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

P. Droogers, R.S. Malik, J.G. Kroes, W.G.M. Bastiaanssen and J.C. van Dam

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

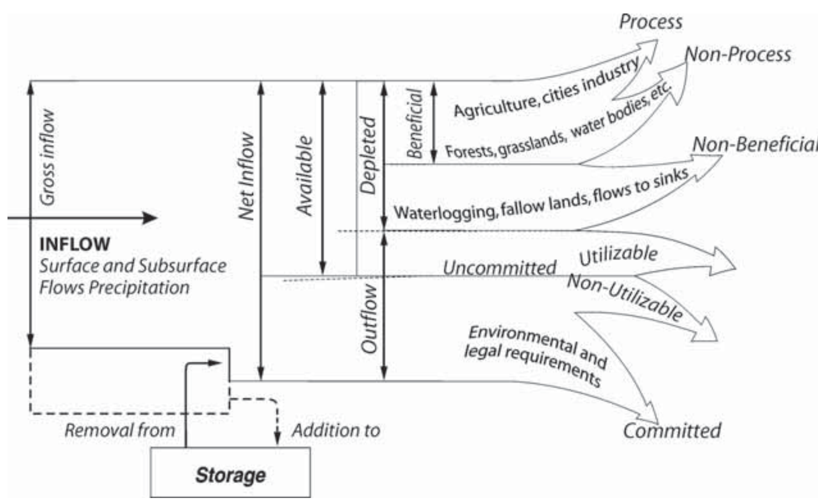

Figure 9.1 Concept of Water Accounting to be used to express the water term in Water Productivity according to *Molden and Sakthivadivel* (1999).

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, nonprocess 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

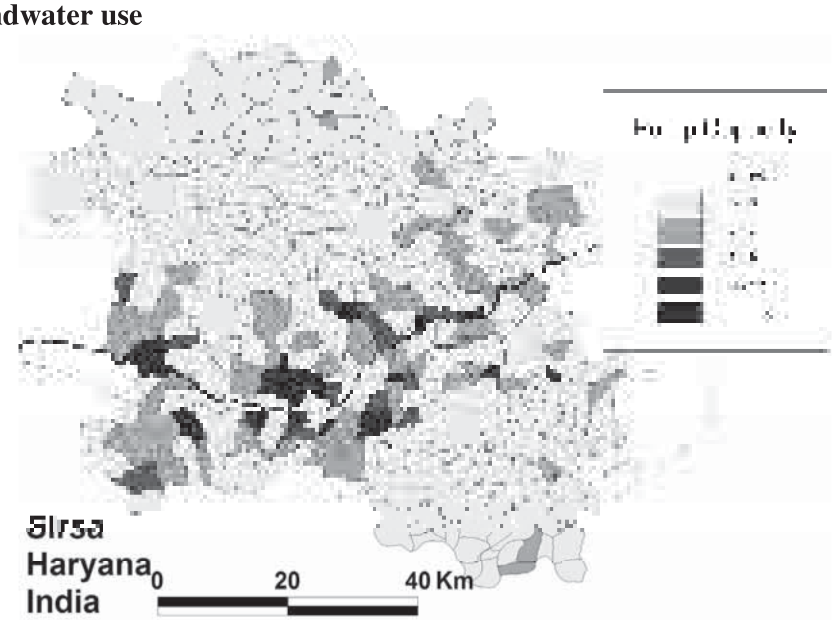

Figure 9.2 Installed pump capacity per village.

