STUDY OF WATER AND SALT BALANCES FOR EIGHT SAMPLE WATERCOURSE COMMANDS IN CHISHTIAN SUB-DIVISION, PUNJAB, PAKISTAN

E.G. van Wayjen

JUNE 1996
INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
LAHORE, PAKISTAN

Study of water and salt balances for eight sample watercourse commands in Chishtian Sub-division, Punjab, Pakistan

Table of contents

List of figures

List of tables

FOREWORD

Traditionally, salinity in Pakistan has been associated with the rise in water tables brought about by the advent of large-scale irrigation. However, in the late seventies, the Soil Survey of Pakistan (SSP) provided evidence that salinization, was much more complex. They distinguished between primary salinization, caused by weathering of parent material, and secondary salinization induced by either capillary rise from high water tables or by use of low quality groundwater. SSP further warned about the risk of sodicity, which appeared to be a bigger problem than salinity per se. This was substantiated by a survey undertaken by WAPDA from 1977-1979, which indicated that of 16.72 million ha of irrigated land, 4.22 million ha was affected by salinity, which is about 25%. The same survey showed that of these affected lands only about one quarter (28%) was qualified as saline, while the remainder was found to be (saline-) alkaline. Recent research studies show that the rapid development of tubewells, especially in the Punjab, and the subsequent increased use of groundwater, which is of a much lower quality than canal water, are likely to accelerate sodification.

Since 1989, the International Irrigation Management Institute (IIMI) has carried out research on problems of salinity associated with irrigated agriculture in Pakistan. The aim of the research is to provide tools and methodologies for policy makers and irrigation managers to evaluate the economic and environmental impact of irrigation management interventions. One such tool that has been proposed by IIMI is the application of a simple spreadsheet-based salt and water balance. The approach was tested for Egypt and Pakistan with data aggregated at the level of an irrigation system. The present study carries the approach further by verifying the predicted results of the tool with measured values of water tables and soil salinity for eight watercourses in south-east Punjab. For these eight watercourses, very detailed information is available, which would be impossible to collect for larger areas, but allows us to test the validity of the approach. In addition to that, this study provides insights into the added value of combining the relatively straightforward salt & water balance approach with modelling exercises using an agro-hydrological model, which is based more on physical processes.

The author of the study, Erik van Waijjen, had worked for IIMI in Pakistan from 1991 to 1993 on inter-related aspects of irrigation and salinity. He was asked to come back to carry out the present study as a consultant. The paper capitalizes on the large database that is available with IIMI. This is one of several outputs that have been recently produced on salinity in Pakistan

Marcel Kuper

WATER AND SALT BALANCES FOR EIGHT SAMPLE WATERCOURSE COMMANDS IN CHISHTIAN SUB-DIVISION, PUNJAB, PAKISTAN

Context of study

When IIMI started working in Pakistan, it first adopted a correlation approach to study the relation between irrigation (canal, tubewell) and soil salinity: Some correlations were found, but not always the same in different areas, and the mechanism of cause and effect could only be surmised. A three-month water balance study of one watercourse command was also done, without the inclusion of effects on soil salinity. These studies were later complemented with attempts to understand the increase/decrease of soil salinity with deterministic models that simulated the transport of water and salt in the soil under irrigated cropping (SOWATSAL, SWATRE, SWAP93). Calibration of these models requires many detailed data at the field level, so only a few fields can be covered, which poses a question of representation. IIMI has taken on the challenge to apply the models to farmers fields, which are of course much more representative of the general picture in the Punjab than trial fields at a research station, but for which it is consequently more difficult to collect accurate data. Calibration of the moisture regime (suction, volumetric water content) was satisfactory (S. Smets, 1996), but predictions of soil salinity are more difficult to match with field measurements due to several reasons:

- Effects of imperfect leaching caused by preferential flow, non-uniform irrigation application over a field. In SWAP93, this is simulated by introducing a division of the soil moisture into a mobile and an immobile fraction (water transport only through the mobile fraction), a concept which differs from the more conventional one as presented (e.g. in van Hoorn and van Alphen 1994) where some water passes quickly through preferential flow paths, and the rest percolates slowly while mixing with the soil moisture. (See a later comment on the consequence for the equilibrium salt profile of these different concepts.)
- Field measurements of the soil salinity are only done at the beginning and end of the studied seasons, so the predicted development of the salinity through the season and its response to irrigation and evapo-transpiration cannot be checked against field data as is the case with soil moisture changes. With samples so widely spaced in time, one can question the usefulness of a simulation model that uses time steps of hours and even minutes.
- Effects of precipitation and dissolution of salts are as yet not incorporated in the used model. The expected process is a precipitation of slightly soluble salts such as gypsum ($CaSO_4.2H_2O$) and lime ($CaCO_3$) when the irrigation water is concentrated in the soil due to evapo-transpiration, thus giving rise to a smaller increase in soil salinity but a bigger increase in sodicity (high sodium content of soil moisture harmful to soil structure) than would be otherwise expected.

Yet, these models have proved to be useful as a research tool, to further the understanding of the processes underlying soil salinization. Compared with experiments in trial fields, they have enabled researchers to test in a much faster and cheaper way the effects of different irrigation scenarios for one season or for many years. However, as long as problems with the calibration persist, especially with regard to soil salinity levels, these results should be mainly judged in comparison to a reference simulation, more than attaching great significance to the absolute values.

As a complement to the use of detailed field level simulation models, IIMI decided to also study the water and salt balances of larger hydraulic units, such as a watercourse, distributary or branch/main canal commands, and at a larger time step, such as a month or season. A start with this approach was made by Kijne (forthcoming), who developed water and salt balances for canal commands in three IIMI research locales; Chasma Right Bank Canal (NWFP), Gugera Branch Canal (central Punjab), and Chishtian Sub-division of the Fordwah Branch Canal (south-east Punjab). For his study, he used a water balance model developed by C.J. Perry of the Research Division of IIMI-Headquarters in Colombo, Sri Lanka (see Perry, 1996). This model consists of spreadsheets (one for each season) that contain simple water balance equations in a structured way. The user has to input area, cropping intensity, canal inflow, rainfall, a number of loss rates and efficiencies, and percentage of losses recovered by pumping. The model then allocates the water to drain outfall, crop use, groundwater and non-beneficial evaporation, and calculates the amount of pumping. Kijne combined the results of the water balance with additional data on the salt contents of canal water and pumped groundwater, to determine the salt balance at the irrigated field level. The outcome was predictions of changes in soil salinity, with reference to a rather high initial soil salinity. Main findings of his study were the unsustainable changes in groundwater level: a rise in CRBC which might lead to waterlogging; a drop in the Punjab locales that might threaten future groundwater availability. Kijne used the model to calculate which changes in the cropping intensities were necessary to assure sustainability. With regard to soil salinity, results indicated almost no change for the Gugera site, and an increase for the Fordwah site, especially in *kharif* season.

Presently IIMI-Pakistan is developing an integrated approach to evaluate the economic and environmental impact of changes in irrigation management (IIMI-Pakistan, 1996). This approach aims to integrate several multi-disciplinary sub-studies at different levels of the system (field, farm, watercourse, distributary and main/branch canal level). Models used at different levels will have to be coupled. The watercourse command area has been selected as the basic unit of analyses, as the interface between main / secondary levels and farm / field level; between management by Irrigation Department and by farmers. Therefore, this study aims to achieve two things: 1)application of the water and salt balance model to the watercourse command level, to have a better understanding of the effect of irrigation on the agro-hydrology and the soil salinity at this level, and 2) try to apply the SWAP93 model at the watercourse level, taking the calibration at field level as a starting point, to see how the results of the two methods compare and how the two methods can complement each other e.g. by supporting each others assumptions.

Research locale

The present study undertakes to apply the same water and salt balance model to eight sample watercourse commands in Chishtian Sub-division, where IIMI has collected detailed data for several years. The watercourses are fed by Fordwah Distributary and Azim Distributary, both taking off from Fordwah Branch Canal at its tail. Fordwah Distributary is a perennial canal, receiving water all year round except during the canal closure in January. Azim is non-perennial, receiving water only during *kharif* according to Irrigation Department rules, which however allows for three wheat irrigations during *rabi* for non-perennial canals. Some data for the sample watercourse commands are given in Table 1. Watercourses are numbered according to their distance in feet from the head of the distributary, and their location on left (L) or right ® bank. For a lay-out of

Fordwah and Azim distributaries and the location of sample watercourses, see the location map (Figure 1).

Table 1: IIMI's sample watercourses in Chishtian Sub-division.

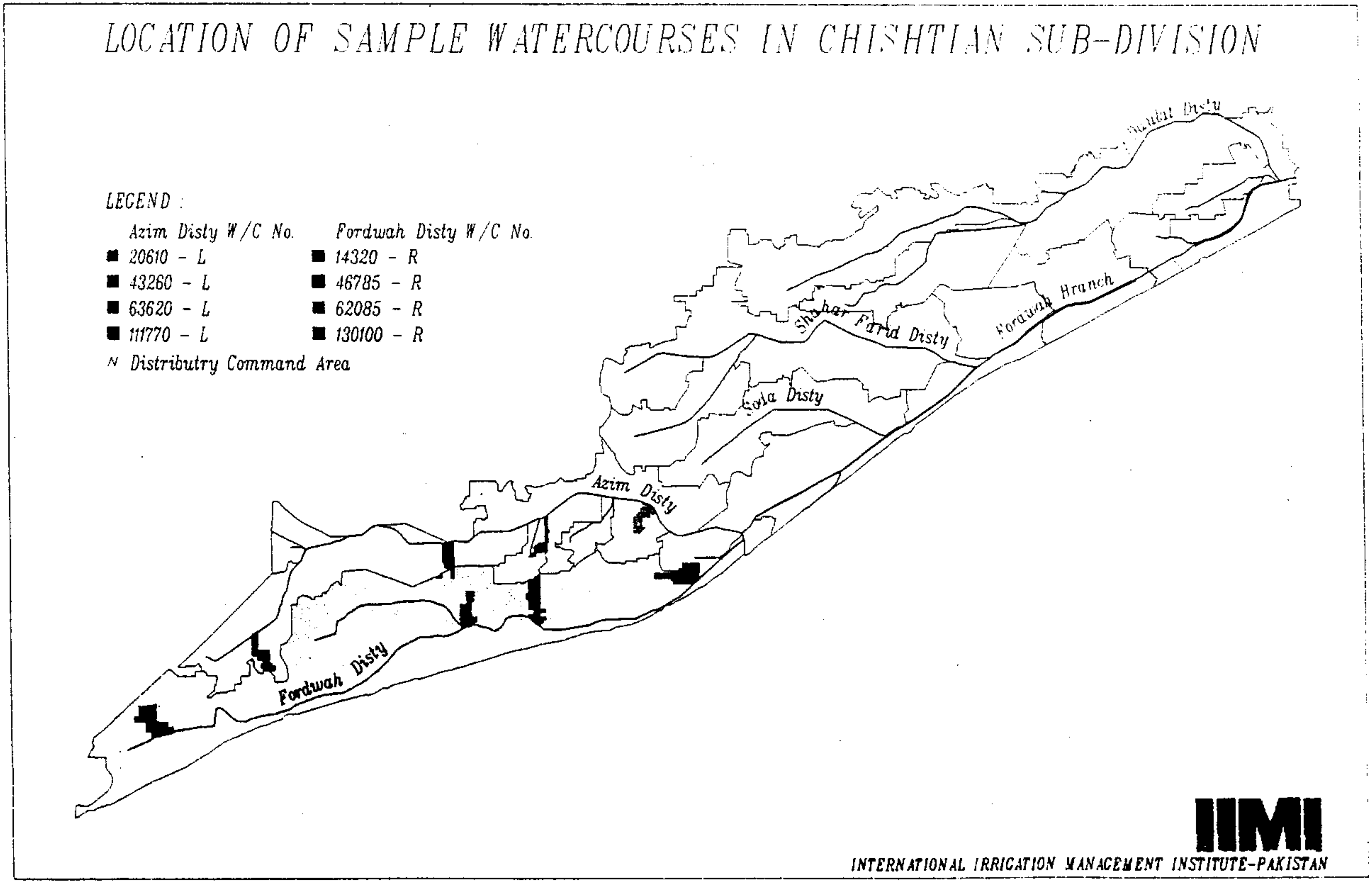
	Fordwah Distributary				Azim Distributary			
watercourse no.	14320R	46725R	62085R	130100R	20610L	43260L	63620L	111770L
GCA in ha / acre	198 / 490	180 / 445	138 / 342	273 / 675	124 / 306	69 / 170	123 / 305	121 / 300
CCA in ha / acre	198 / 490	180 / 445	133 / 328	268 / 663	119 / 294	66 / 164	121 / 298	119 / 294
Q in mm / 6mnth	396	416	397	399	773	1110	773	773

GCA = gross command area, CCA = culturable CA, Q = authorized discharge (Irrigation Department data)

Canal water supply is augmented by groundwater pumped by tubewells, which has allowed cropping intensities to almost double. There are about 110 tubewells in the eight sample watercourse commands, ranging from 6 in Azim 20L to 26 in Fordwah 130R. In most watercourse commands, tubewells are driven by diesel engine or tractor and belt. However, in Fordwah 130R, 4 tubewells are fitted with electric engines, and in Azim 111L even 11 out of 14 tubewells are powered electrically, thus greatly reducing the cost of pumping.

