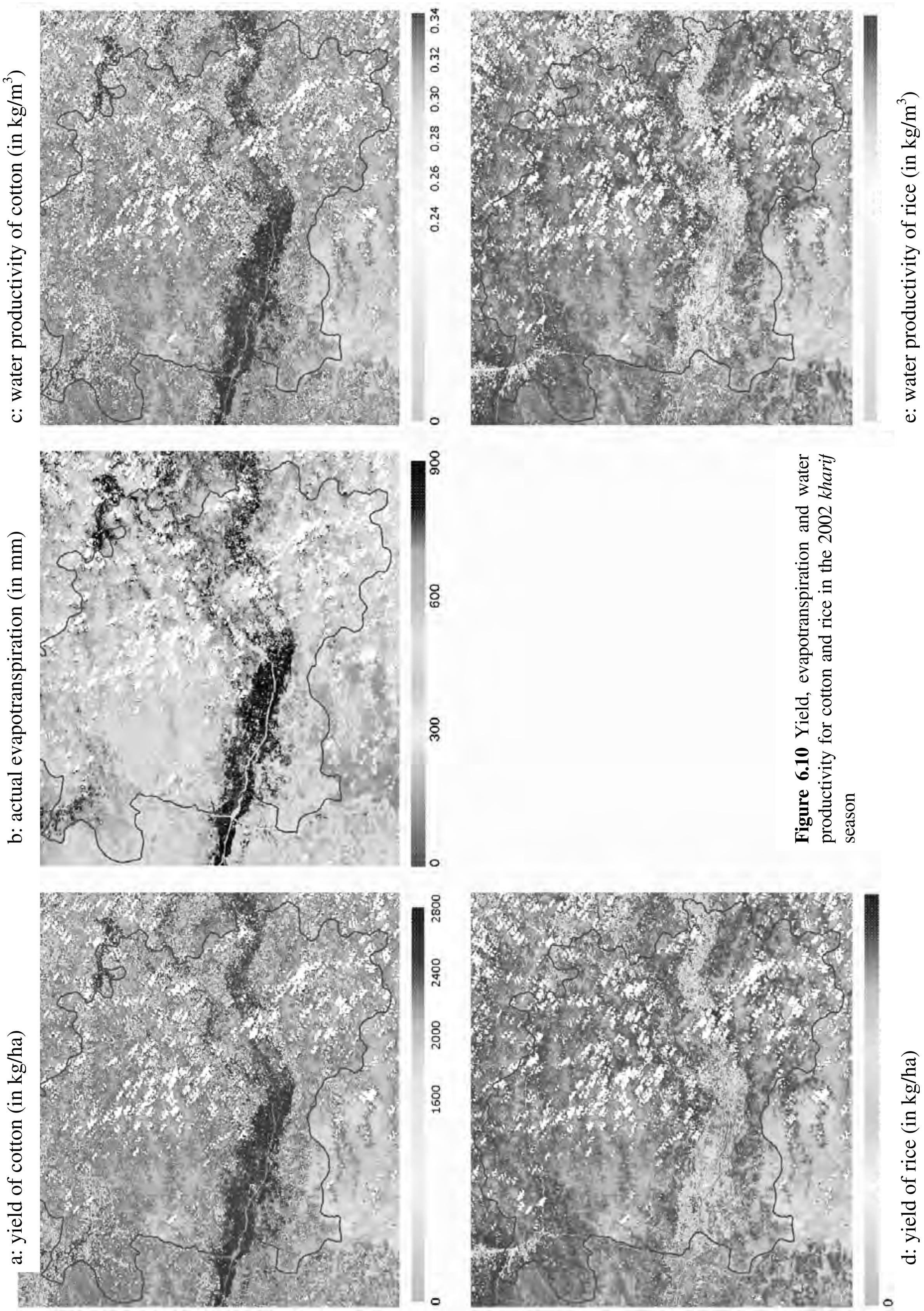


Figure 6.10 Yield, evapotranspiration and water productivity for cotton and rice in the 2002 *kharif* season

The evapotranspiration is with 130 to 140 mm/month rather stable throughout the entire growing season of rice (see Fig. 6.8, part A). In the beginning of the season, the evapotranspiration emerges mainly from the standing water layer in the paddy basins. During the course of the crop's lifetime, canopies take over the evapotranspiration. The total consumptive use for the rice season between June 15 and October 15 is 500 to 600 mm, and this is in good agreement with the data measured by *Ahmad et al.* (2002) who measured a value of 543 mm with the Bowen-ratio surface energy balance method between July 1 and October 31 (120 days) for a paddy field in Pakistani Punjab.

Average calculated WP_{ET} by RS for rice is 0.72 kg/m^3. The maximum value is 0.98 kg/m^3 and the mode is 0.84 kg/m^3. The standard deviation is 0.19 kg/m^3, so that the coefficient of variation becomes 26%, which is significantly larger than the *CV* found for wheat. Using field data from Northwestern India, *Tuong and Bouman* (2003) summarized the water productivity of rice in India to vary between 0.4 to 1.1 kg/m^3, revealing a significant scatter in the farmer practices and management of the irrigation system. *Doorenbos and Kassam* (1979) reported a reasonable water productivity of rice as being 0.7 to 1.1 kg/m^3. This comparison with other data sources suggest that the values obtained are reasonable and that the crop water productivity for rice in Sirsa Circle is a kind of average value for the climate and growing conditions in the Northwest India.

Cotton

Cotton is sown in areas that are more prone to salinity because cotton is more salt tolerant than rice. Part B of Fig. 6.8 shows the average dry matter production per month for five pixels dominated by cotton. There is hardly any growth in May, little production in June and July, and a higher production in August until October. *Boels et al*. (1996) give a growing period starting May 1 until the end of October. *Bastiaanssen et al.* (1996) describes a growing period starting on May 15 until November 15. *Singh and Sharma* (1993) mention a total length of the growing season of approximately 180 days. Based on these data a growing period starting on May 1 and lasting until the end of October has been applied for cotton. Field measurements reveal that the cotton was harvested in the period elapsing from November 20 to December 20, and that for 2001 a growing period of 200 days was common.

Cotton yield is usually expressed into cotton seed and lint, and this is not similar. The average total dry matter production from the 24 fields was 12259 kg/ha, the cotton seed yield was 2189 kg/ha and the lint yield was 822 kg/ha. Hence, lint yield is about a third of the cotton seed, which is common. The experimental data on the harvest index based on dry weights for cotton seed appear to lay in the range between 0.11 and 0.33, with an average value of 0.20. An average HI = 0.21 has been used in the final analysis (cotton seed moisture content 5%), and this value has by absence of other data been calibrated from the SEBAL-based average dry matter production of 10310 kg/ha. A summary of the harvest indices used in this remote sensing study is presented in Table 6.7.

Table 6.7 Harvest indices measured at farmer fields and used in the regional scale remote sensing analysis.

	Wheat	Rice	Cotton
HI_{dry} field measurements	0.42	0.46	0.20
Product moisture content (%)	10	16	5
HI field measurements	0.46	0.53	0.21
HI remote sensing	0.39	0.45	0.21

The prolonged drought during the summer of 2002 has adversely affected the emergence of cotton, but there were not much instances of diseases. Likewise for rice, the cotton dry matter production is the highest during August and September. The mean seed cotton yield is 2189 kg/ha and the maximum value that could be detected is 3223 kg/ha. The mode is with 2410 kg/ha higher than the mean value, which draws the attention to the skewed frequency distribution. The standard deviation is 348 kg/ha.

The evapotranspiration presented in Fig. 6.8 has been accumulated for 180 days. The total water consumption is approximately 700 mm. *Ahmed et al. (*2002) measured for a cotton crop between May 25 and December 5 (191 days) a total consumptive use of 648 mm. The average WP_{ET} derived by RS for cotton is 0.31 kg/m^3 and the maximum value found is 0.42 kg/m^3. The mode of WP_{ET} of cotton is 0.34 kg/m^3 and the standard deviation is 0.04 kg/m^3. The *CV* of WP_{ET} of cotton is with 13% moderate. At the farmer fields (4 sites, 16 fields) the ratio of measured crop yields and simulated actual evaporation with SWAP yielded WP_{ET} values in the range of 0.08-0.70 with an average of 0.31 kg/m3 (Table 8.1). These WP_{ET} levels are comparable to what has been measured elsewhere. An extensive study towards crop water productivity of cotton in Pakistan by the end of the seventies concluded that the average water productivity for cotton was 0.27 kg/m^3 with a maximum value of 0.57 kg/m^3 (PARC, 1982). *Doorenbos and Kasam* (1979) provide a target value of 0.4 to 0.6 kg/m^3.

Table 6.8 summarizes the results of the 3 crops investigated and compares the results with the earlier Indo-Dutch project and against the global mean values. It is concluded that the water productivity of wheat is near to the global mean value, and that rice and cotton are lagging behind. It was concluded earlier that rice exhibits a significant spatial variability in water productivity, so it would be strategic to focus on equalizing and increasing the water productivity of rice. For cotton, it should be mentioned that, apart from the delayed and small monsoon, the lower water productivity values can be ascribed to soil salinity, and that reclamation plans should be endorsed.

Table 6.8 WP_{ET} statistics for wheat, rice and cotton from remote sensing and other water productivity studies.

Study	Wheat (kg/m^3)	Rice (kg/m^3)	Cotton (kg/m^3)
Current study - mean	1.22	0.72	0.31
Current study – mode	1.21	0.84	0.34
Current study – standard deviation	0.07	0.19	0.04
Other studies – same area	1.10	0.5 – 1.1	0.14 - 0.57
Doorenbos and Kassam	0.8 - 1.0	0.7 – 1.1	0.4 - 0.6
Indo-Dutch project 1986 – 1996	1.51	-	0.46
Global mean (Zwart and Bastiaanssen, 2003)	1.08	1.09	0.63

7. A regional approach to model water productivity

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Summary

This chapter describes a step wise regional approach towards modelling of water productivity. First step is data collection and an analysis of available data. Next step integrates the available data sets into a geographical information system and derives distributed calculation units. This requires a stratification of geographically oriented data sets, which in this study were: soil properties, village boundaries and land use. Data were downscaled to a level of 30 x 30 meter to allow comparison with remote sensing data. Parameter values were assigned to the stratified units, resulting in a set of calculation units that were analysed using the SWAP model for evapotranspiration and the WOFOST model for yields. A comparison between results from SWAP model and remote sensing images was carried out showing fair results that allowed scenario analyses. Finally the developed regional model was used to calculate spatial distributed water productivity values.

7.1 Introduction

In the previous chapters two different approaches were applied to look at water productivity in Sirsa district: field scale modelling and regional scale remote sensing. The strength of modelling is that it can be used to get a better understanding of systems and processes, while remote sensing can give a swift regional and spatial distributed overview of water productivity. However, a drawback of the modelling as presented is that it is limited to isolated fields, and a drawback of the remote sensing is that there are no predicting capacities to perform scenario analysis. In this chapter we will provide a methodology where the strength of the two approaches will be combined: a framework for crop, soil and water modelling for regional water productivity analysis.

It might be clear that the development of such an approach is based on the modelling efforts presented in the previous chapters where the calibration and validation of the SWAP-WOFOST model played a dominant role. The remote sensing, as presented in Chapter 6, provided two outputs that are used here: (i) the landcover classification and (ii) the evapotranspiration and yield estimates. The latter one will be used here as a calibration reference set, while the first one is directly input to the regional modelling framework.

In addition to the results of the modelling and the remote sensing analysis, regional analyses of water productivity require extensive additional data sets. Due to a lot of Indian field research and several (inter)national projects the availability of data for the Sirsa region is relatively favourable. Data were stored in appropriate formats which enabled regional analyses using Geographical Information Systems (GIS) and databases.

This chapter gives an overview of available regional datasets and explains the method applied to come to a regional water productivity assessment. Results are presented for the seasons *rabi* and *kharif* of 2001-02, the period during which field monitoring was carried out.

7.2 Available regional datasets

7.2.1 Soils

The soil map of Sirsa (*Ahuja et al*, 2001) was digitized into 10 soil series (Fig. 7.1). For each soil profile a vertical schematization in soil horizons was based on *Ahuja et al.,* (2001). All soil types were reduced to two-layer soil types with top and subsoils based on the proportion of sand, silt and clay. Next this information was used in so-called pedotransfer functions to obtain the soil hydraulic characteristics as described in Chapter 4.

For each soil series, measurements were available of soil salinity. Soil salinity was measured as electric conductivity in a soil-water mixture and transformed into salinity in the liquid phase using Eqs. 3.1-3.3.

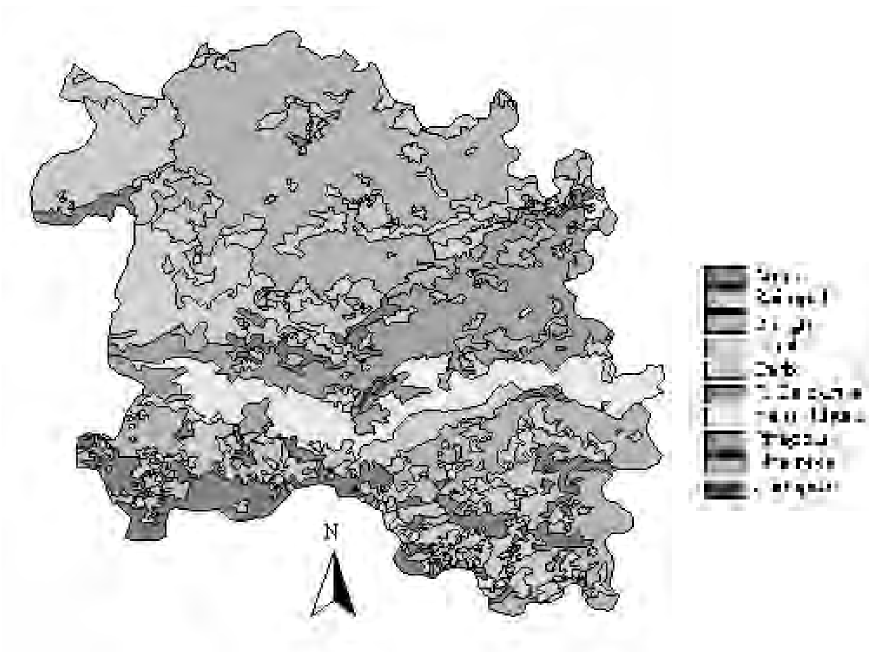

Figure 7.1 Soil map of Sirsa with 10 soil series.

7.2.2 Land use

Climatic conditions allow two crops a year, divided in two crop growing seasons; the summer growing season, called *kharif*, from May up to November and the winter growing season from November up to April, called *rabi*. The main crop during *rabi* season is wheat and during the *kharif* season rice and cotton. Other important crops are raya (oilseeds), gram (chickpea), sugarcane, fodder, guar (clusterbean) and sorghum. At present, cotton-wheat is the most dominant crop rotation in the area.

At village level information is registered with regards to agriculture management. Available data related to land use are: cultivated area, irrigated area and amount of tube wells to extract groundwater for irrigation. Because of its importance the village map was digitised.

Cropped areas were derived from remote sensing images. The combination of NOAA (high temporal resolution) with Landsat ETM (high spatial resolution) resulted in two maps for the land use in 2002. For *rabi* season the Landsat-image of March 18, 2002, and for *kharif* season the Landsat-image of September 10, 2002, was used (Chapter 6).

7.2.3 Climate

The climate of Sirsa district is characterized by its dryness and extremes of temperature and scanty rainfall. The average annual rainfall over the period 1990-2002 is 367 mm. The region can be classified as sub-tropical, semi-arid, continental and is characterised by the occurrence of the Indian monsoon. The period from June to September constitutes the south-west monsoon. However rainfall is highly erratic both in quantity and in distribution.

An extensive data set with daily values measured over the period 1990 – 2002 was available from the meteorological station of Sirsa. These data include minimum and maximum temperature, relative humidity, vapour pressure in the morning and evening, sunshine hours, wind speed and rainfall (Chapter 3). The coordinates of the meteorological station of Sirsa are 29°33'39"N and 75°00'52"E.

For the period 1990-2000 rainfall measurements were available from five additional rainfall stations spread over the area, namely Ottu, Abu Shahar, Khuyan Malkanhana, Panjuana and Kalanwali. The precipitation data of the six stations were assigned to meteo-regions. For the regional analyses rainfall data were assigned to 6 meteo-regions (Fig. 7.2). For the special observation period *rabi – kharif* 2001-02, only data of Sirsa were available.

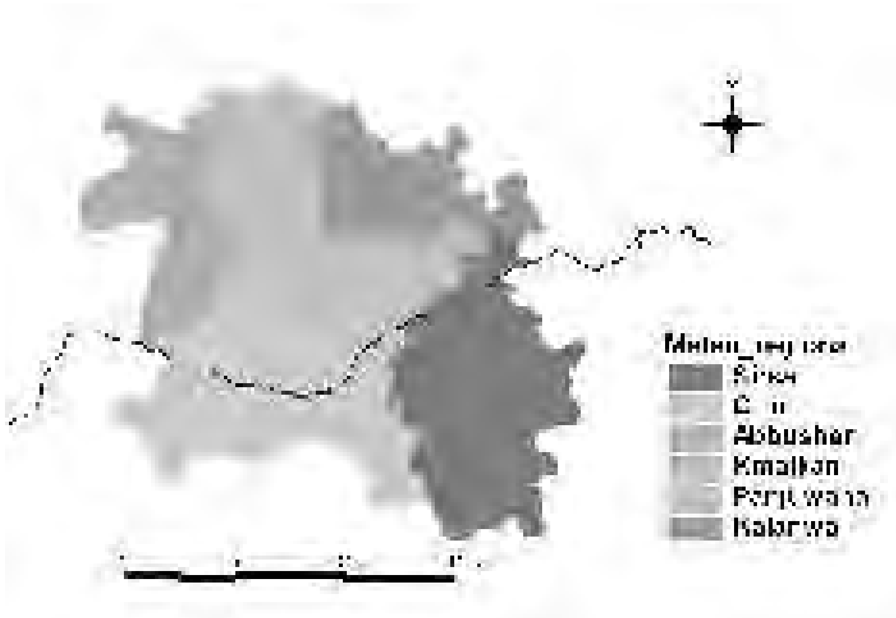

Figure 7.2 Meteo-regions based on the six rainfall stations.

7.2.4 Irrigation: groundwater

Groundwater depth

During the period 1990 – 2000 the groundwater depth was measured twice a year, in June and October, before and after the monsoon. The groundwater depth of June 2000 is given in Fig. 7.3.

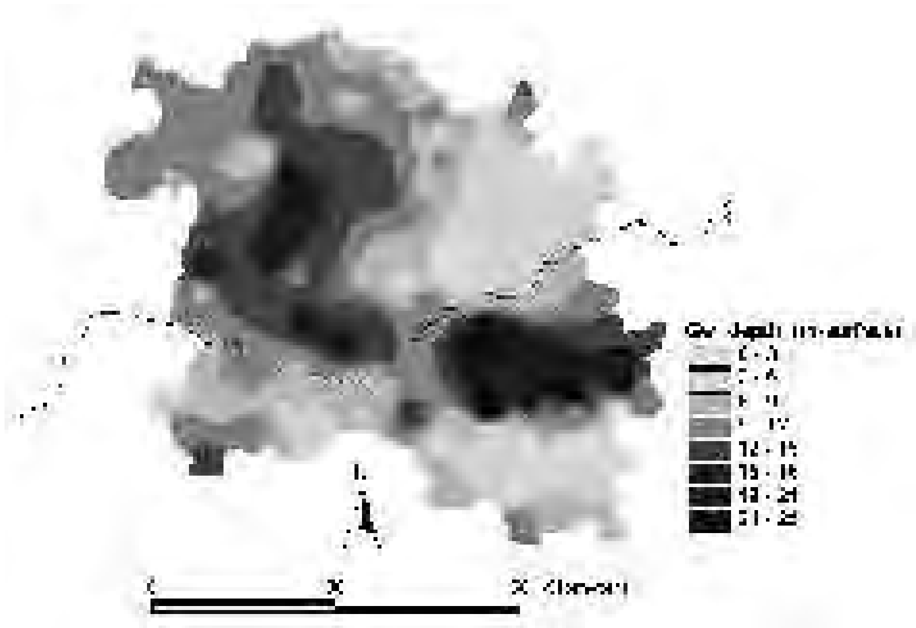

Figure 7.3 Groundwater depth of Sirsa district in June 2000 in meters below surface.

Groundwater trend

Groundwater depth fluctuates over time and space. The spatial trend of groundwater depth over the period 1990 –2000 is shown in Fig. 7.4. The groundwater trend map is based on the difference between the average groundwater depth of 1990 and 2000. The average increase of the groundwater level for entire Sirsa district amounted 9 cm y^{-1} in the period 1990-2000.

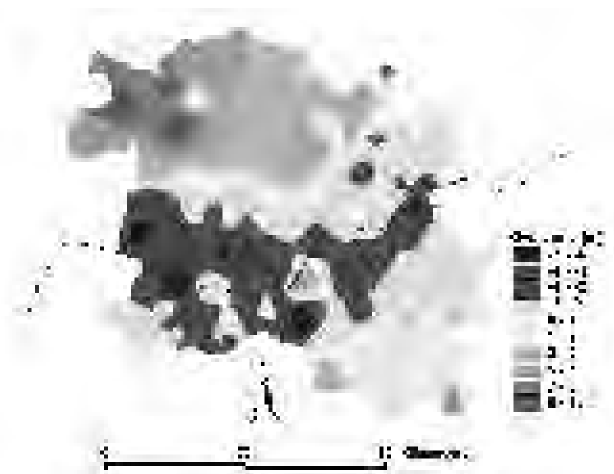

Figure 7.4 Groundwater trend (m / 10 year) of Sirsa district, calculated over the period 1990 to 2000 in meters (negative value is declining groundwater level in period 1990-2000).

Groundwater quality

For several tubewells the quality of groundwater was measured three times a year in June, October and January over the period 1982 –1995. A significant trend could not be derived from these data and therefore the groundwater quality map was based on most current values of 1995 (Fig. 7.5). Somewhat unexpectedly, the spatial distribution in this map does not correspond to the general impression that water logged areas are saline. This is partly due to the presentation form which shows interpolated values of only one year (1995) where a few extreme values may generate an unbalanced picture. A more thorough analysis of salinity levels in groundwater might be desirable but is beyond the scope of this study.

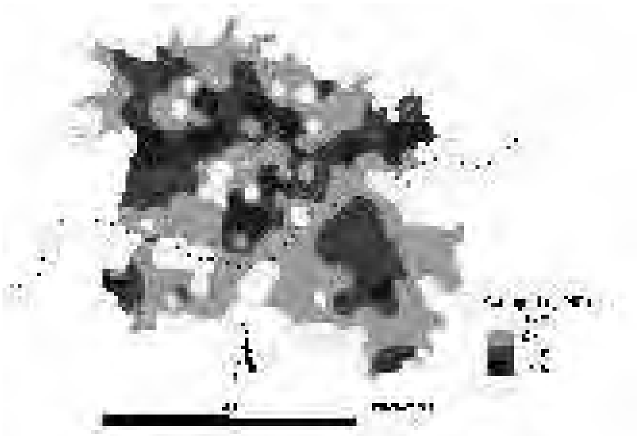

Figure 7.5 Groundwater quality of Sirsa district in dS m^{-1}, based on figures of June 1995.

The model SWAP simulates groundwater quality as a concentration of solutes, which is expressed in mg cm^{-3}. Conversion between the different units is carried out using the relation 1 dS m^{-1} = 0.653 mg $cm^{-3.}$ Applying this relation, the values for quality of groundwater vary from 0.8 to 10.1 mg cm^{-3}. The information on groundwater depth, trend and quality maps originate from measurements of 164 observation wells spread over the Sirsa district. Interpolation between known observations was carried out to estimate values for unknown locations.

Groundwater tube wells

All farmers use tube wells and sometimes mix it with canal water to increase the irrigated area. In Sirsa district three types of tube wells can be distinguished:

- The shallow tube well, installed by local indigenous farmers. The pump capacity values vary considerably (Fig. 7.6) and were derived from Ground Water Cell (2002). Eight hours a day was assumed for working hours.
- Direct Irrigation Tubewells (DIT), installed by Haryana State Minor Irrigation and Tubewell Corporation (HSMITC). The total discharge a year for one tube well is $15 \cdot 10^6$ m^3 y^{-1}.
- Augmentation tube well, installed by HSMITC with an annual discharge of $71.5 \cdot 10^6$ m^3 y^{-1}.

For each type of tube well the number is known per village boundary. The annual discharges of the tube wells were transformed to daily discharges.

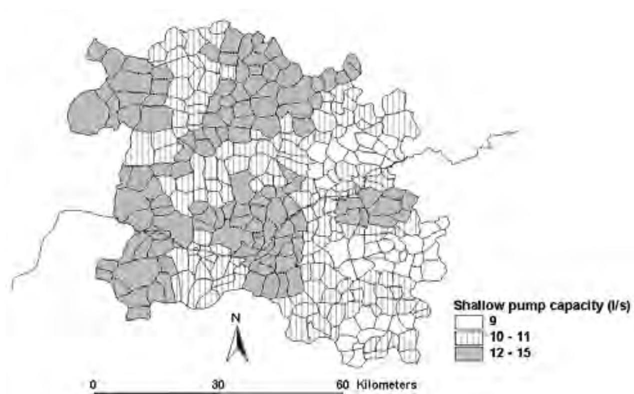

Figure 7.6 Variation in Sirsa district of pump capacity of shallow tube well in litre per second.