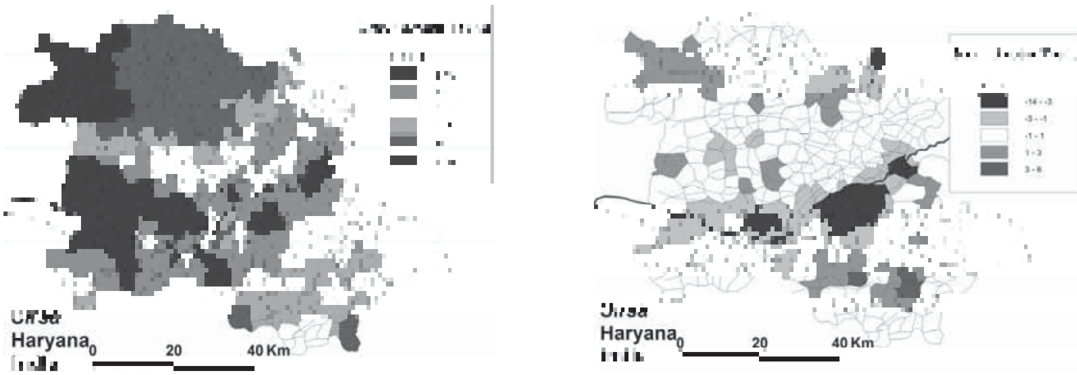

Figure 9.3 Trend in observed groundwater depths for the period October 1990 – October 2000 (left), and October 1999 – October 2000 (right). Negative (blue) figures indicate declining levels, positive (red) indicate rising levels. Note the difference in scale of the two maps by a factor 10 (m $10y^{-1}$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

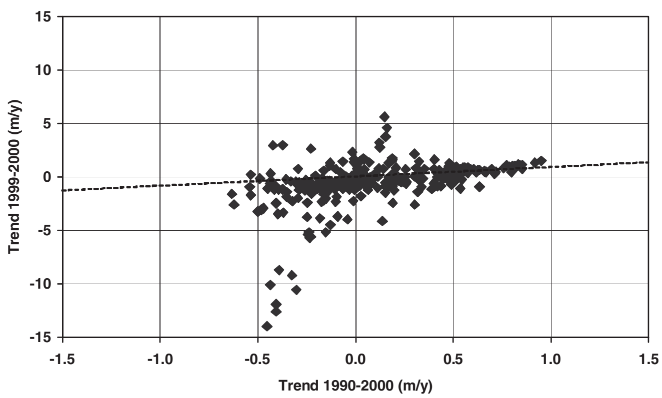

Figure 9.4 Comparison between the 10 year and the 1 year observed groundwater trends. Note the factor 10 in scales between X and Y-axis.

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

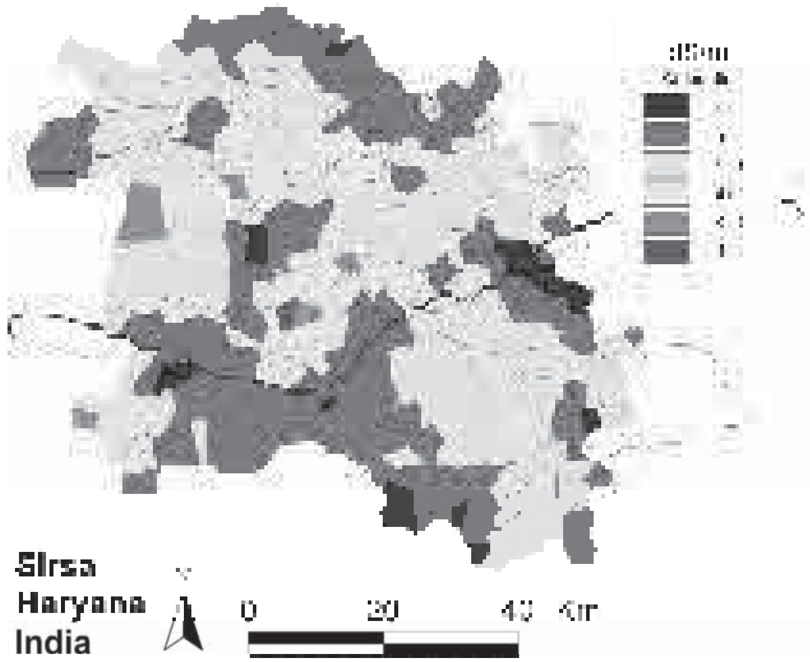

Figure 9.5 Observed salinity levels of groundwater.

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.