The climate is semi-arid having a very hot summer (*kharif*) with on average of 150 mm rainfall, and a cool winter (*rabi*) with about 40 mm rainfall. A wheat / cotton rotation is the main cropping pattern, other important crops being fodder and sugarcane. The salt and water balances were determined for two seasons: *kharif* 1994, and *rabi* 94/95. In contrast to adjacent areas, groundwater levels are quite deep (2 – 10 m) in most of the study area. Surface drainage is absent in the cropped areas due to the flat topography and the dense network of field bunds that prevent surface runoff.

Figure 1: Location map of eight sample watercourses.



Brief theoretical framework

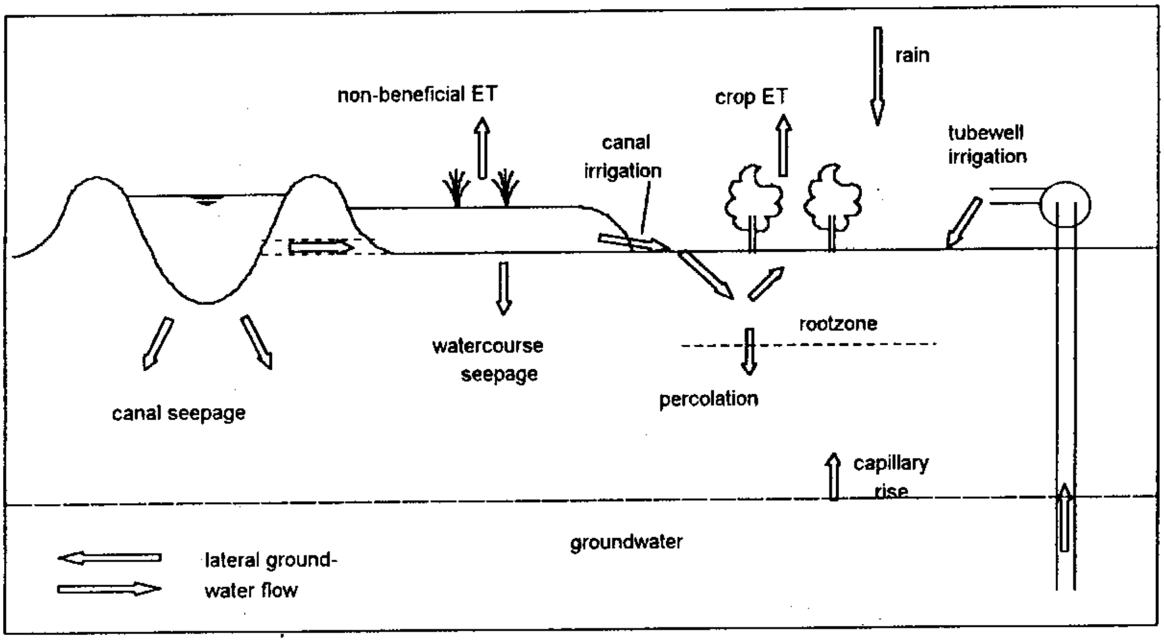


Figure 2: Elements of the water balance in the study area.

In Figure 2, the components of the water balance for the study area are shown. An important feature is the absence of surface drainage, which simplifies the water balance somewhat. A complication in the water balance stems from the fact that a watercourse command area is too small to include the groundwater in an accurate way. Part of the recharge to the groundwater comes from distributaries and larger canals outside the watercourse command, and also lateral in- and outflow of groundwater through the aquifer is not known. Therefore, this study focuses on the water balance of the root zone. The results hereof are then used to determine the salt balance of the root zone, and its effect on the sustainability of irrigated agriculture. Observed groundwater fluctuations will be used as a background against which to assess the outcomes of the water balances.

Over a longer time period, the change in storage of moisture in the soil can be ignored, so the water balance equation for the root zone becomes:

I (irrigation) + P (rain) + G (capillary rise) = ET (evapo-transpiration) + R (percolation)

If there is no change in the salt content of the soil, the simple salt balance can be written as:

$$I \times Ci + G \times Cg = R \times Cr$$

where C means salt concentration, i stands for irrigation water, g for groundwater and r for percolation water.

Introducing Rnet = R – G, and assuming that either no capillary rise occurs (G = 0) or that the salt content of the groundwater is equal to that of the percolation water (Cg = Cr), the following relation between the quantities and salt contents of irrigation and percolation can be derived.

$$\text{Rnet} \times \text{Cr} = \text{I} \times \text{Ci} \quad \text{or} \quad \frac{\text{Rnet}}{\text{I}} = \frac{\text{Ci}}{\text{Cr}}$$ in which $\frac{\text{Rnet}}{\text{I}}$ is the leaching fraction

If the irrigation water mixes well with the soil moisture, then Cr will be equal to the salt content of the soil moisture at field capacity, Cfc. In this case, the last equation can be used to calculate the leaching fraction required to keep the salt content of the soil moisture below a certain level, or to calculate the resulting Cfc for a given irrigation and percolation. To be more precise, Cr will be equal to Cfc of the soil moisture at the bottom of the root zone. Near the surface, Cfc will be nearer to Ci, as long as there is frequent irrigation. Thus, the soil salinity is being overestimated when alculating Cr with the leaching fraction and considering it representative for the whole root zone.

However, leaching of salts from the soil moisture by percolating water is not 100% efficient. Upon irrigation, some water passes through cracks, larger pores, zones of higher conductivity, or otherwise preferential flow paths and percolates with an almost unchanged salt content Ci. The rest of the water moves slowly through the soil while mixing with the soil moisture, leaving the root zone with approximately the soil moisture salt content Cfc. Uneven distribution of irrigation water over a field also makes the leaching process less efficient. If the symbol fr[1] is used for the leaching efficiency, defining it as the fraction of the percolated water that passed through the soil slowly while mixing, the new equilibrium salt balance looks like this:

$$\text{I} \times \text{Ci} = (1 - \text{fr}) \times \text{R} \times \text{Ci} + \text{fr} \times \text{R} \times \text{Cfc} \quad \Rightarrow \quad \text{Cfc} = \frac{\text{I} \times \text{Ci}}{\text{fr} \times \text{R}} - \frac{1 - \text{fr}}{\text{fr}}$$

Leaching efficiencies depend on soil type and on the way of irrigation application. Values are in the order of 80% for sandy soils, 60% for loams and 40% for clays. The effect of a leaching efficiency less than 100% is, of course, to increase the equilibrium soil salinity, so soil salinity is underestimated when ignored. This underestimation is, however, partly canceled by the overestimation caused by the lower Cfc near the surface as mentioned above. In this study, therefore, leaching efficiencies have been used from 100% for the lighter soils (loamy sand), to 70% for the heavier soils (sandy clay loams).

In the following sections, the components of the water and salt balance will be discussed. For some fluxes, good measurements are available; other terms have to be judged from field observation or from literature, and one component can be the dependent variable derived from the balance. Since percolation 'losses'[2] from irrigated

---

[1] Van Hoorn and van Alphen prefer the use of fi defined as the fraction of the irrigation water that mixes with the soil moisture. Their argument is not fully convincing, and complicates matters unnecessarily.

[2] Losses is put here between quotes because a minimum percolation is necessary to remove excess salts from the root zone, so this should labeled as a beneficial use of irrigation water. If more percolation occurs due to over-irrigation or non-uniform water application, this extra percolation is really a loss at the field level. Again quotes could be put, because in an area with tubewell irrigation, the percolation that joins the groundwater can be

fields are an important element in the salt balance, but difficult if not impossible to measure. In this study, they are first estimated, and then corrected for the rate of over- or under-irrigation that takes place.

For the sake of readability, the set up of the balances is discussed step-by-step, and the final results are then compared with the field observations. The actual process of determining the balance was more trial and error, repeatedly comparing results with measurements and making adjustments to improve the fit. Also, errors and omissions in the data were found, sometimes as a result of extra scrutiny because of a poor fit, and correction of these data equally improved the match between predicted and measured values.

Determination of water supply at field level and crop water requirements

In Perry's model, only one watercourse command can be evaluated at a time, and eight watercourses will produce 48 pages of (printed) output. Another limitation of the model in the context of this study is the utilization of pump recovery as a percentage of groundwater recharge, whereas for the studied areas, the actual groundwater pumping by tubewells has been observed. Crop water uptake is calculated in the model as a fixed percentage of irrigation water and rainfall, on the basis of user input conveyance and application efficiencies, regardless of whether there is over- or under-irrigation. For this study, detailed crop surveys were available, which were used to calculate the evapo-transpiration requirements of the cropped areas. For all of these reasons, it was decided to set up one spreadsheet combining the salt and water balances for all eight watercourses.

Canal water supplies were monitored by daily observation of the up- and down-stream water levels of the outlet structures (*moghas*) of the watercourses. These water levels were then converted into discharges using formulas derived from hydraulic theory, supplemented with discharge measurements for calibration. Problems were encountered of frequent tampering with the outlet structures, by farmers to increase discharges and by Irrigation Department (ID) to restore the design discharges. Also cuts and illegal pipes were observed that increased discharges to watercourse commands. Therefore, uncertainty in figures for canal supplies is estimated at +20%/–10%. Between mogha and field, water is lost from watercourses and field channels. For some watercourses, measurements of losses by IIMI, including a study by Barral (1994) were available. Based on these data and with an eye on the prevailing soil types, loss rates were determined and used to calculate the supply of canal water at the field level. Soil types and loss rates for each watercourse are given in Table 2, along with some other parameters used in the water and salt balance. The resulting canal water supplies at field level are given in line 1 of Table 3A for *kharif*, 3B for *rabi* and 3C for the whole year, expressed in mm of water depth over the cropped area. For Azim, a clear trend can be seen of decreasing canal water supply from head to tail, with Azim 111L receiving no canal supplies at all. Also, for Fordwah, the watercourse near the tail (130R) has a low canal water supply, but 14R at the head receives less water as well, due to the size and the crest level of the *mogha*. Canal water supplies in *rabi* to the Azim watercourses constitute only 17% of total irrigation water supply, because of Azim being a non-perennial distributary. In Fordwah Distributary, the water supply is smaller during *rabi* than during *kharif* due to the general canal closure for maintenance each year in January.

---

pumped and used for irrigation again, if groundwater quality allows. However, there is an end to this constant recycling of water, because in the long run the water quality will gradually deteriorate.

Tubewell water supplies were measured by asking farmers the number of hours they operated their tubewells after every 2 days. These hours were multiplied with the measured discharge of each tubewell. Errors stem from inaccuracies of the farmers answers, and changes in pump r.p.m., especially for pumps driven by diesel engine and by tractor power take-off. Again, the margin of error will be about ±15%.

From Tables 3, (line 2), it is clear that tubewell pumping is supplementary to canal water supply. Watercourses with a generous canal water supply, such as Fordwah 46R and Azim 20L, have the lowest groundwater pumping, while Azim 111L with no canal water supply has the highest groundwater pumping by far (facilitated by cheap electric power, so that it even has the highest total irrigation supply).

Rainfall was measured in four of the eight sample watercourse commands. As the difference between the seasonal totals was small, the average of the four values was taken and applied to all eight watercourse commands (line 3). Total water supplied by irrigation and rain is printed in line 4 of Tables 3. Capillary rise is not yet taken into account here, because it is estimated in a later step of the water balance, dependent on the Relative Water Supply RWS.

For both seasons, crop surveys were done covering the complete watercourse commands. For each crop, potential evaporation was calculated using reference evapo-transpiration ETo following Penman/Monteith (meteoroligical data from stations in the area) and appropriate crop factors Kc based on figures in FAO (1977). Details of these calculations are given in Annex 2. In the case of rice (a minor crop), the percolation losses were not included in the crop water requirements. These calculations yielded a theoretical crop water requirement, valid if the crop faces no constraints. Under actual conditions in the study area, constraints are plenty, even when not counting constraints of soil moisture and soil salinity that are here under study. Only a few farmers apply optimal practices, crops of most farmers suffer from a range of causes such as lack of fertilizer, late sowing, poor seed bed preparation, pests and diseases, etc. Therefore, a reduction factor was applied to the theoretical crop water requirements to arrive at the real crop water requirements. This factor was taken to be 0.8 for *kharif* and 0.9 for *rabi*. The *rabi*-crop wheat is more sensitive to water stress (FAO, 1979) and therefore its actual water requirement is assumed to be closer to its theoretical water requirement than for *kharif* cotton,, that even needs a bit of water stress to attain maximum fiber yield. Choice of reduction factors is based on best judgment (no data are available on this topic).[3]

In Tables 3, line 9, the resulting crop water requirements are given. Over the *kharif* season, values range from 700 to 836 mm, with higher values for watercourse commands with a larger acreage under sugarcane. For *rabi* crop, water requirements are close to 420 mm, since wheat is the predominant crop in all watercourse commands.

[3] As a side-track not pursued further, another approach can be mentioned to estimate crop water requirements or actual crop water consumption: the reversal of production functions relating crop yields to crop water consumption. For many crops, research has been done to determine how the yield responds to the amount of water that is available for evapo-transpiration. Considering the low yields obtained in Pakistan's Punjab, on average less than half of the potential yields, it would be interesting to pursue the idea of reversing this relationship and to predict the amount of water consumed by the crops as a function of the actual yields obtained in the farmers' fields. This would most likely give a rather low water consumption and relatively high amount of water available for percolation and leaching.