7.2.5 Irrigation: canal water

Sirsa district consists of four divisions (Fig. 7.7), where inflow and outflow of the main-distributaries are measured twice a day. Each division has three subdivisions. It was not possible to analyse the water availability on the more detailed level of subdivision, because most of the discharges of the minor canals were measured in gauge readings.

Figure 7.7 Four Water Service Divisions within Sirsa district: Rori, Sirsa, Ghaggar and Nehrana.

The quality of canal water is mostly good and constant throughout the year. In this case the quality of canal water was estimated at 0.3 dS m^{-1} or 0.2 mg cm^{-3}. Leakage losses from the main canals were estimated based on soil type according to *Roest* (1996). In his report average values of entire Sirsa district were derived by model calculations for on-farm water losses and canal seepage losses. On farm losses were in this report defined as losses caused by seepage losses from the field irrigation channels, percolation and leaching losses during field irrigation and leaching losses due to rainfall events. Based on their findings and taking into account the soil texture distribution, for each division a percentage of leakage losses was estimated (Table 7.1).

The Cultivable Command Area (*CCA*) is the area around an outlet on which the amount of canal water supply is based. The *CCA* is known per village boundary and varies throughout the years. However big differences did not occur in *CCA* during years and therefore the *CCA* values of 2001 were used for the whole calculation period.

Table 7.1 Estimation of leakage losses of main canals per water service division

Name of division	Main subsoil texture	Estimated percentage leakage losses of main canals
Rori	Loamy sand	30
Sirsa	Silt loam	20
Ghaggar	Silty Clay Loam	15
Nehrana	Sandy loam	25

7.3 Methodology

An essential part of the regional analysis was the schematization of Sirsa district into more or less homogeneous areas. These are required to allow detailed analyses of a limited amount of unique soil-water-crop systems (calculation units). To obtain these homogeneous areas a process is followed referred to as stratification. The procedure of stratification is important, because it has a large influence on amount and size of the calculation units.

The soil map and the village map were digitized and the land use map was derived from remote sensing analysis as described in Chapter 6. The land use map derived from Landsat images was considered as the basis for the soil and village maps. The pixel-size of satellite-images is 30x30 m. The soil and village maps were converted into maps with the same cell size and extent. In this way overlays of the three maps could be made without increasing the number of unique plots too much. Once the stratification procedure was finished, parameter values were assigned to the calculation units.

The SWAP-WOFOST was employed to simulate the soil-water-crop system. The regional groundwater flow has not been simulated. This was justified by the fact that the main objectives of the WATPRO study were related to crop-soil-water interactions. However, detailed groundwater modelling activities have been presented earlier (*Boonstra et al.,* 1996).

7.3.1 Stratification

Land use map

This map is a combination of land use in *rabi* season and *kharif* season. Both maps are derived from satellite-images. The *rabi*-image represents land use at 18 March 2002 and the *kharif*-image at 10 September 2002 (Chapter 6). In the original images 9 and 6 classes are distinguished, respectively for *kharif* and *rabi*-image. Reclassification was required because the local crop data were limited to the main crop rotations wheat/rice and wheat/cotton. Therefore the *kharif*-image is brought back to 3 and *rabi*-image to 2 classes (Table 7.2 and Fig. 7.8).

Table 7.2 Reclassification of land use values of remote sensing images for both *rabi* and *kharif* (old = before reclassification and new = after reclassification)

Land use *kharif* old	Land use *kharif* new	Land use *rabi* old	Land use *rabi* new
Cloud	Bare soil/rice / cotton	Bare soil	Bare soil
Cotton	Cotton	Early wheat	Wheat
Desert	Bare soil	Late Wheat	Wheat
Other crops	Rice or cotton	Oil seed	Wheat
Rice	Rice	Other crops	Wheat
Shadow/water	Bare soil/rice / cotton	Unclassified	Bare soil
Sugarcane	Rice		
Unclassified	Bare soil/rice / cotton		
Urban	Bare soil		

This implies that what is presented in this regional analyses as wheat, cotton and rice is in fact a mixture of crops (see Table 7.2) and will show deviations from reality. However, this

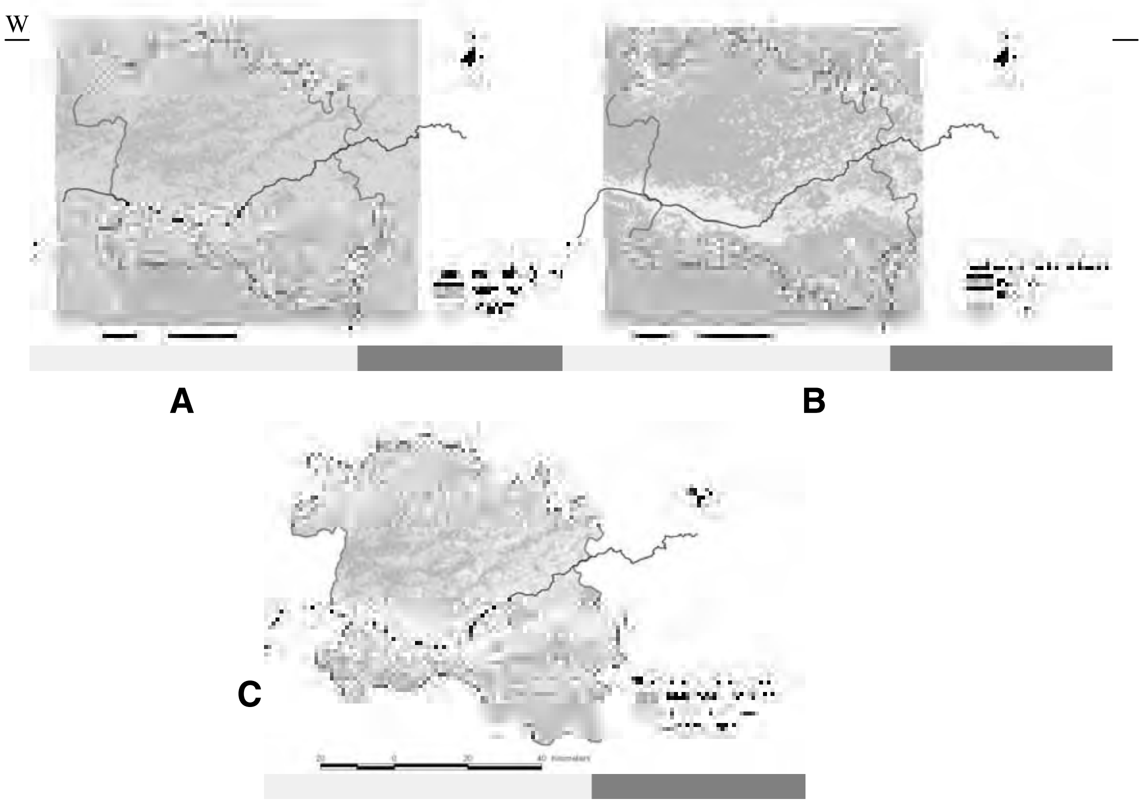

Figure 7.8 Reclassified land use for *rabi* (A) and *kharif* (B) and the resulting land use for the regional analyses (C).

simplification was assumed to be acceptable, because the remaining land uses wheat/rice and wheat/cotton are the dominating crop rotations in the area.

Soil map

The soil map, used for stratification, was derived by reclassifying the original one in which 10 soil types were distinguished, into a soil map with 6 soil types. All soil types were reduced into a two-layer soil type with a top and subsoil. Soil series with the same classification of both topsoil and subsoil, were merged (Table 7.3). The classification was based on the proportion of sand, silt and clay.

Table 7.3 Classification of soil series.

Series number	Series name	New soil type after merging	Topsoil	Subsoil
1	Nimla	1	Sand	Loamy sand
2	Saimpal	2	Sand	Sand
3	Ganga	1	Sand	Loamy sand
4	Lambi	3	Loamy sand	Sandy Loam
5	Darbi	4	Loam	Silt Loam
6	Fatehpur Baidwala	5	Silt Loam	Silt Loam
7	Harni Khurd	6	Loam	Silty Clay Loam
8	Phaggu	3	Loamy sand	Sandy Loam
9	Khaireke	5	Sandy loam	Sandy loam
10	Jhunpra	5	Loamy sand	Sandy clay loam

Village boundaries

Since many spatially allocated data were available at village level, it was decided to use a map with village boundaries as one of the maps for the stratification procedure. The total number of villages is 323. At village level information is available, such as *CCA*, potential pump-discharge, pump-density and net-irrigated area. By using the interpolated grid maps for groundwater depth and quality, these gridded data were also available at village level.

Final stratification
An overlay of the 3 maps resulted in 2404 calculation units (Fig. 7.9). Bare soil and wheat-rice each occupy 26 % of the total area (Table 7.4) and wheat-cotton covers 48% of the area. However one should keep in mind that, due to the stratification process the different forms of land use were limited and wheat accounts for several other kinds of land use. Results presented here might therefore be different from results presented in Chapter 6.

Table 7.4 Size (in % of total area of 3878 km^2) of the land use and surface water division.

	Land use (*rabi – kharif*)			
Division	Wheat-cotton	Wheat-rice	Bare soil	Total
Ghaggar	5	10	2	16
Nehrana	12	6	9	27
Rori	17	4	8	30
Sirsa	14	7	6	27
Total	48	26	26	100

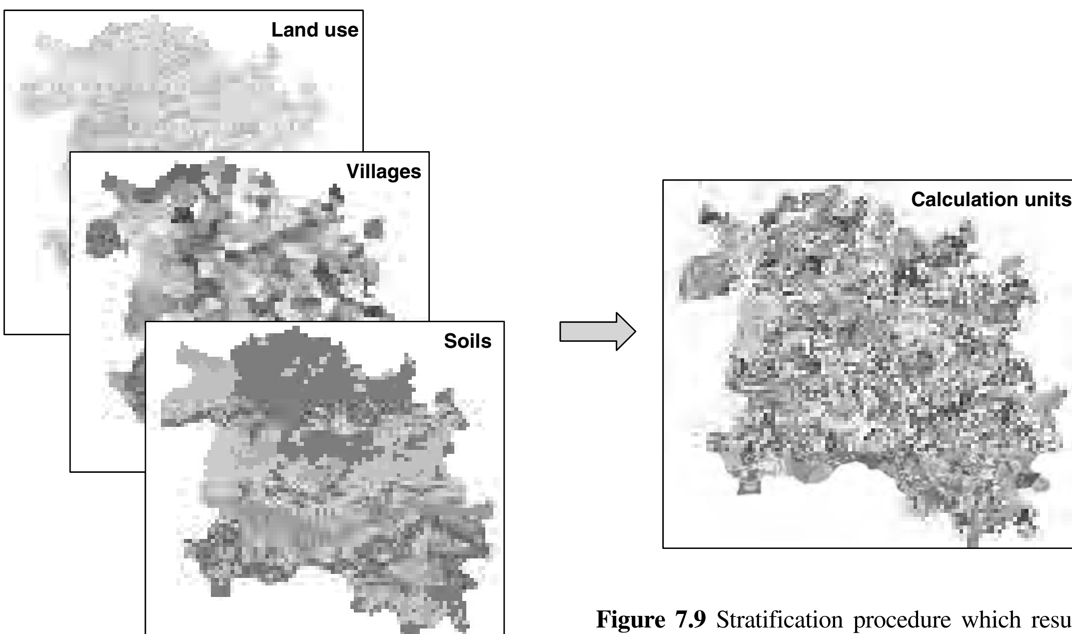

Figure 7.9 Stratification procedure which results in geographically fixed calculation units.

7.3.2 Parameterisation

Once the calculation units were fixed, parameter values had to be assigned.

Climate/Weather
Daily weather data were used. Within the Sirsa district the meteorological station of Sirsa is the only station with extensive weather data; these were applied to calculate evapotranspiration for the whole area. Precipitation data from the 6 stations were assigned to

calculation units within corresponding meteo-regions. The SWAP model requires the following weather data as input: shortwave radiation, minimum and maximum temperature, humidity expressed as vapour pressure, wind speed and precipitation.

The data obtained from the meteorological station Sirsa showed some missing values. These missing values were filled up using a statistical comparison with data from the meteorological station of Hisar. Especially sunshine hours and wind speed were adapted from Hisar. For the years 2001 and 2002, the data of the Sirsa station were applied to the whole region.

Table 7.5 Annual supply of canal water per division where *L* is leakage losses from the main canals.

Division	Water sup. (m^3 y^{-1})	*L* (-)	Water sup. (m^3 y^{-1})	*CCA*/ div. (ha)	Annual depth (mm)	Annual depth (incl. losses) (mm)
Rori	725,141,913	0.30	507,599,399	107,580	674	472
Sirsa	288,377,669	0.20	230,702,136	103,893	278	222
Ghaggar	173,031,455	0.15	147,076,736	54,589	317	269
Nehrana	297,450,662	0.25	223,087,997	118,759	250	188
Total based on divisions	1,484,001,699		1,150,101,317	384,821	386	299
Total based on in- and outflow of Sirsa district	1,208,555,398	0.225	936,630,433	384,821	314	243
According to Indo-Dutch project	2,000,000,000			555,500	360	

Irrigation - canal water

The supply of irrigation water plays an important role in water productivity. According to the *warabandi* system irrigation water is supplied homogeneously. To analyse this principle of equal water availability in the district, the divisions were taken into account. Per village the amount of *CCA* falling in one of the divisions is registered. A village might have *CCA* in different divisions. In that case the smallest part of *CCA* was assigned to the largest, so a village had only *CCA* in one particular division. With GIS it was possible to derive the map of the divisions. The borders of the divisions were fitted with the village boundaries. For each division the entry and exit points of the distributaries were determined. The difference between the discharge per day of all outgoing distributaries and the discharges per day of all entering distributaries within a division was regarded as storage per day.

Leakage losses from the main canals were estimated, as not all water stored in the area was used for irrigation water, but instead percolated to deeper soil layers (Table 7.1). In this study it was assumed that the rest of canal water was used for irrigation. To transform the discharge into irrigation depth, the total amount of *CCA* within a division was calculated. The calculation of the annual irrigation depth per division with canal water mentioned in Table 7.5 is expressed as:

$$D_{\text{cw}} = \frac{(1-L)\sum_{n=1}^{365}(Q_{\text{inflow},\,n} - Q_{\text{outflow},\,n})}{10\sum^{Div.} CCA_{\text{vill}}} \qquad (7.1)$$

where D_{cw} is irrigation amount of canal water per year per division (mm y^{-1}), Q_{inflow} is discharge of incoming distributaries (m^3 d^{-1}), $Q_{outflow}$ is discharge of outgoing distributaries (m^3 d^{-1}), L is fraction leakage losses of canal system (-), n is day number, and CCA_{vill} is Cultivable Command Area of a village (ha), which is summed over the division. For the *CCA* as well for the discharges of the main canals data of 2001 were used. The annual depth of canal water per division varies from 472 mm in the north to 188 mm in the south of Sirsa district. According to the Indo – Dutch project the size and water supply is larger than the values calculated with division information, because it was based on the Sirsa district, which is slightly larger than Sirsa District. Besides, the water supply in this project was based on figures of 1996, which was a wet year. The reason that the annual depth in the most northern division is still higher than the other divisions, despite the higher percentage leakage losses, is probably due to the fact that this region is compensated for the lower quality of groundwater.

A fixed irrigation schedule was used. This means that a fixed date and fixed depth is described. For each division the amount of canal water (m^3 d^{-1}) was calculated, including some leakage losses as explained above. Next these values were transformed into an irrigation depth by dividing over the area of *CCA* per division.

Groundwater
The total maximum groundwater discharge per day per block was calculated based on the density of the various tube wells (deep and shallow). Villages without data received a ground water discharge based on shallow and deep tube wells.

The final irrigation supply per calculation unit is the sum of groundwater supply from the nearest village and canal water supply from the division. For each crop-rotation irrigation days were determined based on field observations. On irrigation days water was supplied per calculation unit in the following way:

$$D_I = \frac{Q_{canal}\,CCA}{A_{crop}} + \frac{Q_{gw}}{10A_{crop}} \qquad (7.2)$$

where D_I is total irrigation depth (mm d^{-1}), Q_{canal} is canal water discharge (mm d^{-1}), *CCA* is Cultivable Command Area (ha), A_{crop} is cropped area derived from remote sensing images (ha) and Q_{gw} is maximum groundwater discharge (m^3 d^{-1}).

One week before and one week after the irrigation date, the calculated daily irrigation depth is assigned to that particular date. As a result of a mismatch between remote sensing data (A_{crop}) and statistical data obtained from local governments (maximum groundwater discharge derived from tube wells) an upper limit of D_I had to be defined. When a small area has a relative high maximum groundwater discharge, unrealistically high values of total irrigation depth per day could be assigned. Therefore a maximum irrigation depth of 80 mm d^{-1} has been used.

Next to the quantity of irrigation water, the quality of irrigation water was taken into account as a weighted average based on depth and quality:

$$C_I = \frac{C_{gw}D_{gw} + C_{cw}D_{cw}}{D_I} \qquad (7.3)$$

where C_I is quality of irrigation water (mg cm^{-3}), C_{gw} is quality of groundwater (mg cm^{-3}), D_{gw} is depth of groundwater supply (mm), Q_{cw} is quality of canal water (mg cm^{-3}), and D_{cw} is depth of canal water supply (mm).

Crop

For the regional analysis emergences dates of crop growth and periods of irrigation scheduling were determined by means of average values obtained from the farmer fields. These dates for the crops wheat, cotton and rice are listed in Table 7.6. The number of irrigation applications was spread over the period between the first and last irrigation according to local observations.

Table 7.6 Croping patterns, based on average of farmer fields

Crop-rotation	Emergence	End	First irrigation	Last irrigation	Number of Irrigation applications
Wheat	01-11	24-04	03-11	07-04	8
Rice	20-06(1)	9-10	20-06	22-9	25
Cotton	01-05	31-10	10-05	19-9	4

(1) Transplanting

Because of the close interaction between water availability, *LAI* development and *DM* production, crop growth was simulated with WOFOST. The WOFOST module was calibrated for wheat, cotton and rice with data from local experiments. For light use efficiency and maximum CO_2-assimilation rate of wheat and cotton lower values were used than obtain during calibration in order to take into account, implicitly, the effect of management. Using WOFOST we calculated potential above ground *DM*, water limited above ground *DM*, potential *DM* production in storage organs, and water limited *DM* production in storage organs. In case of bare soil only soil evaporation was calculated.

Soil

For each soil layer defined in the soil profile, the relations between the soil water pressure head, the soil moisture content and the unsaturated hydraulic conductivity should be specified. All soil types were reduced into a two layer soil type since the actual evaporation, like surface soil moisture, is usually controlled by only the top few centimetres of soil (*Jhorar*, 2002). The topsoil exits of first 15 centimetres and the subsoil of 3.85 meter. In this study the Mualem - Van Genuchten functions were applied to describe the soil physical relations (Eqs. 4.9 and 4.10). The parameter values were taken directly from the farmer field study (Chapter 4).

Boundary conditions

A soil profile with a thickness of 4 meter was considered, assuming that most important processes occur within this upper part of the soil. For the lower boundary two conditions were distinguished: shallow and deep groundwater. Calculation units were assumed to have a shallow groundwater when the average groundwater level during the years 1999-2000 was less than 4 meter below the soil surface; all other units were assumed to have a deep groundwater level. About 10% of all units turned out to have an average groundwater less than 4 meter below surface.

For the situation with deep groundwater a free drainage condition was applied for the bottom boundary. As initial condition h = -500 cm was adopted.

For the situation with shallow groundwater the bottom flux was calculated as a function of a given hydraulic head and a vertical resistance of flow towards deeper soil layers:

$$q_{\mathrm{bot}} = \frac{\phi_{\mathrm{aquif}} - \phi_{\mathrm{gwl}}}{c} \qquad (7.4)$$

where q_{bot} is the flux at bottom of soil profile (cm d^{-1}), ϕ_{aquif} is the hydraulic head in a semi-confined layer (cm), ϕ_{gwl} is the groundwater level (cm) and c is the vertical resistance (d), taken here as 1000 d. The fluctuation of ϕ_{aquif} in time was assumed to have a sinusoidal wave. The amplitude of the ϕ_{aquif} sinus wave was derived from the difference between measured groundwater levels in June and October. The top of the sinus was either June or October, depending on the occurrence of the highest measured groundwater levels. Measured groundwater levels were used as initial conditions.

7.3.3 Regional modeling

For each of the 2404 calculation units, water and salt balances and crop growth were simulated. In this study the *rabi* and *kharif* seasons of the period of 2001-02 were analysed, because during this period measurements were available from both remote sensing and monitored farmer fields. The analysis was carried out using the SWAP model version 2.07 (*van Dam et al.*, 1997). A description of the SWAP and WOFOST models is presented in Chapters 4 and 5.

The SWAP model was adjusted for the simulation of paddy rice fields. An option was introduced to adjust the saturated conductivity of the soil horizon which represents the puddle layer. This layer received a value for the saturated conductivity of 1.0 cm d^{-1}. In spite of this adjustment it turned during the calibration phase that it was impossible to achieve reliable model results for the wheat-rice combination. Especially rice turned out to be very sensitive to the saturation percentage of the soil. Realistic values for rice could only be achieved after introducing a correction factor, which accounts for the uncertainty in the irrigation from groundwater tube wells. In order not to disturb the regional water balance, a sensitivity analysis was carried out for the second calculation unit. The analysis showed that a multiplication factor of 3 for the amount of tube well irrigation water would give reasonable yields without strongly influencing the leakage to deeper soil layers (Fig. 7.10). In other words, the estimation of the groundwater extraction rates was a factor 3 too low. In Chapter 9 this is elaborated and explained in more detail and the factor 3 appeared to be justified.

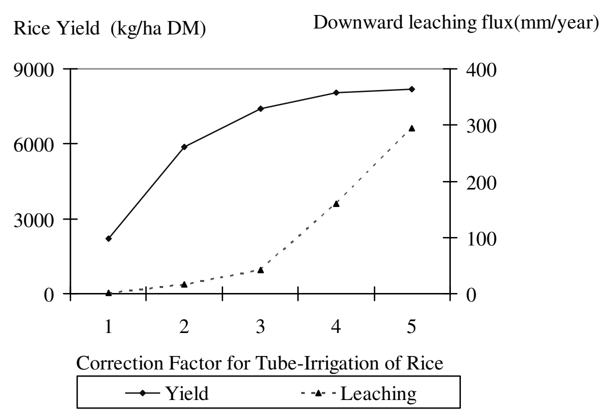

Figure 7.10 Yield and leaching as a function of a correction factor for tube irrigation of rice.

7.4 Results

7.4.1 Reference situation

The resulting water balance for the simulated period November 1, 2001 till November 1, 2002 showed that the high evapotranspiration is achieved with a large contribution of irrigation water. Rainfall and irrigation with canal water each supply about 20 % of the water. Irrigation with groundwater dominates the supply with a contribution of 60 % of the total supply to the upper part of the soil system (Table 7.7). Transpiration by the crops and soil evaporation take care of respectively 42 and 26 % of the total water discharge. Leaching (including drainage) is about 17% of the discharge.

Table 7.7 Overall water balance (mm y^{-1}), 1 Nov 2001 – 1 Nov 2002, based on the regional SWAP modelling.

IN		OUT	
Rainfall	188	runoff	5
Irrigation -–canals	210	Interception	5
Irrigation -groundwater	607	transpiration	421
		soil evaporation	260
		leaching	170
		storage	144
Total	1005	total	1005

A large part of the area (about 26%) consists of bare soil and receives no irrigation. The cropped area receives, however, high amounts of irrigated water, especially from groundwater (Table 7.8). Especially, wheat-rice receives large amounts of irrigation water through tube wells; ranging from 810 to 1465 mm/year. In the Rori division the supply from groundwater is relatively low, whereas the largest groundwater extractions occur in the Ghaggar division.

Table 7.8 Irrigation with groundwater and surface water, 1 Nov 2001 – 1 Nov 2002.

	Average depth of irrigation with canal water (mm y^{-1})		Average depth of irrigation with groundwater (mm y^{-1})	
Division	wheat-cotton	wheat-rice	wheat-cotton	wheat-rice
Ghaggar	339	245	720	1465
Nehrana	251	252	667	1285
Rori	591	531	375	810
Sirsa	247	227	684	1355
Average	334	294	624	1254

Actual evapotranspiration is highest for rice during *kharif* in the Ghaggar Division due to the large amounts of supplied of irrigation water. Lower values were calculated for the *rabi* season. Bare soils have an average evaporation of about 20 mm during *rabi* and 104 mm during *kharif*.

Transpiration reduction due to water and salinity stress is high for cotton, where an average value for T_a/T_p of 0.6 was calculated for all surface water divisions (Table 7.10). Rice hardly experiences stress in the Ghaggar division where T_a/T_p is 0.9; in the Sirsa division the reduction for rice was most severe with the lowest value of 0.7. Wheat, growing during *rabi*, was hardly afffected by water and/or salinity stress.