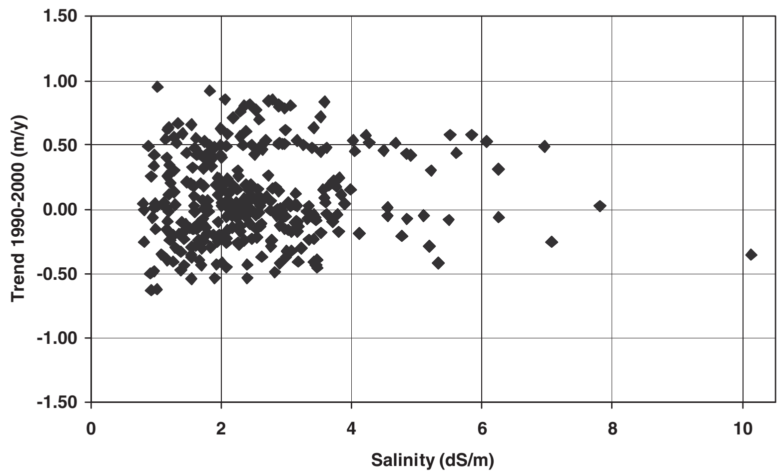

Figure 9.6 Correlation between average observed groundwater changes over the last 10 years and groundwater salinity levels.

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.

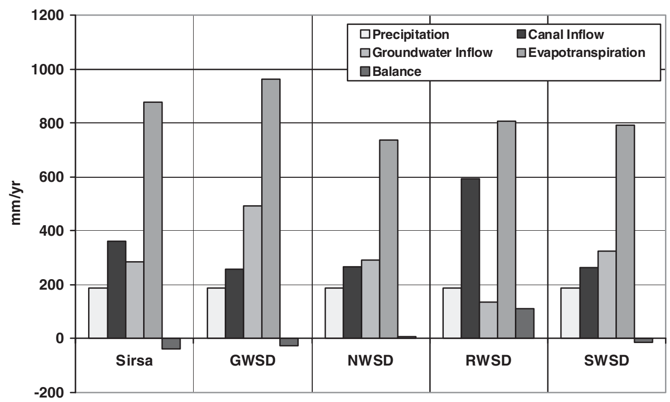

Figure 9.7 Terms of the water balance for the entire Sirsa Irrigation Circle as well as the four divisions: GWSD is Ghaggar, NWSD is Nehrana, RWSD is Rori, and SWSD is Sirsa Water Service Division. Data are based on observations and remote sensing.

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.