Table 2: Soil types, losses and efficiencies: values used in the balance

	FD14R	FD46R	FD62R	FD130R	AZ20L	AZ43L	AZ63L	AZ111L	avg
avg soil type:	sa loam	sa loam	sa loam	lo sand	si loam	si loam	si loam	clay loam	
w.c. losses	35%	30%	30%	35%	25%	25%	25%	20%	28%
a: field irrigation efficiencies when RWS = 100%									
non-rice crops	0.75	0.75	0.75	0.70	0.80	0.80	0.80	0.80	0.77
rice	0.47	0.47	0.47	0.40	0.53	0.53	0.53	0.60	0.5
all crops	0.75	0.75	0.73	0.70	0.75	0.80	0.79	0.77	0.75
b: deep percolation as % of irrigation water delivered to the field, when RWS = 100%									
non-rice crops	0.2	0.2	0.2	0.24	0.16	0.16	0.16	0.16	0.185
rice	0.45	0.45	0.45	0.5	0.4	0.4	0.4	0.35	0.425
all crops	0.20	0.20	0.21	0.24	0.21	0.16	0.17	0.19	0.20
c: leaching efficiencies corrected for effect of low ECe at surface									
	0.9	0.9	0.9	1	0.8	0.8	0.8	0.7	0.85

Table 3A: KHARIF 94 Water and salt balance at irrigated field level (in mm and dS/m)

	FD14R	FD46R	FD62R	FD130R	AZ20L	AZ43L	AZ63L	AZ111L	avg
1 canal water	294	439	432	228	681	510	253	4	355
2 tubewell	185	64	138	313	52	148	223	903	253
3 rain	135	135	135	135	135	135	135	135	135
4 Irr + Rain	614	638	705	676	868	794	611	1041	743
5 percol. RWS=1	113	118	138	146	168	123	99	190	137
6 ET non-benef.	31	32	37	41	39	32	25	43	35
7 capillary rise	200	70	45		70				
8 avail. for ET	670	557	575	489	732	638	487	808	620
9 ET potential	785	740	747	738	836	798	711	700	757
10 RWS trial	85%	75%	77%	66%	88%	80%	69%	115%	82%
11 percol. actual	80	60	75	48	126	74	37	298	100
12 ET act	703	616	639	588	773	688	549	700	657
13 RWS act	90%	83%	86%	80%	93%	86%	77%	100%	87%
14 EC tubewell	1.76	0.86	0.96	1.34	0.65	0.80	0.76	1.07	1.03
15 EC I+P+G	0.90	0.29	0.35	0.69	0.23	0.28	0.36	0.93	0.50
16 Leach. frac.	10%	8%	10%	7%	13%	9%	6%	29%	12%
17 ECfc equil.*	10.10	3.66	3.78	9.74	1.90	3.48	7.26	4.20	5.51
18 ECe equil.*	5.05	1.83	1.89	3.25	0.95	1.74	3.63	2.10	2.55

Table 3B: RABI 94/95 Water and salt balance at irrigated field level (in mm and dS/m)

	FD14R	FD46R	FD62R	FD130R	AZ20L	AZ43L	AZ63L	AZ111L	avg
1 canal water	214	345	329	171	150	80	39	5	167
2 tubewell	88	66	128	343	151	220	326	481	225
3 rain	54	54	54	54	54	54	54	54	54
4 Irr + Rain	355	465	511	568	355	353	419	540	446
5 percol. RWS=1	67	89	98	130	55	54	65	84	80
6 ET non-benef.	18	23	26	34	14	14	17	22	21
7 capillary rise	100	20			35				
8 avail. for ET	371	373	388	404	321	285	337	434	364
9 ET potential	399	406	408	403	396	411	418	427	408
10 RWS trial	93%	92%	95%	100%	81%	69%	81%	102%	89%
11 percol. actual	57	75	88	131	34	21	40	92	67
12 ET act	380	387	397	403	342	318	362	427	377
13 RWS act	95%	96%	97%	100%	86%	77%	87%	100%	92%
14 EC tubewell	1.75	0.87	0.89	1.33	0.64	0.81	0.85	1.15	1.04
15 EC I+P+G	0.81	0.30	0.35	0.86	0.38	0.55	0.68	1.03	0.62
16 Leach. frac.	13%	15%	17%	23%	9%	6%	9%	17%	14%
17 ECfc equil.*	7.08	2.03	2.16	3.74	5.27	11.40	8.71	8.16	6.07
18 ECe equil.*	3.54	1.02	1.08	1.25	2.63	5.70	4.36	4.08	2.96

* The equilibrium EC for a season has no absolute value and is indicative of the direction of change only.

Table 3C: YEAR Water balance at irrigated field level (in mm and dS/m)

	FD14R	FD46R	FD62R	FD130R	AZ20L	AZ43L	AZ63L	AZ111L	avg
1 canal water	508	784	761	400	831	590	292	9	522
2 tubewell	273	130	266	655	203	368	549	1384	478
3 rain	189	189	189	189	189	189	189	189	189
4 Irr + Rain	969	1103	1216	1244	1223	1147	1030	1582	1189
11 percol. actual	137	135	163	179	160	95	76	390	167
6 ET non-benef.	49	55	62	75	53	46	42	65	56
7 capillary rise	300	90	45	0	105	0	0	0	68
12 ET act	1083	1003	1036	991	1115	1006	912	1126	1034
9 ET potential	1184	1146	1154	1141	1232	1209	1129	1126	1165
13 RWS act	92%	88%	90%	87%	90%	83%	81%	100%	89%
14 EC tubewell	1.75	0.87	0.93	1.33	0.64	0.81	0.81	1.10	1.03
15 EC I+P+G	0.87	0.29	0.35	0.77	0.27	0.36	0.49	0.96	0.55
16 Leach. frac.	11%	11%	13%	14%	12%	8%	7%	25%	13%
17 ECfc equil.	8.84	2.76	2.90	5.34	2.61	5.23	8.02	5.14	5.10
18 ECe equil.	4.42	1.38	1.45	1.78	1.30	2.61	4.01	2.57	2.44

Table 4: Water balance at watercourse command level (in mm, gw change in m)

	FD14R	FD46R	FD62R	FD130R	AZ20L	AZ43L	AZ63L	AZ111L	avg
g.w. depth	-1.25	-2	-2.5	-4	-2	-4	-4	-6	-3.22
drain. por.	0.15	0.17	0.18	0.2	0.17	0.2	0.2	0.22	0.19
KHARIF									
w.c. losses	117	149	146	71	128	138	65	1	102
to ETnon-ben.	23	30	29	14	26	28	13	0	20
w.c. percolation	94	119	117	56	102	110	52	1	81
field percolation	59	48	59	27	71	60	28	208	70
total to g.w.	153	167	176	84	173	170	80	209	151
t.w. pumping	137	51	109	179	29	120	171	631	178
capillary rise	148	56	35	0	39	0	0	0	35
net recharge	-132	61	32	-96	104	50	-91	-422	-62
g.w. change (m	-0.88	0.36	0.18	-0.48	0.61	0.25	-0.46	-1.92	-0.29
RABI									
w.c. losses	89	114	108	55	23	16	7	1	52
to ETnon-ben.	18	23	22	11	5	3	1	0	10
w.c. percolation	71	91	86	44	19	13	6	1	41
field percolation	44	58	67	78	16	13	22	63	45
total to g.w.	115	149	154	122	34	25	28	64	86
t.w. pumping	68	51	98	204	70	132	179	331	142
capillary rise	77	15	0	0	16	0	0	0	14
net recharge	-29	82	55	-82	-52	-106	-151	-267	-69
g.w. change (m	-0.20	0.48	0.31	-0.41	-0.31	-0.53	-0.76	-1.21	-0.33
YEAR									
w.c. losses	206	263	254	126	151	154	72	2	153
to ETnon-ben.	41	53	51	25	30	31	14	0	31
w.c. percolation	165	211	203	100	121	123	57	1	123
field percolation	103	105	126	105	86	72	50	272	115
total to g.w.	268	316	329	206	207	195	107	273	238
t.w. pumping	204	102	207	384	99	252	350	962	320
capillary rise	225	71	35	0	56	0	0	0	48
net recharge	-161	143	87	-178	52	-56	-242	-689	-131
g.w. change (m	-1.08	0.84	0.48	-0.89	0.31	-0.28	-1.21	-3.13	-0.62

Water balance of the root zone

Next, the total water supply to the irrigated fields is subdivided into percolation to the groundwater, non-beneficial evapo-transpiration and actual evapo-transpiration (ETact) by the crop. To determine the amount of water that percolates from the root zone to the groundwater, an approach could be adopted where percolation is the resulting dependent variable in a balance:

R (or, to be precise, Rnet) = I + P – ETact

The problem is how to make an accurate estimate of ETact for a crop under less than optimal crop husbandry and under varying amounts of water stress. A first assumption could be that if irrigation plus rainfall is equal to or less than the (adapted) potential evapo-transpiration, all water is consumed by the crop and nothing is left for percolation. However, field application of irrigation does not happen with 100% efficiency, so there will always be percolation. Field application efficiency is less than 100% because water cannot be distributed uniformly over the field, and because distribution over time is non-uniform as well, alternating between periods of excess water with periods of shortage. The SWAP93 model is an excellent tool to study this last process. ETact and percolation is calculated as a function of irrigation quantity and timing, capacity of the soil to store moisture, and ETpot.

Therefore, as a first step, the same approach used by Perry in his water balance model is adopted here. In Perry's model, the percolation from the root zone is calculated as a fixed fraction of the irrigation and rain supplies, derived from the field application efficiency and effective rain percentage, both to be input by the user. This means the estimation of the field application efficiency is critical, especially for the study of salt balances where percolation serves to remove salts from the root zone. In Table 2 the values used in this study are given. They are based on data from FAO (1980) as cited in van Hoorn and van Alphen (1994, p. 561) for well leveled and shaped basins, which make a distinction between soil types. These irrigation efficiencies apply in a situation of 'normal' irrigation, where there is not much over-or under-irrigation (in Table 2, referred to by 'RWS = 100%').

Likely, field application efficiency for tubewell water is higher than for canal water, because farmers directly bear the cost of pumping and because discharge and timing are more under the control of the farmer. This saving of water will, however, be largely canceled by the losses occurring in the field channels between the tubewell and the field, so neither effect has been taken into account in this study.

Rice is not an important crop in the area. In the crop survey for *kharif* 1994, the two watercourse commands with the highest percentage of rice fields were Azim 20L and Azim 111L, with both being 12% of the cropped area. Because percolation from rice fields is, obviously, much higher than for other crops, separate field application efficiencies for rice fields were estimated based on soil types (see Table 2), and overall weighted average efficiencies were calculated.

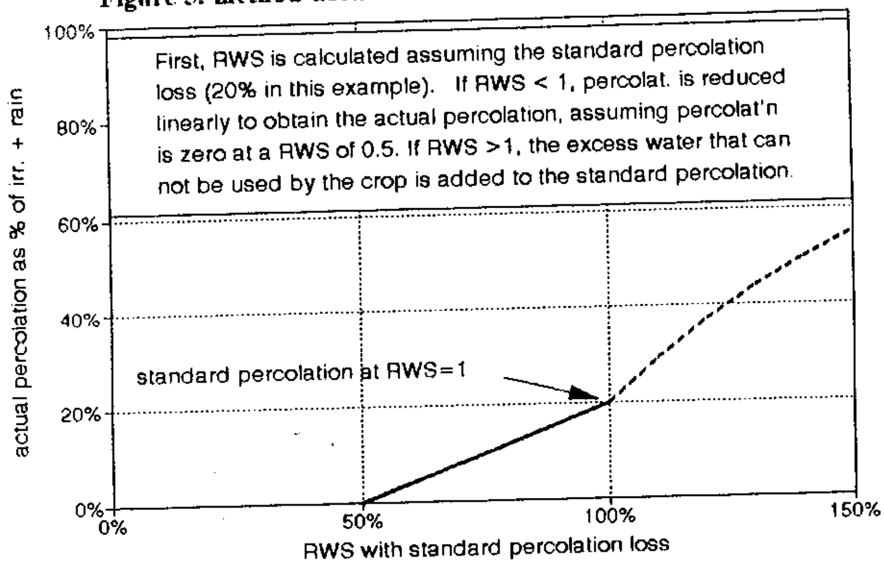
The 'efficiency' of rainfall (effective rain; the percentage of the rain used by the crop) has been set at 85%. Runoff does not occur in the area, rain is 'applied' uniformly over the field, and the practiced under-irrigation allows for enough free storage capacity in the root zone for the very limited rainfall.

The field losses as determined with these field efficiencies are divided between 80% percolation to groundwater and 20% non-beneficial evapo-transpiration. Again, the fraction of the losses that goes to non-beneficial ET is based on best judgment, since no data are available. Vegetation between fields, especially shrubs and trees with deep roots, will have an influence on this. Thus, the percolation given in line 5 is calculated by multiplying the field losses (fraction) with 1 plus 0.12 (= 80% of (1 - percentage effective rain (0.85) = 0.15)) multiplied by P. For the non-beneficial evapo-transpiration (1 + P) are multiplied by the fraction of field losses.

The resulting values for percolation and non-beneficial evapo-transpiration are presented in Tables 3A and 3B, lines 5 and 6. In the first instance, only the above factors were taken into account. First, results indicated a very low Relative Water Supply (RWS) for Fordwah 14R. However, this watercourse has relatively shallow groundwater tables between 1 and 1.5 m below field level. A shortage of irrigation water will be easily supplemented with capillary rise of groundwater. Farmers report that crops in some fields need only two irrigations in a season (N. Kielen, 1996). Therefore, an entry for capillary rise was made in the water balance (line 7), choosing a conservative value that was judged to be the minimum that can be delivered by capillary rise. Apart from Fordwah 14R, the same was done for three other watercourses with intermediate groundwater depths, choosing small values for capillary rise with an eye on groundwater depth and RWS. (For groundwater depths see Table 4). Groundwater depths of 2 m might seem quite deep to be providing a significant capillary rise, but it has to be kept in mind that the water only needs to rise into the root zone. In case of cotton, roots go as deep as 160 cm. These entries for capillary rise brought the RWS within acceptable limits, especially into the case of Fordwah 14R. Again the model SWAP93 can be used here to get an insight in the contribution from capillary rise under different sets of circumstances (groundwater depth, RWS, type of sub-soil).

