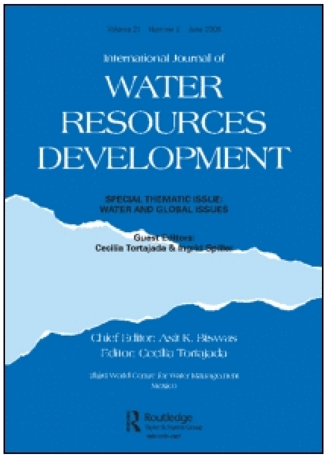

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Assessing Options to Increase Water Productivity in Irrigated River Basins Using Remote Sensing and Modelling Tools

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ABSTRACT *In regions where water is more scarce than land, the water productivity concept (e.g. crop yield per unit of water utilized) provides a useful framework to analyse crop production increase or water savings in irrigated agriculture. Generic crop and soil models were applied at field and regional scale, together with geographical and satellite data to analyse water productivity in Sirsa District (India). In this district certain parts show a serious decline in groundwater levels and water shortage, while other parts experience a serious rise of groundwater levels, causing waterlogging and salinization. The regional analysis showed a large spatial variability of water productivity, net groundwater recharge and salinization. Scenario analysis showed that improved crop husbandry, reallocation of canal water from fresh to saline groundwater areas and reduction of seepage losses in saline groundwater areas are effective measures to increase the overall water productivity and to attain sustainable irrigation in Sirsa District.*

Introduction

In an increasing number of regions the claims for fresh water by agriculture, industries, households and nature reserves exceed the amounts of fresh water available, thus demanding a better management of fresh water. Since irrigated agriculture is by far the biggest consumer of fresh water, increasing water productivity in irrigated agriculture is a logical way to save water.

Traditionally, irrigation engineers focused on irrigation efficiency, which commonly relates the amount of water diverted from rivers or reservoirs to the amount of water actually benefiting soil moisture storage. Although irrigation efficiency has been useful to detect all kinds of conveyance and distribution losses, water percolation from irrigation canals and farmer fields is not necessarily bad. When farmers use groundwater or drainage

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water for irrigation, this recycling of water resources will increase irrigation efficiencies at regional scale to values, substantially greater than the nominal field scale values.

Another serious limitation of the irrigation efficiency concept is that it considers only water transport. No attention is paid to the productivity potential of the water supplied. When choices have to be made in an area on the allocation of fresh water, it should be known how much water is used to obtain a certain crop yield, industrial product, health care or quality of nature reserve. This conversion of used water into the required commodity, allows sensible choices on the allocation of limited water resources in a region.

Extending the concept of irrigation efficiency, water productivity (WP) relates to the value or benefit derived from the use of water. Definitions of WP are not uniform and change with the background of the researcher or stakeholder involved (Table 1). For example, obtaining more kilograms of dry matter per unit of water transpired is a key issue for plant breeders. However, at a basin level, policy-makers may wish to maximize the economic value of the irrigation water used. There are several definitions of WP, so a decision has to be made about 'which crop' and 'which drop' is referred to (Molden *et al.*, 2003).

Each definition of WP may lead to a different optimal allocation of water for an area. This is important for effective communication within multi-stakeholder platforms on water use. The water productivity framework as listed in Table 1 may serve to clarify and quantify the interests of involved stakeholders. For instance, irrigation engineers and groundwater policy-makers may like to cultivate dry rice instead of paddy rice, as less irrigation water is required to produce a certain rice yield. However, for farmers the shift from paddy rice to dry rice might be not attractive at all, since they face loss of rice production while water is available at relatively low costs.

In order to compare WP values between different areas in a meaningful way, the produced commodity (numerator) and the amount of water consumed (denominator) should be clearly defined. The ratio of harvestable product and evapotranspiration is one of the most widely used definitions of WP. Bessembinder *et al.* (2005) show a number of factors which may affect these WP values by 10–25%:

- Grain yield can be defined as dry matter or as fresh matter; for instance in the case of wheat, grain fresh matter contains about 14% moisture.
- Cultivars differ in their distribution of assimilates to roots, stems, leaves and reproductive organs, in maximum assimilation rate, day length sensitivity and

Table 1. Some examples of stakeholders and their targets in the water productivity framework as related to agriculture

Stakeholder	Definition	Scale	Target
Plant physiologist	Dry matter / transpiration	Plant	Utilization of 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

Source: Adapted from Molden *et al.*, 2003.

length of growing season. This may all lead to differences in harvest index (ratio of marketable yield to total above ground dry matter) and final yield.

- The period for evapotranspiration may be defined from emergence to crop maturity, from sowing to harvest, or may cover the entire growing season, including land preparation.
- The meteorological conditions during crop growth will affect crop transpiration; in the case of relatively low air humidities and relatively high air temperatures, WP values will be lower; this results in variability of WP between years and climate zones.
- Crop management, such as cultivation and level of control of weeds, pests and diseases, and nutrient level, may seriously affect crop yield and thus WP.
- The level and timing of water and/or salinity stress; high levels of stress or stress in relatively sensitive stages of crop development will reduce WP.

Bessembinder *et al.* (2005) recommend including information on these factors in scientific literature to allow better WP comparisons.

Traditionally, WP has been derived by measurements of water use and crop yields at experimental stations and in farmer fields. These measurements are very valuable, but also take much time and effort and apply to very specific conditions: one cultivar, irrigation regime, weather period, crop management and soil type. Operational remote sensing may alleviate partly the burden of data collection, as it allows a quick scan of biomass production and evapotranspiration at large scales with resolutions as fine as 15–30 m (Bastiaanssen *et al.*, 2000). Using the harvest index, the biomass production can be converted into harvestable product. Therefore, remote sensing provides valuable information on the geographic distribution of the ratio yield / evapotranspiration. However, with remote sensing it is not possible to look into the future. In addition, the evaluation of all kinds of management options is hard with remote sensing. For these aspects generic simulation models can be used. In the past decades, researchers devoted much effort to the development and calibration of field scale simulation models for water flow, solute transport and crop growth. These simulation models are now in a phase where they can play an important role in analysing WP at field and regional scales for all kind of water allocations and environmental conditions. Therefore, in many cases a combination of remote sensing and simulation models is the most effective way to assess current and potential WP values.