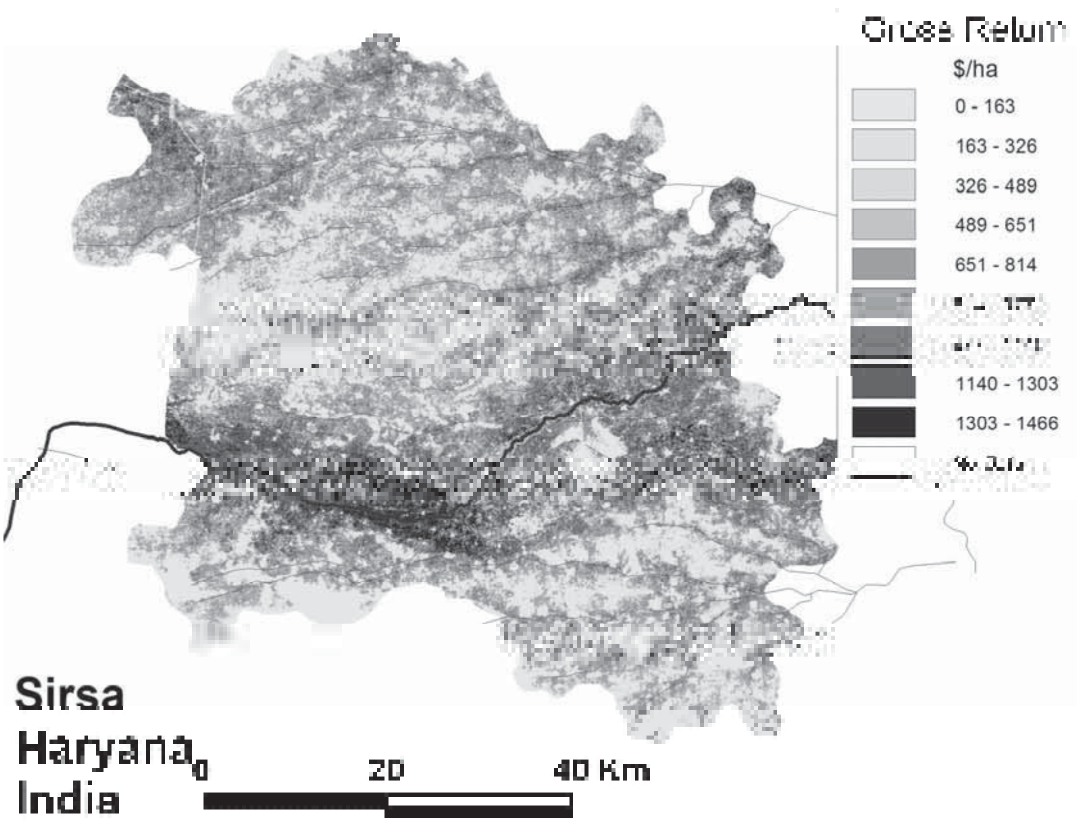

Figure 9.8 Gross return based on crop production (derived from SEBAL results) and crop market prices. Period included is Rabi and Kharif 2001-02.

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.

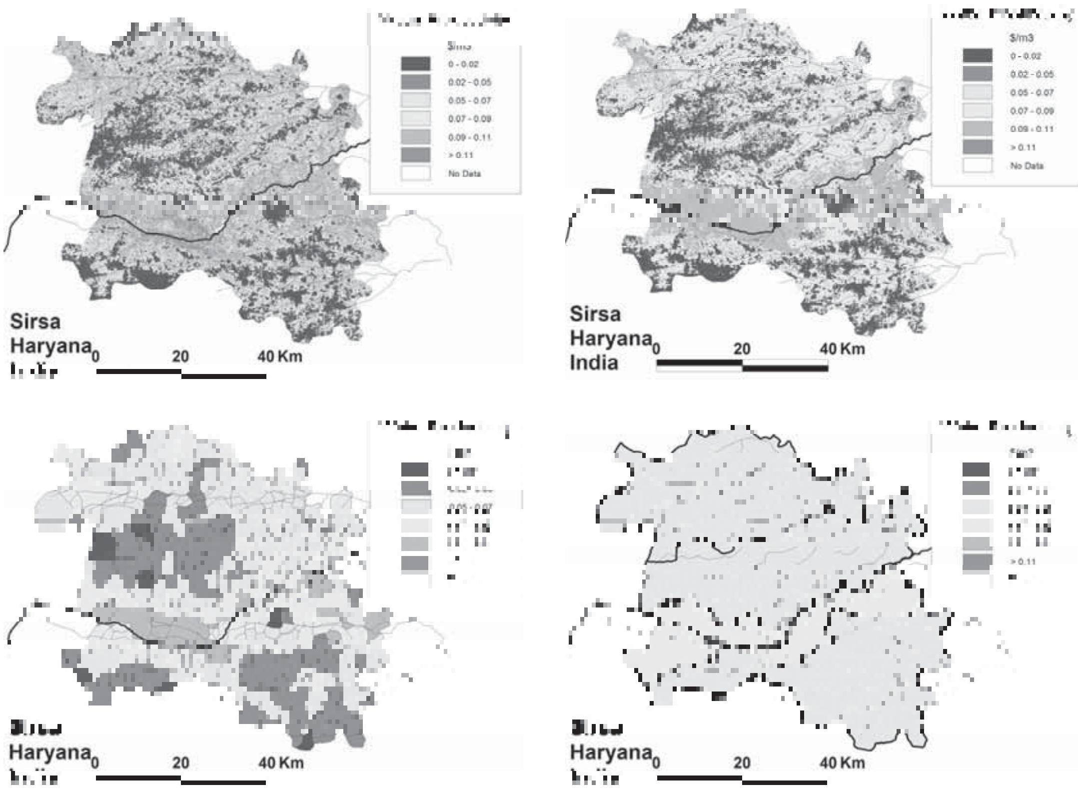

Figure 9.9 Water Productivity, expressed as gross return ($) per amount of water consumed (m^3) for four spatial scales: field (top-left), calculation unit (top-right), village (bottom-left), and irrigation district (bottom-right). Period included is *rabi* and *kharif* 2001-02 and are based on measurements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

