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

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

Summary

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

8.1 Defining water productivity

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

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

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

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

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

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

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

8.2 An appraisal of the water productivity definitions

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

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

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

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

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

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

8.3 Calculation, aggregation and validation of water productivity

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

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

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

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

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

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

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

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

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

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

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

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

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

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

8.4 Application at investigated farmer fields

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

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

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

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

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

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

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

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

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

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

8.5 Proposed measures in Sirsa district

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

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

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

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

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

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

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

Replace paddy rice by dry rice or corn

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

Decrease soil evaporation

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

Improve land levelling to decrease distribution losses

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

Divide the available irrigation water over more land

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

Optimize leaching fraction

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

Use sprinkling irrigation

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

Increase groundwater recharge in monsoon period

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

More reservoirs and dams

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

Complete canal lining and increase canal maintenance

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

Organise reliable canal water in saline groundwater areas which prevents water spill

No data are available on irrigation water spill due to unreliable canal water supply.

Optimize conjunctive use of canal and groundwater in saline groundwater areas

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

Drainage in waterlogged areas

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

Improve water management at secondary level

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

Improve water management at tertiary level

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

Grow more eucalyptus trees to extract excessive water

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

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

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

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

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

8.6 Concluding remarks

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

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

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