Now, to calculate the amount of water available for actual crop evapo-transpiration is possible, and from this the Relative Water Supply (line 10; RWS trial). When these values were used to develop the salt balance, it resulted in predicted soil salinity levels that were much lower than the measured values (by almost a factor of two), and also differences between watercourses were not very well predicted. These observations suggested that percolation 'losses' were over-estimated, at least for some watercourses. Indeed, it is not realistic to assume that percolation losses are a fixed percentage of the amount of irrigation. If there is over-irrigation, crops will not consume more than ETpot, so the excess can only percolate to the groundwater (in the absence of surface drainage). In the case of under-irrigation, percolation will be reduced more than proportional, because with reducing irrigation, more water can be stored in the dryer soil, until at a certain low RWS (here taken as 50%), percolation will cease altogether. The method used for reducing / increasing the percolation is explained in Figure 3.

Figure 3: method used to estimate actual percolation



The amounts of percolation obtained with this method, and the resulting new and final values for actual ET and RWS (=ETact/ETpot), are presented in Tables 3A and 3B, lines 11, 12 and 13. In *kharif*, the first estimate of 137 mm percolation (average for the eight sample watercourses) has been reduced to 100 mm, but this includes Azim 111L where the first estimate of 190 mm increased to 298 mm percolation because tubewells pump more water than crops can evaporate. In *rabi*, a smaller reduction from 80 to 67 mm is calculated, because the average RWS is closer to 100%.

On average, the crops were supplied with 89% of their consumptive needs, resulting in water stress and a yield reduction that depends on whether this stress occurred inside or outside sensitive periods in the crop development. On Fordwah Distributary, this water stress is more severe in *kharif* (RWS = 85%) and much less in *rabi* (97%), a pattern that was also observed in other IIMI research areas. As mentioned before, cotton needs some water stress for good yields; over-irrigation results in more vegetative growth and less yield. For the Azim watercourse commands, RWS in *rabi* (88%) is just as low as in *kharif* (89%), indicating that water from tubewells makes good for the lack of canal water supplies in *rabi*., but Azim farmers do not supply their wheat crop more generously than their cotton, as do the Fordwah farmers. It is possible that commercially oriented farmers with large land holdings, who are found in the Azim area, are more willing to spend their resources on irrigation of the cash crop cotton, than on wheat which is grown more for subsistence. The same argument could explain the larger area of fallow land in *rabi* on Azim than on Fordwah.

Salt balance of the root zone

For all tubewells in the sample watercourses, a chemical analysis of the pumped water was done. Its electrical conductivity (EC) in dS/m was used as a measure for the total salt content. With the volumes pumped by each tubewell, a weighted average EC of the irrigation water from tubewells was calculated (see Tables 3A and 3B, line 14). These weighted averages are slightly smaller than plain averages, indicating that farmers prefer to use tubewells with a better water quality. The worst groundwater quality is encountered in Fordwah 14R, followed by Fordwah 130R and Azim 111L. Next, the average quality of total supplied water was calculated from the respective volumes and salt contents of tubewell water, canal water (EC = 0.2 dS/m) and rain (EC = 0) (line 15 in the tables). Capillary rise is considered as another source of irrigation water with the same salt content as the tubewell water. (So further calculations are done with R (percolation) and G (cap. rise) separately, and not with Rnet.) Azim 111L has the worst quality of total water supplies because of the lack of canal water supply, with Fordwah 14R as second worst in *kharif* and Fordwah 130R in *rabi*. In spite of poor tubewell water quality, there is still a large amount of pumping in Fordwah 14-R during *kharif*, because canal water supply is much less than authorized.

According to the FAO classification, these waters are non-saline (< 0.7 dS/m) or slightly saline (0.7 – 2 dS/m) and should pose no threat of soil salinization, provided sufficient leaching by percolation water occurs. That's where the shoe pinches, because farmers are used to spreading scarce irrigation water thinly, allowing crops to be stressed to increase the cropped area. This is an optimal practice with good quality canal water, but can be dangerous with tubewell water when even the relatively small leaching requirement is not observed. Furthermore, it can be misleading to look only at the average quality of all the waters combined. Out of the 110 tubewells in the eight sample watercourses, nine have an EC > 2 dS/m, all of them situated in Fordwah 14R. Though farmers try to avoid using the worst tubewells, at least some farmers with less access to canal water face a very real threat of salinization of their land.

In the last section of Tables 3A and 3B, the results of the salt balance calculations are presented. The leaching fraction (line 16) is the ratio of percolation to irrigation plus rain plus capillary rise. Line 17 gives the predicted salt concentration of the soil moisture at field capacity, as calculated with the last formula in the section on the theoretical framework. ECe values (line 18) are derived y dividing ECfc by 2, except for Fordwah 130R where a factor of 3 was used in view of the sandy soils. These values are equilibrium soil salinity levels that would be reached after a number of years. Of course, the equilibrium values for individual seasons will not be reached, because one season is followed by another with different irrigation practices and water demands. Seasonal equilibrium EC gives an indication of the direction in which the soil salinity changes during the season, fluctuating around the equilibrium EC calculated for the whole year. Yearly values are given in Table 3C, in which the intermediate steps used in the seasonal calculations (lines 5, 8 and 10) are left out. The resulting predicted soil salinity levels will be discussed more in detail in the section on the comparison between model output and observations.

Patterns of measured soil salinity

At the beginning of each cropping season, soil samples were collected in a large number of fields and analyzed in the laboratory of the Soil Survey of Pakistan (July[4] 1995) or Directorate of Land Reclamation (December '94 and July '94). In July '94, 16 fields were sampled in each watercourse command, and about 65 fields per watercourse in both July '95 and December '94. For each field and for each depth (15, 30, 60 and 90 cm), soil was taken from three random spots and mixed together to obtain one sample for each depth for each field.

In Annex 3A, average values are given for the salinity and sodicity of the soils, expressed in electrical conductivity (ECe) and sodium adsorption ratio (SARe) of the saturated soil extract. The results are differentiated between watercourses, depths in the soil profile, and season. Since the saturated water contents for most soils is about

[4] July is short for: last week of June and first week of July. Same for December mutatis mutandum.

twice the water content at field capacity (except for sand where this ratio goes up to four), the ECe values have to be multiplied with two (sand: four) to obtain ECfc values.

Taking a closer look at these figures, a few trends are visible. One absent trend is the expected lower ECe near the surface and higher ECe at the bottom of the root zone (see opening remark of the section about SWAP93). This can be explained by the fact that soil samples were collected between the cropping seasons when there were no crops in the fields. Due to the evaporation from the bare soil surface, an upwards moisture flux develops that brings the salts from deeper down closer to the surface. This process will also bring some salts from below the root zone back into it, increasing total soil salinity. These salts are again leached downward with one or two pre-irrigations with canal water (*rouni* irrigations). For the SARe values, however, the data do show an increase with depth, presumably because SAR values do not respond so quickly to a temporary upwards flux of water and salts as ECe values. Looking at the data for individual fields, some fields have low ECe and SARe values near the surface, increasing (greatly) with depth; these fields presumably already received a *rouni* irrigation before the sample was taken. Other fields have (very) high ECe and SARe levels in the upper soil layers, decreasing with depth; these fields did not yet get a *rouni* irrigation and could have even lain fallow during the previous season.

The water and salt balances as described in the previous sections were set up only for the irrigated fields. Therefore, the results of these balances should be compared with soil sample data only from irrigated fields. Combining the soil sample data with the data of the crop survey for the corresponding season, sampled fields which were cropped both the season before sampling and the season after sampling (which had already started at the time of sampling, at least with the rouni irrigations), could be separated from sampled fields that were fallow either before or after during sampling. A few sampled fields that were classified as barren land in the crop survey, and had very high ECe and SARe levels, were discarded. Thus, only the obtained average ECe and SAR values for the cropped fields are given in Annex 3B, and for the fields that were fallow before or during sampling (further referred to as 'fallow fields') in Annex 3C.

In Figure 4, the levels and changes between seasons of the soil salinity (average 0-90 cm depth) are plotted. The 'fallow fields' not only have a higher ECe, but also do not follow the seasonal changes that the cropped fields exhibit. The higher ECe levels of the 'fallow fields' can be caused by the absence of irrigation, especially in areas where capillary rise is significant, but it is equally possible that farmers prefer cropping the better fields and let the more saline fields lie fallow more often. For most watercourses on both Fordwah and Azim, ECe and SARe values in December 94 are higher than in July 94 and July 95. These seasonal changes are not easily explained, apart from the observation that they should be the result of irrigated cropping, since the fallow fields do not show the same fluctuation. There is also room for concern about the comparability of the standards of the different laboratories where the chemical analyses were done.

Figure 4: Change of measured soil salinity in different groups of fields

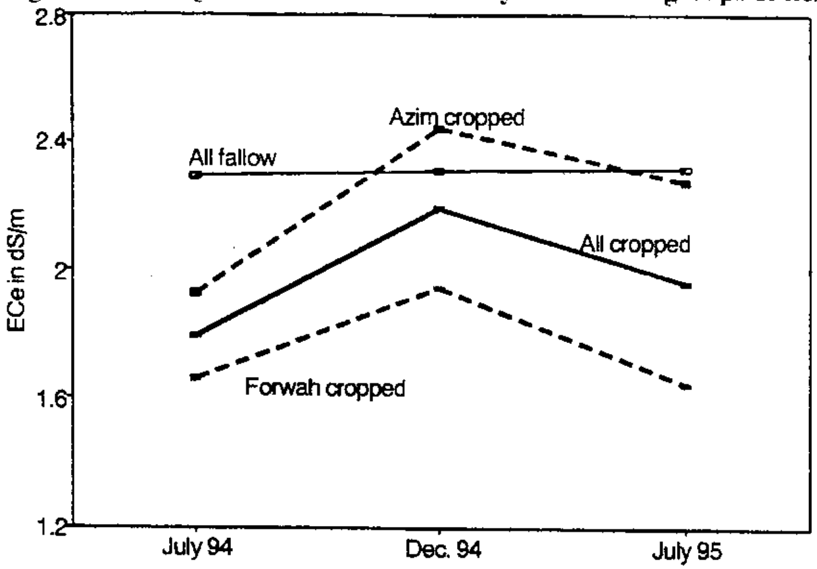


Figure 6: Relation between soil salinity and irrigation

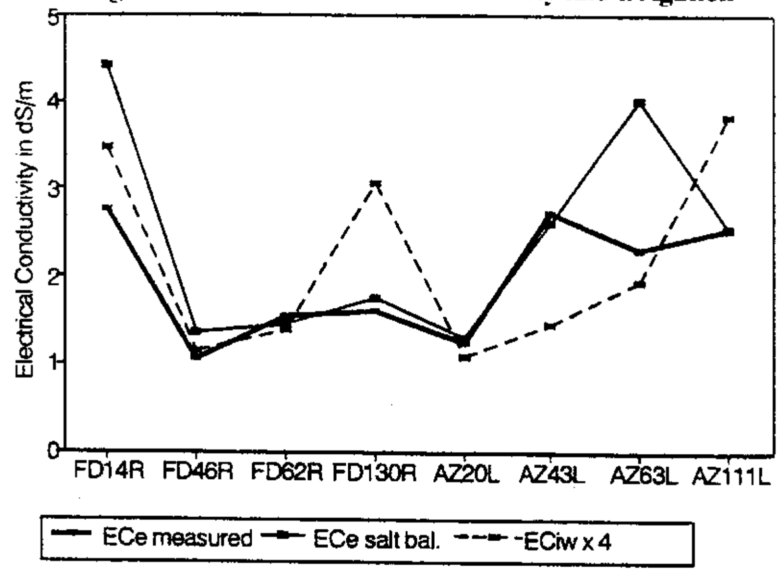


Figure 5: Change of soil salinity predicted by balance model

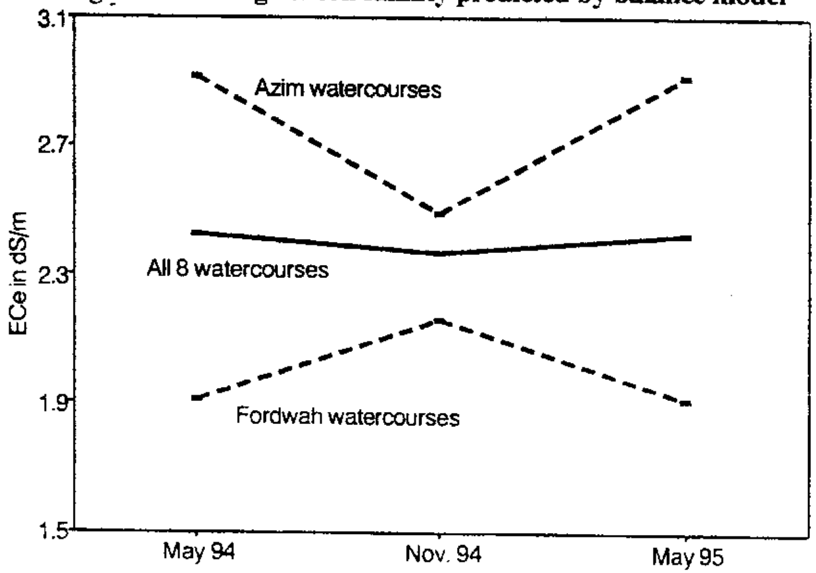
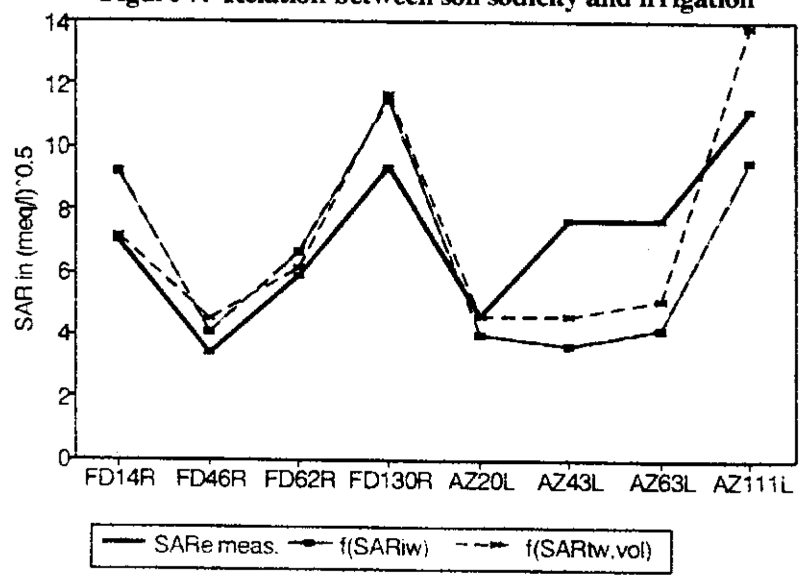