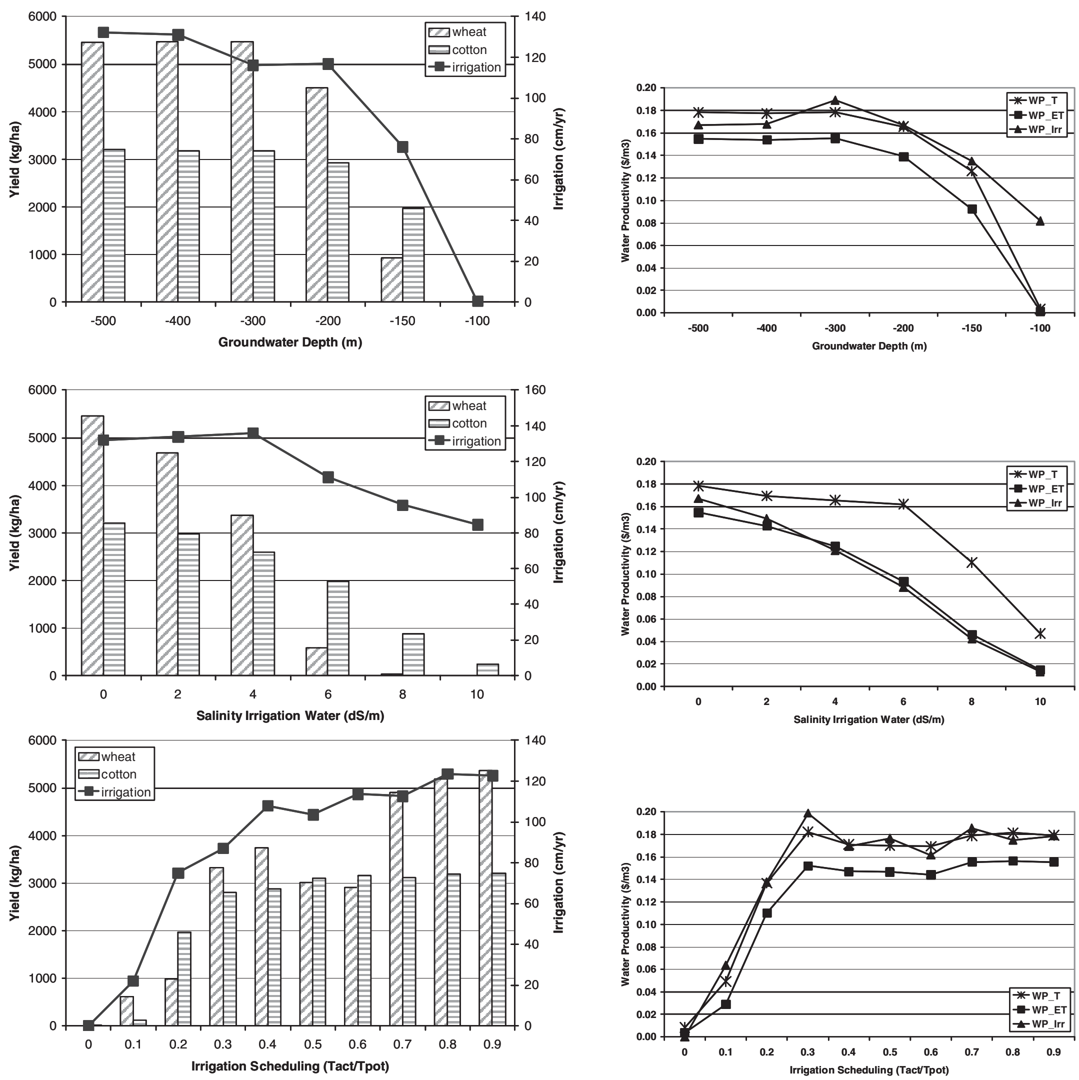

Figure 9.10 Impact of changes in groundwater depth (top), salinity (middle) and irrigation depth (bottom) on yields (left) and water productivity (right). Results are obtained using SWAP-WOFOST for farmer field 16.