Key elements in the discussion on WP are the nominal values and the ranges for certain cropping systems. If the range is narrow, there is little scope to improve WP. Zwart & Bastiaanssen (2004) performed an extensive literature review on WP values (ratio yield / evapotranspiration) of wheat, rice, cotton and maize. They report wide ranges (e.g. mean value (kg m^{-3}) and (between brackets) coefficient of variation: wheat: 1.09 (0.40); rice: 1.09 (0.36); cotton: 0.65 (0.35); maize: 1.80 (0.39)), indicating an enormous potential for improving WP.

The objective of this study is to present nominal WP values and to demonstrate how the WP framework can be used to select effective measures to save water at field and regional scale. The proposed methodology is applied to an irrigated basin in a semi-arid region of India, and combines field measurements, remote sensing and simulation models. An important reason to include the field scale is that with regard to crop and water management, which directly affect WP, many choices are made by the farmer. Much of our scientific knowledge on crop-soil-water interactions also applies to field scale processes. The regional scale is important as many decisions on water management and agricultural policies are made at this level. Another reason to consider regional scale is that water management in one region may affect other regions in the catchment. For instance, reduced groundwater recharge upstream will result in reduced groundwater availability downstream. In order to evaluate options for improvement of WP at regional scale, a detailed crop and soil model will be applied at this scale.

This paper will consider two main water losses: evapotranspiration and soil water percolation. Although from a plant physiological point of view it is interesting to consider plant transpiration (T) and soil evaporation (E) separately, at experimental stations and in farmer fields generally E and T are determined together as evapotranspiration (ET). Water that has been lost through ET is no longer available for reuse in the region or basin to other stakeholders, so ET should be used as productively as possible. This WP value will be denoted as WP_{ET} (kg m^{-3}). Percolation (P) will not be considered as a loss in areas with a good groundwater quality. However, percolation should be considered as a loss when it percolates into groundwater that cannot be used anymore for irrigation due to its low quality. The WP value which includes both P and ET will be denoted as WP_{PET} (kg m^{-3}). Unless otherwise stated, fresh matter of harvestable products will be considered as yield, and the water losses in the period will be taken from crop emergence to crop maturity.

Sirsa District

The study area, Sirsa District, is located in the western part of Haryana State, India, and covers about 4270 km^2 (Figure 1). The soil texture in Sirsa District varies from sand to sandy loam, with a belt of silty loam to silty clay loam along the Ghagger river, which flows from East to West through the central part of the district. The climate of the region can be defined as sub-tropical, semi-arid and continental with monsoon (July to September). Average annual rainfall in Sirsa District varies from 100 to 400 mm, which represents only 10 to 25% of the reference evapotranspiration (Jhorar *et al.*, 2003).

The temperature conditions in Sirsa District allow growing of crops throughout the year. However, farmers generally grow two crops per year: a *rabi* crop (winter, from October to April) and a *kharif* crop (summer, from April to October). Crop production is very limited without irrigation, even in the summer period. Since the mid 1950s, the Bhakra Irrigation System has distributed the surface irrigation water among the farmers in Sirsa District. The district has an extensive canal network with three main canals: the Bhakra Main Branch (BMB) in the northern, the Suckhain distributary (SUK) in the central and the Fatehabad Branch (FB) in the southern part. Tails of these canals supply water to the adjoining state of Rajasthan. During the monsoon period, water from the ephemeral Ghagger river is partly diverted to canals for irrigation in the central and the southwest parts (GHG) of Sirsa District (Figure 2). The canal water distribution among farmers follows the ‘principle of equity’, which means that they receive canal water amounts in proportion to their land holdings. The limited canal water supply in Sirsa District forces farmers to extract groundwater for supplementary irrigation. Groundwater quality determines the amounts of groundwater used for irrigation. Groundwater quality in the northern and the southern parts is generally poor compared to the central and south-western parts of the district. In the period 1990–2000, the northern and southern parts of Sirsa District have experienced a rise in groundwater levels (in some parts $+10$ m) whereas groundwater levels are declining in the central parts (in some parts -7 m).