Figure 7: Relation between soil sodicity and irrigation



Results of salt balance compared with measured soil salinity

Comparing the measured seasonal changes of ECe levels with those predicted by the water and salt balances (see Figure 5), the balance predictions for the Fordwah watercourses follow the same pattern, but predicted changes for Azim have a reversed trend. On Fordwah, the average water quality is about constant throughout the year, but Relative Water Supply is higher in rabi, leading to more leaching during rabi and a lower predicted ECe in May. On Azim, the average EC of the irrigation water is higher in rabi due to the greatly reduced canal water supplies. Add to this a somewhat lower leaching fraction during rabi, and the result is a higher predicted soil salinity at the end of rabi than at the end of kharif.

In Figure 6, the predicted yearly ECe levels are plotted for each watercourse, alongside the measured values for only cropped fields, averaged over three seasons. The fit is remarkably good for six watercourses.

The predicted ECe level for Fordwah 14R is higher than the measured one. Interestingly, before inclusion of capillary rise in the water balance, the fit was even worse. Without capillary rise, there is under-irrigation, leading to very little percolation and a build-up of soil salinity. With capillary rise, the soil is more wet, so more of the irrigation water will go to percolation. The salts removed from the root zone by the percolation (with salt content ECfc) are more than the salt inflows by capillary rise (salt content equal to groundwater / tubewell water). The misfit in the case of Azim 63L is hard to explain. The high predicted value is mainly due to the low RWS during kharif, with a resulting low leaching fraction. It is possible that the illegal cuts of the bank of Azim Distributary, observed frequently by IIMI's field staff, have had a beneficial effect on the water balance of this watercourse that does not show in the field data.

In Figure 6, also the values are plotted for the salt content of the total irrigation, rain and percolation water, multiplied by four. These points only match the observations for four watercourses. This shows that setting up a water and salt balance does give a better idea of expected salinity levels, rather than merely looking at average irrigation water quality.

To end this section, a brief observation on soil sodicity will be made. Values for SARe are included in Annex 3. Average values have been plotted in Figure 7. The highest soil sodicity levels are observed in Azim 111L (high groundwater pumping and fairly high SAR of tubewell water) and Fordwah 130R (high SAR of tubewell water and fairly high groundwater pumping). In spite of the high soil salinity in Fordwah 14R, the soil sodicity is only medium. This could be explained by the fact that the soil salinity is at least partly induced by capillary rise from the shallow groundwater table which does not leach the calcium out of the soil as irrigation with tubewell water does.

To see whether there is a relation between soil sodicity and the quality of the irrigation water, the average SAR of the irrigation water was calculated with the following formula:

$$SARiw = (SARtw - SARcnl) \times \{Itw / (Itw + Icnl + P)\}^{0.5} + SARcnl$$

The best fit was obtained by modifying SARiw in the following way:

$$SARe \approx 2.5 + 1.5 \times SARiw$$

In Figure 7, values obtained with this equation are plotted with the label f(SARiw). According to this crude correlation, SARe will be about 2.8 in case of irrigation with only canal water (SARcnl = 0.22), under the average irrigation environment in the study area.

The above approach only looks at the average irrigation quality, not taking into account how much tubewell water is actually used for irrigation. To see whether the soil sodicity can be explained from only the volume of tubewell water pumped and its SAR, the following indicator (which does not have a physical meaning) was plotted in Figure 7:

$$Itw / 700 \times SARtw + 4$$

The match is similar to the previous one, except that the obtained value for Fordwah 14R is closer to the observed SARe. The rather low groundwater pumping in 14R seems to compensate for the poor quality of the irrigation water, with respect to sodicity.

These are just some preliminary observations on sodicity. IIMI-Pakistan is currently addressing this issue much more in detail in a number of studies.

Results of water balance compared with ground water level observations

To compare the results of the water balance in terms of recharge or depletion of the groundwater with field observations, the water balance at field level has to be extended to a water balance for the whole watercourse command area. This is done in Table 4. Besides percolation from the irrigated fields, there is also percolation (seepage) of water lost from the watercourse and from the field channels. These losses have been determined in the section on the water supply at field level, using the loss rates given in Table 2 as a percentage of the total flow in the watercourse. Just as the field losses, the watercourse losses are divided into water going to percolation (80%) and water going to non-beneficial ET (20%). Percolation from the watercourse added to percolation from irrigated fields gives the total amount of water that joins the groundwater. Extraction of groundwater takes place through pumping by tubewells, and through capillary rise where the groundwater table is not too deep. Subtracting these from the total percolation yields the net recharge to the groundwater, in mm of water depth.

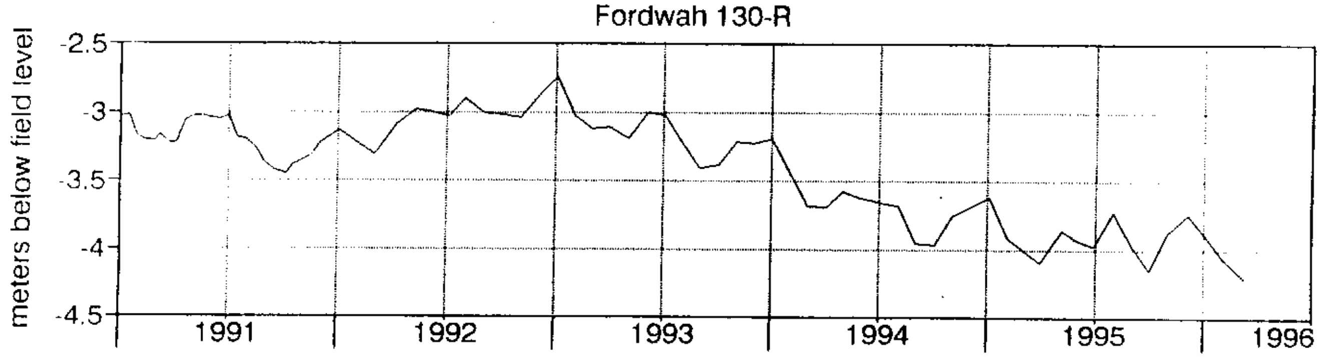
For the fallow and barren land, no net fluxes to/from the groundwater have been taken into account. Most rainfall is lost again to evaporation from the soil and wild plants, and the little percolation that might occur is assumed to be canceled by a small amount of capillary rise. Groundwater recharge from non-irrigated land is negative in most years except those with heavy rainfall. In the era before irrigation, groundwater levels in the Punjab were as deep as 20 to 30 m in the middle of the *doab*, the land between two rivers, and more shallow near the rivers. This meant a groundwater flow, albeit a small one, from the rivers to the *doab* (flow in the direction of the sea is negligible due to the very small slope in this direction). This water was lost from the *doab* by evapo-transpiration, most probably mainly from deep-rooting trees and shrubs.

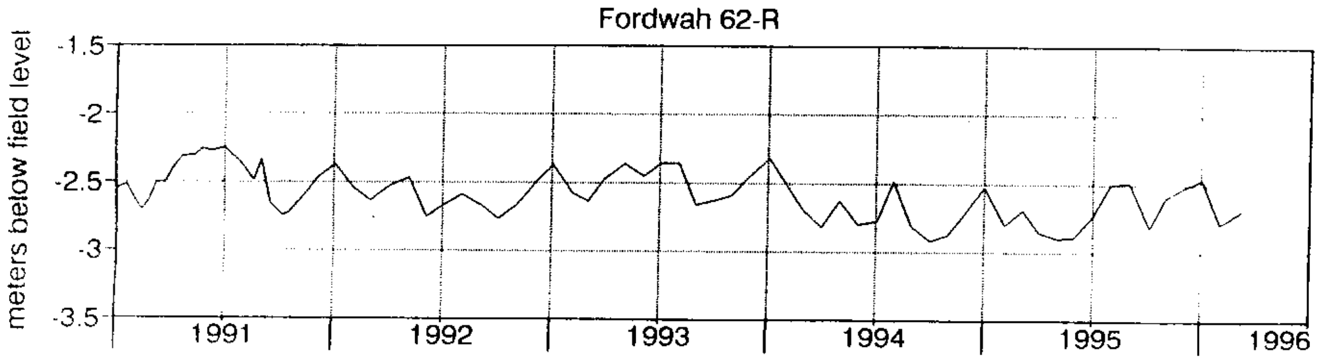
The rise or drop of the groundwater level resulting from the calculated recharge depends on the pore space of the soil that has to be filled or drained to store or deliver this amount of water. It also depends to a lesser extend on the depth of the groundwater (i.e. the depth of the vadose zone). For example, if groundwater is pumped away, part of the water will come from the zone between the initial groundwater level and the new lower level, and part of the water will come from the vadose zone above the groundwater where the water suction will increase due to the lower groundwater and thus the moisture content will decrease. In case of a deep groundwater table, as in Azim 111L, the so-called drainable porosity equals the saturated volumetric water content minus the water content at field capacity. Drainable porosity decreases with a shallower groundwater table. The values used in this study for the sandy sub-soils in the area are given at the top of Table 4. Groundwater level changes as predicted by the water balance, are given in the last line of each section of Table 4. These are theoretical values, assuming there is no horizontal groundwater flow supplying or removing water. Yet, it is interesting to compare them with the observed groundwater level fluctuations.

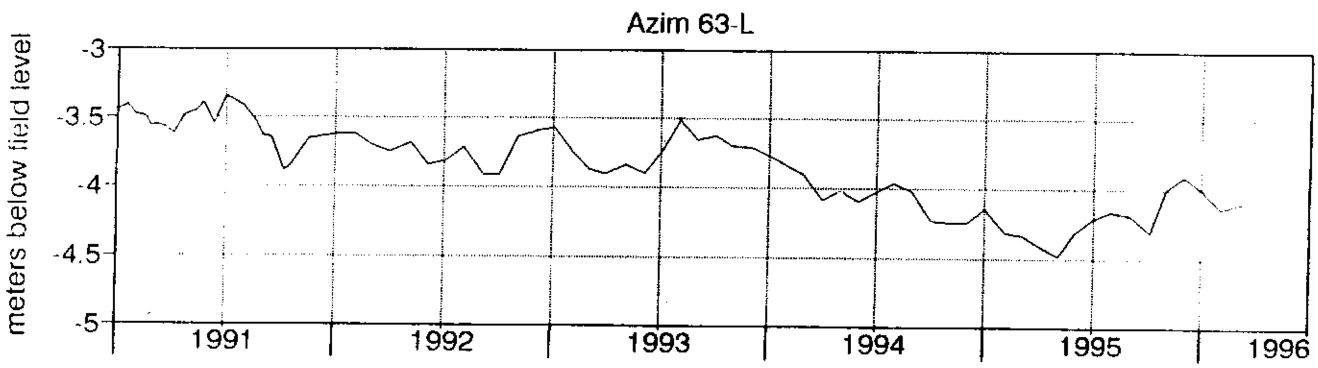
At the beginning of 1991, IIMI installed groundwater observation wells in four of the eight sample watercourse commands, ten wells in each. At the start of 1995, three wells were installed in each of the other four watercourses. Readings were taken once every month. In Figures 8A and 8B, these data are plotted as averages per watercourse. To obtain these lines, data were cleaned both of data entry errors and computation errors, and observation wells that were discontinued (because they were tampered with) or newly installed during the period, were disregarded altogether. If, for instance, a well with a relatively deep groundwater level suddenly stops giving data, and it would have been included in the calculation of the average groundwater depth, there would be a sudden calculated reduction in the groundwater depth that has not really happened.