Table 7.9 Actual evapotranspiration (mm) during *rabi* and *kharif*

Division	*rabi*		*kharif*		
	wheat	bare soil	cotton	rice	bare soil
Rori	238	15	653	699	99
Sirsa	240	21	663	702	105
Ghaggar	251	28	706	802	109
Nehrana	237	16	652	731	103
Average	241	20	665	731	104

Table 7. 10 Transpiration reduction (T_{act}/T_{pot}) during *rabi* and *kharif*

Division	*rabi*	*kharif*	
	wheat	cotton	rice
Rori	1.0	0.6	0.8
Sirsa	1.0	0.6	0.7
Ghaggar	1.0	0.6	0.9
Nehrana	1.0	0.6	0.8
Average	1.0	0.6	0.8

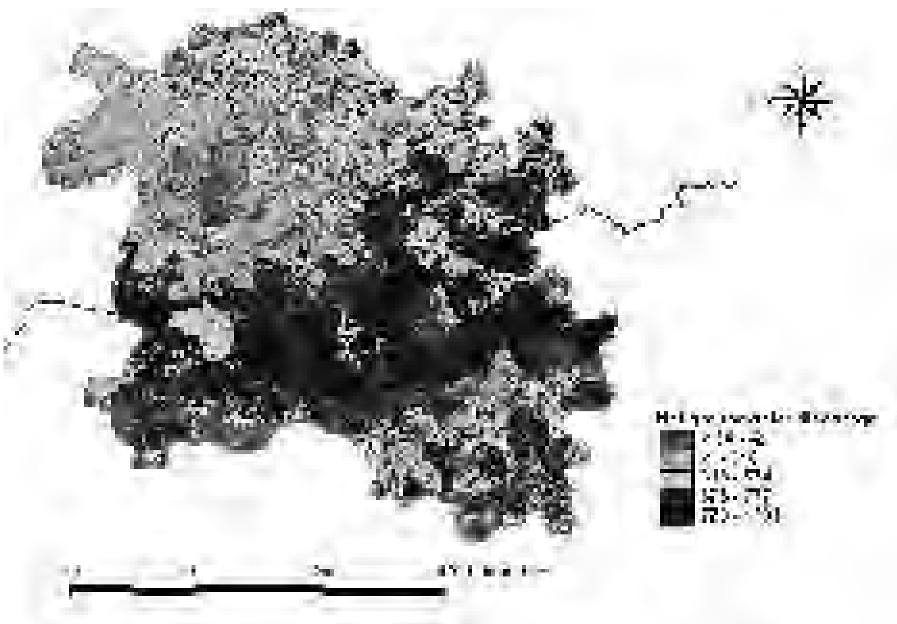

Fig. 7.11 Net groundwater discharge (mm year^{-1}) in Sirsa during 2001/02.

The net groundwater discharge was determined as the difference between the irrigation from groundwater and the downward losses to deeper soil layer. The spatial distribution of this net groundwater discharge (Fig. 7.11) shows high discharges in the areas around the Ghaggar river and low discharges in the Northern and Southern regions. Near the Ghaggar river supply of irrigation water from canal and groundwater is sufficient and the relatively shallow groundwater levels enable an easy withdrawal, which is only partly compensated by an increase in leakage.

During *rabi*, the actual yield of wheat is not reduced by any stress conditions and reaches high values of around 7000 kg ha^{-1} grain *DM* (Table 7.11). During *kharif* the yield of cotton is almost 5000 kg ha^{-1} *DM*, which is relatively high considering the water stress conditions that were faced. Simulated wheat and cotton yields were higher than the measured yields. The yield of rice is on average 5500 kg ha^{-1} *DM*, which is relatively low. This could not be improved without largely influencing the regional water balance (section 7.3.3) but was regarded as acceptable for a comparative analysis in the scenario study (Chapter 9).

Table 7. 11 Actual yield (kg *DM* ha^{-1}) during *rabi* and *kharif*.

Division	*rabi*	*kharif*	
	wheat	cotton	rice
Rori	6744	4932	5179
Sirsa	6627	4659	3931
Ghaggar	6956	4965	6816
Nehrana	6532	4751	6000
Average	6682	4799	5406

Once evapotranspiration and yield were determined, water productivity was calculated for the 3 crops. Lowest water productivity was achieved for rice in the Sirsa surface water division (Table 7.12). Highest water productivity was achieved for wheat in nearly all divisions.

Table 7. 12 WP_{ET} (kg m^{-3}) during *rabi* and *kharif*.

Division	*rabi*	*kharif*	
	wheat	cotton	rice
Rori	2.80	0.8	0.7
Sirsa	2.75	0.7	0.5
Ghaggar	2.75	0.7	0.8
Nehrana	2.75	0.7	0.8
Average	2.80	0.7	0.7

7.4.2 Comparison with remote sensing

A comparison between remote sensing results (Chapter 6) and results from the SWAP model can be analysed at various spatial scales:

- 30 x 30 m pixel, the scale of the Landsat images to which all Swap simulations were downscaled;
- villages; many input data of the SWAP model were assigned to this level;
- the entire Sirsa district.

At pixel-level (30 x 30 m) a comparison was carried out for actual evapotranspiration (ET_{act}) during the two seasons. Results on ET_{act} show a relatively good agreement for the *kharif* season (Fig. 7.12).

However the spatial accuracy of the input parameters was such that an analysis at a scale smaller than village level does not seem appropriate. Average values for *rabi* are in poor agreement (Table 7.13: 167 mm by SWAP model versus 314 mm by remote sensing), but for *kharif* the average deviation is negligible (Table 7.13: 499 mm by SWAP model versus 499 mm by remote sensing). Results were aggregated to village level and presented in Fig. 7.13

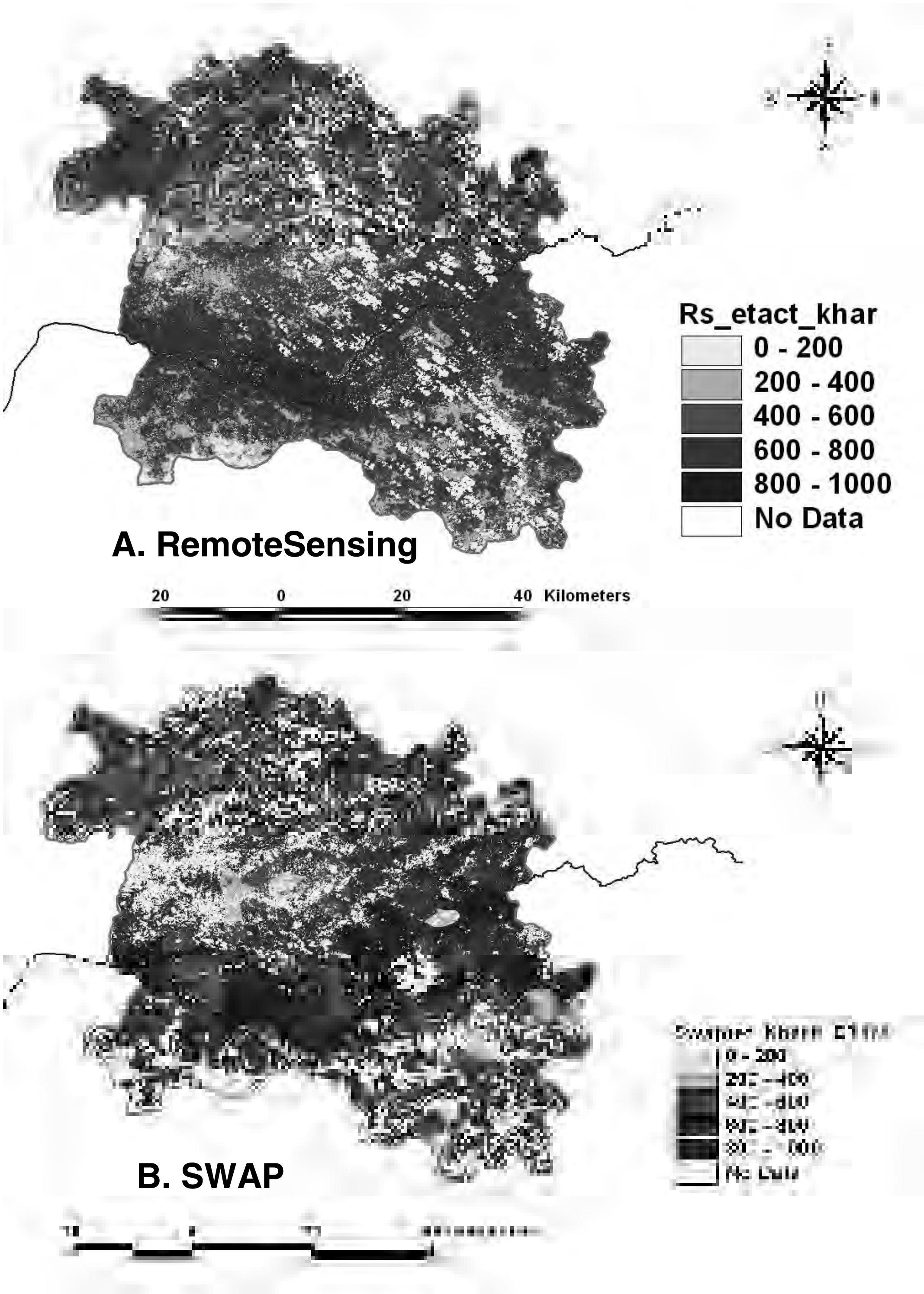

Fig. 7.12 Actual evapotranspiration (mm year^{-1}) in Sirsa during *kharif* 2002; spatial maps derived from remote sensing images (A) and the SWAP model (B).

for a comparison of actual evapotranspiration (ET_{act} in mm y^{-1}) in Sirsa during the *kharif* of 2002.

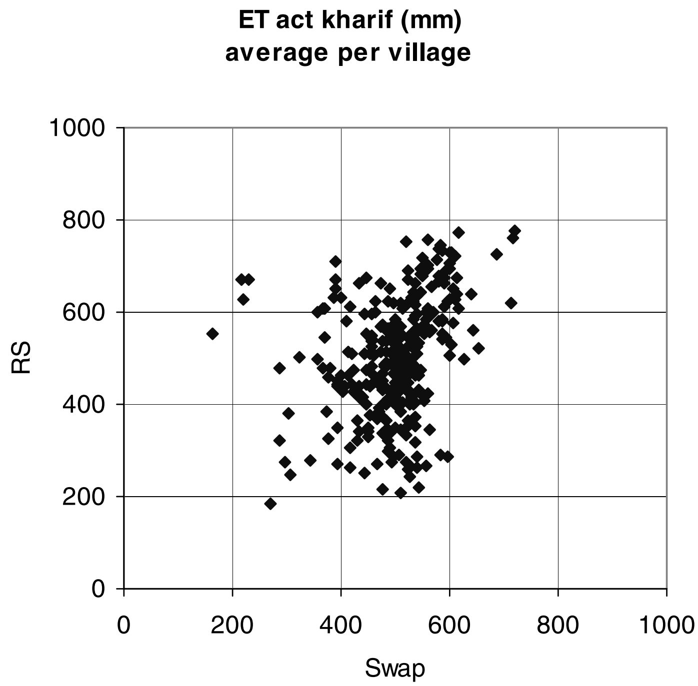

Fig. 7.13 Comparison of actual evapotranspiration (ET_{act} in mm $year^{-1}$) in Sirsa during *kharif* 2002; average values per village from remote sensing images (RS) as a function of the values from the SWAP model (Swap).

Table 7.13 Statistics on ET_a (mm y^{-1}) in Sirsa during *rabi* and *kharif* of 2001-02.

Season	Criteria	Remote sensing	Model (SWAP)
rabi	Mean value	314	167
	Standard Error	2	1
	Median	322	165
	Standard Deviation	39	20
kharif	Mean value	499	499
	Standard Error	7	4
	Median	504	509
	Standard Deviation	125	77

In spite of the differences between the results from remote sensing and SWAP model the achieved values were regarded as acceptable for scenario analyses. A more detailed analysis is recommended for future studies, which should pay more attention to dynamic interactions between the soil-water-system, regional groundwater flow and the surface water system.

7.5 Conclusions and recommendations

The following conclusions can be drawn from the regional analysis:

- The substantial amount of monitoring and data collection in India made it possible to perform the regional analysis within a relative short period of time.
- Evapotranspiration from remote sensing and the SWAP model are in good agreement during *kharif* season.

- The deviation between actual evapotranspiration from remote sensing and the SWAP model is large in the *rabi* season; this is probably due to poor irrigation water parameterization.

The following recommendations can be made:

- The database that will be distributed with this report should be maintained and extended to facilitate future regional studies.
- The spatial interaction between the various calculation units in this study was neglected; this should be improved and in future the irrigation system should become part of the stratification procedure.
- Regional groundwater was considered to be a boundary condition; a sensitivity analysis or a more detailed study should confirm the reality of this assumption.
- Modelling of puddled layers in paddy rice in rotation with wheat cultivation should get more attention; modelling of a dynamic change of hydraulic conductivity should be considered.
- The results of the regional analyses are such that it is recommended to use the modelling framework for comparative qualitative scenario studies; improvement of both instrument and data sets may enable a more quantitative approach.

8. Integration of remote sensing and simulation of crop growth, soil water and solute transport at regional scale

P.A. Leffelaar, J.C. van Dam, J.J.E. Bessembinder and T. Ponsioen

Summary

Water productivities (*WP*) are defined for different scales that can be considered in an agricultural area, such as the crop, the field and the regional scale. This is appropriate because at one hand there exists often confusion about what is meant by *WP*'s as provided by literature, and at the other hand differences in *WP*'s among the different scales clarify where improvements in water management in the agricultural system will be most beneficial. Aggregation formulae to scale-up from crop scale to field- and regional scale are presented. Water productivities derived from observations at experimental stations as well as farmer fields and from a crop-water simulation model integrating the physiological and physical processes of the agricultural system, are analysed and confronted with each other. This confrontation finally leads to a proposal of measures for Sirsa district to reduce water usage while crop yields keep the same level.

8.1 Defining water productivity

Water productivity (*WP*, expressed in kg of dry matter per m^3 of water) can be defined in different ways (e.g. *To Phuc Tuong*, 1999; *Molden et al*., 2001). The nominator may refer to different types of dry matter (*DM*), e.g. total *DM* or yield *DM*. The denominator may refer to different types of water, e.g. water transpired by the crop, or water needed for the crop and for leaching salts from the soil or the total amount of water given to a region. To prevent confusion in this respect and to structure this chapter, we define five *WP*'s:

(1) crop scale, considering crop physiology: WP_T, kg of *DM* per m^3 of water transpired;
(2) field scale, including the water evaporated from the soil: WP_{ET}, kg of *DM* per m^3 of water evapotranspired;
(3) field scale, also including the amount of water needed to maintain the salt concentration in the soil profile at an acceptable low value: WP_{Leach}, kg of *DM* per m^3 of water evapotranspired plus leached from soil;
(4) regional scale, including the losses from the irrigation canal system: WP_{Reg}, kg of *DM* per m^3 of water evapotranspired plus leached from soil and lost from canals;
(5) regional scale, as calculated from remote sensing data: WP_{RS}. This number will give a regionally integrated number for WP_{ET}, in kg of *DM* per m^3 of water evapotranspired.

The basic WP_T at the crop scale is the highest possible value attainable in a cropping system and only depends on the crop type (C_3, e.g. wheat, rice, cotton, potato or C_4, e.g. maize, sorghum, sugar cane) and variety. It is a time integrated result of the ratio between seasonal dry matter production (with or without roots) or, using a harvest index, dry matter yield, and the amount of water transpired. Since under a fixed set of environmental conditions, the diffusion rates of both CO_2 and H_2O molecules vary proportionally to the size of stomatal aperture, the ratio of these rates remains constant, and one would expect a constant WP_T for a certain crop. However, in contrast to a fairly constant CO_2 concentration in the air, resulting in stable CO_2 diffusion rates, temperature and hence vapour pressure deficit may vary substantially over a given period of time (day or season). These changes cause the evaporative demand to vary, and subsequently, also the transpiration rate at a given stomatal aperture. Hence, in the course of time WP_T may show considerable variation as a result of continuously changing environmental conditions. Furthermore, under extreme conditions such as high radiation levels in e.g. arid regions, assimilation may become light saturated while transpiration may still increase, resulting in low WP_T values. Also, under an extreme moisture deficiency production may not change proportionally to transpiration, due to biochemical adaptations in CO_2 assimilation and respiration (*Lövenstein et al.*, 1992; *Zur and Jones*, 1984). The above results in a range of WP_T values that, for instance for wheat, amounts from 1.5 to 2.5 kg of *DM* yield per m^3 of water (*Lövenstein et al.*, 1992). WP_T sets the lower limit of water use in agriculture which is substantially high. Take a harvest index of 0.5, an average WP_T of 4 kg of *DM* per m^3 of water and a growing season of 100 days. Further, assume that about 200 kg *DM* per ha per day is produced (*Sibma*, 1968). In that case minimally 500 mm of water is transpired per season, equivalent to 5000 m^3 of H_2O per ha per season!

The field scale WP_{ET}, in kg of *DM* per m^3 of water evapotranspired, will inevitably be lower than the WP_T, because the denominator is enlarged by soil evaporation.

WP_{Leach}, expressed in kg of *DM* per m^3 of water evapotranspired plus leached, also refers to the field scale. It is especially considered for Sirsa district, because of the adverse effects of salts on crop growth. To leach salts from the soil profile, an extra amount of good quality water is needed.

The water productivity for the regional scale, WP_{Reg}, expressed in kg of *DM* per m^3 of water evapotranspired plus percolated from the soil and lost from the irrigation canals, will have to be calculated from the total regional yield and the difference between the total amount of water entering and leaving the region through the canals, assuming that the water stored in the saturated and unsaturated soil profile remains unchanged. As will be discussed later, "losses" from the conveyance system are in many cases only local losses and might be reused by downstream users, or, in the case of Sirsa district, pumped from the groundwater.

WP_{RS} refers to the regional scale and is calculated from remote sensing data. It uses the estimated amount of *DM* produced in the region divided by the measured evapotranspired water (Chapter 6).

8.2 An appraisal of the water productivity definitions

The different water productivity values obtained by using different crop varieties, and different definitions can be compared. WP_T may be improved by choosing other varieties which are acceptable by farmers and consumers. We should be careful in the calculation of WP_T: often roots are not accounted for in this value, e.g. in the case of wheat and wheat yield, harvest index relates to the above ground crop, and moreover, yields contain about 14% of moisture in practice. This means that the *DM* in the nominator of the ratio between *DM* and water use must often be recalculated. Crops may show sensitive and insensitive periods to drought. This means that WP_T may be improved by well chosen crop sowing dates and by distributing the water according to the drought sensitive periods.

Comparing *WP* values of WP_T and WP_{ET} should give an indication of the need to reduce soil evaporation by management actions such as mulching, or conservation tillage. Soil evaporation will usually be small after crops have been well established, i.e. when the leaf area index (*LAI*) is about 4 m^2 of leaf per m^2 of soil surface. Soil conservation measures could also diminish the amount of water needed for preliminary land preparation.

A comparison of WP_{ET} and WP_{Leach} will give an indication about leaching losses, but the difference between these numbers is less easy to interpret than between WP_T and WP_{ET}. This is due to scale effects. It is often thought that beyond the water productivity as determined by the crop physiology, *WP* values will decrease with increasing spatial scale. This holds for WP_{ET} because the denominator in the ratio between *DM* and water use is enlarged, while the *DM*-production remains the same. For the field scale WP_{Leach} will also decrease as compared to WP_{ET}, because of the extra water used for leaching salts from the soil profile, but on a larger scale WP_{Leach} is not necessarily smaller than WP_{ET}. Especially in the Sirsa district, the water used for leaching might be pumped up elsewhere and used for crop cultivation, thus increasing the value of WP_{Leach}. For the *WP* including canal losses this may also hold. Thus, recycling of water may increase its productivity when a larger scale is considered (*Seckler et al.*, 2001; *Droogers and Kite*, 2001).

The values of WP_{Leach} and WP_{ET} will also be affected by water quality. For example at the crop scale, water with high salinity levels will affect the crop transpiration adversely or, similar to moisture deficiency, induces more root growth and a lower production. At the field scale more water of bad quality is needed to leach salts from the soil profile than water of good quality. If water quality is low, recycling may perhaps not be possible, resulting in a decreasing water productivity with increasing scale. A suitable management action could be the mixing of salty water with water of good quality.

Apart from the spatial scales, also the temporal scale is involved in the analysis. There may be differences in crop rotations and weather over the years and one can thus not simply use data of one year for the future.

The comparison of water productivity values may indicate where the largest water savings are possible. For a proper comparison some of the water productivity figures have to be aggregated. For the case of the aggregated value for the region as a whole excluding leaching and canals, so WP_{ET}, this may be compared to the WP_{RS} as obtained by remote sensing (Chapter 6), and, if also leaching and canals are included (WP_{Reg}), to the result of the data analysis of regional water productivity described in Chapter 7. Data aggregation is discussed in the next section. Depending on where savings would be most appropriate different stakeholders will be involved, e.g. farmers, irrigation officers, NGO's, politicians. Knowledge of different scientific disciplines is needed to improve water productivity at different scales, e.g. crop physiology, soil science, irrigation science, (watershed) hydrology, logistics of partitioning of the water.

8.3 Calculation, aggregation and validation of water productivity

Water productivities can be derived from measurements at farmers fields or research stations (Chapter 3), from literature, from theory and simulation (e.g using the SWAP/WOFOST model, Chapter 4 and 5), and from the remote sensing data (Chapter 6). The experimental data can be divided into integral data such as yields of *DM*, and data that feed the models, such as hydraulic characteristics, specific leaf area and weather data. The theoretical calculations as performed by the SWAP/WOFOST model enable us to calculate data such as WP_{T}, WP_{ET} and WP_{Leach} for the field scale. These data can be generated with or without including roots in the *DM*, and with or without 14 % of moisture in the yield, because all relevant processes are included in this explanatory, mechanistic model. Also, since the feedbacks between crop growth, water flow and salt transport are accounted for in the model, water shortage or excess affecting root water uptake and crop growth (which affects the evapotranspiration), and the effect of a high salt concentration on root water uptake and crop development (which affects the amount of water needed by the crop and the amount of leaching to the groundwater) may all be explicitly quantified in terms of *WP*'s.

To calculate regional scale *WP*'s from the field scale values, we have to either know data from all cropped fields, or we have to ascribe a representative area to certain crop data and then calculate the regional *WP*. Since *WP*-values are intensity variables, they can not directly be used in aggregation. Rather, we should use variables of extension, so variables representing amounts. Thus, the aggregated water productivity must be calculated by the ratio of the independent summations of the *DM* and the amounts of water per (representative) area. To calculate for instance the WP_{ET} for the region and for *DM* yield, $(WP_{\mathrm{ET}})_{\mathrm{Reg}}$, we use:

$$(WP_{\mathrm{ET}})_{\mathrm{Reg}} = \frac{\sum_{j=1}^{p} \sum_{i=1}^{n} Y_{i,j} \; a_{i,j}}{\sum_{j=1}^{p} \sum_{i=1}^{n} W_{i,j} \; a_{i,j}} \tag{8.1}$$

where $Y_{i,j}$ is the amount of dry matter yield for crop j, on field i, (kg *DM* ha^{-1}), $W_{i,j}$ is the amount of water evapotranspired (m^3 ha^{-1}), $a_{i,j}$ is the crop area (ha), p is the number of crops cultivated in the area and n is the number of fields or representative cropped areas that make up the region. If $W_{i,j}$ would not be known for the fields or the representative areas, but rather $(WP_{\mathrm{ET}})_{i,j}$, the equation would become:

$$(WP_{\mathrm{ET}})_{\mathrm{Reg}} = \frac{\sum_{j=1}^{p} \sum_{i=1}^{n} Y_{i,j} \; a_{i,j}}{\sum_{j=1}^{p} \sum_{i=1}^{n} \frac{Y_{i,j}}{(WP_{\mathrm{ET}})_{i,j}} \; a_{i,j}} \tag{8.2}$$

To calculate $(WP_{\mathrm{T}})_{\mathrm{Reg}}$ or $(WP_{\mathrm{Leach}})_{\mathrm{Reg}}$ similar equations can be used when referring to the appropriate *DM* and amount of water used.

For the calculation of WP_{Reg} the denominator in the equations should be extended by adding the conveyance losses in the canal system and the distribution losses of irrigation water at the farmer fields. The conveyance losses are generally defined as the ratio between the water delivered to the field and the water delivered from the reservoir. The distribution losses are generally defined as the ratio of the water infiltrated in the soil below the root zone and water delivered to the field (*Wolters*, 1992). In case canal water is used for irrigation, we should account for both the conveyance and distribution losses. In case of tube well irrigation water, the main losses will be distribution losses.

Further, as a first approximation to calculate WP_{Reg}, we could assume that the amount of water stored in the soil profile and the groundwater table hardly changes. This relates to a somewhat longer time scale, for example a year or so. In other cases the change in storage capacity of water in the soil profile and groundwater table should be estimated separately.