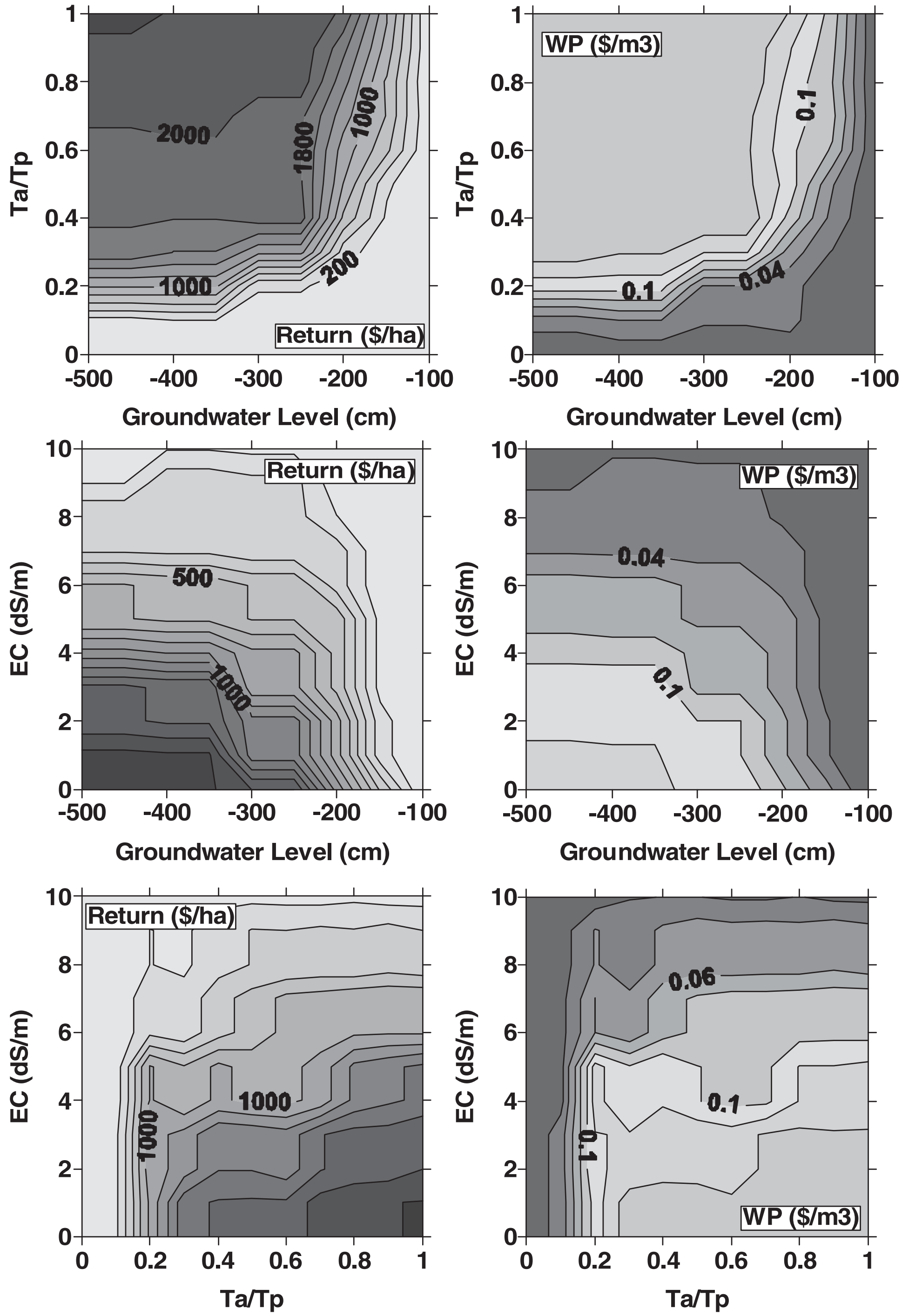

Figure 9.11 Scenario analysis of the combined effect of changes in groundwater depth, salinity level of irrigation water and irrigation scheduling on yields (left) and water productivity expressed as WP_{ET} (right). Results are obtained using SWAP-WOFOST for farmer field 16.

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.