Three of the four watercourses that have five years of observations show a descending trend for the groundwater table. At the same time, these are the sample areas with the lowest groundwater tables, suggesting that the lowering of the groundwater table has been going on there since quite some time. These three watercourses, Fordwah 130R, Azim 63L and Azim 111L, also happen to be the ones with the lowest (most negative) net groundwater recharges as calculated from the water balance. This shows that, even for areas as small as watercourse commands, setting up a water balance can give an insight into the direction of the groundwater level change and the sustainability of groundwater pumping, or danger of waterlogging. However, the absolute values of the predicted changes are much bigger than the observed changes. For Fordwah 130R and Azim 111L, the field observations show a drop of about 30 cm per year, but predicted groundwater level changes are respectively 89 and 313 cm. For Azim 63R, the observed drop is 15 to 20 cm per year, against a prediction of 121 cm. Obviously, most of the groundwater that is extracted by tubewells in these areas is supplied by groundwater flow from adjacent areas with a positive net groundwater recharge. Azim 63L represents such an area, because it borders on Fordwah 62R. This watercourse has a net recharge of 87 mm and an expected groundwater rise of 48 cm per year (see Table 4), but the observations show a slight drop of the groundwater level over the years. Also, in Fordwah 46R and Azim 20L, there is a net groundwater flow out of the area. Yet, in our sample watercourse commands, the overall yearly recharge of the

Figure 8A: Groundwater levels for sample watercourse commands
Averages of selected (reliable) IIMI observation wells







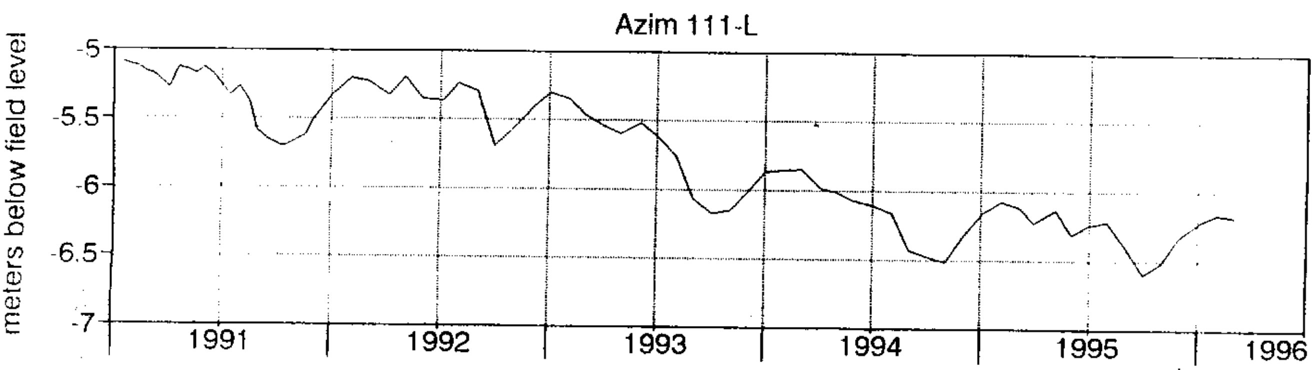
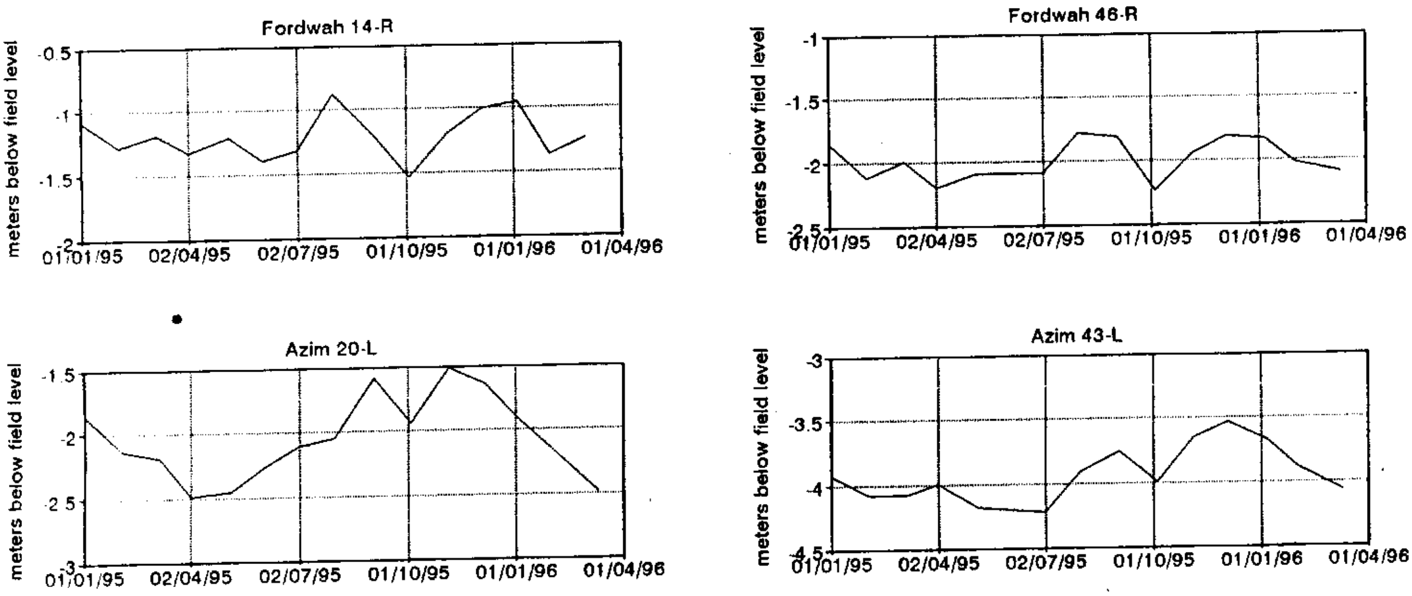


Figure 8B: Groundwater levels for sample watercourse commands
Averages of IIMI observation wells



groundwater is negative. In the water balance of larger units, such as distributary command areas or a sub-division, the seepage losses from the distributaries, main canals and even rivers should also be taken into account. In the application of Perry's water balance model to Chishtian Sub-division, Kijne choose a fraction of 25% of the total inflow for the seepage losses from main canals and distributaries, and 30% of the watercourse inflow (= 21% of total inflow) for the losses from watercourses, making groundwater recharge from canals slightly larger than from watercourses. If the same assumption is applied to the data for the eight sample watercourses, where the average yearly seepage from the watercourse is 123 mm, a yearly seepage can be added to the groundwater of about 140 mm from distributaries and main canals. This would just about balance groundwater recharge with groundwater extraction (-131+140=9 mm). But even if recharge and extractions are balanced over a large area, there can still be smaller areas with a positive net recharge and problems of waterlogging, and areas with excessive groundwater pumping not met by percolation, seepage and groundwater inflow, where dropping groundwater levels will jeopardize future groundwater use. This is another reason to continue stressing the importance of an equitable distribution of canal water, preventing tail areas from solely relying on groundwater pumping for irrigation. This can even be a reason to question the concept of perennial and non-perennial distributaries; the short supply of river water in *rabi* could also be distributed in a rotation between all distributaries.

From the water balance at the watercourse level, it is not clear why Fordwah 14R should have such a shallow groundwater table. The inclusion of capillary rise in the water balance has made the net recharge of the groundwater negative, to the extent that a theoretical drop of about 1 m per year is predicted. Obviously, this does not take place, indicating that this area receives a considerable net inflow of groundwater (seepage from distributary, elsewhere?).

Application of SWAP93 on watercourse level

In the section about the observed ECe values, it was remarked that the expected increase in ECe values with increasing depth through the soil profile does not show in the field measurements. This trend is expected as a combined result of the leaching downwards of salts by irrigation water and the concentration of salts resulting from water extraction by roots. Introducing a leaching efficiency of less than 100% increases the predicted soil salinity levels, but does not change the basic shape of the predicted soil salinity profile; interestingly, the concept of preferential flow as incorporated in the model SWAP93 does. In this concept, water and salt transport is assumed to occur only in a certain fraction of the soil, called the mobile fraction. In the rest of the soil, the immobile fraction, no water transport takes place and salt transport only occurs through diffusion to/from the mobile fraction. This means, that in the immobile fraction, salts are not removed from the top downwards, but laterally. If water extraction by roots and surface evaporation are allowed to take place from the immobile fraction, a higher ECe level can be expected in the upper soil levels than deeper down, and quite high overall ECe levels will occur in the immobile fraction. In the mobile fraction, where the leaching takes place, there will be a gradient from very low ECe levels near the surface to higher (but still low) ECe's further downwards. For the soil profile as a whole, a more even distribution of salts can be expected, matching more closely the field observations.

Unfortunately, the way in which the concept of mobile / immobile fractions is implemented in SWAP93 is not well adapted to the circumstances of irrigated land in the Punjab. The concept was developed for sandy soils that become water-repellent upon drying. When water is again applied, some parts of the soil resist absorbing water completely. Therefore, in the model, the moisture content in the immobile fraction is fixed at a certain level which cannot change, and there is no root extraction of water from the immobile fraction. This has two consequences: a) The salt content in the immobile fraction does not get concentrated, but will fluctuate around the average salt concentration in the mobile fraction; and b) when the program starts running, the distribution of salts between the mobile and immobile fractions depends on the initial moisture content (moisture content in the immobile fraction is fixed, but initial salt concentration is assumed to be equal in the mobile and immobile fractions). For instance, if the program starts with a dry soil, there is little moisture in the mobile fraction, so almost all salts will be allocated by the program to the immobile fraction. This will greatly reduce the calculated leaching of salts, especially when the coefficient of exchange between the mobile and immobile fractions is set at or near zero as was done in Smets (1996) during the calibration of SWAP93.

The most realistic way to simulate preferential flow through the soil would be to have an immobile fraction where no vertical transport of water takes place, and only enough lateral flow to keep the moisture content in the immobile fraction equal to that in the mobile fraction. Roots would take water from both fractions, and salts are exchanged (very) slowly between the two fractions by diffusion and the small lateral flow.

Incorporation of this concept into the SWAP model was, of course, far beyond the scope of this study. Therefore, a more simple method for simulating preferential flow was tried. The efficiency of leaching salts from the root zone is not only affected by preferential flow through cracks, macro-pores, or zones of higher conductivity in the soil, but also by the non-uniform application of irrigation water across a field. In the prevailing practice of basins of 0.05 to 0.25 ha, more water infiltrates near the field inlet than at the far side of the field, lower parts of the field receive more water than higher ones, and infiltration rates are different in different parts of the field. This is easily simulated by doing several runs with the model with different degrees of over- and under-irrigation, and taking the weighted (to the areas of the simulated sections) average of the results for all of the runs. In a study by Kuper and van Wayjen (1993) with the model SOWATSAL, it was found that the results of simulations with non-uniform irrigation application gave a better match with field observations of soil salinity.

For the present study, some preliminary trials were done to use the SWAP model at the watercourse level, in order to compare its results with the results and the assumptions of the water and salt balance approach. The model can be run with watercourse averages for soil type, groundwater depth, irrigation quantity and quality, and soil salinity. It is more difficult to envisage an 'average crop', when, apart from cotton and wheat, other crops such as sugar cane and fodder are important in the cropping pattern. In that case, SWAP will have to be run for each crop individually. For this limited exercise, this problem was avoided by selecting four watercourses with only small acreages of other crops. The calibrations of SWAP93 (Smets, 1996) for four closely monitored fields with different soil textures were taken as a starting point. Firstly, it was checked whether replacing the method of mobile/immobile fraction with simulating non-uniform irrigation could give a similar match of predicted soil salinity with the measured one. In the simulations, the fields were split in 3/8 part receiving 67% irrigation, 3/8 part 100% and 1/4 part 150%. Results at the field level were quite encouraging, although the predicted soil salinity levels were generally lower than the measured ones, especially in the upper layer.

SWAP93 was run with the aggregate data for the four selected sample watercourses, as obtained from the water balances. Just like the four fields for which the model was calibrated, each of the four selected watercourses represent a soil texture class. They are, sorted from lighter to heavier soil texture: Fordwah 130R, Fordwah 62R, Azim 63L and Azim 111L.

Results at the watercourse level were disappointing, probably for the reasons pointed out above (average soil type, groundwater depth, irrigation quantity, quality, soil salinity). For this reason, only the elements of the water balance are compared, as shown in Table 5.

Table 5: Comparison of results of SWAP93 applied at watercourse level and results of water balance in terms of relative crop water use and percolation (mm/year)

	SWAP93, uniform irr		SWAP93, non-unif. irr.		water balance	
	Ta/Tpot	percol.	Ta/Tpot	percol.	ETa/ETpot	percol.
Fordwah 62R	99%	217	93%	264	90%	163
Fordw. 130R	88%	343	86%	366	87%	179
Azim 63L	93%	83	85%	144	81%	76
Azim 111L	99%	411	97%	425	100%	390

The water stress for the crops predicted by SWAP93 (non-uniform irrigation) agrees quite good with the results of the water balance approach. The soil evaporation Ta in SWAP93 is always near 44% of Tpot; it does not change much with irrigation quantity, but only depends on how often the soil is wetted. So, in SWAP93, ETa/ETpot is rather low, which explains the high percolation. The predicted percolation is also high due to the method of simulating non-uniform irrigation. It was found that a simulation with an immobile fraction gave a better prediction of both percolation and soil salinity level. Therefore, if the problem of the dependency of the amount of salts in the immobile fraction on the initial moisture content could be solved, simulations with an immobile fraction should be preferred over simulations of non-uniform irrigation. Most likely, a combination of both methods would give the best results, but would be rather laborious.