Both experimental and theoretical values of water productivities for the fields contain uncertainties, because of the many variables that have to be estimated with some error, and e.g. because of field heterogeneities that are not accounted for in the model. As a result the aggregated values, such as $(WP_{\mathrm{ET}})_{\mathrm{Reg}}$, and WP_{Reg} will also contain uncertainties. Evaluation of errors or uncertainties can probably best be done by statistical data analysis, but this means that a sufficient volume of data should be available. Although we have gathered in our project quite some data, there are not enough replicates available to perform such a statistical analysis. Another method is to calculate the propagation of errors in the composing parameters and variables on the resulting aggregated numbers, by assuming measurement errors in these parameters and variables. The aggregated numbers can than be represented with their uncertainty, and compared with independently determined values, such as those from remote sensing and from the regional analysis (Chapter 7). The differences between the aggregation procedures, sometimes called upscaling, and those from remote sensing and regional analysis, sometimes called downscaling, can be explored and usually leads to re-viewing of the methods used and to improved insight and results.

The error of propagation can be calculated by (*Berendts et al.*, 1973):

$$S_{\mathrm{gz}} = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial i}\right)^2 S_{\mathrm{gi}}^2} \qquad (8.3)$$

where the $\partial f / \partial i$ are the partial derivatives of e.g. $(WP_{\mathrm{ET}})_{\mathrm{Reg}}$ with respect to all the variables i and j, here $Y_{i,j}$, $W_{i,j}$ and $a_{i,j}$. S_{gi} is the estimated error in each of the variables, and S_{gz} is the absolute error in $(WP_{\mathrm{ET}})_{\mathrm{Reg}}$.

To get some idea about uncertainties, the numbers have to be checked or validated against other independent methods to assess the *WP*'s. From remote sensed images water productivity numbers can be derived (WP_{RS}) which include actual evapotranspiration and actual biomass and thus correspond to WP_{ET}. The WP values obtained at field scale level or through upscaling can be compared to remote sensing images with the appropriate pixel size. In WATPRO the field scale will be compared to LANDSAT images (pixel size 30x30 m^2) and at regional scale the NOAA image (pixel size 1.1x1.1 km^2) will be used (Chapter 9).

Remote sensing data on evapotranspiration and biomass growth at a fine grid can also be used to calibrate field scale models as SWAP/WOFOST. For instance *Jhorar et al.* (2002) used successfully remotely sensed evapotranspiration data to derive soil hydraulic functions in SIC. However, a precondition for such type of inverse modeling is that the number of unknown parameters is limited, enough clear sky satellite images with the appropriate pixel size are available, and the remaining model input data are reliable. One should be aware that the inaccuracies in remaining model input data and simplifying model schematizations will affect the optimized parameter values. This is not problematic when the model is used for similar environmental conditions, as the integrated model is calibrated.

8.4 Application at investigated farmer fields

Table 8.1 Water productivity at farmer fields with wheat-cotton rotation in period Dec 2001 - Nov 2002, derived from measured crop yields and simulated water balance components.

	Field number	**11**	**16**	**20**	**24**	**Mean**
Rabi	Canal (mm)	48	0	0	87	34
	Tubewell (mm)	382	396	568	249	399
	Total irrigation (mm)	**430**	**396**	**568**	**336**	**433**
	Water quality (dS/m)	3.73	0.89	0.50	1.29	1.60
	Wheat grain (kg/ha)	**4440**	**5180**	**4348**	**1756**	**3931**
	Wheat total (kg/ha)	11250	11413	9223	4196	9021
	Transpiration (mm)	244	190	255	126	204
	Evaporation (mm)	95	89	113	82	95
	Percolation (mm)	77	21	171	141	103
	WP_ph (kg/m3)	1.82	2.73	1.71	1.39	1.93
	WP_ph+evap (kg/m3)	**1.31**	**1.86**	**1.18**	**0.84**	**1.32**
	WP_ph+evap+leach (kg/m3)	1.07	1.73	0.81	0.50	0.98
	WP_ph+evap+leach+canals (kg/m3)	0.75	1.20	0.60	0.34	0.69
	WP_ph ($/m3)	0.215	0.322	0.201	0.164	0.220
	WP_ph+evap ($/m3)	**0.155**	**0.219**	**0.139**	**0.100**	**0.150**
	WP_ph+evap+leach ($/m3)	0.126	0.204	0.095	0.059	0.112
	WP_ph+evap+leach+canals ($/m3)	0.089	0.142	0.071	0.040	0.079
Kharif	Canal (mm)	162	0	0	285	112
	Tubewell (mm)	139	554	737	0	358
	Total irrigation (mm)	**301**	**554**	**737**	**285**	**469**
	Water quality (g/cm3)	2.61	0.60	0.35	0.90	1.12
	Cotton seed (kg/ha)	**338**	**2101**	**2098**	**3108**	**1911**
	Transpiration (mm)	277	572	685	339	468
	Evaporation (mm)	150	171	142	102	141
	Percolation (mm)	87	83	132	21	81
	WP_ph (kg/m3)	0.12	0.37	0.31	0.92	0.41
	WP_ph+evap (kg/m3)	**0.08**	**0.28**	**0.25**	**0.70**	**0.31**
	WP_ph+evap+leach (kg/m3)	0.07	0.25	0.22	0.67	0.28
	WP_ph+evap+leach+canals (kg/m3)	0.05	0.21	0.17	0.42	0.21
	WP_ph ($/m3)	0.027	0.081	0.067	0.202	0.087
	WP_ph+evap ($/m3)	**0.017**	**0.062**	**0.056**	**0.155**	**0.066**
	WP_ph+evap+leach ($/m3)	0.014	0.056	0.048	0.148	0.059
	WP_ph+evap+leach+canals ($/m3)	0.010	0.046	0.038	0.092	0.044

We apply the methodology to the 4 investigated sites with wheat – cotton rotation (Chapter 3). By using the data of the farmer fields rather than the data of the experimental fields, the results resemble more the current farmer practices. The crop yields are based on direct measurements, while the water balance components have been derived with the calibrated SWAP/WOFOST combination (Chapters 4 and 5). The results are listed in Table 8.1. Fields 11 and 24 use both canal and groundwater, fields 16 and 20 use only groundwater. The total amount of irrigation water of the wheat-cotton combination ranges between 621 mm (Field 24) and 1305 mm (Field 20). The mean wheat grain yield is 3931 kg/ha, and the mean cotton seed yield is 1911 kg/ha. The differences between minimum and maximum crop yields are large, suggesting that ample scope exists for improvements in yields at field conditions. The average actual evapotranspiration (ET_a) during *rabi* and *kharif* amounts to 299 mm, and 609 mm, respectively. The sum of the rainfall and the canal water amounts to 34+112+187=333 mm, while the sum of ET_a equals 299+609=908 mm. This means that a net extraction of groundwater reserves occurs, which might be compensated by conveyance and distribution losses of the canal water or by regional groundwater flow.

If we assume that the groundwater quality is good enough for irrigation, the amount of water consumed corresponds to WP_{ET}, because leached water can be reused. In case of wheat the mean WP_{ET} at the four sites equals 1.32 kg/m^3. With remote sensing we found WP_{ET} = 1.0 – 1.4 kg m^{-3} (Chapter 6). *Hussain et al*. (2003) measured in the same region 1.36 kg m^{-3}. Similar as with crop yields, the WP_{ET} range of 0.84 – 1.86 during *rabi* and 0.08 – 0.70 during *kharif* indicates that in farmer fields large amounts of water can be saved.

In order to compare crops and relate savings to required investments and alternative water use (industry, domestic water, natural resources) we might express *WP* in \$ m^{-3}. *Hellegers* (2003) reports the following crop prices: wheat 449 \$ ha^{-1}, cotton 406 \$ ha^{-1} and rice 327 \$ ha^{-1}. This gives in case of wheat for the mean WP_{ET} 0.15 \$ m^{-3}, and in case of cotton a mean WP_{ET} of 0.07 \$ m^{-3}. For the same area *Hellegers* (2003) reports for wheat a WP_{ET} of 0.18 \$ m^{-3}, and in case of cotton a WP_{ET} of 0.09 \$ m^{-3}. The values show that during *rabi* the water is used more productively than during *kharif*. The main reasons for this are that during *kharif* more canal and rain water is available, the potential *ET* fluxes during *kharif* are larger and cotton is less profitable than wheat.

WP_{Reg} is relevant when we are in saline groundwater areas. In order to calculate WP_{Reg} we need to include the conveyance and distribution losses of canal water. *Wolters* (1992) investigated these efficiencies for a large number of irrigation systems. The mean conveyance efficiency amounted to 75%, and the mean distribution efficiency was also 75%, yielding an overall efficiency of 56%. In spite of lining of the main canals in SIC, according to *Sharma* (1995) and *Bastiaanssen et al.* (1996) the overall efficiency in SIC is about 50%. Thus, the amount of water lost from canals is as high as the amount of water used for irrigation! Therefore, in the calculation of WP_{Reg}, the loss of the applied canal water was estimated as (50/50) x 100% = 100% of the amount irrigated, whereas the loss of the applied tubewell water was estimated as (25/75) x 100% = 33% of the amount irrigated. The conveyance and distribution losses decrease the mean *WP* in case of wheat from 0.98 to 0.69 kg m^{-3}, and in case of cotton from 0.28 to 0.21 kg m^{-3}.

Farmer field 16 is showing a high water productivity with moderate water demands and appropriate salt leaching. The conditions of this field have been used for a long term analysis of 10 years with the calibrated SWAP/WOFOST model. The results are listed in Table 8.2, showing the *WP* and yield variability due to climate, the sustainability of the system and the long term averages. The mean wheat grain yield is 5587 kg ha^{-1}, the mean cotton seed yield is 2356 kg ha^{-1}. The average actual *ET* during *rabi* amounts to 296 mm, and during *kharif* amounts to 800 mm. The mean WP_{ET} equals 1.89 kg m^{-3} (or 0.223 \$ m^{-3}) for wheat and 0.29 kg m^{-3} (or 0.065 \$ m^{-3}) for cotton.

The long term simulated data for field 16 are a significant improvement compared to the current average situation at the 4 measured sites in the 2001-2002 season, as listed in Table 8.1. The wheat grain yield increases from 3931 to 5587 kg ha^{-1}, and the cotton seed yield from 1911 to 2356 kg ha^{-1}. The total amount of irrigation water increases slightly from 902 to 950 mm y^{-1}. WP_{ET} for wheat increases from 1.32 to 1.89 kg m^{-3}; for cotton it remains about the same (from 0.31 to 0.29 kg m^{-3}). This means that improved crop management may increase the wheat yield considerably with the same amount of water.

Table 8.2 Simulated water productivity at farmer field 16 in period Dec 1992 - Nov 2002 with current groundwater quality.

	Year	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**Mean**
	Rainfall	173	343	441	455	669	424	286	255	392	187	363
Rabi	**Tube well irrigation (mm)**	**396**	**396**	**396**	**396**	**396**	**396**	**396**	**396**	**396**	**396**	**396**
	Wheat grain (kg/ha)	**4985**	**4679**	**6247**	**5823**	**7170**	**5462**	**4796**	**5468**	**6060**	**5180**	**5587**
	Wheat total (kg/ha)	10203	10290	13105	12964	15929	12465	11188	12425	15258	11413	12524
	Transpiration (mm)	211	205	173	206	223	189	186	203	212	190	200
	Evaporation (mm)	94	94	103	112	102	90	88	92	95	89	96
	Percolation (mm)	15	22	105	84	83	178	153	38	33	21	73
	WP_ph (kg/m3)	2.36	2.28	3.61	2.83	3.22	2.89	2.58	2.69	2.86	2.73	2.80
	WP_ph+evap (kg/m3)	**1.63**	**1.56**	**2.26**	**1.83**	**2.21**	**1.96**	**1.75**	**1.85**	**1.97**	**1.86**	**1.89**
	WP_ph+evap+leach (kg/m3)	1.56	1.46	1.64	1.45	1.76	1.20	1.12	1.64	1.78	1.73	1.51
	WP_ph+evap+leach+canals (kg/m3)	1.11	1.04	1.22	1.09	1.33	0.93	0.86	1.18	1.29	1.20	1.12
	WP_ph ($/m3)	0.279	0.269	0.426	0.334	0.379	0.341	0.304	0.318	0.337	0.322	0.330
	WP_ph+evap ($/m3)	**0.193**	**0.185**	**0.267**	**0.216**	**0.260**	**0.231**	**0.207**	**0.219**	**0.233**	**0.219**	**0.223**
	WP_ph+evap+leach ($/m3)	0.184	0.172	0.193	0.171	0.207	0.141	0.133	0.194	0.210	0.204	0.179
	WP_ph+evap+leach+canals ($/m3)	0.131	0.122	0.144	0.129	0.157	0.110	0.101	0.139	0.152	0.142	0.132
Kharif	**Tube well irrigation (mm)**	**554**	**554**	**554**	**554**	**554**	**554**	**554**	**554**	**554**	**554**	**554**
	Cotton seed (kg/ha)	**2098**	**2570**	**2318**	**2731**	**2988**	**3307**	**1753**	**2075**	**1624**	**2101**	**2356**
	Transpiration (mm)	624	732	634	751	719	695	684	575	690	572	668
	Evaporation (mm)	129	130	114	115	121	118	147	140	134	171	132
	Percolation (mm)	36	49	221	104	281	101	59	135	164	83	123
	WP_ph (kg/m3)	0.34	0.35	0.37	0.36	0.42	0.48	0.26	0.36	0.24	0.37	0.35
	WP_ph+evap (kg/m3)	**0.28**	**0.30**	**0.31**	**0.32**	**0.36**	**0.41**	**0.21**	**0.29**	**0.20**	**0.28**	**0.29**
	WP_ph+evap+leach (kg/m3)	0.27	0.28	0.24	0.28	0.27	0.36	0.20	0.24	0.16	0.25	0.26
	WP_ph+evap+leach+canals (kg/m3)	0.22	0.23	0.20	0.24	0.23	0.30	0.16	0.20	0.14	0.21	0.21
	WP_ph ($/m3)	0.074	0.077	0.080	0.080	0.091	0.105	0.056	0.079	0.052	0.081	0.078
	WP_ph+evap ($/m3)	**0.061**	**0.066**	**0.068**	**0.069**	**0.078**	**0.089**	**0.046**	**0.064**	**0.043**	**0.062**	**0.065**
	WP_ph+evap+leach ($/m3)	0.058	0.062	0.053	0.062	0.059	0.080	0.043	0.054	0.036	0.056	0.056
	WP_ph+evap+leach+canals ($/m3)	0.047	0.052	0.044	0.052	0.050	0.066	0.036	0.044	0.031	0.046	0.047

8.5 Proposed measures in Sirsa district

In addition to equity and reliability, integrated water management in Sirsa Irrigation Circle should include the following goals:

– increase water productivity;
– stop further decline of deep groundwater levels;
– decrease waterlogging;
– decrease salinization.

Box 8.1 Proposed measures to increase and maintain water productivity in Sirsa district.

- improve crop management (cultivation, fertilizer application, weed and pest control)
- replace paddy rice by dry rice or corn
- decrease soil evaporation
- improved land levelling to decrease distribution losses
- divide the available irrigation water over more land
- optimize leaching fraction in saline groundwater areas which prevents waterlogging and salinization
- use sprinkling irrigation to diminish percolation
- increase groundwater recharge in monsoon period
- more reservoirs and dams to retain excess surface water
- complete canal lining and more canal maintenance to decrease conveyance losses
- organise reliable canal water in saline groundwater areas which prevents water spill
- determine optimal conjunctive use of canal and groundwater in saline groundwater area's
- install drainage in waterlogged areas
- improve water management at secondary level
- improve water management at tertiary level
- increase the use of tube-well water to prevent further groundwater rise
- grow more eucalyptus trees to extract excessive water

In order to attain these goals, various measures have been proposed as listed in Box 8.1. The described water productivity analysis is useful to determine which measures are the most effective. Such an analysis requires close collaboration of scientists in plant growth, agronomy, soil physics, hydrology, civil engineering, remote sensing, computer modeling and data handling. At the decision level of politicians and water managers other aspects should be included, such as cost-benefit analysis and socio-economic implications. In this stage we will shortly discuss each measure of Box 8.1.

Improve crop management (cultivation, fertilizer application, weed and pest control)

Here exists ample scope for water savings. At the experimental stations WP_{ET} amounts 2.58 kg m^{-3} in case of wheat and 0.58 kg m^{-3} in case of cotton (Table 5.7). Using the average water productivity values at the farmer fields WP_{ET} amounts 1.32 kg m^{-3} in case of wheat and 0.31 kg m^{-3} in case of cotton (Table 8.1). The figures are not entirely comparable: those at the experimental station only refer to the cropping period, while those at the farmer fields include pre-irrigation and the fallow period in between crops. If we neglect this difference, by proper crop management for the same amount of crop production in case of wheat 100x(1-1.32/2.58)=48% less water is evaporated! In case of cotton the potential water savings would amount 100x(1-0.31/0.58)=46%! Even if we would assign about half of the difference in WP's to the land preparation before and fallow conditions after crop cultivation, water savings would be in the order of 25%. Various measures might be needed to attain these substantial water savings: appropriate cultivation, optimum irrigation, effective weed and disease control.

Replace paddy rice by dry rice or corn

In Haryana the irrigation water requirements of paddy rice fields are very high: 1200-1300 mm (*Giriappa*, 1983; this study). The high water consumption is mainly due to high amounts of percolation and evaporation. At productivity levels of farmer fields of about 5000 kg ha^{-1}, WP_{Leach} amounts 0.4 kg m^{-3} only. Currently much research effort is devoted to increase the water productivity of rice. The International Platform for Saving Water in Rice (*IPSWAR*, 2003) intends to increase the efficiency and enhance the coherence of research in water savings in rice-based cropping systems in Asia. *Bouman and Tuong* (2000) used experimental data from central-northern India and the Philippines. Water input was reduced by reducing ponding depths to soil saturation and by alternate wetting/drying. Water savings under saturated soil conditions were on average 23% with yield reductions of only 6%. Yields were reduced by 10-40%, however, when water pressure heads in the root zone were allowed to reach –100 to –300 cm. In clayey soils, intermittent drying may lead to shrinkage and cracking, thereby risking an increased soil water loss and root damage. Water productivity in continuous flooded rice was typically 0.2-0.4 kg m^{-3} in India and 0.3-1.1 kg m^{-3} in Philippines. Water-saving irrigation increases water productivity, up to a maximum of about 1.9 kg m^{-3}. However, the yield per ha will decrease. Total rice production can be increased by using water saved in one location to irrigate new land at another location (*Bouman and Tuong*, 2000). One of the major practical challenges will be to minimize weeds that are introduced by dryland rice farming. The observed substantial increase in weeds is easier to tackle at experimental plots than at farm fields. A second obstacle is the dependency on reliable irrigation deliveries since the buffer capacity of the water layer is not available under dryland farming.

Decrease soil evaporation

Due to soil evaporation, *WP* decreases for wheat from 1.93 to 1.32 kg m^{-3} and for cotton from 0.41 to 0.31 kg m^{-3} (Table 8.1). The total amount of soil evaporation equals 236 mm y^{-1}, or 35% of the transpiration. Soil evaporation might be decreased by mulching (*Unger and Stewart*, 1982). Suppose that due to mulching the amount of soil evaporation can be reduced by 25% to 177 mm y^{-1}. The largest effect occurs in fresh groundwater areas (Table 8.3). WP_{ET} then increases from 1.32 to 1.43 kg m^{-3} in the case of wheat, and from 0.31 to 0.33 kg m^{-3} in the case of cotton. However, other aspects such as alternative uses of the plant material, extra weed growth, more water retention and cultivation demands should be included in such an analysis.

Improve land levelling to decrease distribution losses

Land levelling may increase the current distribution efficiency from 75 to about 85%. This would increase WP_{Reg} in the case of wheat from 0.69 to 0.79 kg m^{-3}, and in the case of cotton from 0.21 to 0.23 kg m^{-3}. Thus, the water savings at the investigated fields are about 10%.

Divide the available irrigation water over more land

Currently, in Sirsa district deficit irrigation is often already applied. The regional analysis (Chapter 7) shows that in case of wheat transpiration relative to the total water used amounts 87% and in case of cotton the relative transpiration amounts 46%. The crop growth analysis (Chapter 5) shows that deficit irrigation has only a minor effect on WP_{ET}. An important condition is that the water shortage is applied at the right time, preferably at the end of the growing season. Only in case of excessive irrigation gains can be expected.

Optimize leaching fraction

Optimizing the leaching fraction is especially relevant in areas with saline and rising groundwater. An optimal leaching fraction for such areas means that leaching is sufficient to maintain an acceptable low salinity level and, at the same time, is as small as possible to prevent groundwater rise. In case of wheat/cotton with critical salt tolerance levels of 6.0 (wheat) and 7.7 dS/m (cotton), the *LF* can be as low as 5% in case of fresh groundwater (*EC* < 1.5 dS/m) and should be 15% in case of moderately saline groundwater (*EC* = 5.0 dS/m) (*Hoffman*, 1990).

Use sprinkling irrigation

Sprinkler irrigation may increase the distribution efficiency and facilitates the attainment of the optimal leaching fraction. Important drawbacks are increased direct evaporation and the high investment and operation costs.

Increase groundwater recharge in monsoon period

Excessive rainwater in the monsoon period might be diverted to permeable, waste lands in depressions or might be brought back into the aquifer using the wells themselves. In this way the damage due to flooding is decreased and the extra water in reservoirs or good quality groundwater recharge can be used for irrigation. In Sirsa district the amount of rainfall ranges from 150 (dry monsoon) to 600 mm (wet monsoon). No hard data are available on the amount of water diverted out of Sirsa in years with wet monsoons. The amount is estimated to be in the order of 100 mm and should be distributed over 3-4 years with smaller monsoons. This means that each year 25 mm fresh groundwater extra is available for irrigation. This amount is a relatively small amount compared to the average amount of canal (362 mm) and tube well water (286 mm). The effect on *WP* in fresh groundwater areas is zero. Also the effect on *WP* in saline groundwater areas will be small as the positive effects of improved irrigation water quality and more water available will be counteracted by increased groundwater levels. Of course, an increased groundwater recharge might have a negative impact on downstream users and therefore, such an option should be analysed at a higher spatial scale than SIC.

More reservoirs and dams

More surface water might be retained in reservoirs and dams and be used for supplementary irrigation. The recently constructed dam in the Ghaggar river near Sirsa serves this purpose. Also this option should be analysed at a higher spatial scale as this will affect downstream water use.

Complete canal lining and increase canal maintenance
Improving canals may increase the conveyance efficiency from the current 65% to 85%. This would increase WP_{Reg} in case of wheat from 0.69 to 0.71 kg m^{-3}, and in the case of cotton from 0.21 to 0.22 kg m^{-3}. The savings at the investigated fields are relatively small, because of the small portion of canal water compared to tube well water.

Organise reliable canal water in saline groundwater areas which prevents water spill
No data are available on irrigation water spill due to unreliable canal water supply.

Optimize conjunctive use of canal and groundwater in saline groundwater areas
In this way the groundwater level rise may be stopped, while the poor quality groundwater is used effectively. Water productivities will increase in waterlogged areas. At the same time the potentially available amount of water for irrigation is enlarged significantly. Care should be taken that sodicity remains below a critical level in connection with the loss of soil structure.

Drainage in waterlogged areas
Waterlogging decreases water productivity severely. In Table 8.1 field 24 has a shallow groundwater level within 1.5 m from the soil surface. In case of wheat at this field WP_{ET} = 0.844 and WP_{Reg} = 0.339 kg m^{-3}, while the average for the 4 sites amounts to WP_{ET} = 1.317 and WP_{Reg} = 0.694 kg m^{-3}. Since waterlogging in Sirsa is associated with salinity problems, reduction in WP for cotton is not manifest as cotton is more salt tolerant. The effects of waterlogging show strong spatial differences as shown in Chapter 9. Therefore, mean values for the four investigated sites can not be given.

Improve water management at secondary level
The secondary level is managed by Haryana Irrigation Department (HID). Currently rostering periods of 3 times 8 days are applied with full canal supply as described in Chapter 2. Smaller flows in the canals are avoided, because the seepage losses increase, siltation may occur and the streamsize may become too small for decent on-farm irrigation (Jacobs and De Jong, 1997). A more flexible supply could be based on local soil physical conditions and crop water demands. Although this is advocated by many crop and water scientists, the implementation effort and costs at secondary level are huge. Besides the physical constraints of the irrigation structures, HID is presently not able to anticipate on supplies and has not the administrative and scientific capability to manage flexible supplies correctly (Jacobs and De Jong, 1997).

Improve water management at tertiary level
The *warabandi* system guarantees that the duration of irrigation is the same for each farmer in a water course. However due to seepage losses tail-end farmers usually get less water than head farmers (Chapter 2). Lining of the water courses would decrease the losses for the tail-end farmers. *Jacobs and De Jong* (1997) asked farmers and HID officials whether they would prefer a more flexible distribution within the water course. Most people pleaded to maintain the warabandi system for practical reasons. Poor infrastructure (seepage losses), political interference and flaws in the execution of designs are the main reasons that water distribution is not as equitable as intended. This is partly solved by current borrowing/lending practices within the water course (*Jacobs and De Jong*, 1997).