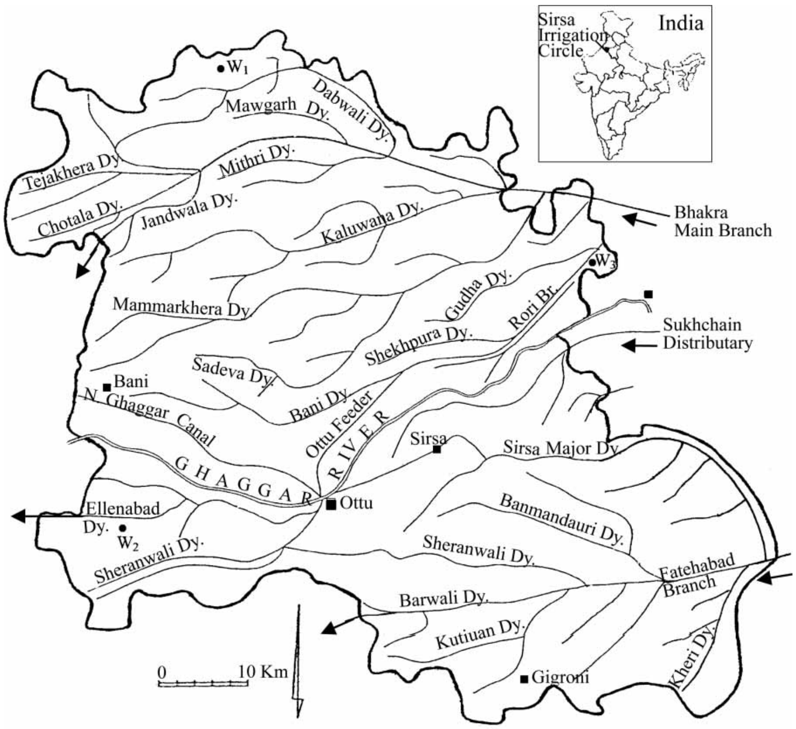

Figure 1. Location and canal network of Sirsa District

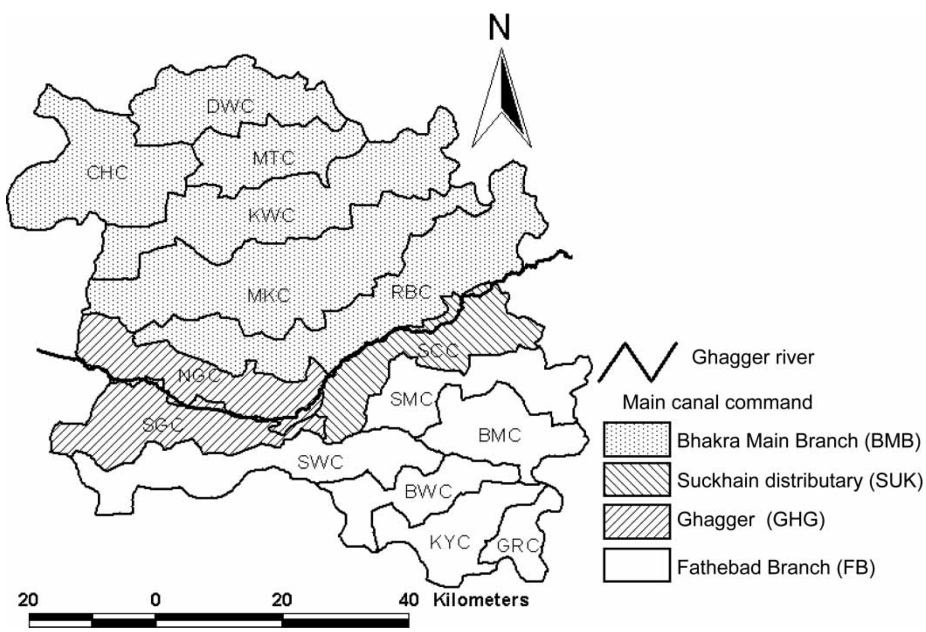

Figure 2. Sirsa District with its four main canal command areas

Water management in Sirsa District is thus complex due to low and erratic rainfall, canal water scarcity, high evaporative demands, sandy soils with low water holding capacity, marginal to poor groundwater quality and rising and declining groundwater levels. Marketable yield in the farmer fields is considerably less than at the experimental stations. These water management problems, combined with extensive knowledge from earlier studies in the region (Aggarwal & Roest, 1996; Bastiaanssen *et al.*, 1996; Tyagi, 1998; Jhorar, 2002; Hussain *et al.*, 2003), availability of regional information and active support by CCS Haryana Agricultural University made Sirsa District a perfect pilot area for a water productivity analysis.

Materials and Methods

Modelling Tools

This study uses the agrohydrological model SWAP (Soil-Water-Plant-Atmosphere), crop growth submodel WOFOST (WOrld FOod STudies) and the image processing model SEBAL (Surface Energy Balance Algorithm for Land).

SWAP simulates water flow and solute transport in soils near the earth surface (Kroes & Van Dam, 2003). The model calculates field scale transport processes in a deterministic, physical way. Water flow is described with Richards' equation (including root water extraction), and solute transport with the convection-dispersion equation. In the unsaturated zone one-dimensional flow is assumed. The top boundary is located above the canopy and requires daily meteorological data. The lower boundary may extend to the upper part of the groundwater flow system, and may include lateral drainage to drains or ditches. SWAP simulates the interaction between the unsaturated zone and the groundwater. Table 2 lists the main input parameters that are required to parameterize SWAP and the measurements that can be used to calibrate and validate the model.

WOFOST (Supit *et al.*, 1994; Boogaard *et al.*, 1998), the crop growth submodel, calculates daily crop photosynthesis on the basis of the radiation absorbed by the canopy

Table 2. Overview of main input parameters and measurements for calibration and/or validation for SWAP and WOFOST

SWAP		WOFOST	
Input	Calibration/validation	Input	Calibration/validation
Meteorological data	Soil water contents	Crop development stages in time	Leaf area index
Irrigation amount and quality	Salinity concentrations	Dry matter partitioning during crop growth	Dry matter in different plant parts during crop growth
Soil hydraulic properties	Groundwater levels[a]	Light interception as function of leaf area index	
Root water uptake under dry and/or saline conditions	Drainage rates[a]	Efficiency of assimilate conversion and respiration needs	
Drainage conditions		Root development	

[a] Not used in this study.

and possible water and/or salinity stress. The photosynthesis products are used for maintenance respiration and for growth of leaves, stems, roots and reproductive organs. The dry weights of the plant organs are obtained by integrating the differences between growth and senescence rates. The water and salinity stress is related to root water uptake as calculated by SWAP according to Feddes *et al.* (1978) and Maas & Hoffman (1977). WOFOST as incorporated in SWAP, does not account for nutrient stress or growth reduction due to weeds, pests and/or diseases (the standalone version includes a module that allows calculation of effects of limited nutrient (NPK) availability). Table 2 also lists the main input parameters and calibration/validation data of WOFOST.

SEBAL calculates actual and potential evapotranspiration rates from cropped and bare land (Bastiaanssen *et al.*, 2005). The key input data for SEBAL consist of satellite images with spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum. 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 physical conditions near the soil surface, such as soil water potential (and thus soil moisture and soil salinity), wind speed and air temperature. Satellite radiances are converted first into land surface characteristics, such as surface albedo, leaf area index, vegetation index and surface temperature. These land surface characteristics can be derived from different types of satellites. First, instantaneous evapotranspiration is computed, that is then subsequently scaled up to 24 hours and longer periods. In addition to satellite images, the SEBAL model requires daily average data on wind speed, humidity, solar radiation and air temperature.

In this study, a clear interaction exists between SWAP and WOFOST as water and salt stress affects crop growth and vice versa. In the regional scale analysis, SWAP-WOFOST and SEBAL have been used independently to calculate WP values. Although the authors expect a further integration of simulation models and remote sensing in the future, this paper presents the results of both approaches separately.

Measurements

In order to run the SWAP-WOFOST model, data were collected at experimental stations and in farmer fields. Trials at experimental stations in the area were used to calibrate input parameters of the main crops (Bessembinder *et al.*, 2003). A total of 24 farmer fields with different crops, soils, groundwater levels and canal water allocation were monitored to identify the yield gap between experimental stations and farmer fields. Regional geographical data were collected and digitized to perform a regional analysis with distributed modelling.