Some trials were done with the model to see the effect of capillary rise from the groundwater on the crop water uptake. With a groundwater table depth of 2.5 m (Fordwah 62R), the effect of capillary rise is negligible when sufficient irrigation is applied, but in case of under-irrigation (67%) the crop transpiration is 20 mm less if free drainage is simulated. During *kharif*, upwards cumulative fluxes from the groundwater of more than 100 mm can be observed, but these are largely canceled by percolation during *rabi*. In Smets (1996), the same was done for a groundwater depth of 2 m, with a more loamy soil. Again, in the case of slight over-irrigation, the effect on the crop transpiration was very small. Interestingly, the introduction of a groundwater table at 2 m depth increased the percolation due to the increased wetness of the soil profile. This corroborates the approach used in the water balance, where the introduction of an entry for capillary rise increased the RWS and hence increased the percolation, which had a lowering effect on the calculated soil salinity. In case only 50% of the original irrigation was applied, the introduction of a groundwater table at 2 m deep increased Ta/Tpot from 0.59 to 0.79 (i.e. a net capillary rise of about 160 mm). This means that the values for capillary rise assumed in the water balance are easily obtainable under the prevalent practice of under-irrigation.

Conclusions and recommendations

The starting point for this study of water and salt balances was the spreadsheet model developed by Perry (1996). This model was extended with input and output sections to include the salt balance at the field level (root zone). Although the approach adopted in this model was found useful, a new spreadsheet was set up both for practical and more basic reasons:

1. Putting the balances of 8 areas in one sheet was much more efficient in terms of combined calculations and easy comparison. Improving the fit between model results and field observations was not done for individual watercourses, but with an eye on all watercourses together.
2. Amount of groundwater pumping is an output of Perry's model, but in IIMI's research areas (admittedly an exception) it has been observed in the field. Input for the model is 'groundwater recovery', which is not known a priori because the recharge of the groundwater cannot be observed. So, a process of trial and error would be called for to match the output groundwater pumping with the observed values.
3. Percolation from irrigated fields to the groundwater, very important in the salt balance of the root zone, is calculated in the original model as a fixed percentage of the amount of irrigation water, determined by the chosen field irrigation efficiency and percentage of losses going to non-beneficial evapo-transpiration. In the new spreadsheet, this approach is used for a first estimation of the percolation, which is then corrected in view of the Relative Water Supply to the field.
4. In one sample watercourse with a shallow groundwater table, capillary rise is an important element in the water balance, and in three other watercourses it is not negligible. Hence, capillary rise had to be included in the new spreadsheet. Under certain circumstances, the introduction of capillary rise has a lowering effect on soil salinity. This happens when the salts carried to the root zone by the capillary rise are less than the salts removed by extra percolation that occurs due to the incresed wetness of the profile.

Other elements included in the spreadsheet, such as water going to, or pumped from, open drains are not applicable in the studied area, but this is no problem as zero values can be entered.

A ready-made model such as the one developed by Perry can be a stimulant to do a quick review of the water and salt balance of an irrigated area, and give an insight into the relative importance of different fluxes, and how much is known about each of them. The model can be used to assess the effect of changes in one flux on the rest of the water balance, but with caution. For instance, a reduction in canal water supply in the model input will result in less groundwater pumping by tubewells in the model output, because groundwater pumping is dependent on the amount of percolation to the groundwater. In reality, however, farmers respond to a reduction in canal water supply with an increase in groundwater pumping.

There is a multitude of possible hydrological processes. Perry lists eleven elements of the water balance that are taken into account in his model. Each element constitutes either a source of water, or an outflow of water, or both (e.g. groundwater). An outflow at one level of the system can be a source at another level. His model evaluates 31 interactions between these elements. It should be kept in mind, however, that in every studied area , there can be a unique combination of hydrological processes, and that there is no substitute for a careful analysis of the relative importance of all possible elements of the water and salt balance.

One benefit of the setting up of a water and salt balance is that it requires one to look at the available data in a systematic way. Obvious omissions and/or errors in the data were traced and corrected.The fact that the water and salt balance yielded a good prediction of the measured soil salinity gives some confidence regarding correctness of the several assumptions and estimates that had to be made. and the method followed. As a first estimate for field irrigation efficiency (when sufficient irrigation is applied), a value of 75% was used (average for rice and non-rice crops), with 20% of irrigation and rain water percolating to the groundwater and 5% lost to non-beneficial evapo-transpiration. After correcting this for the prevalent under-irrigation, field irrigation efficiency turned out to be 81%, with percolation 14% and non-beneficial ET 5%. Individual watercourses show a large variation around these averages, with percolation ranging from 7% to 25% of irrigation and rain water. These leaching fractions are sufficient to keep the predicted average ECe values below 4 (only yields of very sensitive crops restricted), except in the case of Fordwah 14R where groundwater quality is poor and canal water supply is short, and Azim 63L, where the leaching fraction is very small due to under-irrigation. The field observations, however, do not show such high ECe values for these two watercourses.

The agro-hydrological model SWAP93 is an appropriate tool to determine elements of the water balance at the field level that are difficult to measure directly, such as percolation, capillary rise and actual crop evapo-transpiration. Effects of different irrigation scenarios can be assessed quickly. In this study, a first effort was done to use SWAP93 at the watercourse level, and compare its results with the water balance approach. This methodology needs further development. Soil salinity changes are more difficult to predict with SWAP93, because some of the processes affecting salt transport arr either difficult to quantify (e.g. preferential flow, uniformity of irrigation), or not incorporated in the model (e.g. precipitation/dissoluton, adsorption, chemical processes).

In contrast to findings by Kijne (1996), it was found that recharge to, and extraction from, the groundwater are balancing each other, if a rather crude estimate for losses from distributaries and main canals is taken into account. This is based on an extrapolation of the findings for the eight sample watercourses. A more representative picture would be obtained with a water and salt balance for the entire Chishtian Sub-division, but this will require the processing of large amounts of data that have been collected on cropping patterns, tubewell water quality, groundwater depths, soil salinity, etc. Presently, these data are being analyzed with a Geographic Information System, which will be helpful in setting up a water and salt balance for the area. The differences between the studied watercourses show that there are areas of net recharge with high groundwater tables, and areas of net extraction with lowering of groundwater tables. It would be useful to monitor and model groundwater levels and flows in larger areas to study how recharge and extractions are balanced with groundwater flows, and to see if waterlogging in some areas (especially near heads of canals) and too low groundwater levels in other areas (especially near the tails) could be counteracted by redistributing canal water supplies.

Acknowledgments

This paper is the result of a six week study with IIMI-Pakistan in Lahore. I want to thank Jacob Kijne and Marcel Kuper for their comments which helped me to improve the first draft. Marcel Kuper did the runs with SWAP93 for non-uniform irrigation and for the watercourse level, without which the comparison between SWAP and the water balance approach would not have been possible. I am also grateful to Samee Ullah and his colleagues for making available the required data from the large data base of IIMI-Pakistan.

References

Barral, J.P., 1994: Development of a watercourse based model to assess canal water supply at the farm level. Msc thesis. ENGREF, Montpellier, and IIMI, Lahore.

Doorenbos, J. and W.O. Pruitt, 1977: Crop water requirements. FAO Irrigation and Drainage paper no. 24. Food and Agricultural Organization of the United Nations, Rome.

Doorenbos, J. and A.H. Kassam, 1979: Yield response to water. FAO Irrigation and Drainage paper no. 33. Food and Agricultural Organization of the United Nations, Rome.

Kielen, N.,1996: Farmers' perceptions on salinity and sodicity. A case study into farmers' knowledge of salinity and sodicity, and their strategies and practices to deal with salinity and sodicity in their farm systems. IIMI, Lahore.

Kijne, J.W. and M. Kuper, 1995: Salinity and sodicity in Pakistan's Punjab: A threat to sustainability of irrigated agriculture? Water Resources Development, Vol. 11, No. 1.

Kijne, J.W., forthcoming: Water and salinity balances for irrigated agriculture in Pakistan. IIMI, Colombo.

Kuper, M. and E.G. van Wayjen, 1993: Farmers irrigation practices and their impact on soil salinity in the Punjab, Pakistan: Is salinity here to stay? Paper presented at the Internal Program Review, IIMI, Colombo.

IIMI-Pakistan, 1996: Analyzing large-scale irrigation systems in an integrated approach: application to the Chishtian Sub-division. Paper presented at the eleventh Internal Program Review, IIMI, Colombo.

Perry, C. J., 1996: A framework for the analysis of water balances at project level. Paper presented at the Internal Program Review, IIMI, Colombo.

Smets, S.M.P., 1996: The effects of irrigation management on soil salinity and crop transpiration at the field level, by using the agro-hydrological model SWAP93. MSc thesis. IIMI, Lahore and Wageningen Agricultural University.

Soil Survey of Pakistan, 1996: Soils of eight watercourses of Azim and Fordwah distributaries. Unpublished report, Lahore.

Van Hoorn, J.W. and J.G. van Alphen, 1994: Salinity Control. Chapter 15 in Drainage Principles and Applications, H.P Ritzema, Ed., ILRI Publication 16, Second Edition. Wageningen, The Netherlands, pp. 533-600

Annex 1: Explanation of spreadsheet containing balance calculations

The water and salt balances of the eight sample watercourses were set up in a Quattro Pro spreadsheet named WC_BALAN.WQ1.

In the left part of the spreadsheet (columns A to K), input data about the irrigation and rain supply are entered, and a few preparatory calculation are performed. Canal water supplies were first entered as monthly values, but later only the seasonal totals were used in the balance.

Below this (from row 43), Irrigation Department data on GCA (gross command area) and CCA (culturable command area) are entered, only used for comparison. The fallow, cropped and total areas were calculated from IIMI's crop surveys. Cropping intensities are calculated which are not further used in the balance calculations.

At the bottom of this left part of the spreadsheet there is a block (A74..J101) with data and labels to make three figures. Data from soil sample analyses are entered here to compare them graphically with results of the water and salt balance.

The right part of the spreadsheet (columns L to V) is the main part, formatted as tables that have been printed in this report. Printing should be done with the 'break pages' option set to off. This right part starts with the calculation of water requirements for the individual crops, using ET_0 calculated (by S. Smets) with CROPWAT with data from Bahawalpur / Bahawalnagar, and Kc values from FAO publication no. 24. In rows 22 to 35, the acreages of the main crops in the crop surveys are entered, in the same units in which they were recorded: kanals (1 kanal = 1/8 acre, 1 acre = 0.4047 ha). With the area of each crop, the total water requirement per season per watercourse is calculated in cubic meters. The water requirement for an optimal crop is reduced with a factor 0.8 or 0.9 to obtain the water requirement of a real crop, as explained in the report. Input data from the left part of the spreadsheet are summarized in block M37..U47, still in cubic meters.

Below this follow, the tables which are discussed in detail in the report. Volumes in m^3 are converted into mm water depth by dividing by the cropped areas as observed in the crop surveys. For the water balance at the watercourse level, these values were multiplied with the ratio of cropped area over total area (GCA). Some of the assumption, such as fraction of losses going to non-beneficial ET, have not been entered in separate input cells, but directly in the formulas that calculate the values in the tables. This could be changed to make the spreadsheet more user-friendly.

Annex 2: Calculation of crop water requirements

month	ETo	cotton		rice		scane		fodder&other	
KHARIF		Kc	ETcrop	Kc	ETcrop	Kc	ETcrop	Kc	ETcrop
5-94	7.6	0.2	47	0.2	47	1	236	0.9	212
6-94	8.6	0.45	116	0.2	52	1.1	284	0.9	232
7-94	6.1	0.85	161	1.15	217	1.15	217	0.9	170
8-94	6	1.15	214	1.3	242	1.15	214	0.9	167
9-94	5.4	1.15	186	1	162	1.15	186	0.9	146
10-94	4.1	0.95	121	0.9	114	1.15	146	0.9	114
kharif total			845		834		1283		1042

RABI	ETo	cotton		wheat		scane		fodder&other	
11-94	2.7	0.7	56.7			1.15	93	0.9	73
12-94	2.1			0.35	23	0.95	62	0.9	59
1-95	1.9			0.75	44	0.65	38	0.9	53
2-95	2.8			1.1	86	0.30	24	0.9	71
3-95	3.7			1.1	126	0.50	57	0.9	103
4-95	5.4			0.7	113	0.8	130	0.9	146
rabi total			56.7		393		404		504

crop survey (in kanal=1/8 acre), and the ensueing crop water requirement in m ^ 3

KHARIF '94	FD14R	FD46R	FD62R	FD130R	AZ20L	AZ43L	AZ63L	AZ111L	
cotton	1735	1830	1421	1954	424	632	1434	1231	
sugar cane	680	202	270	166	522	320	58	28	
rice	16	22	73	4	185	9	69	212	
fodder&other	526	653	351	758	307	146	288	197	
ETpot,ideal	1467012	1266799	998462	1344180	759998	558615	831500	737651	
ETpot,real	1173610	1013440	798770	1075344	607998	446892	665200	590121	= 0.8 * ETpot
RABI 94/95									
wheat	2290	2095	1524	2453	612	495	1157	1066	
sugar cane	286	95	142	73	315	196	34	4	
fodder&other	471	410	363	496	263	135	96	564	
ETpot,ideal	683294	592707	465137	684833	265166	190939	302444	391756	
ETpot,real	614964	533436	418623	616350	238649	171845	272199	352580	= 0.9 * ETpot

Annex 3A: Soil salinity and sodicity data: ECe in dS/m and SARe in (meq/l) ^ 0.5
Averages for ALL FIELDS, except a few fields classified as barren.