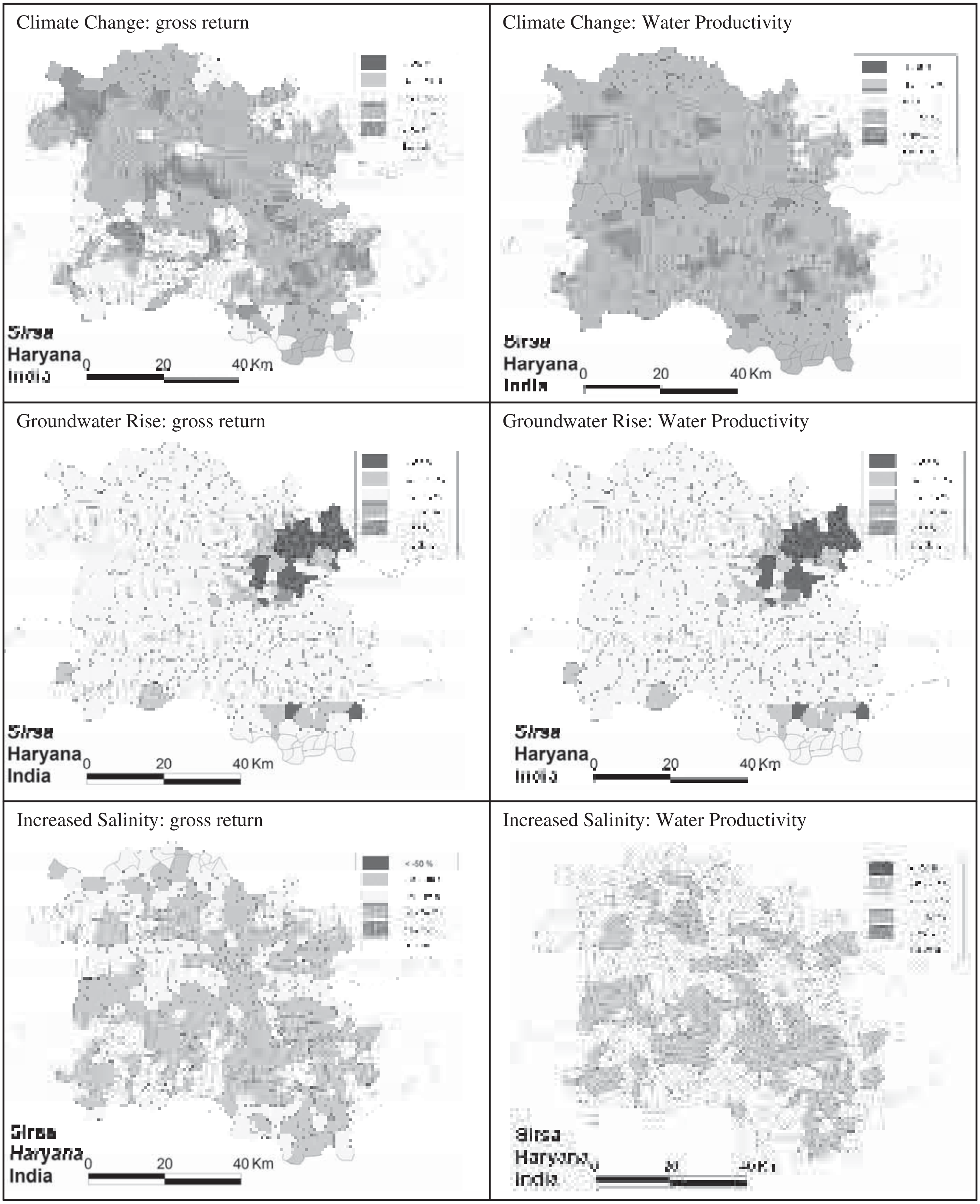

Figure 9.12 Scenario analysis and its impact on gross return (left) and water productivity (right). *WP* is expressed here gross production over ET (WP_{ET}). Values indicate changes in percentages taking the reference as presented in Figure 9.15 as base.

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.