Experimental stations. To obtain the data required for calibration of WOFOST, extensive crop experiments were conducted at the Cotton Research Station in Sirsa in wheat-cotton rotations and at the Regional Research Station in Karnal in wheat-rice rotations. For wheat, cotton and rice different cultivars were included and different amounts of irrigation were applied. Details on soil properties, crop growth parameters, irrigation timings and amounts are given in Malik *et al.* (2003).

Farmer fields. In Sirsa District, six sites with four farmer fields at each site, 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 three fields at each site were monitored more extensively and served for verification of the measurements at the intensively monitored fields. Soil texture was sandy loam in the wheat-cotton fields and clay loam to sandy clay loam in the wheat-rice fields. The main source of irrigation water was canal water in the wheat-cotton fields and groundwater in the wheat-rice fields. The groundwater quality varied from good (< 2 dS m^{-1}) to poor (> 6 dS m^{-1}) at the wheat-cotton fields and was good (< 2 dS m^{-1}) at the wheat-rice fields.

Regional scale. Regional WP analysis by distributed modelling with SWAP-WOFOST requires extensive spatial information on weather, land use, soil type, irrigation and groundwater. Satellite remote sensing techniques generate some of the required spatial information such as land use. Most of the required information on climate, irrigation, groundwater and agricultural statistics was obtained from the state government agencies in Sirsa District.

Bastiaanssen *et al.* (2003) analysed satellite images to classify land use and to determine actual evapotranspiration (*ET*) and dry matter (*DM*) production in Sirsa District during the agricultural year 2001–02. Two land-use maps were produced using the Landsat TM7 image of 18 March 2002 (*rabi* season), and of 10 September 2002 (*kharif* season). In addition, at 249 locations in Sirsa District actual land use was observed. The land-use classification was achieved by performing a series of unsupervised steps based on the ISODATA clustering algorithm, and its accuracy with respect to administrative data has been verified by Singh (2005). Bastiaanssen *et al.* (2003) also applied the SEBAL algorithm to analyse 12 NOAA-AVHHR (Advanced Very High Resolution Radiometer of the National Oceanic and Atmospheric Administration) images with a resolution of 1100 m and two Landsat TM7 images with a resolution of 30 m. The estimated total *DM* production was converted with the harvest index HI_{dry} to the spatial grain (or seed in the case of cotton) yields Y_g ($HI_{dry} = 0.35$, 0.39 and 0.20 kg kg^{-1} for wheat, rice and cotton, respectively). Subsequently, the estimated Y_g and *ET* were used to calculate WP_{ET} for wheat, rice and cotton in addition to WP_{ET} values from distributed modelling with SWAP-WOFOST. Further details of procedures and results of this satellite remote sensing analysis are reported in Bastiaanssen *et al.* (2003).

The Cotton Research Station (Sirsa) provided an extensive meteorological dataset with daily values of minimum and maximum temperature, relative humidity, vapour pressure, sunshine hours, wind speed and rainfall. Rainfall is highly variable in occurrence and spatial distribution. Therefore, rainfall records of seven rain gauges spread over Sirsa District were collected and rainfall amounts were spatially distributed using Thiessen polygons.

Spatial soil information in Sirsa District was derived from a comprehensive soil survey by Ahuja *et al.* (2001). This survey was carried out using Landsat TM images in conjunction with ground observations. In the derived soil map (scale 1:50 000) 10 soil types are distinguished with typical profiles of soil texture.

The Department of Agriculture at Sirsa provided village level statistics on cultivable area, net sown area, irrigated area, and location and discharge of tubewells. The tubewell information was used to quantify potential groundwater pumping in Sirsa District. The Irrigation Department of Sirsa provided detailed information on design characteristics and layout of the irrigation canal network. In order to attain equal water distribution, this

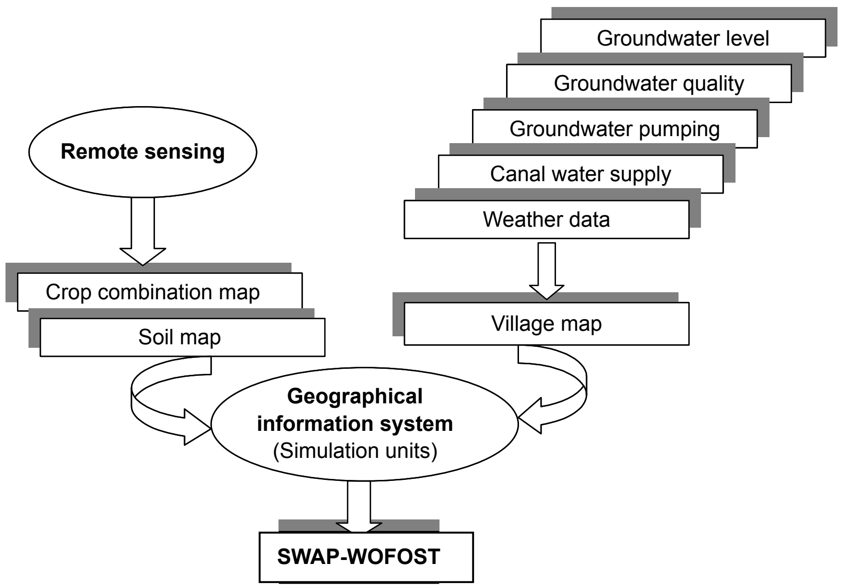

Figure 3. Schematic representation of the aggregation procedure to derive unique simulation units for SWAP-WOFOST at regional scale. *Source:* Singh (2005).

department maintains records on canal water inflow and area served by each canal. Records on agricultural area attached to canal water rights were also available at watercourse level.

Groundwater Cell (Sirsa) is responsible for groundwater level and quality measurements in Sirsa District. They use 164 observation wells widely distributed over the area, and visit them twice a year: in June (pre-monsoon) and in October (post-monsoon).