Grow more eucalyptus trees to extract excessive water

Eucalyptus trees have a considerable higher transpiration rate than the evaporation rate of bare soil with a shallow groundwater table. In addition the trees may serve as wind breaks, provide shadow and supply wood. Near Sirsa no scientific experiments with eucalyptus trees are known (*Jacobs and De Jong*, 1997). Although eucalyptus are probably not the solution to diminish waterlogging, they may be very effective along canals or in depressions with too much seepage and groundwater rise. In the climate of Sirsa District it is estimated that eucalyptus trees transpire about 500 mm/y more than bare soil with a shallow groundwater table. The average excess groundwater recharge amounts to 10 mm/y (Chapter 9). This means that a certain area of eucalyptus trees may remove the average excess groundwater recharge of an area 50 times as large! In southern Australia clearing of the native vegetation for annual crops and pastures is recognized as a major cause of water logging and secondary salinization. Extensive experiments commenced in 1995 to evaluate the effects of belts of eucalyptus trees, drains and perennial pasture (*Turner and Ward*, 2002; *White et al*., 2002). The experimental results suggest that in southern Australia a combination of belts of trees and perennial pasture can mitigate and even reverse water logging and secondary salinity, while maintaining crop production at near-current levels.

Table 8.3 Water productivities as affected by different measures at the investigated farmer fields.

Measure	WP_{ET}		WP_{Reg}	
	Wheat	Cotton	Wheat	Cotton
Current situation (Table 8.1)	1.32	0.31	0.69	0.21
Management at experimental sites (Table 5.7)[(1)]	2.58	0.58	n.a.	n.a.
Mulching	1.43	0.33	0.72	0.22
Optimal leaching fraction	1.32	0.31	0.74	0.21
Distribution efficiency (from 75 to 85%)	1.32	0.31	0.79	0.23
Conveyance efficiency (from 65 to 85%)	1.32	0.31	0.71	0.22

[(1)] WP_{ET} at experimental sites has been calculated for the cropping period only. All other water productivity values in Table 8.3 include pre-irrigation and a fallow period between the crops.

Table 8.3 summarizes the effects of the proposed measures for which quantitative data are available. If we assume reuse of fresh groundwater, WP_{ET} applies to fresh groundwater areas, while in saline groundwater areas WP_{Reg} denotes the amount of water lost. By far the highest increase of water productivity is expected from improvement of crop management as illustrated by WP_{ET} at the experimental sites. Of the other measures only mulching affects WP_{ET} by about 10%. The effects of an optimal leaching fraction and increase of distribution and conveyance efficiency are relatively small due to the high use of tube well water (84%) compared to canal water (16%) at the investigated fields.

8.6 Concluding remarks

The importance of defining water productivity is illustrated by the different values given in this report. For example in Chapter 5, WP_{ET} is calculated on the basis of the time period between emergence and ripening, whereas others calculate WP_{ET} on the basis of the period between seeding and harvesting. Calculations of WP_{ET} for both of these periods give values of 2.7 and 2.3 kg of DW yield per m^3 of water, respectively. This difference is caused by the additional week before emergence and after ripening, and is of the same order of magnitude as variations between years. The latter, however, can clearly be ascribed to variations in the weather conditions. Differences between *WP*'s in the different chapters are also due to the use of water limited production (Chapter 5) or the actual production (Chapter 5 and 6), where also yield reducing factors such as pests and diseases are included. Calculations of water productivities over longer time periods, where also pre-irrigation and fallow periods (Section 8.4) are included, will give lower *WP* values, too. We suggest strongly to distinguish between water productivities for cropped fields and the use of water for other purposes on the land. Water management as a whole includes cropped and fallow land, but the measures that can be taken to reduce losses of water are different in both situations. Clearly, without appropriately defining water productivity, comparisons between crops and areas can not be made.

The work described refers to one inland catchment or region. If there is a possibility that water be distributed or shared among catchments or regions, calculations in the SYSNET project (*Lansigan*, 2000) have shown that water sharing may be beneficial and improves the water productivity at the higher scale, thus confirming *Seckler et al*. (2001) and *Droogers and Kite* (2001).

The crop growth component in the SWAP/WOFOST model was originally based on an early version of SUCROS (*van Laar et al*., 1997) that, among other things, describes the photosysthesis process rather detailed. This mechanistic way of modelling has the advantage that effects of drought and salt stress may be accounted for in studies such as on water productivity. In our study, however, we have seen a large number of situations where e.g. salt stress was not serious at all. In such cases we could also use the simpler LINTUL approach (Light INterception and UtiLization), where the linear relationship between biomass production and the amount of radiation intercepted by the crop canopy is beneficially used (*Monteith*, 1977; *van Ittersum et al*., 2003): the production of assimilates is summarized in terms of a Light Use Efficiency (*LUE*) that directly converts intercepted light (expressed in photosynthetically active radiation *PAR*) into grams of dry matter (for wheat, for instance, *LUE* is about 3 g of *DM* MJ^{-1} of *PAR*). In the LINTUL approach the model is much simpler, but, of course, the explanatory power is less as compared to the WOFOST approach. If, however, there would not be much salt stress, this approach might be as good as the more complex one. A major advantage would be that the data requirements are significantly reduced as compared to WOFOST. Therefore, LINTUL might form an interesting intermediate between the simple crop model used in SWAP (currently especially used for the calibration process of the soil water model) and the complex Wofost option. LINTUL might also replace the simple crop model used in SWAP, so that a feedback between *LAI* and growth be introduced, which is now lacking. To get an impression about the values and the (in)variability of the *LUE* in the present Wofost model, we used SWAP/WOFOST as if it were an experimental set up and calculated *LUE* values from it. Results showed that *LUE* values were around 3.0 ± 0.4 and 2.5 ± 0.6 g of *DM* MJ^{-1} of *PAR* for potential and water limited aboveground dry matter wheat production, respectively. These figures support the use of the light use efficiency concept at low salinity levels.

9. Future water management in Sirsa district: options to improve water productivity

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Summary

Options for future water management in Sirsa district are explored. water productivity, calculated for different spatial and temporal scales, based on remote sensing and observations, varies substantially between these different scales and between the different terms used in the definition of water productivity. A field scale modelling approach and a regional modelling approach were used to explore the impact of different scenarios on yields, gross return and water productivity. Four scenario have been explored indicating that (i) climate change will have a positive effect, (ii) increased salinity levels will have a negative impact on the performance of wheat and especially rice, (iii) proper irrigation scheduling is more important for wheat than for cotton, and (iv) a rise in groundwater levels will have a detrimental impact in some areas. The key recommendations for future water management in Sirsa, emerging from WATPRO are in summary: (a) construction of a proper drainage system is economically feasible, (b) integrated agronomy-water management programs can enhance yields and water productivity, (c) inter-provincial water rights should be enforced, (d) climate change will alter current water availability, yields and water productivity, (e) groundwater extraction should be reduced by enforced regulation based on variation in rainfall, (f) irrigation application should be reduced.

9.1 Introduction

This chapter will explore options to improve agricultural water management in Sirsa district, with special emphasis on increasing water productivity (*WP*). Techniques, tools, concepts and results from the WATPRO project as described in previous chapters are used to develop and explore scenario options of future conditions.

We will first focus on expanding and integrating data and remotely sensed information with special focus on scale issues (spatial as well as temporal) and on the different definitions of water productivity. Second part will demonstrate how the models developed at field scale can be used to explore options for the future to increase water productivity. This will be expanded in the last section to the regional modelling approach, where four scenarios for future water management will be explored.

9.2 Scale issues in water productivity

We will follow here the general approach to *WP* as outlined in Chapter 1, but will focus somewhat more on scale issues and will also focus more on expressing the *WP* in economic values ($\$ m^{-3}$ in addition to the more classical kg m^{-3}). The economic productivity is more appropriate for comparing different crops or different regions. Obviously, this is blurred by fluctuations in market prices, but is still preferable if ones want to compare different crops. In this chapter we will therefore present *WP* in kg m^{-3} as well as $\$ m^{-3}$.

For the Sirsa district we have selected here to follow the *WP* indicators as applied in similar studies (*Droogers et al.*, 1999; *Droogers et al.*, 2000) and expand these with economic terms (*Murray-Rust et al.*, 2003). In summary the four following definitions of *WP* will be used here:

WP_T = $ / crop transpiration
WP_{ET} = $ / evapotranspiration
WP_{Irr} = $ / irrigation
WP_{Supply} = $ / total water supply

It should be emphasized that not one *WP* definition is the best, but that a combination of the different *WP*s will provide insight in the current situation and how this can be improved. The WP_{Irr} can be very high if a substantial part of the water supply originates from rain. Similarly, WP_{Supply}, which includes rainfall, can be very low in high rainfall conditions, which is not always bad as long as downstream users make use of water not consumed at the field considered. These downstream users are not necessarily farmers but can be industry, urban areas, or the environment as well.

Also ratios between the different *WP* definitions are useful in analysing systems. The ratio between WP_T and WP_{ET} indicates the effectiveness of light interception and photosynthetical activity. Similarly, the ratio WP_{Irr} and WP_{Supply} can provide insight in the regional scale water recycling mechanisms.

Another factor that should be considered is the variation in *WP* with scale. It might be clear that *WP* of an irrigation system differs from that of the entire basin comprising several agro-ecosystems. Also, the water productivity of one growing season will differ from other seasons (and years). This temporary scale relates thus to the prevailing weather conditions and is for this study important as the period of analysis, 2001-02, was below average (188 mm against a longer term average of 367 mm).

For this chapter we will use the following spatial and temporal scales:

- spatial scales
  - Sirsa district (1)
  - Divisions (4)
  - Calculation Units (2404)
  - Pixels (4308939)
- land cover scale
  - entire area
  - cropped area
  - per crop
- temporal scales
  - one year
  - rabi
  - kharif

9.3 Water productivity under current conditions: the remote sensing approach

9.3.1 Linking remote sensing and models

Over the last decade advances in remote sensing (*RS*) from satellites have resulted to practical applications of *RS* in water resources research and applications (*Droogers and Kite*, 2002). In the early days of *RS*, images were mainly used qualitative, but increase in accuracy of sensors, and especially a better understanding of processes, have evolved in the development of quantitative algorithms to convert raw data into useful information.

In the context of the WATPRO study the main focus was on integrating remote sensing technology with numerical simulation models. Although a strict calibration and validation process was not performed, the simulation models were to a fine-tuned using the *RS* actual evapotranspiration estimates.

In Chapter 6 the concepts of the SEBAL algorithm as used to derive actual evapotranspiration and crop yields have been described in detail and results were presented for Sirsa. In the same chapter a first water productivity analysis was presented as well, but mainly concentrating at the field (in fact pixel) scale and only considering the WP_{ET} which is based solely on actual evapotranspiration. In the following sections this will be expanded to different spatial scale levels and different definitions of *WP*. Some of these *WP*s require additional information based on observations, which will be discussed first.

9.3.2 Components of water productivity

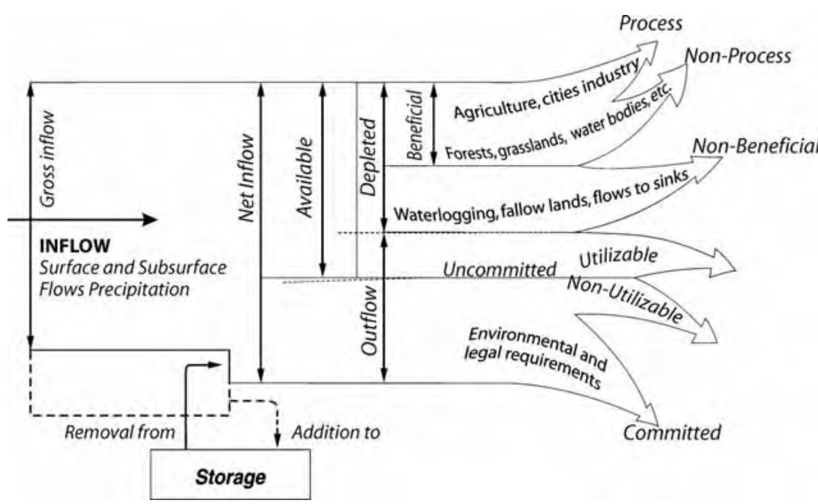

Figure 9.1 Concept of Water Accounting to be used to express the water term in Water Productivity according to *Molden and Sakthivadivel* (1999).

The first step in deriving water productivity is to assess all the components of the water balance for Sirsa at different spatial scales. Although this seems to be a straight-forward task, quite some assumptions and analysis were required to obtain this information. In terms of benefits from water use we consider for Sirsa that this can be represented by the crop yields. Some additional benefits have been excluded to keep the methodology transparent but one can think about: straw used for animals, drinking water for people and cattle, small vegetable plots, fruit trees, etc. In other areas these additional benefits are huge and should be included such as environmental benefits (*Torabi et al.*, 2002) or grazing lands and forests (*Droogers and Kite*, 2001). The following components are required over different spatial scales for the full water productivity analysis: precipitation, canal water use, groundwater use, actual evapotranspiration, and crop yields. As emphasized by *Molden* (1997) important in the water productivity analysis is that the different categories of water used, such as process, non-process and non-beneficial depletion and committed and uncommitted outflow, will be distinguished (Fig. 9.1).

Precipitation

Reliable rainfall records were only available for Sirsa meteorological station. The period considered, December 1, 2001, to November 31, 2002, was dry, with only 188 mm of precipitation. The year 2001 was wetter with 392 mm in total. Although spatial variation in precipitation occurs the total contribution of rainfall to crop growth is relatively low, especially for 2002, so we can assume that the Sirsa data can be used to represent the entire study area.

Canal water use

The inflow from surface water was obtained by using measurements from a total of 18 streamflow gauges. Proper accounting was done by extracting outflows from canals from inflows, to get only the real amount of water applied to Sirsa district (Table 9.1). The appropriate spatial scale on which sufficient data was available was at the division level, and four divisions can be distinguished in Sirsa Circle: Rori, Sirisa, Ghaggar and Nehrana Water Service Division.

Table 9.1 Stream gauges used to determine canal in- and outflows for the four divisions in Sirsa. Sign + indicates inflows and sign – indicates outlows.

RWSD	SWSD	GWSD	NWSD
+ RD 100 BMB	+ BMB (outletsin SWSD)	+ RD-115	+ Bigar Fall
- Head Mamerkhera	+ Head Mamerkhera	+ RD-54 SKC	+ Sharanwala P/C
- Head Rori Branch	+ Head Rori Branch	+ Mangala Direct mr	- Tail Baruweli
- Phaggu dis	+ Phaggu dis	+ NGC old	
- BMB (outletsin SWSD)	- Head Ottu Fdr	+ N.G.C P/C	
- Tail JandwalaShare/ RD 432 BMB	+ Ottu fdr (outletsin SWSD)	+ Head S.G.C	
		- Tail S.G.C	

Streamflow gauges are very sensitive to measurement errors and it is well documented that a whole range of factors can hamper accurate estimates. For this specific case, where inflows and outflows have to be combined, accuracy is even more problematic.

During the period 1977-1990 the annual canal water supply was more than $2200 \cdot 10^6$ m^3, with a range of $1720\text{-}2623 \cdot 10^6$ m^3 (*Jhorar*, 2002). Even in the driest year in this period, 1984, canal water supply was still $1720 \cdot 10^6$ m^3, which is still higher than the $1484 \cdot 10^6$ m^3 found for the 2002-2003 period as can be seen in Table 9.2.

Table 9.2 Water balance for the entire Sirsa district and the four divisions for *rabi* and *kharif* 2001-02, using the original groundwater extraction estimates. Values reflect the entire area: cropped as well as bare soil. Data are based on observations and remote sensing.

	mm	10^6 m^3
Precipitation	188	772
Canal Inflow	362	1484
Groundwater Inflow	97	400
Total Inflow	647	2656
Evapotranspiration	876	3595
Balance	-229	-940

Important in the discussion of canal flow are the seepage losses, which have been estimated between 15 and 30% for Sirsa (*Agarwal and Roest*, 1996). Other values can be found as well, but more important is to have a detailed look at what will happen with the water that is considered to be “lost”. In Sirsa groundwater irrigation is a common practice and although some lateral flow occurs, most of the water that is pumped originates from “losses” from these main canals, but also from secondary and tertiary canals as well as from percolation. In other words, these “losses” are reused to a certain extent and should be considered as such. In some parts of Sirsa groundwater is too saline and unsuitable for irrigation. Leakage, leaching and percolation to the groundwater should then be considered as true losses in these areas. For the moment we assume that all the water that is “lost” by seepage from the canals, is reused through groundwater irrigation and should not be considered as a loss. This assumption is in principle only valid if we estimate groundwater use as net use. If the total amount of water pumped is used, double counting occurs and seepage losses should be subtracted from the canal water use.

Groundwater use

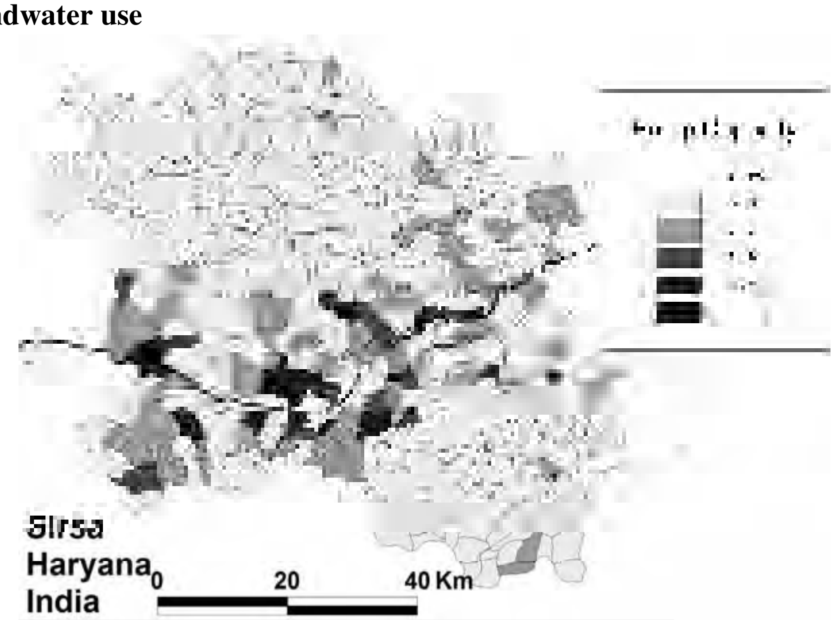

Figure 9.2 Installed pump capacity per village.

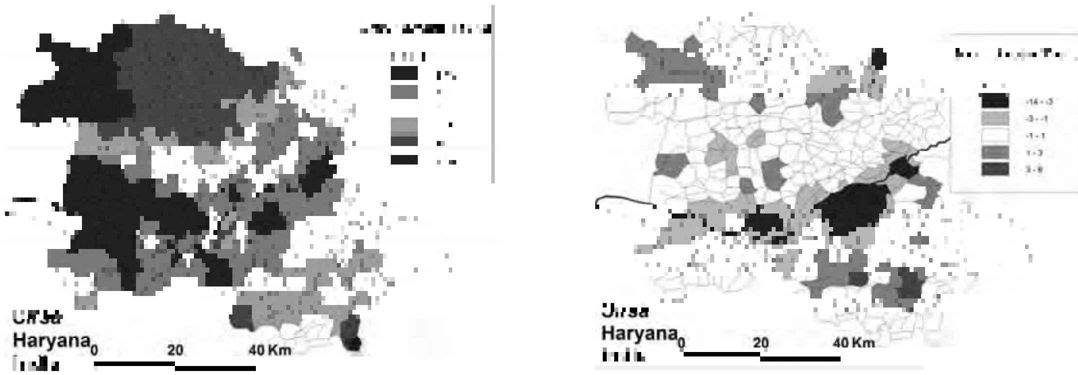

Figure 9.3 Trend in observed groundwater depths for the period October 1990 – October 2000 (left), and October 1999 – October 2000 (right). Negative (blue) figures indicate declining levels, positive (red) indicate rising levels. Note the difference in scale of the two maps by a factor 10 (m $10y^{-1}$ vs. m y^{-1}).

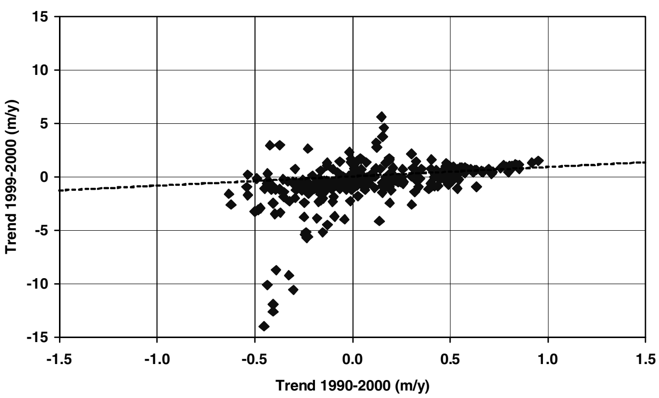

Figure 9.4 Comparison between the 10 year and the 1 year observed groundwater trends. Note the factor 10 in scales between X and Y-axis.

On a global scale, groundwater is increasingly becoming an important source for irrigated agriculture, as pumps are affordable and assessable to many farmers nowadays. Shortage of surface water and unreliable delivery are also factors that boost investments in pumps. This trend is also visible in Sirsa and the installed capacity is estimated at $11{\cdot}10^6$ m^3 d^{-1}, which corresponds to 2.5 mm d^{-1} over the entire area. Obviously, this capacity is not fully utilized and estimates based on observations and interviews show that about 10% of the time pumps are actually used (*Roelevink*, 2003), which means that the annual groundwater pumping is $400{\cdot}10^6$ m^3, which translates to about 100 mm annually over the entire Sirsa (4104 km^2). According to the groundwater atlas of district Sirsa (2002), the annual groundwater discharge is $300{\cdot}10^6$ m^3. Considering an average cropped area of about 75% (3042 km^2) leads to an average amount of groundwater applied to the crops of 130 mm. However, huge spatial differences exist in terms of installed pumping capacity as can be seen from Fig. 9.2. The data from Fig. 9.2 do not match with the location of the rice growing regions (see Chapter 6) which is somewhat unexpected.

Similarly to the discussions about the losses from canals, irrigation by groundwater will also have losses by leaching and percolation. However, it is expected that these losses will be much lower. A couple of reasons can be given for this: groundwater is more expensive than canal water so farmers will manage this water with greater care; groundwater is demand-driven, while canal water is supply driven; groundwater comes generally at a lower flow rate

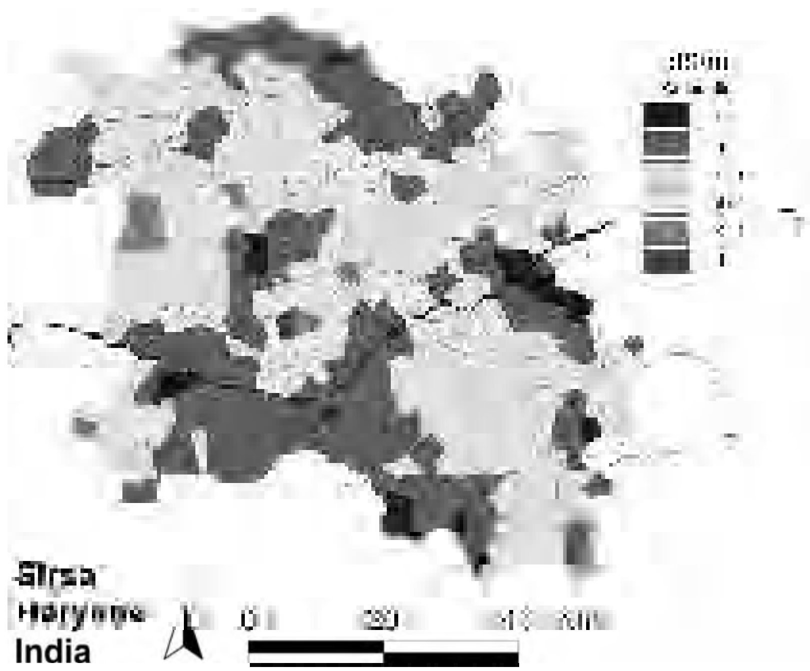

Figure 9.5 Observed salinity levels of groundwater.

than canal water. To examine this we can also estimate the net groundwater use by looking at groundwater levels. Average groundwater levels for the entire Sirsa were in October 2000 9.92 m below surface, while in October 1999 this was 9.42 m, so a decline of 50 cm in one year. Considering a specific yield of about 15% means that the net groundwater use was about 90 mm, which is close to the estimate based on the pump capacity and pump usage.

Interesting is that the average annual change in groundwater levels over the last 10 years shows an upward trend of 9 cm y^{-1}. So it is clear that the drought in 2001-02 has brought down the average groundwater level much more than the long term trend (Fig. 9.3 and 9.4). Interesting is that this long-term trend of rising groundwater levels of 9 cm y^{-1}, (translated to about 13 mm y^{-1} water supply, assuming a specific yield of 15%), is close to the drainage requirement estimated by *Agarwal and Roest* (1996). *Boonstra et al.* (1996) concluded after an intensive numerical groundwater modelling study of the Sirsa area estimated the net groundwater inflow to be 59 mm y^{-1}. One of the main unknown factors in this respect is the impact of regional groundwater flows in the region.