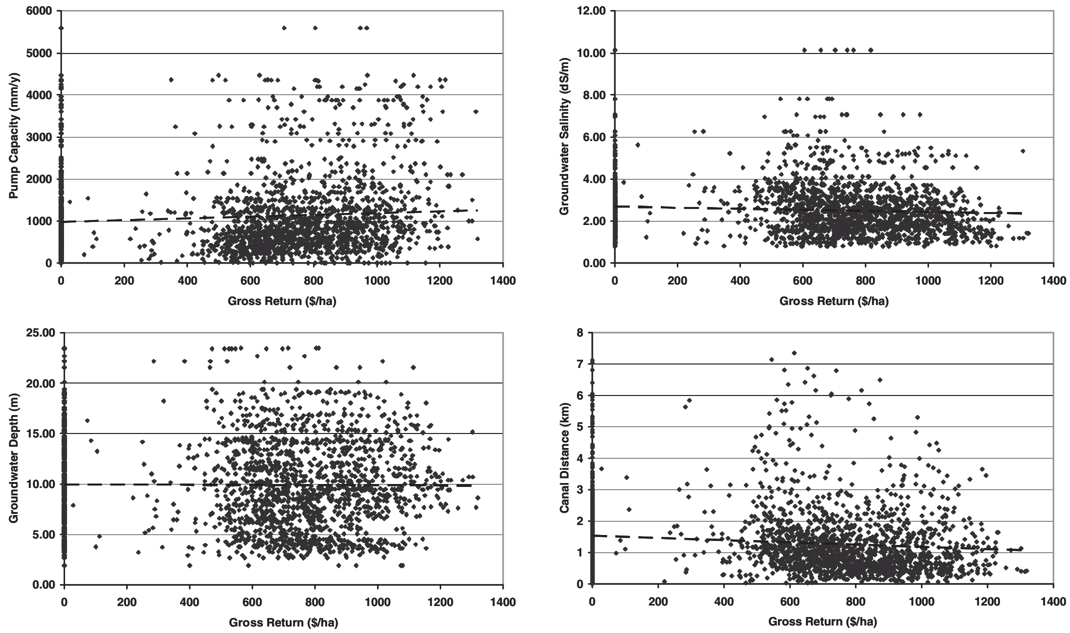

Figure 9.13 Correlation between gross return and pump capacity (top-left), groundwater salinity (top-right), groundwater depth (bottom-left) and distance to nearest canal (bottom-right). Analysis are based on calculation unit level using observations and remote sensing.

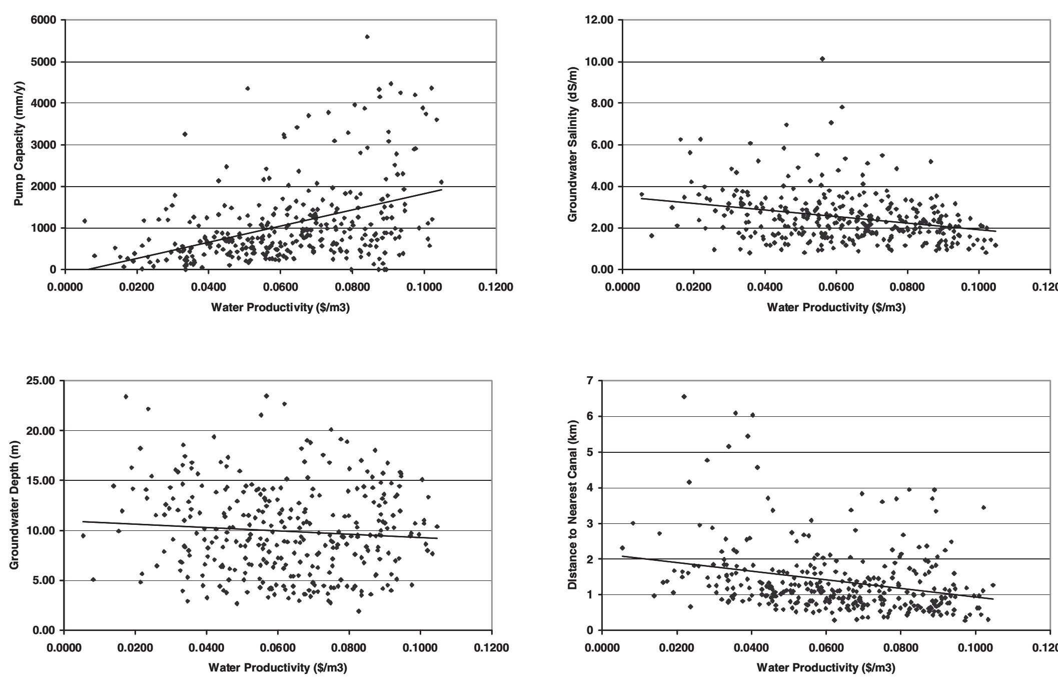

Figure 9.14 Similar to Figure 9.11 but based on village scale.

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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