Most of the regional information in Sirsa District is available at village level. Therefore, the maps of the village boundaries of Sirsa District were also obtained and digitized. The collected information was processed on this village map, which was subsequently used in the aggregation of simulation units (Figure 3). The data on weather, canal water distribution and groundwater levels were collected for the period 1990–02, and are available on a CD-ROM accompanying the final report of this research project (Van Dam & Malik, 2003).

Analysis and Discussion

Water Productivity at Field Scale

The actually measured crop yields (grain in the case of wheat and rice, seed in the case of cotton) and the simulated water balance components with SWAP-WOFOST were used to derive WP values for the experimental stations and farmer fields. Although direct measurements are generally the most accurate, transpiration, evaporation and percolation fluxes are difficult to measure and had to be derived from SWAP-WOFOST. Table 3 provides an overview of the results. For wheat, *ET* at the experimental station and in farmer fields are both about 290 mm. As the maximum wheat yield at the experimental farm (7.4 Mg ha^{-1}) is considerably higher than the average crop yield in farmer fields

Table 3. Water productivity at experimental stations and farmer fields for wheat, rice and cotton in period December 2001 – November 2002, derived from measured crop yields (fresh matter) and simulated water balance components (WP_{ET} and WP_{PET}) and for entire Sirsa District from remote sensing (WP_{RS}). WP_{ET} and WP_{RS} use only evapotranspiration (*ET*) as water loss, WP_{PET} uses the sum of *ET* and percolation (*P*) as water loss

	Experimental stations			Farmer fields		
	Wheat	Rice[a]	Cotton	Wheat	Rice	Cotton
Rainfall (mm)	11	-	177	11	177	177
Irrigation (mm)	388	-	283	433	1156	469
Transpiration (mm)	231	-	427	204	475	468
Evaporation (mm)	56	-	98	95	396	141
Percolation (mm)	112	-	0	145	462	37
Crop yield (Mg ha^{-1})	7.4	8.6	2.9	4.6	8.1	2.1
WP_{ET} (kg m^{-3})	2.58	-	0.55	1.54	0.93	0.34
WP_{PET} (kg m^{-3})	1.85	-	0.55	1.04	0.61	0.33
WP_{RS} (kg m^{-3})	-	-	-	1.22	0.72	0.31

[a] Irrigation amounts not available.

(4.6 Mg ha^{-1}), its WP_{ET} is much higher (2.58 kg m^{-3}) than in farmer fields (1.54 kg m^{-3}). For cotton, *ET* at the experimental station (525 mm) is smaller than in farmer fields (609 mm), while maximum cotton yield at the experimental farm (2.9 Mg ha^{-1}) is 38% higher than the average in farmer fields (2.1 Mg ha^{-1}). Hence, WP_{ET} is 62% higher at the experimental farm (0.55 kg m^{-3}) than in farmer fields (0.34 kg m^{-3}). Low rainfall resulted in restricted percolation in the cotton crop. Therefore WP_{PET} is similar to WP_{ET}. Unfortunately, the irrigation amounts of rice at the experimental station were not available. Maximum rice yield at the experimental station (8.6 Mg ha^{-1}) is only slightly higher than the average crop yield at the farmer fields (8.1 Mg ha^{-1}). The large percolation losses of paddy rice cause a large difference between WP_{ET} (0.93 kg m^{-3}) and WP_{PET} (0.61 kg m^{-3}). The mean values of WP_{RS} determined by remote sensing for entire Sirsa District correspond well with the mean WP_{ET} in farmer fields for wheat and cotton, but are lower for rice. The difference in the case of rice is caused by the fact that the selected rice farmer fields showed high yields in comparison to average yields in Sirsa District.

Table 4 lists the simulated water- and salt-limited yields and the measured yields. For rice, both are similar, indicating proper cultivation and nutrient, weed, pest and disease management. For wheat and cotton, large gaps exist between the simulated water- and salt-limited yields and the measured yields, indicating suboptimal crop management In the case of wheat the mean simulated water- and salt-limited yield in farmer fields (8.2 Mg ha^{-1}) is higher than the measured yield at the experimental station (7.4 Mg ha^{-1}). This is attributed to late sowing and some water stress at the experimental station, and minor salt stress in the monitored farmer fields. For wheat and cotton, the gap between

Table 4. Average measured actual yield and simulated water- and salt-limited yield (fresh matter, Mg ha^{-1}) in farmer fields in the agricultural year 2001/2002. In case of cotton the yield of seed is taken

	Wheat	Rice	Cotton
Measured actual	4.6	8.1	2.1
Simulated water- and salt-limited	8.2	8.1	2.6

potential yields as measured at the experimental stations (Table 3) and the simulated water- and salt-limited yields at the farmer fields (Table 4) is much smaller than the gap between the simulated water- and salt-limited yields at the farmer fields and the measured yields (Table 4). This shows that the reduction due to water and salt stress at the monitored farmer fields is less than the reduction due to cultivation and nutrient, weed, pest and disease management.

The calibrated SWAP-WOFOST combination is very useful to quantify the effects of various water management options on WP_{ET}. The next section explores options with respect to deficit irrigation and early sowing.

Deficit Irrigation

In many irrigation schemes, irrigation water availability is not sufficient to meet all crop water requirements. Therefore, the effect of providing 20% less irrigation water (absolute amount) was simulated at different stages of crop development (Table 5). When all irrigations are reduced by 20%, wheat yield is reduced from 6.9 to 6.3 $Mg\,ha^{-1}$. Deficit irrigation at the start of the growing season has a large impact on leaf area development, and thus on yield (reduction from 6.9 to 4.8 $Mg\,ha^{-1}$). In the crop ripening stage, deficit irrigation hardly affects grain yield. In general, one growing season may expect a more or less constant ratio yield/*T*, unless water stress occurs in a critical stage of crop development. In the case of the ratio yield/*ET*, which equals WP_{ET}, this is the sum of *T* and *E*, which has a non-linear relationship with yield. Therefore, WP_{ET} may vary as a function of irrigation amount. When the irrigation amounts are proportionally reduced or when the reduction occurs at the end of the growing season, the simulated WP_{ET} remained more or less the same. However in the case of irrigation reduction at the start of the growing season, WP_{ET} declined from 2.62 to 2.07 $kg\,m^{-3}$, a reduction of 21%, as yield declined more than *ET*. Therefore, for high WP_{ET} values, water stress at the start of the growing season should be avoided.