Surprisingly, there seems to be no correlation between the changes in groundwater levels and salinity of the groundwater. One would expect that in areas with saline groundwater less pumping would occur, while areas having groundwater of good quality pumping would show overdraft (Fig. 9.5).

A spatial plot of changes in groundwater levels shows a clear trend that water levels are going down in the central part of Sirsa along the Ghaggar River, while a rise in groundwater levels, so risk of water logging, can be observed in the Northern and South-Eastern part of the region. No correlation can be seen comparing these changes with a map of salinity levels of the groundwater (Fig. 9.6). Salinity levels are for most areas lower than 4 dS m^{-1}, which is about the limit for irrigation, and more saline groundwater seems to be randomly distributed.

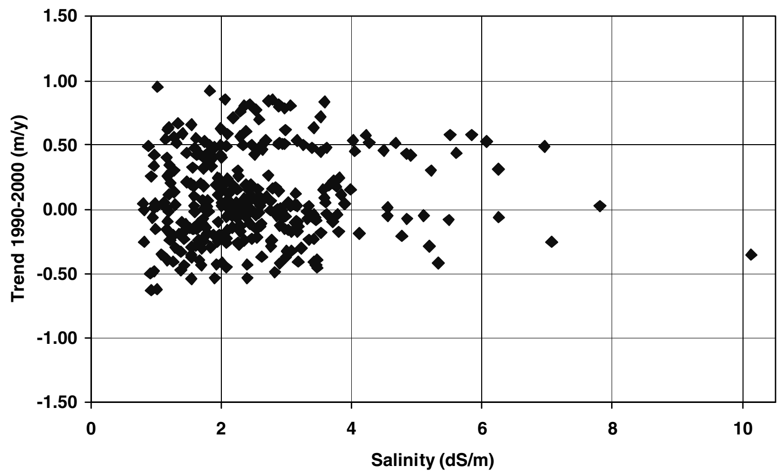

Figure 9.6 Correlation between average observed groundwater changes over the last 10 years and groundwater salinity levels.

Evapotranspiration

The actual evapotranspiration rates were determined using the SEBAL approach, which is based on solving the energy balance using remotely sensed images from satellites. Details of this approach can be found in Chapter 6. For Sirsa evapotranspiration was determined using Landsat-7 ETM for detailed land cover classification and 12 NOAA-16 images were used to measure the energy balance. Some generalizations have been applied as described in Chapter 7, which includes mainly a simplification of the land cover classification. Therefore, results presented here can slightly deviate from those of remote sensing (Chapter 6). Main reason for this generalization of the remote sensing results is to follow a consistence approach with the regional modelling activities as described in Chapter 7. Besides the generalization, we have also applied a cloud removal procedure to ensure a full coverage for comparison with model results.

Crop yields

The SEBAL algorithm includes also the option to estimate biomass production, which was converted to harvested (=fresh) yield, in order to derive the effective harvest index *HI*. Details of this approach are described in Chapter 6. Since the model analyses are based on a simplified cropping pattern as described in Chapter 7, the remotely sensed obtained yields were adapted to this simplified cropping pattern resulting in slightly different yield figures as presented in Chapter 6.

9.3.3 Water balance

The terms of the water balance as discussed in the previous sections are combined in Table 9.2 for the entire Sirsa district as well as for the four districts. It is clear that the balance is not closed and for Sirsa district as a whole more than 200 mm is not accounted for. In terms of reliability the most uncertain parameter is, by all means, the groundwater inflow. Although the two independent methods discussed (net pump capacity and changes in groundwater levels), result in similar groundwater extraction rates, farmer experiments as described in Chapter 2 have shown that groundwater use is much higher.

The groundwater inflow based on the installed pumping capacity multiplied by correction factors for time of use might be too low for two reasons. During a dry year, the usage factor of 10% is probably much higher and more in the order of 20-30%. Second, the installed pumping capacity is often underestimated since farmers tend to conceal pumps in fear of governmental restrictions or tax. We assume here that this 20-30% is the net inflow, so actual pumped minus percolation, and that net regional groundwater flow is negligible.

The groundwater use estimates based on the average levels in October 1999 and October 2000 do not coincide with a dry year neither do they include regional groundwater flows. A rough estimate might therefore be that also this figure is about 2-3 times too low for the period considered in this study (2001-02).

Considering these points we assume that the installed pump capacity is for 30% used during the *rabi-kharif* 2001-02 period. Table 9.3 and Fig. 9.7 show that using these more realistic values the water balance error for the entire Sirsa is in the order of 40 mm. This error can have several reasons, such as: inaccuracy in data, regional groundwater flow, changes in storage in the unsaturated zone. Water balances for the four districts separately, show clearly the trend of a surplus of water for the Rori division and a water shortage for the Ghaggar district. Obviously, these differences are visible in the net groundwater trends as shown in Fig. 9.3.

Table 9.3 Water balance for the entire Sirsa district and the four divisions for *rabi* and *kharif* 2001-02. Values are based on the corrected groundwater extraction rates (see text). GWSD is Ghaggar, NWSD is Nehrana, RWSD is Rori, and SWSD is Sirsa Water Service Division. Values reflect the entire area: cropped as well as bare soil areas. Data are based on observations and remote sensing.

	Sirsa mm	Sirsa 10^6 m^3	GWSD mm	NWSD mm	RWSD mm	SWSD mm
Precipitation	188	772	188	188	188	188
Canal Inflow	362	1484	256	267	593	265
Groundwater Inflow	286	1174	492	290	134	325
Total Inflow	836	3430	936	745	915	778
Evapotranspiration	876	3595	999	820	857	878
Balance	-40	-166	-63	-75	58	-100

9.3.4 Water productivity for the entire Sirsa district

From the matrix of water Productivities considered in this study (Chapter 9.2) the entire Sirsa district will be discussed here in detail. In this section we will concentrate on using measurements combined with Remote Sensing, next section will be focused on water productivity analysis, including options for the future, based on simulation models.

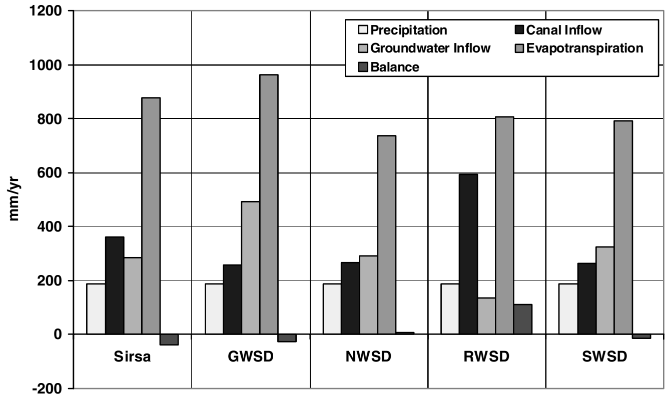

Figure 9.7 Terms of the water balance for the entire Sirsa Irrigation Circle as well as the four divisions: GWSD is Ghaggar, NWSD is Nehrana, RWSD is Rori, and SWSD is Sirsa Water Service Division. Data are based on observations and remote sensing.

Table 9.4 shows the complete calculation procedure, where different time and spatial scales are considered. In terms of time, a distinction is made between the entire year, only *rabi* and only *kharif*. In terms of spatial scale cropped vs. total area is considered. If we look at the range of all the *WP*s than we find values from 0.09 to 1.12 kg m^{-3}, and from 0.04 to 0.15 \$ m^{-3}. Which one to be used depends on the question to be answered and more often a mix of a few will provide information about the system as explained before.

Table 9.4 Water productivity estimates based on observations and remotely sensed evapotranspiration and yield for the entire Sirsa district (*rabi* and *kharif*) and for only cropped area (Wheat, Rice, Cotton). Cropped areas are based on the cropping pattern as used with the regional modelling approach.

	Year	**Rabi** (entire area)	**Wheat** (cropped area)	**Kharif** (entire area)	**Rice** (cropped area)	**Cotton** (cropped area)
Area (km2)	4104	4104	3042	4104	1076	1966
ET_a (mm)	876	311	344	565	702	585
ET_a STD (mm)	210.0	74.7	78.7	151.1	138.2	95.7
Crop (kg/ha)	N/A	N/A	3546	N/A	3830	574
Crop STD (kg/ha)	N/A	N/A	798	N/A	1809	373
Crop (10^6 ton)	N/A	N/A	1.078	N/A	0.412	0.113
Crop (10^6 \$)	249	147	147	102	51	52
P All (mm)	188	11	11	177	177	177
P All (10^6 m^3)	772	45	33	726	190	348
Canal (mm)	362	91	123	226	305	305
Canal (10^6 m^3)	1484	373	373	927	328	599
Pump (mm)	286	143	193	143	193	193
Pump (10^6 m^3)	1174	587	587	587	208	379
Total Inflow (mm)	836	245	327	546	675	675
Total Inflow (10^6 m^3)	3430	1005	993	2240	726	1327
WP ET (kg/m3)	N/A	N/A	1.03	N/A	0.55	0.10
WP ET (\$/m3)	0.07	0.11	0.14	0.04	0.07	0.04
WP Inflow (kg/m3)	N/A	N/A	1.09	N/A	0.57	0.09
WP Inflow (\$/m3)	0.07	0.15	0.15	0.05	0.07	0.04
WP Irrigated (kg/m3)	N/A	N/A	1.12	N/A	0.77	0.12
WP Irrigated (\$/m3)	0.09	0.15	0.15	0.07	0.09	0.05

All the *WP*s of cotton are low in comparison to other data presented in previous chapters as a result of the low average yields. Observations from the farmer fields show average yields of

1850 kg ha^{-1}, and according to the original results from the remote sensing analysis about 2000 kg ha^{-1}, while Table 9.4 shows 574 kg ha^{-1}. This low value is a result of the simplified cropping pattern used for the regional modelling as followed here. Likely, areas not under cotton according to the RS crop classification, are considered here as cotton. These areas have a low biomass growth and therefore a low cotton yield. According to the original crop classification is 435 km^2 covered by cotton, while the simplified classification assumes 1966 km^2.

In general, *WP*s expressed in kg m^{-3} are useful in comparing the same crop over different regions, years, or scenarios. *WP*s in \$ m^{-3} are better in comparing different crops, but are also a function of market prices and thus can differ between years and between regions. In order to compare the different areas in Sirsa district the total gross return was calculated based on yields multiplied by price per crop. Following *Hellegers* (2003), the following prices were used:

- rice, 5.8 Rs kg^{-1} ~ 0.123 \$ kg^{-1}
- wheat, 6.4 Rs kg^{-1} ~ 0.136 \$ kg^{-1}
- cotton, 21.5 Rs kg^{-1} ~ 0.457 \$ kg^{-1}

Using these market prices for each field (pixel of 30 x 30 m) the gross return has been calculated (Fig. 9.8), which is used in the water productivity calculation.

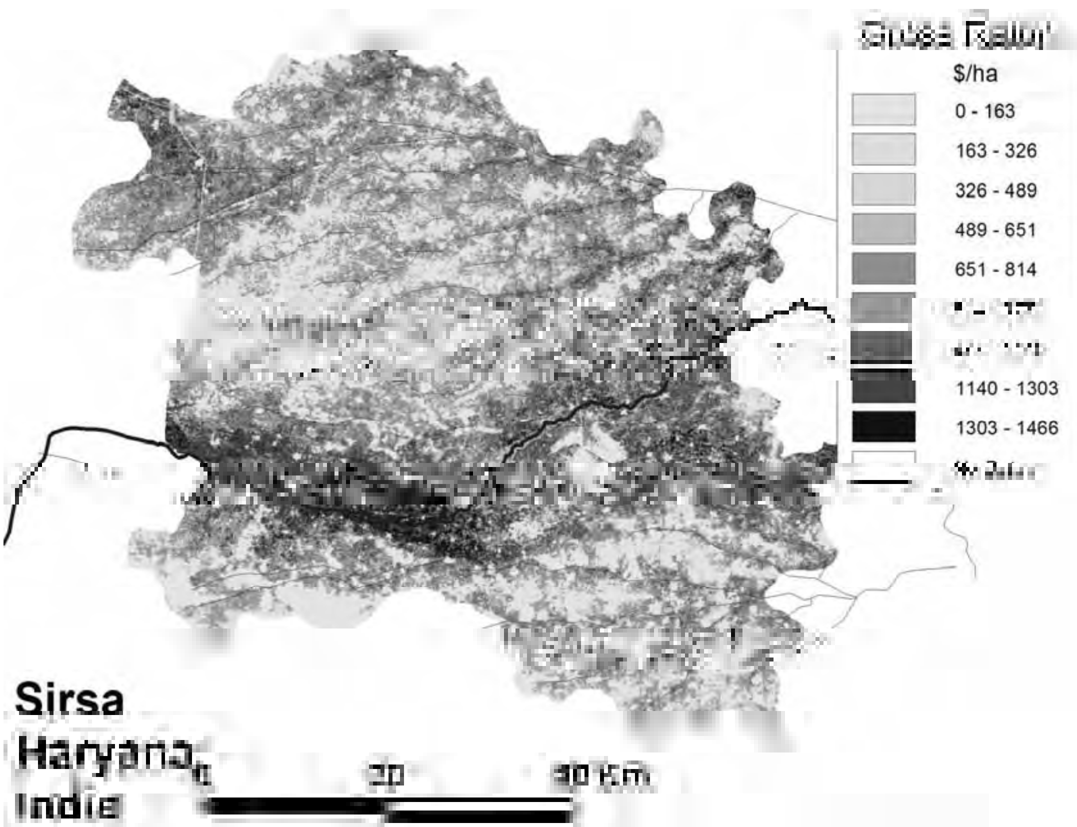

Figure 9.8 Gross return based on crop production (derived from SEBAL results) and crop market prices. Period included is Rabi and Kharif 2001-02.

The differences between the 3 *WP*s (WP_{ET}, WP_{Irr}, WP_{Supply}) are small here. Main reason is that an entire region is used for which the water balance is almost closed. The term inflow is based on net inflow, while gross inflow will be much higher. Difference between these two is reuse of drainage water, percolation, and seepage. From the observations and remote sensing results these data are not obtainable, but will emerge from modelling as will be discussed in the next section. Also, WP_T is not obtainable from RS, since the distinction between crop transpiration and soil evaporation requires specific detailed measurement techniques. Alternatively, simulation models can provide estimates of these factors.

The WP_{ET} is the best indicator on how the system as a whole functions, since this factor is based on the actual water consumed, which is an integrated term of all the water processes in a system (see Chapter 1). Some water used for field preparation is included in the ET, but most of this water will be reused, as discussed before. If we consider the entire year and area and the three crops distinguished this value is 0.07 \$ m^{-3}. In other words: every m^3 water used in Sirsa district will generate \$ 0.07 in the agricultural sector. There exists however a big difference between the three major crops: 0.14, 0.07 and 0.04 \$ m^{-3} for wheat, rice and cotton, respectively. These values are in the same order as given by *Hellegers* (2003): 0.18, 0.05, and 0.09 \$ m^{-3}, respectively. The difference in cotton originates most likely from the simplified cropping pattern used here (see Chapter 7), where the cotton area has been overestimated.

Fig. 9.9 shows the impact of spatial scale on the WP_{ET}. It is clear that the field scale and the calculation unit scale show almost identical patterns, even while there is a big difference in number of elements considered: 4,308,939 fields (pixels) vs. 2404 calculation units.

9.4 Options to increase water productivity: the modelling approach

The simulation models as described in previous Chapters serve two purposes: (i) understanding the current situation and processes and (ii) explore options for the future. Understanding the current situation and processes includes also a detailed analysis of performance assessment for the different crops, farms, regions, etc., which is helpful in defining possible options or scenarios for the future. Strictly speaking there is a difference between scenarios and options, where a scenario is somewhat more a projection of the future which cannot be easily altered (climate change, population growth, economic growth), while options are seen as responses to these changes (water allocation, cropping patterns). We will use here a mixture of scenarios and options for the future, and concentrate on four factors that might change in the future or that can be used as measures to improve water productivity:

- changes in groundwater level *(field and regional)*
- changes in salinity level of irrigation water *(field and regional)*
- changes in irrigation applications *(field)*
- climate change *(regional)*

Obviously more scenarios and options can be defined, but these four factors should be considered as the most relevant ones as outlined in Chapters 1 and 2. These four scenarios function also as an example on how others can be analysed as well.

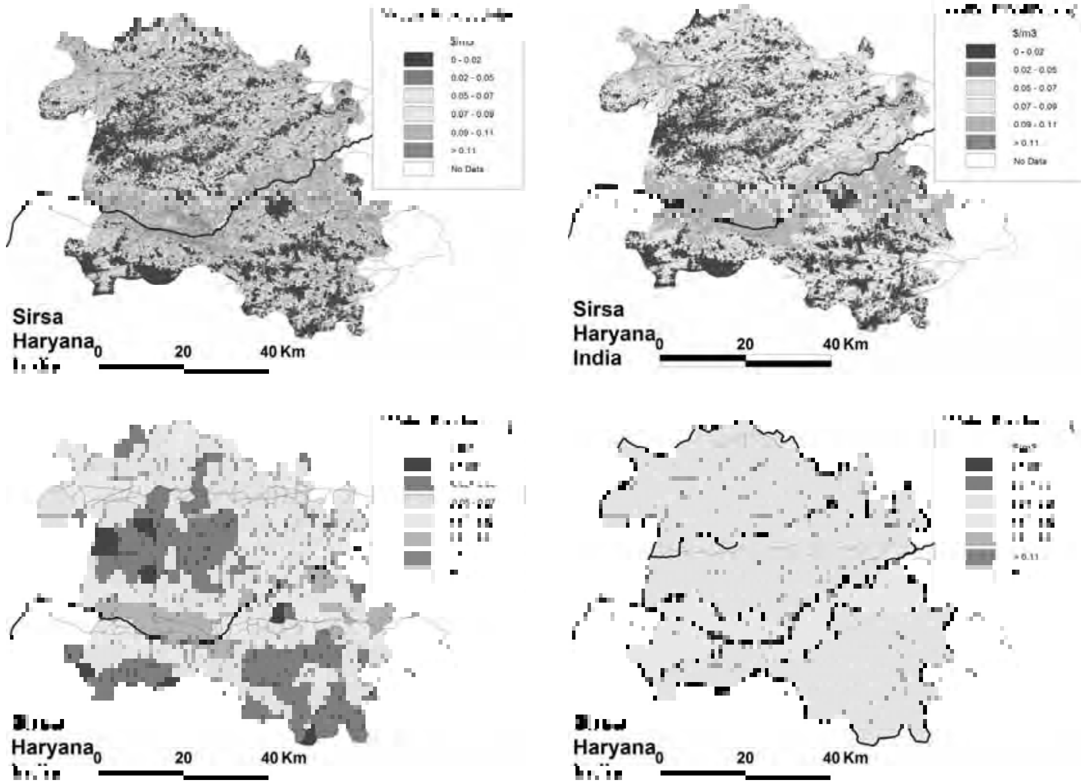

Figure 9.9 Water Productivity, expressed as gross return ($) per amount of water consumed (m^3) for four spatial scales: field (top-left), calculation unit (top-right), village (bottom-left), and irrigation district (bottom-right). Period included is *rabi* and *kharif* 2001-02 and are based on measurements and SEBAL analysis.

Ideally, these scenarios should be analysed with the full regional model as presented in Chapter 7. However, since one model run takes about 10 hours, only three scenarios were analysed at the regional level: (i) an overall increase in groundwater level of 2 meters, (ii) wetter conditions by taking climatic data of 1995, and (iii) a doubling of salinity levels of irrigation water. The second scenario does not reflect only the conditions as in 1995, but reflects more what could happen if climate change will occur and climate will become wetter.

These three scenarios were implemented in the regional modelling set-up by the following approaches:

- **Climate change.** The year 1/11/1994 – 1/11/1995 was simulated (a precipitation of 441 mm, in stead of 188 mm).
- **Rising groundwater tables.** In the reference situation 36 of the 324 villages, or 10 % (36856 ha) of the whole area, has an average water table within 4 m below the soil surface. The average groundwater table at village level was raised by 2 meter, which implied that 101 of the 324 villages, or 25 % (98746 ha) of the area, have an average water table within 4 m.
- **Increasing salinity.** Salinity of groundwater was doubled with a maximum of 10 dS m^{-1}, by changing the concentration of the groundwater at village level.

For one field, farmer field 16 as described in Chapter 4, changes in groundwater level, salinity level of irrigation water and depth of irrigation applications have been analysed for a range of changes. So, for the regional analyses only one change was considered, while for one field an entire range was used.

All analyses are based on the calibrated SWAP-WOFOST combination as described in detail in Chapter 5 and in Chapter 7 for the regionalization. It should be emphasized again that SWAP-WOFOST is able to generate potential and water limiting yields, but limitations as a consequence of nutrients or management are not included as such. As shown in Chapter 5, the difference between the water limited yield and the actual one is, especially for wheat, substantial. In Chapter 5 statistical relationships have been used, derived from farmers' field observations, to include other than water limitations. For practical reasons, we have included these limitations directly in the WOFOST parameters as explained in Chapter 7.

9.4.1 Field scale scenarios

Fig. 9.10 shows for the three scenarios considered what the impact is on yield and water

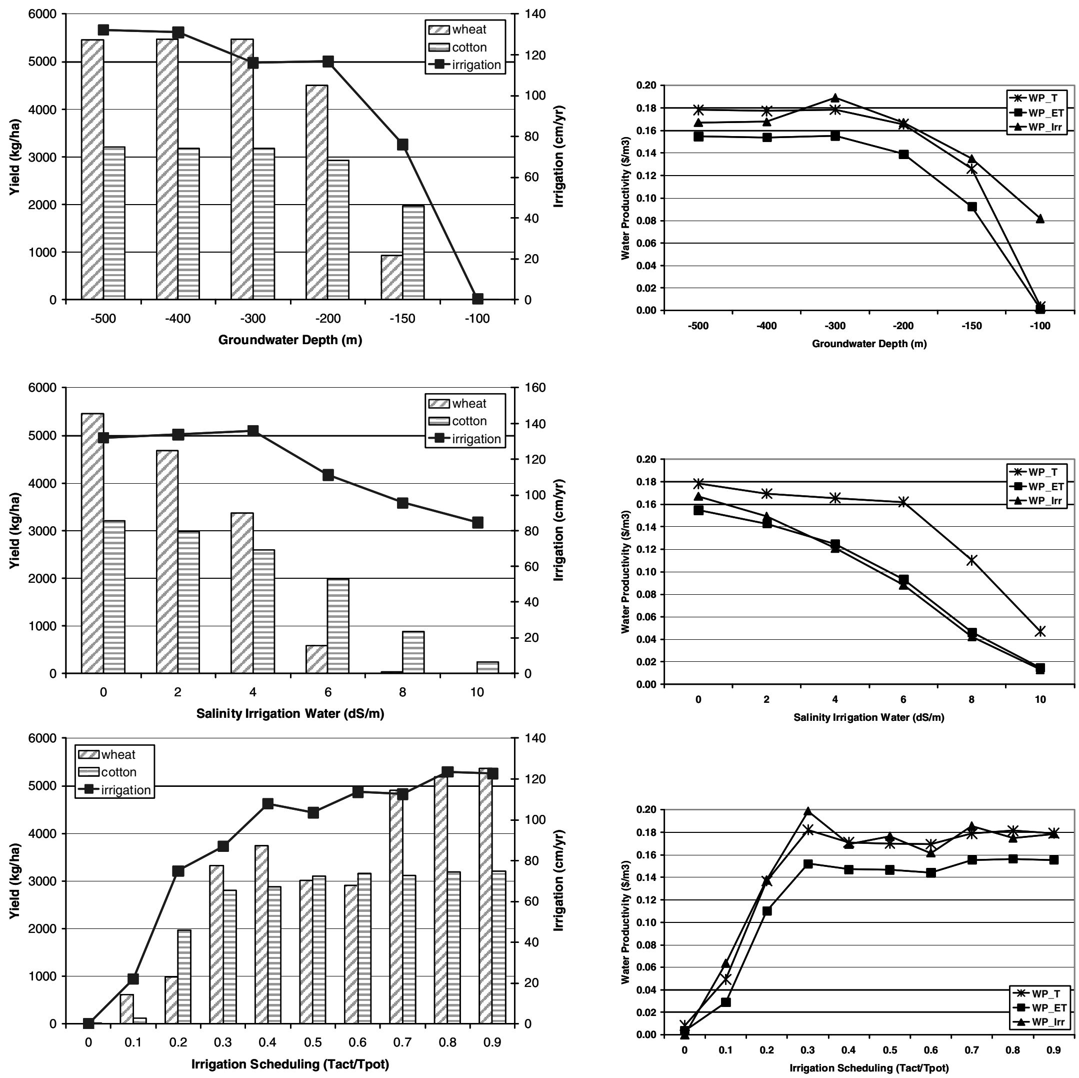

Figure 9.10 Impact of changes in groundwater depth (top), salinity (middle) and irrigation depth (bottom) on yields (left) and water productivity (right). Results are obtained using SWAP-WOFOST for farmer field 16.