Early Sowing

Crop growth was simulated at sowing dates ranging between 10 November and 10 December (Table 6). In the case of early sowing, the time between emergence, flowering and maturity will increase. Crop development in the period around flowering is also relatively sensitive to day length and air temperature. For wheat this results in a higher harvest index and higher grain yield. Combined with a small increase in total evapotranspiration during the actual growing period, WP_{ET} increases substantially from

Table 5. Simulated water productivity of wheat for experimental station Sirsa during 2001/2002 (emergence date 13 December). Evapotranspiration is calculated from crop emergence to maturity. The optimum irrigation schedule refers to irrigation as soon as $T/T_{pot} = 0.80$

Irrigation schedule	Grain ($Mg\,ha^{-1}$)	WP_{ET} ($kg\,m^{-3}$)
Optimum schedule	6.9	2.62
Reduce all irrigations with 20%	6.3	2.53
Reduce irrigation with 20% at start of growing season	4.8	2.07
Reduce irrigation with 20% at end of growing season	6.9	2.61

Source: Adapted from Bessembinder *et al.* (2005).

Table 6. Effect of different sowing dates on crop growing period, evapotranspiration *ET* (between emergence and maturity), grain yield and water productivity WP_{ET} (2001/2002, soil of experimental station Sirsa, irrigation as soon as $T/T_{pot} = 0.90$)

	Sowing date (2001)			
	10 Nov.	20 Nov.	30 Nov.	10 Dec.
Crop growing period (E-M, days)	142	135	126	118
Grain yield (Mg ha^{-1})	9.4	9.0	8.3	7.4
ET (mm)	319	322	315	302
WP_{ET} (kg m^{-3})	2.95	2.79	2.64	2.45

Source: Adapted from Bessembinder *et al.* (2005).

2.45 kg m^{-3} (sowing date 10 December) to 2.95 kg m^{-3} (sowing date 10 November). This is a very interesting piece of information that needs more attention, especially as there are efforts ongoing to shorten the crop growing season in order to reduce ET and to increase WP_{ET} (Bastiaanssen, personal communication). This seems to be in contradiction with the results here and needs more elaboration.

Water Productivity at the Regional Scale

Current Situation

Aggregation of spatial information was performed by overlaying information on climate, land use, soil, irrigation, groundwater level and quality. Most of the spatial information on irrigation, groundwater level and quality was available at village level (323 villages). Therefore, the stratification of Sirsa District was performed by overlaying three thematic maps: crop rotation, soil and village boundary (Figure 3), yielding 3168 unique simulation units (Singh *et al.*, 2005a).

The water and salt balance of each simulation unit during a 10-year period (1991–2001) have been derived with SWAP-WOFOST (Singh *et al.*, 2005b). Table 7 shows these balances, aggregated for the four main canal commands (Figure 2) and for the entire district. From the total amount of canal water which is diverted to Sirsa District (446 mm), 265 mm or 59% reaches the farmer fields, while 41% is lost by seepage in the conveyance system. The average amount of tubewell water (318 mm) is larger than the amount of canal water that is available for the farmers (265 mm). In the SUK command the amount of tubewell water (629 mm) is even 5.5 times higher than the amount of canal water (115 mm). Average transpiration amounts to 520 mm, and constitutes 72% of the average evapotranspiration (722 mm). Average percolation (109 mm), in combination with the total amount of irrigation ($265 + 318 = 583$ mm), gives an overall leaching fraction of $109/583 = 0.18$. Net groundwater recharge equals percolation from fields and conveyance system minus extraction by tubewells. For the entire Sirsa District a net groundwater recharge of -27 mm y^{-1} is derived (Table 7). Thus, extraction by tubewells exceeds percolation. However, in the period 1991–2001, measured groundwater levels in Sirsa District show an average rise of 90 mm y^{-1}. When multiplied with a specific yield of 0.12 mm^{-1}, this corresponds to a net groundwater recharge of $+11$ mm y^{-1}. The difference between measured and simulated groundwater recharge thus equals to $11 - (-27) = 38$ mm y^{-1}. This difference is attributed to net lateral groundwater inflow and seepage from the Ghagger river, which have not been taken into account in the regional

Table 7. Average annual terms of the water and salt budget for the entire Sirsa District and its four main commands: BMB, SUK, GHG and FB (see Fig. 2 for different canal commands). Results are based on the distributed SWAP-WOFOST simulations for the unsaturated zone (0–300 cm) over a period of 10 years (1 November 1991–31 October 2001), and apply to the entire area (cropped as well as bare soil)

	Sirsa District	BMB	SUK	GHG	FB
Component	Water balance (mm y^{-1})				
Rainfall	256	248	292	113	324
Inflow canal water	446	549	190	382	328
Canal water at fields	265	318	115	244	204
Irrigation tubewell water	318	224	629	666	283
Transpiration	520	505	668	635	468
Evapotranspiration	722	694	909	879	669
Percolation from fields	109	89	123	143	132
Net groundwater recharge	−27	97	−432	−385	−26
Component	*Salt balance (Mg ha^{-1} y^{-1})*				
Influx	7.3	6.4	11.3	12.0	5.9
Outflux	5.3	3.9	6.7	10.4	5.6
Change	2.0	2.5	4.6	1.6	0.3

Source: Adapted from Singh *et al.* (2005b).

SWAP-WOFOST analysis. The small overall net groundwater recharge indicates an almost closed water balance for the entire Sirsa District. However, large differences in net groundwater recharge exist among the four commands. In the central SUK and GHG commands large quantities of tubewell water are used, yielding net groundwater recharges of −432 and −385 mm/y, respectively, and resulting in groundwater decline. In the northern BMB command, large amounts of canal water are used, yielding a net groundwater recharge of +97 mm, and resulting in groundwater rise. The large amounts of groundwater used cause a larger mean influx of salts (7.3 Mg ha^{-1} y^{-1}) than mean outflux (5.3 Mg ha^{-1} y^{-1}). Salinization is strongest in the SUK (4.6 Mg ha^{-1} y^{-1}), where groundwater quality is lowest.

Table 8 contains the mean crop yields as derived by distributed SWAP-WOFOST modelling and by remote sensing (SEBAL). Both methods result in similar average yields for wheat, rice and cotton. The standard deviation of the yield is underestimated by remote sensing, in comparison to distributed modelling and measurements in farmer fields. A possible explanation is the difference in resolution between remote sensing (30 m) and distributed modelling and measurements (1 m). This requires further investigation.

Table 8. Mean crop yields and standard deviations (fresh matter, Mg ha^{-1}) of wheat, rice and cotton as obtained by distributed SWAP-WOFOST modelling, remote sensing (SEBAL) and field measurements at farmer fields in Sirsa District during the agricultural year 2001–2002

	Wheat		Rice		Cotton	
Method	Mean	Std	Mean	Std	Mean	Std
SWAP-WOFOST	4.8	1.0	3.5	2.5	2.0	0.5
SEBAL	4.4	0.3	3.7	1.1	2.2	0.3
Field measurements	4.5	1.5	8.1	0.6	2.1	1.1

Source: Adapted from Singh *et al.* (2005a).

Table 9. Water productivity WP_{ET} (kg m^{-3}) derived with SWAP-WOFOST (distributed modelling) and with SEBAL (remote sensing) in Sirsa District during the agricultural year 2001–2002. Evapotranspiration is calculated during the entire growing season

	Wheat		Rice		Cotton	
	Mean	Std.	Mean	Std.	Mean	Std.
SWAP-WOFOST	1.37	0.20	0.47	0.30	0.36	0.05
SEBAL	1.22	0.07	0.43	0.19	0.31	0.04

The mean yield of rice as predicted by SWAP-WOFOST (3.5 Mg ha^{-1}) and SEBAL (3.7 Mg ha^{-1}) is much lower than that measured in farmer fields (8.1 Mg ha^{-1}), but corresponds well to statistical data by the Department of Agriculture for Sirsa District in 2001 (2.8 Mg ha^{-1}). This means that for rice the monitored farmer fields were not representative for the district.

As mentioned earlier, SWAP-WOFOST and SEBAL determine *ET* and crop yield with independent methods. Therefore, it is interesting to compare the water productivity values as derived by distributed modelling and remote sensing (Table 9). The mean WP_{ET} values for the main crops are very close. The WP_{ET} standard deviation is larger for the results derived from distributed modelling than for the results derived from remote sensing. This is caused by the wider range in crop yields in the case of distributed modelling.

Scenarios

In order to realize the dual objectives of meeting the growing food demands and restricting water use, water management in Sirsa District should aim at higher crop yields per unit water consumed. At the same time, the irrigated agriculture should be sustainable. This means higher water productivity, less groundwater rise and lower salinity levels in the northern commands, and less groundwater level decline in the central commands.

The good result of the deterministic SWAP-WOFOST simulation model for the current situation provides a solid base to apply the distributed modelling to evaluate proposed water management changes to attain the above goals. Four measures were evaluated (Table 10) and compared to the current situation for a 10-year period, using the weather data of 1991–2001 (Singh *et al.*, 2005b).

Scenario 1, 'Reference situation', mimics the current situation with the same cropping pattern as measured during 2001–02, and with the same crop and water management

Table 10. Alternative water management scenarios that were analysed for Sirsa District

Scenario	Description	Required action
1	Reference situation	Business as usual
2	Increased crop yields (15%)	Improved crop varieties, better nutrient supply, effective pest and disease control
3	Reduced seepage losses (25–30%)	Lining and improved maintenance of irrigation canals
4	Canal water reallocation (15%)	Divert canal water from northern parts to central parts
5	Combination of scenarios 2, 3 and 4	All actions as described above

(business as usual). Scenario 2, 'Increased crop yields (15%)', quantifies the impact of improved crop cultivars, cultivation and nutrient, weed, pest and disease management. These developments are expected to increase crop yields by about 15%. To achieve this in the WOFOST crop growth routine, the input parameters maximum CO_2 assimilation rate and light use efficiency were increased accordingly (Singh *et al.*, 2005b). Scenario 3, 'Reduced seepage losses (25–30%)', targets the rising groundwater levels in the northern parts of Sirsa District. The current seepage losses from the conveyance system are estimated at 41% of the net canal inflow during the agricultural year 2001–02 (Singh *et al.*, 2005b). In this scenario, the seepage input parameters were adjusted to reduce the seepage losses by 25 to 30%. Proper lining and adequate maintenance of the irrigation system should be able to achieve this reduction. Scenario 4, 'Canal water reallocation (15%)', was formulated to divert canal water from the northern BMB command with rising groundwater levels to the central SUK and GHG commands with declining groundwater levels. The extra canal water inflow of SUK and GHG was divided proportionally to the agricultural area attached to canal water rights. This type of water reallocation seems more realistic with respect to costs and management than allocation of canal water on demand (e.g. based on local crop rotation and soil type), as advocated in some other studies (Agarwal & Roest, 1996). Scenario 5, 'Combination of scenarios 2, 3 and 4', evaluates the impact of all above measures together.

Table 11 shows the simulated *ET*, crop yield and WP_{ET} for the main crops for the five scenarios. Only crop yield increase due to improved crop management will significantly increase WP_{ET}. Seepage decrease makes more good quality canal water available for irrigation, which increases the yields, but WP_{ET} stays more or less the same. Canal water reallocation hardly affects overall *ET*, crop yield and WP_{ET}.

Figure 4 shows net groundwater recharge for the five scenarios. Reduction of seepage losses (scenario 3) induces a moderate change in net groundwater recharge. Due to less seepage, larger quantities of canal water reach the fields, resulting in less groundwater pumping by the farmers. Reduced seepage is almost entirely compensated by reduced groundwater extraction, resulting in a moderate reduction in net groundwater recharge. However, canal water reallocation (scenario 4) will result in significantly less groundwater recharge in the northern BMB command, counteracting groundwater rise and waterlogging, and in significantly more groundwater recharge in the central SUK and GHG commands, counteracting the groundwater decline in these areas.

Table 12 lists the salt build up in the soil profile. From the three considered water management measures, seepage reduction is most effective to reduce salinization (from current 2.0 to 1.3 $Mg\,ha^{-1}\,y^{-1}$). In case of less seepage, more good quality canal water is available for farmers. They will pump less saline groundwater for irrigation, and therefore salinization will decrease.