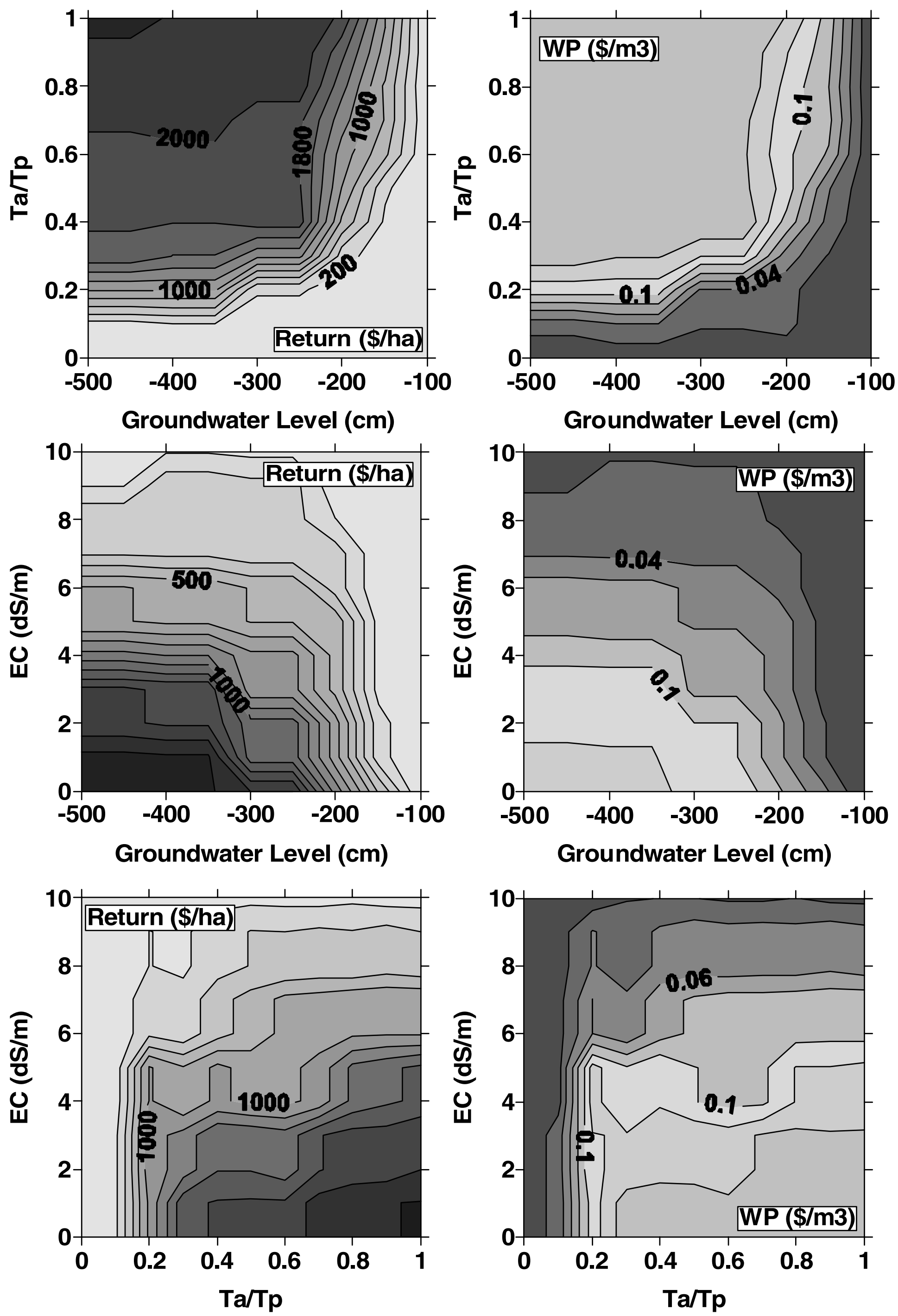

Figure 9.11 Scenario analysis of the combined effect of changes in groundwater depth, salinity level of irrigation water and irrigation scheduling on yields (left) and water productivity expressed as WP_{ET} (right). Results are obtained using SWAP-WOFOST for farmer field 16.

productivity. It is clear that an increase in groundwater level has no impact on yield as long as the water table depth is lower than about 200 cm. High water tables decrease the irrigation demand, but will at the same time have a negative effect on yield and on water productivity. Exception on this is the WP_{Irr} which will be highest at groundwater levels of about -300 cm.

Salinity levels of irrigation water have a strong impact on wheat and a moderate impact on cotton. The impact on rise, not analysed here, will be even more adverse. Somewhat surprisingly, the irrigation demand is reducing under increasing salinity levels, while the general understanding is that higher salinity levels require higher application rates for leaching purposes. However, since SWAP-WOFOST was set-up to automatic irrigation scheduling the likely positive impact of leaching was not considered. Moreover, the long term positive impact of leaching was not explored here since the simulations were performed over one year only. A more in-depth analysis of these long-term effects can be found elsewhere (*Droogers et al.*, 2001).

Finally, if we look at yields as function of irrigation applications it is clear that wheat is more sensitive to lower irrigation applications than cotton. The well-documented positive benefits from deficit irrigation do not emerge from this analysis as can be seen from the WP_{ET} graphs. Only a slightly higher WP_{ET} is found at irrigation levels of 850 mm y^{-1} (reached at T_{act} / T_{pot} = 0.3), while for the rest WP_{ET} is constant. It is not clear whether this is a result the way SWAP-WOFOST deals with water stress or whether this is a result of specific local conditions.

Obviously, the combined impact of changes in these three factors has to be considered as well. Fig. 9.11 shows the interaction of these factors on yield as well as on WP_{ET}. These figures are a nice example how complex modelling efforts can be translated to swift scenario interpretation. Water managers can directly see what the impact will be from a certain impact or decision on yields as well as water productivity.

Some examples how these figures can be used:

- If the groundwater level is between -300 and -500 cm the T_a/T_p is an important factor to change yields and WP_{ET}. Under shallow groundwater conditions this factor is of minor importance.
- Salinity levels exceeding 4 dS m^{-1} restrict the limit of the water productivity to a maximum of 0.10 \$ m^{-3}, whatever other factor will be altered.
- A more intense irrigation scheduling than 0.3 (T_a/T_p) will hardly increase water productivity, while for maximizing yields no limit exists.

9.4.2 Regional scale scenarios

The SWAP-WOFOST regional modelling approach as described in Chapter 7 will be used here to demonstrate the possibility to analyse scenarios. As mentioned previously, scenarios should be considered here as changes that might happen in the future as well as possible options to improve water management.

The first scenario considered here was what would happen if the climate will change. The Intergovernmental Panel on Climate Change (IPCC) projections for the year 2100 are consistent in that temperatures for the North-West of India will increase substantially. However, it is not clear what exactly is going to happen with precipitation, but there is some consensus amongst the seven Global Circulation Models included in the IPCC that precipitation will increase in Jun-Jul-Aug. A full analysis of these IPCC projections is beyond the scope of this study, but we have focused here on using climate data of the year 1995 to represent the expected wetter climate.

The second scenario assumes a rise of groundwater levels over the entire area of 2 meters. Such a scenario will indicate what would happen in the long run if no additional drainage will be installed and current practice of irrigation will continue. This scenario is a clear example of a management decision referred to as "business as usual": do nothing and let the system function as it did over the last decades.

Finally, the last scenario is clearly a management option at higher levels: what will happen if irrigation water will be used more intensively with the consequence of an increase in salinity levels. Such a management decisions can be within the Sirsa district, but has clearly a link to upstream irrigation systems. For this scenario we assumed that the current salinity levels will be doubled, with a maximum threshold value of 10 dS m^{-1}. To keep the scenario transparent we assume that this doubling of salinity will take place in canal as well as groundwater.

An overview of the results of the scenario analysis for the entire Sirsa district can be found in Table 9.5. As discussed in Chapter 7 the simplified land cover and cropping calendar provide results that are somewhat different from the actual conditions found in Sirsa. However, the difference between the reference situation simulated and the scenarios simulated indicates the impact a scenario will have in reality. In other words, the relative difference is more accurate than the comparison between model and reality.

Table 9.5 Scenario analysis at regional scale as determined using the SWAP-WOFOST regional approach.

	Reference	Climate	Groundwater rise	Salinity increase
ET (mm ha^{-1})	736	680	712	716
Wheat (kg ha^{-1})	6484	7822	6175	6353
Rice (kg ha^{-1})	4595	5195	4219	1951
Cotton (kg ha^{-1})	1916	2405	1758	1831
Gross Return (10^6 $)	501	608	469	453
WP_T ($ m^{-3})	0.26	0.34	0.26	0.25
WP_{ET} ($ m^{-3})	0.17	0.22	0.16	0.15
WP_{Irr} ($ m^{-3})	0.15	0.18	0.14	0.13

The climate change scenario, here implemented by using climate data from 1995, has a positive effect on Sirsa. ET goes down, yields will increase and WP_{ET} will increase as well. One factor not included will have an even more positive impact: elevated CO_2 levels. Despite this apparent positive impact of climate change, extremes will increase putting a lot of stresses on water management (*Droogers and Aerts,* 2003). Moreover, increased temperature will increase evapotranspiration that will have an adverse impact on surface runoff which will affect the canal water availability.

A rise in groundwater levels, considered as a major threat to some areas, will have a negative impact on yields and thus total gross return, but WP_{ET} is hardly affected. The same holds for the increase in salinity levels.

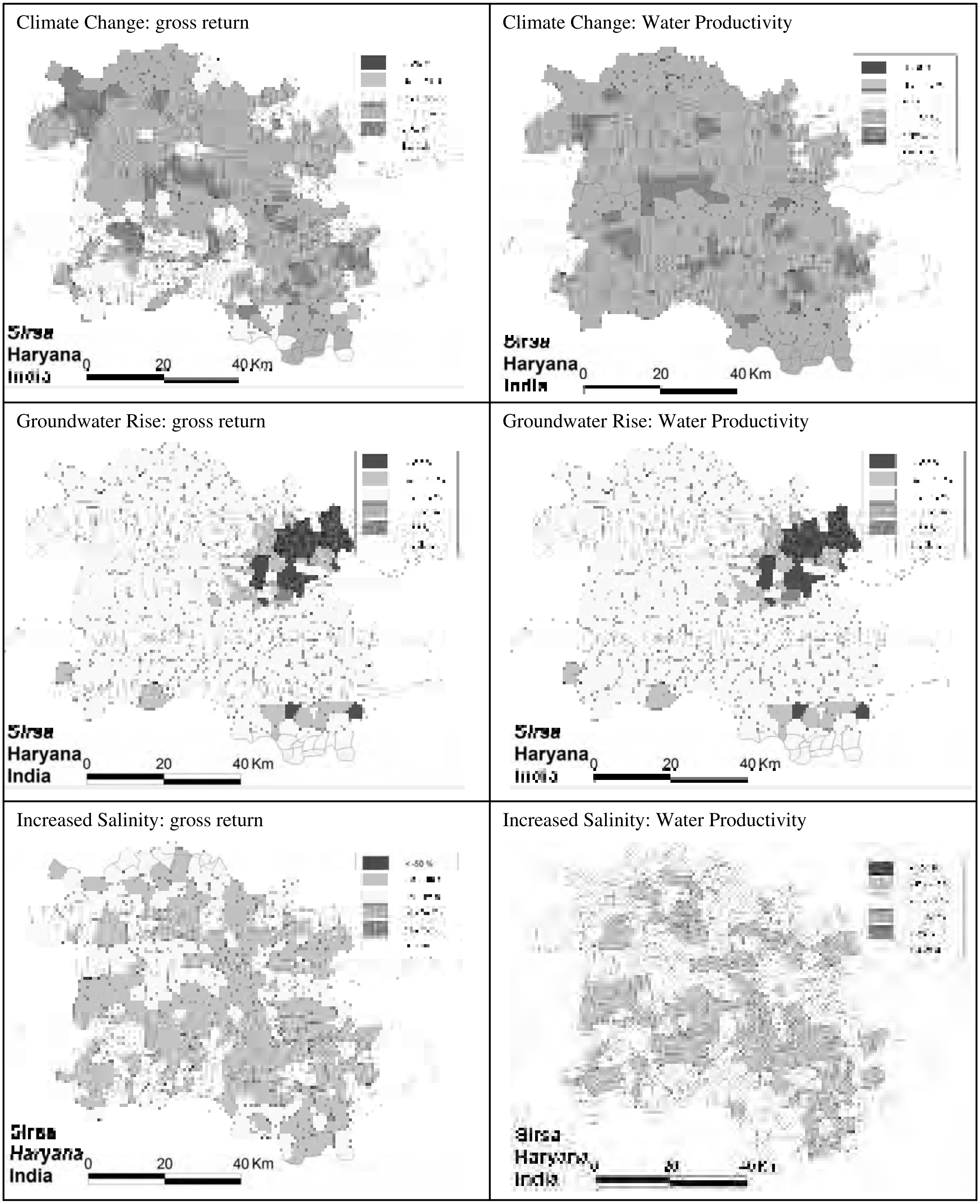

Figure 9.12 Scenario analysis and its impact on gross return (left) and water productivity (right). *WP* is expressed here gross production over ET (WP_{ET}). Values indicate changes in percentages taking the reference as presented in Figure 9.15 as base.

Looking at the entire Sirsa district (Table 9.5) can provide a biased picture and therefore we have plotted at village level these changes taking the reference simulation as base. Fig. 9.12 depicts these regional differentiations in terms of gross return as well as WP_{ET}. Climate change will increase gross production for a substantial number of villages between 10-50%. Some villages will have an increase lower and some will have an increase in gross production of over 50%. WP_{ET} will increase for all villages by more than 10%, and for some villages even more than 50%.

A rise in groundwater has a very negative impact on the north-east region of Sirsa district as well as on some villages in the south (Fig. 9.12). Gross return and WP_{ET} will decrease in some villages with more than 50%. No negative impact on the rest of Sirsa district is simulated as the groundwater level is deep and an increase of 2 meter has no impact on yields. What is not included in the scenario is the positive impact on pumping costs, but since electricity is cheap this effect will be negligible. The Figure is a nice example that averages for larger areas are not providing the right information and downscaling to smaller units is essential.

The increase in salinity levels of irrigation water shows for about half of the villages a decrease in gross return and in WP_{ET} in the order of 10-50%. The villages affected the most are those where rice production is dominant. A logical decision would be to minimize rice production in areas under salinization hazard.

9.5 Overall conclusions and recommendations

9.5.1 Conclusions from the remote sensing analysis

The overall objective of the remotely sensed based water productivity analysis is to assess the current situation, as reflected by the *rabi – kharif* 2001-02 season. We have demonstrated that different spatial and temporal scales should be considered, as well as the different definitions for water productivity.

It was clear that in terms of the three crops included in the analysis, water productivity of wheat was highest, followed by rice and cotton. Interesting is that differences in water productivity between these three crops are substantial.

More interesting is of course what the dominant factors are that determine these differences, since this will be a first step in recognizing options for improvement. Fig. 9.13 explores at calculation unit level for four factors whether any relationship exists between the gross return and these factors. Somewhat surprisingly, no relationship appears to exist. Even while a visual comparison of the maps indicates some kind of trends. A look at Fig. 9.8 for example shows clearly that gross returns are higher closer to canals, but in the scatter plot (Fig. 9.13 bottom-right) no relation can be found.

A reason might be that the distribution of sizes of calculation units is very irregular with a huge dominancy of small calculation units. Therefore, the four factors that are likely to affect the performance of the system are also plotted at village level. Fig. 9.14 shows that water productivity at village level is clearly a function of the installed pumped capacity, the salinity level of groundwater and the distance to the nearest canal. Interesting is that the depth of groundwater determines only to a lesser extent the water productivity.

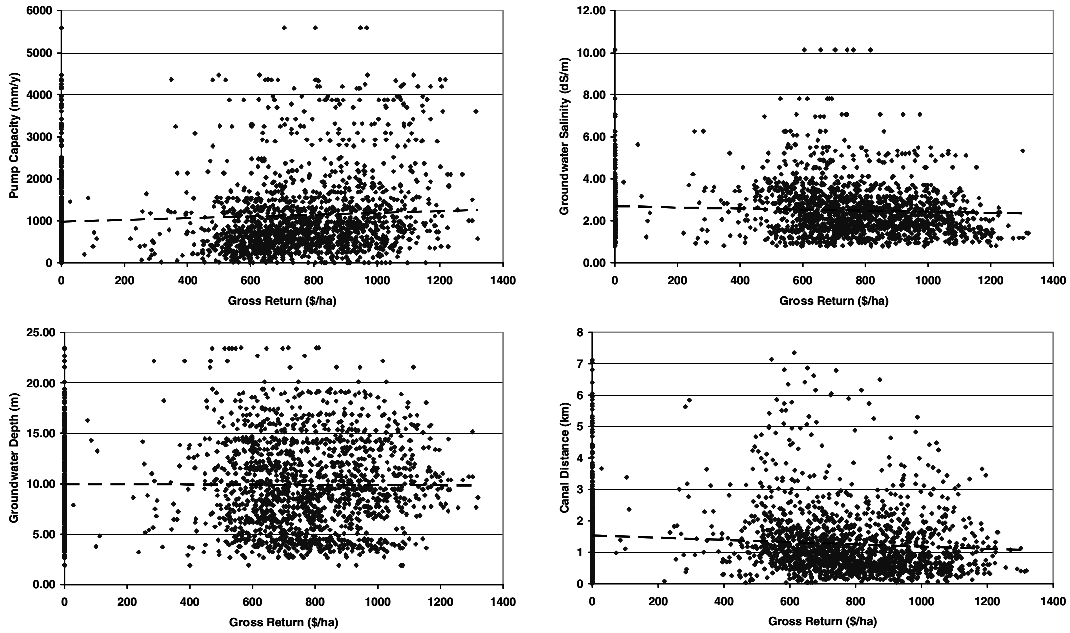

Figure 9.13 Correlation between gross return and pump capacity (top-left), groundwater salinity (top-right), groundwater depth (bottom-left) and distance to nearest canal (bottom-right). Analysis are based on calculation unit level using observations and remote sensing.

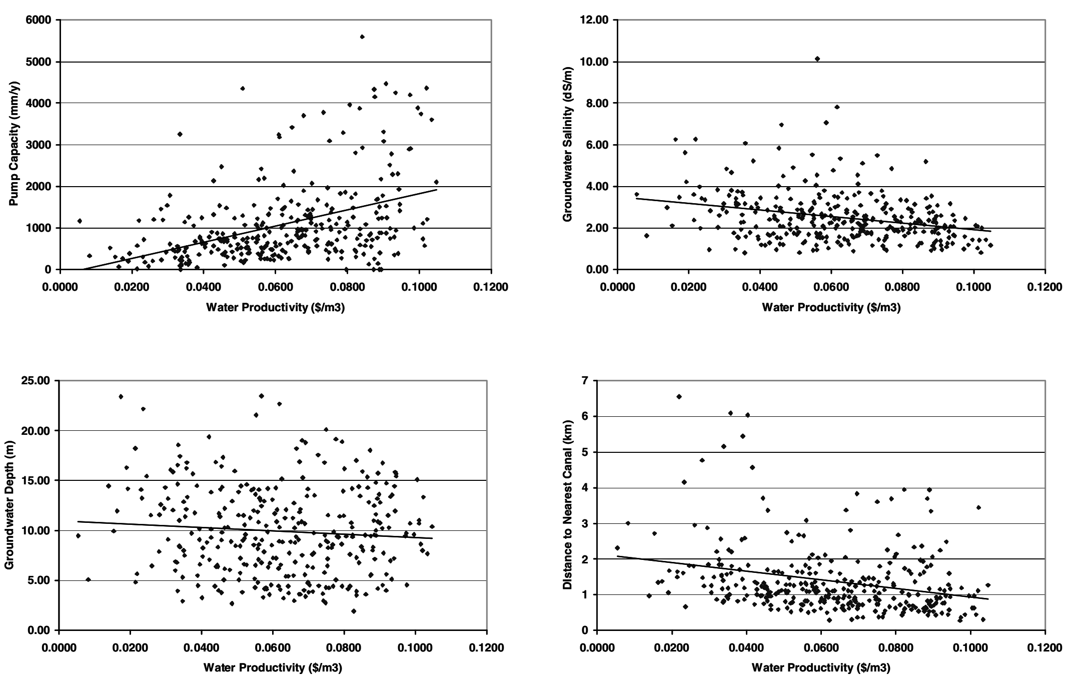

Figure 9.14 Similar to Figure 9.11 but based on village scale.

9.5.2 Conclusions from the modelling analysis

From a conceptual point of view a modelling study is essential if one would like to perform scenario analysis. In this study we have looked at field as well as regional modelling approaches, where the field model was very suitable in exploring scenarios in terms of gradual changes. The regional modelling provided the required spatial impact of scenarios.

In terms of scenarios we have not only focussed on managerial ones, those that can be influenced by farmers or water managers in the region, but we have included also scenarios describing likely changes in the future.

The following key conclusions can be drawn from the model scenario analyses:

- The model package developed can study cause-effect relationships at all desirable spatial and temporal scales, and can be used to construct simple analytical relationships between for instance soil salinity, depth to the groundwater table and water productivity.
- The canal water distribution in Sirsa district is not equal and parcels located in the vicinity of irrigation canals have higher Water Productivities. This implies that groundwater cannot compensate for shortages of canal water supply, and that more emphasize on the allocation of canal water resources should be given.
- There is a yield gap for wheat, but not for rice and cotton. Hence, agronomical research should boost the potential yields for rice and yield and improvements in water management has the potential to increase yields of wheat.
- The critical groundwater level is 2 meters, shallower levels will have a negative impact, as this is in Sirsa district linked with saline groundwater.
- Salinity levels of irrigation water first will have a negative impact on rice, than wheat and finally on cotton.
- Providing sufficient irrigation is more important for wheat than for cotton.
- Climate change will have a positive impact on yields, gross returns and water productivity, but variation between years will be more pronounced. It should be considered that we have focussed here on the precipitation component of climate change, ignoring temperature and CO_2 effects.

9.5.3 Recommendations

water productivity in Sirsa district is in general high, expressed in kg ha^{-1} as well as \$ ha^{-1}. In contrast to many other regions the water productivity for rice is substantially lower than for wheat and the question arises why farmers are eager to grow rice. Obviously, farmers are less interested or focused on water productivity, but more on \$ ha^{-1}. Even in that case rice is still not very profitable (*Hellegers*, 2003) while at the same time rice is more sensitive to diseases, droughts and more labour intensive.

From the methodological point of view the calculation unit approach is useful for the regional modelling, but not very useful for further analysis. The units as defined in this study are too diverse in size and have a huge dominancy by very small units, which might be overcome by using weights based on areas per calculation unit. The approach of scaling-up the results from the calculation units to the village scale has proven to be an essential step.

Groundwater is one of the weakest links in terms of data. From the water balance approach followed here, a reasonable estimate of the net groundwater use over larger areas can be obtained. Groundwater is not the dominant factor in determining the water productivity, but the distance to the nearest canal is the most important one.

The WATPRO study reveals that the combination of remote sensing (RS) and simulation models is strong and that results from RS supports the modelling substantially. This holds true for the actual evapotranspiration estimates, but more importantly, RS was employed to obtain dry matter production as well as land use information and cropping patterns.

A rather substantial amount of conclusions and recommendations emerge from the WATPRO study as described in the previous and this chapter. Here we will repeat only those key recommendations (in summary) that are essential for the future of agriculture in Sirsa district:

- The current gross return for Sirsa is 501 million dollar per year, and this can decrease to 469 and 452 million dollar in cases that rising groundwater tables continues and salinity deteriorates the soil fertility. This implies that drainage investments with a ballpark cost assessment of 30 to 50 million dollars per year are economically worth pursuing.
- There is a considerable gap in water productivity and yields between experimental plots and farm fields, but also between farm fields. An integrated agronomy/water management program should be launched to bridge this gap in water productivity and yields. The agronomical component should focus on practical options, such as earlier sowing, and good nutrient, pest and disease management. The water management component should focus on improving the agro-hydrological growing conditions.
- Sirsa is situated at the end of the Bhakra Irrigation system and water deliveries are therefore sensitive to upstream extraction rates. It is recommended to make inter-provincial water quota to ensure livelihood and combat future climate changes.
- Climate change is projected to increase precipitation, temperatures, evapotranspiration, CO_2 levels, and extremes, leading to a mix of positive and negative aspects on yields and water productivity. Increasing the crop water productivity is a means to keep pace with the agricultural production with these changes in water resources.
- Excessive pumping should be avoided in order to keep groundwater as a natural storage to be used during dry periods. Pricing of water can not be used as instrument, but enforced regulation based on the variability of rainfall is the appropriate method to achieve this.
- Irrigation scheduling based on more detailed information about evaporative demand may result in reduction of water use. This is difficult to achieve for the canal water irrigation since this is based on the Warabandi system, but it possible for groundwater irrigation. Proper real-time information systems and focussed extension services are the appropriate implementation measures.