This regional scenario analysis shows that a combination of better crop management, seepage reduction and canal water reallocation (Scenario 5) will result in higher yields and WP_{ET}, more equal distribution of groundwater recharge and less salinization.

Concluding Remarks

Although computed in an independent manner and by completely different parameterizations (energy balance measurements versus water balance simulations), remote sensing and distributed regional modelling provide similar mean WP_{ET} values for the different

Table 11. Evapotranspiration (during entire growing season), crop yield and water productivity for five different scenarios simulated by SWAP-WOFOST for Sirsa District during the period from November 1, 1991, until 31 October 2001

Scenario	Current			Yield increase			Seepage decrease			C. water reallocat.			Combination		
Crop	Wh	Ri	Cot	Wh	Ri	Cot	Wh	Ri	Cot	Wh	Ri	Cot	Wh	Ri	Cot
ET (mm y^{-1})	34	68	62	35	68	62	34	70	64	33	68	61	35	70	63
	2	7	2	2	7	4	9	0	4	9	8	4	7	1	9
Yield (Mg ha^{-1})	4.9	6.4	2.5	5.6	7.5	2.8	5.1	6.8	2.6	4.8	6.5	2.5	5.7	7.9	2.9
	0	5	6	3	5	7	1	3	8	1	0	3	9	5	5
WP_{ET} (kg m^{-3})	1.4	0.9	0.4	1.6	1.1	0.4	1.4	0.9	0.4	1.4	0.9	0.4	1.6	1.1	0.4
	3	4	1	0	1	6	6	8	2	2	5	1	2	4	6

Source: Adapted from Singh (2005).

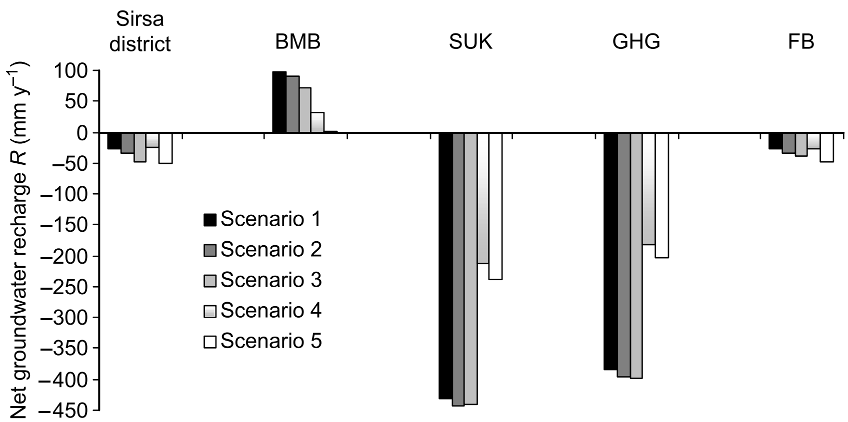

Figure 4. Net groundwater recharge (recharge minus extraction) over the entire Sirsa District and its four main commands under different scenarios (see Table 10) in Sirsa District. Mean values are based on distributed SWAP-WOFOST simulations over the period 1991–2001, and apply to the entire area (cropped as well as bare soil). *Source:* Singh (2005).

irrigation commands in Sirsa District. In the northern commands WP_{ET} is relatively low, due to low yields and relatively high ET. In the central commands WP_{ET} is relatively high. However, these central regions experience seriously declining groundwater levels, whereas groundwater is one of the main sources for irrigation. The analysis suggested three measures to increase WP_{ET} and the sustainability of the irrigation system: (1) improved crop management, resulting in higher crop yields; (2) reduced seepage losses, resulting in less salt accumulation; (3) canal water reallocation, creating more equal groundwater recharge. According to the analysis, a combination of these measures will result in a 15–23% yield increase and a 12–21% increase in WP_{ET} for the main crops, less groundwater rise in the northern commands, less groundwater decline in the central commands, and 20% less salinization in the entire district.

The study shows that the proposed WP framework provides a clear and effective methodology to quantify the interests of different stakeholders in a region. It is relatively cheap and straightforward to derive the values of WP_{ET} by remote sensing. Distributed modelling requires a large amount of soil, plant and irrigation data, although this study

Table 12. Increase in salt content (Mg ha^{-1} y^{-1}) in the top 3 m of soil over the entire Sirsa District and its four main commands for the five scenarios (Table 10). Mean values are based on the distributed SWAP-WOFOST simulations over the period 1991–2001, and apply to the entire area (cropped as well as bare soil)

Scenario/Area	Current	Yield increase	Seepage decrease	C. water reallocat.	Combination
Sirsa District	2.0	2.2	1.3	2.0	1.6
BMB	2.5	2.8	1.7	3.0	2.6
SUK	4.6	5.2	4.4	3.8	3.5
GHG	1.6	2.0	0.6	0.5	−1.0
FB	0.4	0.6	0.1	0.4	0.2

Source: Adapted from Singh (2005).

shows that this is possible with a moderate investment of time and money. Unlike remote sensing, distributed modelling provides all components of the water balance, including net groundwater recharge. This is important to address the different definitions of WP as listed in Table 1. Remote sensing cannot show the future consequences of current practices or evaluate alternative management options, which is the strength of properly calibrated models. Therefore remote sensing cannot replace distributed modelling.

This study used remote sensing and simulation modelling separately to derive WP values. Remote sensing of *ET*, yield and WP_{ET} may also be used to calibrate plant and soil parameters of the crop and soil models. For instance, Jhorar *et al.* (2004) used remotely sensed evapotranspiration to calibrate soil hydraulic parameters. Another way to benefit from both the information produced by generic simulation models and remote sensing, is by so-called data assimilation (e.g. Walker & Houser, 2001; Schuurmans *et al.*, 2003). In this method simulation models are updated with remote sensing information whenever an observation is available. While adjusting the model state variables, both model errors and measurement errors by remote sensing are taken into account. In this combination of simulation models with simultaneous remote sensing data, all information sources are optimally used to increase the accuracy of regional water productivity analysis.

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