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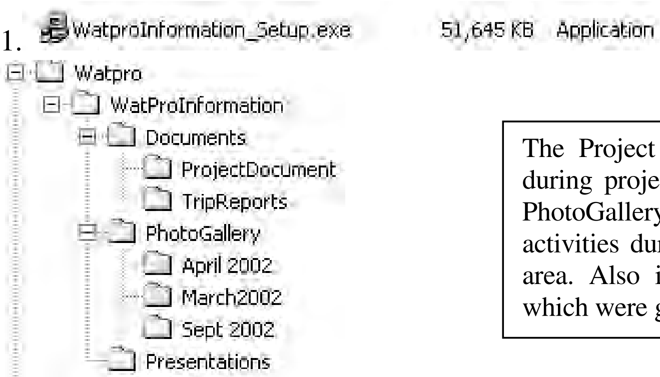
Appendix A. The structure and contents of the CD-ROM

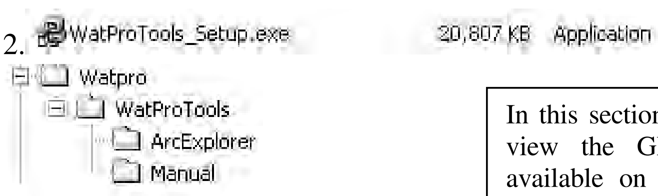
The CD-ROM contains 7 SETUP.EXE files, which after activating will install the folders described below on the directory C:\Watpro of your computer.

1.



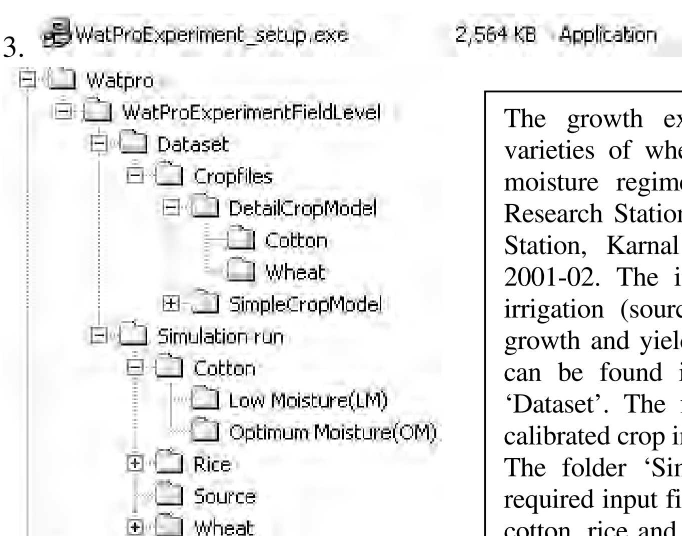
The Project document and reports of visits during project are given in this section. The PhotoGallery provides a view of different activities during the project and of the study area. Also it includes various presentations which were given during the project.

2.



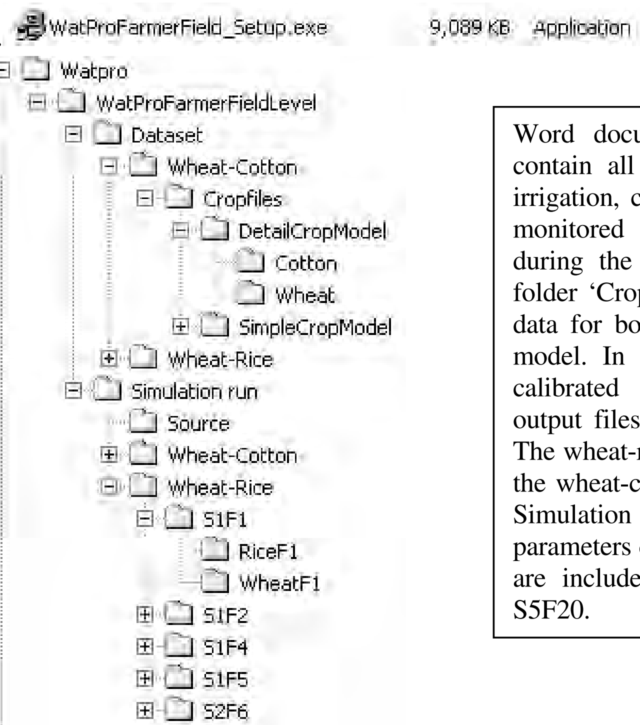
In this section ArcExplorer can be installed to view the GIS information of the project available on the CD-ROM. The manuals of SWAP and WOFOST and the theory of SEBAL are given in pdf format.

3.



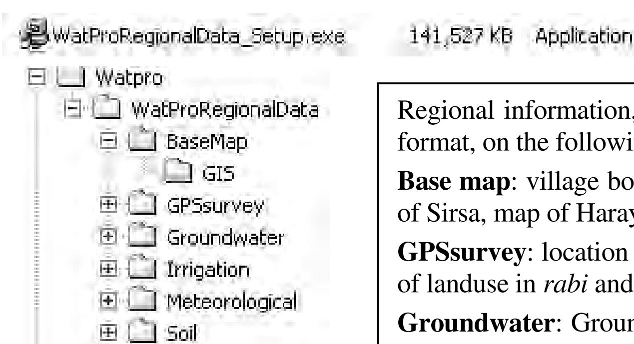
The growth experiments for different crop varieties of wheat, cotton and rice at various moisture regimes were conducted at Cotton Research Station, Sirsa and Regional Research Station, Karnal during the agricultural year 2001-02. The information on soil properties, irrigation (source, amount and quality), crop growth and yield, fertilizers, etc. of these trials can be found in Word documents in folder 'Dataset'. The folder 'Cropfiles' contains the calibrated crop input files for SWAP-WOFOST. The folder 'Simulation run' contains all the required input files to run SWAP-WOFOST for cotton, rice and wheat under different moisture regimes.

4.



Word documents in the folder 'Dataset' contain all information on soil properties, irrigation, crop growth and yield, of the 24 monitored farmer fields in Sirsa district during the agricultural year 2001-02. The folder 'Crop files' contains the model input data for both the simple and detailed crop model. In the folder 'Simulation run' the calibrated SWAP-WOFOST input and output files for 16 farmer fields are given. The wheat-rice rotation contains 5 fields and the wheat-cotton rotation contains 11 fields. Simulation runs using soil hydraulic parameters derived by pedotransfer functions are included at fields S3F11, S4F16 and S5F20.

5.



Regional information, either supplied in spreadsheets or GIS format, on the following topics:

Base map: village boundaries, main roads, railway and cities of Sirsa, map of Harayan and India with states and districts.

GPSsurvey: location of farmer fields, ground truth collection of landuse in *rabi* and *kharif* season of 2001-02 in Sirsa.

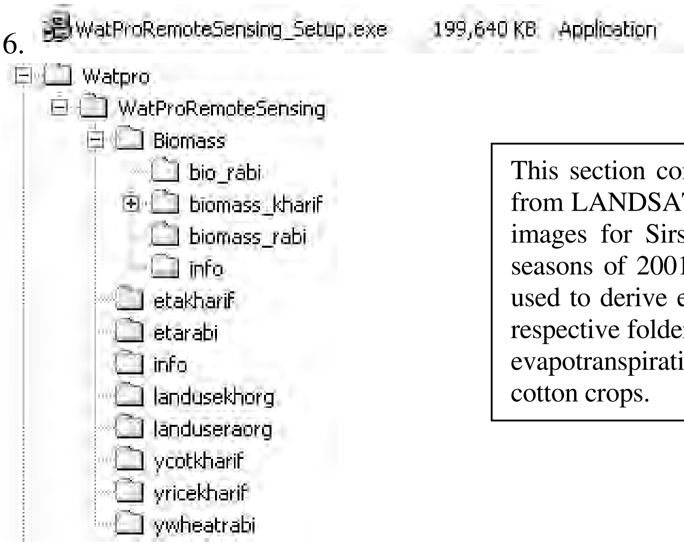
Groundwater: Groundwater depth at 164 observation points for the years 1984-2000; groundwater quality for the period 1984-95; number of tube wells per village in the years 1996-98; tube well depth and discharge capacity.

Irrigation: Canal sections of SIC; canal supply for each canal for the years 1993, 1996, 1997 and 2001; total canal inflow and outflow in SIC from 1990 to 2001; Ghaggar river flow rates measured at the Ottu Weir from 1990 to 2001.

Meteorology: Meteorological data from 1990 to 2002 collected at ICAR Cotton Research Station, Sirsa and CCS HAU, Hisar; rainfall data (1990-2002) of six rain gauges in SIC. A Fortran program to convert sunshine hours to solar radiations using the Angstrom formula.

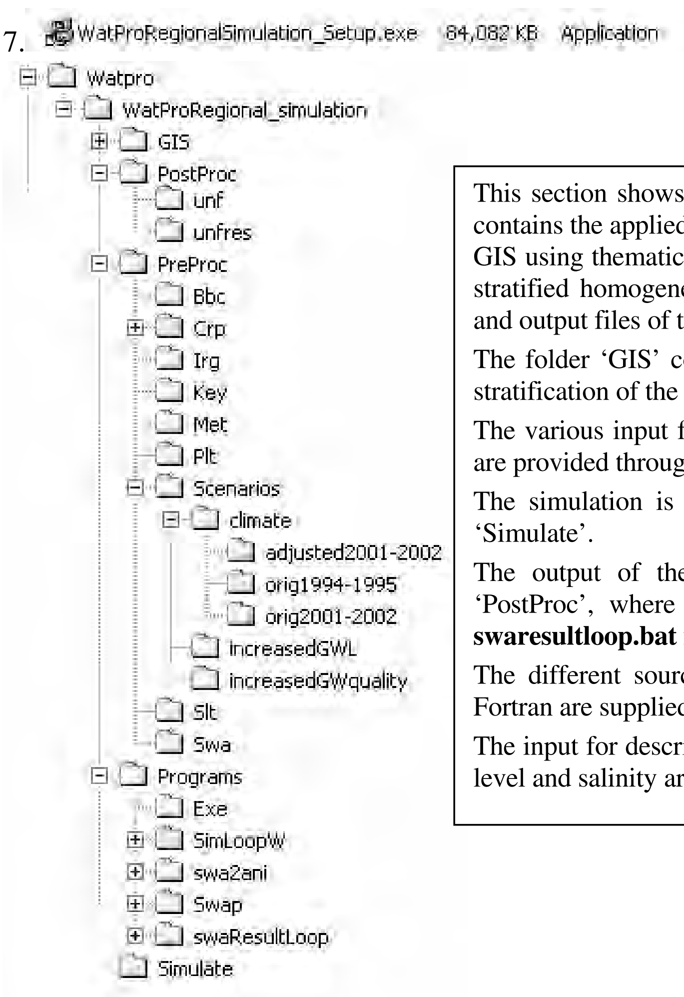
Soil: A digital soil map based on a soil survey in Sirsa district by *Ahuja et. al.* (2001).

6.



This section contains the remote sensing information from LANDSAT (30x30 m) and NOAA (1.1x1.1 km) images for Sirsa district during the *rabi* and *kharif* seasons of 2001-02. The algorithm SEBAL has been used to derive evapotranspiration and crop yield. The respective folders contain landuse classification, actual evapotranspiration, and crop yields of wheat, rice and cotton crops.

7.



This section shows the setup for the regional analysis. It contains the applied stratification of homogeneous units in GIS using thematic maps of study area, and simulation of stratified homogeneous units on regional scale. Also in- and output files of the regional analysis are included.

The folder ‘GIS’ contains the thematic maps used in the stratification of the study area.

The various input files for SWAP on regional simulation are provided through preprocessing in folder ‘PreProc’.

The simulation is launched by **simloopw.bat** in folder ‘Simulate’.

The output of the simulation is stored in the folder ‘PostProc’, where results can be prepared by running **swaresultloop.bat** from folder ‘unfres’.

The different sources along with the program script in Fortran are supplied in the folder ‘Programs’.

The input for described scenarios of climate, groundwater level and salinity are given in folder ‘Scenarios’**.**

Appendix B. SEBAL Evapotranspiration

The primary basis for the SEBAL model is the surface energy balance as illustrated in Fig. B.1. The instantaneous ET_{act} flux is calculated for each pixel of the image as a 'residual' of the surface energy budget equation:

$$ET_a = R_n - G - H \qquad \text{(B.1)}$$

where ET_a is the latent heat flux (W/m^2), R_n is the net radiation flux at the surface (W/m^2), G is the soil heat flux (W/m^2), and H is the sensible heat flux to the air (W/m^2).

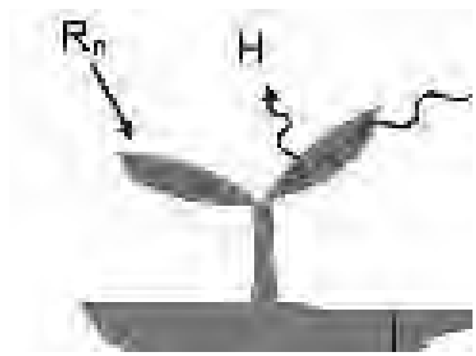


Figure B.1 Surface energy balance.

Net radiation R_n represents the actual radiant energy available at the surface. It is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes (Fig. B.2). This is further specified in the surface radiation balance equation:

$$R_n = R_{s\downarrow} - \alpha R_{s\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1 - \varepsilon_0) R_{L\uparrow} \qquad \text{(B.2)}$$

where $R_{S\downarrow}$ is the incoming short-wave radiation (W/m^2), α is the surface albedo (-), $R_{L\downarrow}$ is the incoming long wave radiation (W/m^2), $R_{L\uparrow}$ is the outgoing long wave radiation (W/m^2), and ε_o is the surface thermal emissivity (-).

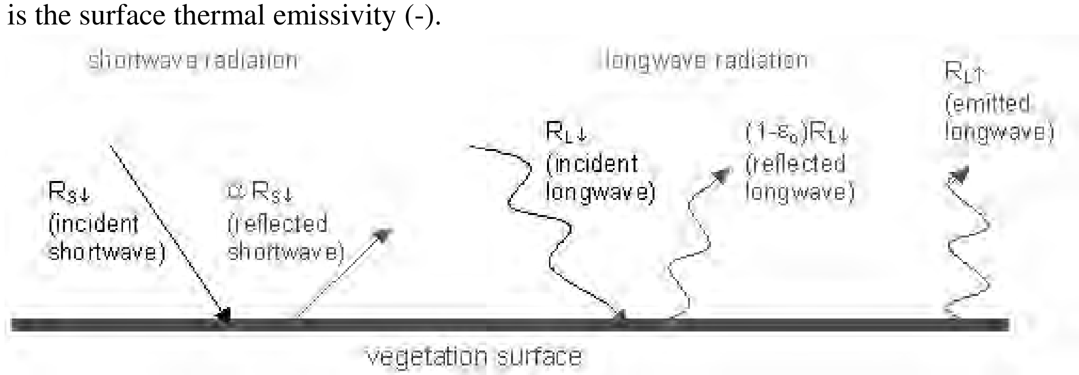


Figure B.2 Surface Radiation Balance

In Eq. B.2, the amount of net short-wave radiation ($R_{S\downarrow}$ - $\alpha R_{S\downarrow}$) that remains available at the surface, is a function of the surface albedo (α). The broad band surface albedo α is derived from the narrow band spectral reflectances $\alpha(\lambda)$ measured by each satellite band. The incoming short-wave radiation ($R_{S\downarrow}$) is computed using the solar constant, the solar incidence angle, a relative earth-sun distance, and a computed broad band atmospheric transmissivity.

This transmissivity can be estimated from sunshine duration or inferred from pyranometer measurements (if available). The incoming long wave radiation ($R_{L\downarrow}$) is computed using a modified Stefan-Boltzmann equation with an apparent emissivity that is coupled to the shortwave atmospheric transmissivity and a measured air temperature. Outgoing long wave radiation ($R_{L\uparrow}$) is computed using the Stefan-Boltzmann equation with a calculated surface emissivity and surface temperature. Surface temperatures are computed from the satellite measurements of thermal radiances.

In Eq. B.1, the soil heat flux (G) and sensible heat flux (H) are subtracted from the net radiation flux at the surface (R_n) to compute the 'residual' energy available for evapotranspiration (λE). Soil heat flux is empirically calculated as a G/R_n fraction using vegetation indices, surface temperature, and surface albedo. Sensible heat flux is computed using wind speed observations, estimated surface roughness, and surface to air temperature differences that are obtained through a sophisticated self-calibration between dry ($\lambda E \approx 0$) and wet ($H \approx 0$) pixels. SEBAL uses an iterative process to correct for atmospheric instability caused by buoyancy effects of surface heating.

The λE time integration in SEBAL is split into two steps. The first step is to convert the instantaneous latent heat flux (λE) into daily λE_{24} values by holding the evaporative fraction constant. The evaporative fraction EF is:

$$EF = \frac{\lambda E}{R_n - G} \tag{B.3}$$

Field measurements under various environmental circumstances have indicated that EF behaves temporally stable during the diurnal cycle. Since $EF \sim EF_{24}$, i.e. the 24 hour latent heat flux can be determined as:

$$\lambda E_{24} = EF\, R_{n24} \tag{B.4}$$

For simplicity, the 24 hour value of G is ignored in Eq. B.4, which is especially true for a longer time scale. The second step is the conversion from a daily latent heat flux into monthly values, which can be achieved by application of the Penman-Monteith equation:

$$\lambda E^{PM} = \frac{s_a R_{n24} + \rho_a c_p \frac{\Delta e}{r_a}}{s_a + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{B.5}$$

where s_a (mbar/K) is the slope of the saturated vapour pressure curve, $\rho_a c_p$ (J/m^3 K) is the air heat capacity, Δe (mbar) is the vapour pressure deficit, γ (mbar/K) is the psychrometric constant, r_a (s/m) is the aerodynamic resistance and r_s (s/m) is the bulk surface resistance to evapotranspiration. The parameters s_a, Δe and r_a are controlled by meteorological conditions, and R_n and r_s by the hydrological conditions through the feedback of soil moisture on surface albedo and leaf water potential.

The SEBAL computations can only be executed for cloudless days. The result of λE_{24} from Eq. 4 has been explored to convert the Penman-Monteith Eq. 5 and to quantify r_s by inverse modelling assuming $\lambda E_{24} = \lambda E^{PM}$ for the day with a satellite image. The values of r_s so achieved, will consequently be used to compute λE^{PM} by means of Eq. 5 for all days without satellite image but with routine weather data (*Bastiaanssen and Bandara*, 2001). The total ET_{act} for a given period can be derived from the longer term average λE^{PM} flux.

SEBAL Biomass growth

The biomass production routine in SEBAL is based on solar radiation absorption by chlorophyll and the conversion of this energy into a dry matter production *DM* (kg/ha) by means of a light use efficiency:

$$DM = \int APAR(t)\,\varepsilon(t)\,\mathrm{d}t \tag{B.6}$$

The absorption of solar radiation *APAR* (W/m^2) for photosynthesis depends on global radiation and light interception. The second component of Eq. B.6 describes the light use efficiency $\varepsilon(t)$ that converts energy into dry matters.

Photosynthetic Active Radiation (*PAR*) (0.4 to 0.7 μm) is part of the short wave solar radiation (0.3 to 3.0 μm) that is absorbed by chlorophyll for photosynthesis in the plants. *PAR* is thus a fraction of the incoming solar radiation, $R_{S\downarrow}$. The *PAR* value describes the total amount of radiation available for photosynthesis if leaves intercept all radiation. This is a rather theoretical value, because leaves transmit and reflect solar radiation. Only a fraction of *PAR* will be absorbed by the canopy (*APAR*) and used for carbon assimilation. *APAR* can be approximated as a fraction of the *PAR* using the Normalized Difference Vegetation Index (*NDVI*) which for arable crops can be made generic according to *Bastiaanssen and Ali* (2003) as :

$$APAR = (-0.161 + 1.275\,NDVI)\,PAR \tag{B.7}$$

The light use efficiency describes the climate impact and environmental stress on crop growth. Carbon dioxide is obtained from the atmosphere through the stomata. The waste products of photosynthesis, oxygen and water vapour, are dispelled from the plant thought the same stomata into the air. The light use efficiency is coupled in SEBAL to the stomata aperture being expressed as the bulk surface resistance r_s (see Fig. 3). The mathematical-biological description of the bulk surface resistance reads as:

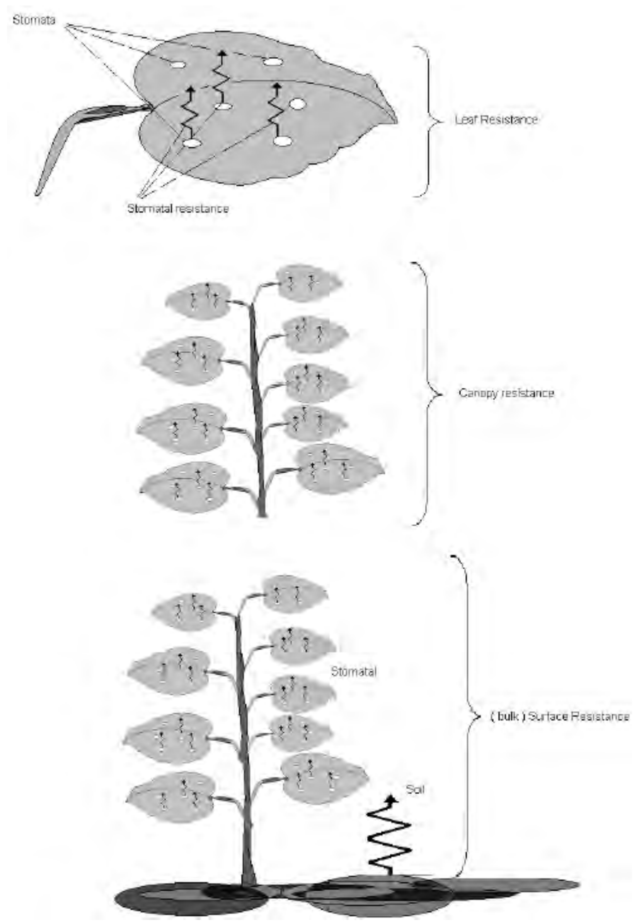
$$r_s = \frac{r_{s\,min}}{LAI\;F_1(T_a)\,F_2(\Delta e)\,F_3(h_{rw})} \tag{B.8}$$

where r_{smin} (s/m) is the leaf or bulk stomatal resistance without any stress, *LAI* (-) is the leaf area index, $F_1(T_a)$ represents a function that describes the effect of air temperature on r_s, the function $F_2(\Delta_e)$ represents the effect of the vapour pressure deficit on the stomatal aperture and the function $F_3(h_{rw})$ is the effect of the soil water potential on r_s. By holding the soil water potential constant between two consecutive satellite overpasses, and making F_1 and F_2 variable, r_s can be re-computed for every individual day.

When the stomata close due to environmentally induced lower leaf water potentials with limiting expansion of the guard cells, light is no longer effectively converted into dry matter because carbon is absent in sufficient quantities. A resistance scalar is used to quantify the day-to-day value of the light use efficiency ε(t). It is from experimental studies known that the light use efficiency has a prescribed maximum ε_{max} that depends on C3 and C4 crops and the chemical composition. This maximum value is multiplied by the resistance scalar to obtain the actual value for light use efficiency ε (g/MJ):

$$\varepsilon(t) = \varepsilon_{max}\ f(r_s) \qquad \text{(B.9)}$$

The SEBAL model formulation for crop growth is on large tracks similar to most numerical crop growth simulation models and global scale ecological production models. A significant difference, though, is that crop development due to soil type, prevailing water management conditions and farmer practices is not computed, but prescribed through satellite measurements of NDVI and surface temperature.



The revisit frequency of Landsat TM is 16 days, therefore chances of obtaining cloud free images are much lower as compared to NOAA. The generation of a time-series on the basis of Landsat TM alone is not feasible (besides the high purchase costs). The revisit frequency of NOAA is one day and the images are free of charge available. As a result, for every cloud free day a NOAA image is available. With a NOAA time-series the growing season can be precisely followed but it lacks the detailed spatial scale. The combination of NOAA (high temporal resolution) with Landsat TM (high spatial resolution) based products combines the best of both satellite systems.

Figure 3 Various resistances that control the evapotranspiration rate.

More information on the assumptions and accuracy of SEBAL can be found in the following publications:

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes and A.A.M. Holtslag, 1998. The Surface Energy Balance Algorithm for Land (SEBAL): Part 1 formulation, *Journal of Hydrology* 212-213, 198-212.

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Bastiaanssen, W.G.M., M. Ud-din-Ahmed and Y. Chemin, 2002. Satellite surveillance of evaporative depletion across the Indus Basin. *Water Resources Research*. 38, 12, 1273-1282.

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Bastiaanssen, W.G.M., E.J.M. Noordman, H. Pelgrum, G. Davids and R.G. Allen, 2003. SEBAL for spatially distributed ET under actual management and growing conditions. *Journal of Irrigation and Drainage Engineering* (accepted).

Schuurmans, J.M., P.A. Troch, A.A. Veldhuizen, W.G.M. Bastiaanssen and M.F.P. Bierkens, 2003. Assimilation of remotely sensed latent heat fluxes in a distributed hydrological model. *Advances in Water Resources* 26, 2, 151-159.

Scott, C.A., W.G.M. Bastiaanssen and M.D. ud-Din Ahmad, 2003. Mapping root zone soil moisture using remotely sensed optical imagery. *Irrigation and Drainage Engineering*, 129, 5, 326-335.

Wang, J., Y. Ma, M. Menenti, W.G.M. Bastiaanssen and Y. Mitsuta, 1995. The scaling up of land surface processes over a heterogeneous landscape with satellite observations. *Journal of Meteorological Society of Japan*, 73, 6, 1235-1244.