July 1994	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	6.03	6.76	7.61	7.17	1.32	1.25	1.28	1.31	6.89	1.29	15
AZ/43-L	4.64	5.33	7.99	8.40	1.73	1.90	2.37	2.09	6.59	2.02	15
AZ/63-L	6.68	7.78	8.74	9.18	2.02	2.05	1.96	1.85	8.10	1.97	19
AZ/111-L	10.83	10.45	10.39	9.06	2.75	2.58	2.44	2.26	10.18	2.51	20
FD/14-R	5.63	5.95	8.05	7.45	2.29	2.18	3.43	3.51	6.77	2.85	15
FD/46-R	2.53	2.61	3.14	3.25	1.04	0.92	0.92	0.93	2.88	0.95	15
FD/62-R	7.47	9.89	10.62	10.17	2.43	2.47	2.29	2.34	9.54	2.38	15
FD/130-R	7.72	7.94	11.65	12.04	1.26	1.12	1.49	1.66	9.84	1.38	13
Averages:	6.44	7.09	8.52	8.34	1.85	1.81	2.02	1.99	7.60	1.92	127

Dec. 1994	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	5.78	5.19	5.50	5.97	1.69	1.50	1.45	1.51	5.61	1.54	64
AZ/43-L	5.46	7.46	9.87	9.49	1.95	2.33	3.15	2.97	8.07	2.60	66
AZ/63-L	8.95	10.02	9.69	10.86	2.64	2.92	2.62	2.62	9.88	2.70	60
AZ/111-L	15.38	16.52	16.20	14.64	3.82	3.35	3.21	2.77	15.67	3.29	70
FD/14-R	7.20	7.43	9.80	10.75	2.93	2.68	3.32	3.30	8.79	3.06	55
FD/46-R	3.81	4.22	5.14	5.36	1.24	1.06	1.21	1.31	4.63	1.21	75
FD/62-R	4.56	5.52	6.17	7.14	1.53	1.49	1.48	1.67	5.85	1.54	57
FD/130-R	8.05	9.56	10.88	10.81	1.80	1.90	2.01	2.09	9.83	1.95	74
Averages:	7.40	8.24	9.16	9.38	2.20	2.15	2.31	2.28	8.54	2.23	521

July 1995	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	4.96	3.66	3.84	3.35	1.78	1.30	1.19	1.18	3.95	1.36	69
AZ/43-L	4.09	5.91	8.33	7.42	2.29	2.76	3.63	3.14	6.42	2.96	66
AZ/63-L	4.76	5.52	5.99	6.35	2.30	2.38	2.70	2.56	5.64	2.48	60
AZ/111-L	8.47	9.83	8.77	9.95	2.39	2.39	2.55	2.48	9.25	2.45	11
FD/14-R	4.01	4.92	6.38	6.55	2.77	2.58	2.79	2.79	5.47	2.73	55
FD/46-R	1.95	2.03	2.57	2.98	1.19	0.88	0.93	1.00	2.38	1.00	88
FD/62-R	3.16	4.18	5.02	4.92	1.49	1.35	1.41	1.37	4.33	1.40	58
FD/130-R	7.93	8.74	9.54	8.57	1.71	1.69	1.74	1.64	8.68	1.69	123
Averages:	4.92	5.60	6.31	6.26	1.99	1.92	2.12	2.02	5.77	2.01	530

avg. 3 seasons	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	5.59	5.20	5.65	5.50	1.60	1.35	1.31	1.33	5.49	1.40	148
AZ/43-L	4.73	6.23	8.73	8.44	1.99	2.33	3.05	2.74	7.03	2.53	147
AZ/63-L	6.80	7.77	8.14	8.80	2.32	2.45	2.42	2.34	7.87	2.38	139
AZ/111-L	11.56	12.27	11.78	11.22	2.99	2.77	2.73	2.50	11.70	2.75	101
FD/14-R	5.62	6.10	8.08	8.25	2.66	2.48	3.18	3.20	7.01	2.88	125
FD/46-R	2.76	2.96	3.61	3.86	1.16	0.96	1.02	1.08	3.30	1.05	178
FD/62-R	5.07	6.53	7.27	7.41	1.82	1.77	1.73	1.80	6.57	1.78	130
FD/130-R	7.90	8.75	10.69	10.47	1.59	1.57	1.75	1.79	9.45	1.67	210
Averages:	6.25	6.98	7.99	7.99	2.01	1.96	2.15	2.10	7.30	2.06	1178

Average Ec_e and SAR values are non-weighed.

Annex 3B: Soil salinity and sodicity data: ECe in dS/m and SARe in (meq/l) ^ 0.5
Averages for fields NOT FALLOW before or after (during) sampling

July	SARe				ECe				avg 0 to 90 cm		no.of
1994	15 cm	30 cm	60 cm	90 cm	15 cm	30 cm	60 cm	90 cm	SAR	EC	fields
AZ/20-L	4.70	5.26	7.64	6.78	1.08	0.94	1.33	1.18	6.10	1.13	8
AZ/43-L	4.59	7.00	9.91	11.53	1.99	2.41	3.02	2.95	8.25	2.59	6
AZ/63-L	6.44	6.12	7.74	7.31	1.57	1.59	1.45	1.49	6.90	1.52	10
AZ/111-L	10.82	10.12	10.22	9.05	2.74	2.45	2.39	2.22	10.05	2.45	17
FD/14-R	5.63	5.90	8.06	7.53	2.11	1.99	3.39	3.35	6.78	2.71	12
FD/46-R	2.74	2.76	3.35	3.34	1.08	0.95	0.97	0.93	3.05	0.98	13
FD/62-R	5.77	7.65	9.09	8.63	1.62	1.73	1.78	1.95	7.78	1.77	11
FD/130-R	7.18	7.47	10.97	12.29	1.17	1.00	1.31	1.30	9.48	1.20	8
Averages:	5.98	6.53	8.37	8.31	1.67	1.63	1.95	1.92	7.30	1.79	85

Dec.	SARe				ECe				avg 0 to 90 cm		no.of
1994	15 cm	30 cm	60 cm	90 cm	15 cm	30 cm	60 cm	90 cm	SAR	EC	fields
AZ/20-L	4.32	3.93	4.93	4.81	1.50	1.34	1.39	1.40	4.50	1.40	41
AZ/43-L	5.63	7.26	10.19	10.36	2.09	2.32	3.07	3.05	8.36	2.63	43
AZ/63-L	9.31	10.66	9.44	11.48	2.73	3.11	2.73	2.75	10.22	2.83	36
AZ/111-L	14.23	16.08	15.77	14.34	3.28	3.09	2.89	2.40	15.11	2.91	42
FD/14-R	6.58	7.43	10.09	11.29	2.64	2.60	3.36	3.37	8.85	2.99	48
FD/46-R	3.87	4.42	5.34	5.49	1.26	1.08	1.25	1.34	4.78	1.23	65
FD/62-R	4.27	5.42	6.15	7.14	1.50	1.48	1.51	1.69	5.74	1.54	52
FD/130-R	8.43	10.00	11.09	11.27	1.86	1.97	2.02	2.11	10.20	1.99	62
Averages:	7.08	8.15	9.12	9.52	2.11	2.12	2.28	2.26	8.47	2.19	389

July	SARe				ECe				avg 0 to 90 cm		no.of
1995	15 cm	30 cm	60 cm	90 cm	15 cm	30 cm	60 cm	90 cm	SAR	EC	fields
AZ/20-L	3.25	3.21	3.41	3.01	1.45	1.20	1.03	1.11	3.22	1.20	48
AZ/43-L	3.86	5.78	8.41	7.10	2.29	2.78	3.78	3.16	6.29	3.00	45
AZ/63-L	4.52	6.20	6.54	7.10	2.18	2.40	2.91	2.84	6.06	2.58	37
AZ/111-L	7.05	8.89	8.08	8.92	2.13	2.20	2.51	2.44	8.24	2.32	10
FD/14-R	3.75	4.87	6.33	6.99	2.44	2.31	2.69	2.90	5.48	2.58	40
FD/46-R	1.97	1.99	2.59	3.02	1.20	0.85	0.92	1.01	2.39	1.00	82
FD/62-R	2.86	3.91	4.84	4.78	1.44	1.31	1.41	1.36	4.11	1.38	50
FD/130-R	7.58	8.47	9.14	8.39	1.65	1.62	1.66	1.60	8.38	1.63	107
Averages:	4.36	5.41	6.17	6.17	1.85	1.83	2.11	2.05	5.52	1.96	419

avg. 3	SARe				ECe				avg 0 to 90 cm		no.of
seasons	15 cm	30 cm	60 cm	90 cm	15 cm	30 cm	60 cm	90 cm	SAR	EC	fields
AZ/20-L	4.09	4.13	5.32	4.87	1.34	1.16	1.25	1.23	4.60	1.24	97
AZ/43-L	4.69	6.68	9.50	9.66	2.13	2.50	3.29	3.05	7.63	2.74	94
AZ/63-L	6.76	7.66	7.91	8.63	2.16	2.37	2.36	2.36	7.73	2.31	83
AZ/111-L	10.70	11.69	11.36	10.77	2.72	2.58	2.60	2.36	11.13	2.56	69
FD/14-R	5.32	6.07	8.16	8.60	2.40	2.30	3.15	3.20	7.04	2.76	100
FD/46-R	2.86	3.06	3.76	3.95	1.18	0.96	1.05	1.09	3.41	1.07	160
FD/62-R	4.30	5.66	6.69	6.85	1.52	1.50	1.57	1.67	5.88	1.56	113
FD/130-R	7.73	8.65	10.40	10.65	1.56	1.53	1.67	1.67	9.35	1.61	177
Averages:	5.81	6.70	7.89	8.00	1.87	1.86	2.12	2.08	7.10	1.98	893

Average Ec_e and SAR values are non-weighed.

Annex 3C: Soil salinity and sodicity data: ECe in dS/m and SARe in (meq/l) ^ 0.5
Averages for fields FALLOW before or after (during) sampling

July 1994	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	7.56	8.47	7.58	7.62	1.59	1.60	1.23	1.46	7.81	1.47	7
AZ/43-L	4.68	4.21	6.70	6.32	1.55	1.57	1.94	1.52	5.48	1.65	9
AZ/63-L	6.96	9.62	9.84	11.27	2.52	2.56	2.52	2.24	9.42	2.46	9
AZ/111-L	10.83	12.33	11.30	9.13	2.80	3.33	2.72	2.43	10.90	2.82	3
FD/14-R	5.67	6.17	8.00	7.17	3.00	2.97	3.60	4.17	6.75	3.43	3
FD/46-R	1.15	1.65	1.75	2.70	0.75	0.75	0.63	0.90	1.81	0.76	2
FD/62-R	12.15	16.08	14.83	14.43	4.68	4.50	3.70	3.43	14.37	4.08	4
FD/130-R	8.57	8.69	12.73	11.65	1.40	1.31	1.78	2.23	10.41	1.68	5
Averages:	7.20	8.40	9.09	8.78	2.29	2.32	2.26	2.30	8.37	2.29	42

Dec. 1994	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	8.39	7.45	6.51	8.02	2.04	1.80	1.55	1.70	7.59	1.77	23
AZ/43-L	5.16	7.85	9.29	7.88	1.68	2.34	3.30	2.82	7.54	2.54	23
AZ/63-L	8.42	9.06	10.07	9.93	2.51	2.65	2.45	2.43	9.37	2.51	24
AZ/111-L	17.08	17.19	16.86	15.10	4.62	3.74	3.69	3.33	16.52	3.85	28
FD/14-R	11.43	7.40	7.83	7.07	4.90	3.19	3.10	2.83	8.43	3.50	7
FD/46-R	3.37	2.94	3.83	4.49	1.14	0.95	0.95	1.12	3.66	1.04	10
FD/62-R	7.68	6.56	6.42	7.12	1.79	1.67	1.24	1.48	6.95	1.55	5
FD/130-R	6.07	7.30	9.78	8.40	1.50	1.51	1.93	1.96	7.89	1.72	12
Averages:	8.45	8.22	8.82	8.50	2.52	2.23	2.28	2.21	8.49	2.31	132

July 1994	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	8.87	4.69	4.83	4.13	2.51	1.53	1.55	1.34	5.63	1.73	21
AZ/43-L	4.58	6.21	8.17	8.09	2.28	2.73	3.32	3.11	6.81	2.87	21
AZ/63-L	5.14	4.45	5.10	5.14	2.49	2.33	2.35	2.10	4.96	2.32	23
AZ/111-L	22.60	19.24	15.60	20.20	4.98	4.22	2.96	2.87	19.41	3.76	1
FD/14-R	4.72	5.05	6.53	5.37	3.67	3.30	3.04	2.51	5.42	3.13	15
FD/46-R	1.76	2.66	2.24	2.44	1.04	1.32	1.00	0.89	2.27	1.06	6
FD/62-R	4.98	5.90	6.17	5.78	1.79	1.61	1.43	1.43	5.71	1.57	8
FD/130-R	10.24	10.58	12.21	9.81	2.13	2.19	2.27	1.86	10.71	2.11	16
Averages:	7.86	7.35	7.61	7.62	2.61	2.40	2.24	2.01	7.62	2.32	111

avg. 3 seasons	SARe 15 cm	SARe 30 cm	SARe 60 cm	SARe 90 cm	ECe 15 cm	ECe 30 cm	ECe 60 cm	ECe 90 cm	avg 0 to 90 cm SAR	avg 0 to 90 cm EC	no.of fields
AZ/20-L	8.28	6.87	6.31	6.59	2.05	1.65	1.45	1.50	7.01	1.66	51
AZ/43-L	4.81	6.09	8.05	7.43	1.84	2.21	2.85	2.48	6.61	2.35	53
AZ/63-L	6.84	7.71	8.34	8.78	2.51	2.51	2.44	2.26	7.92	2.43	56
AZ/111-L	16.84	16.25	14.59	14.81	4.13	3.76	3.12	2.88	15.61	3.47	32
FD/14-R	7.27	6.21	7.45	6.54	3.86	3.15	3.25	3.17	6.87	3.36	25
FD/46-R	2.09	2.41	2.61	3.21	0.98	1.01	0.86	0.97	2.58	0.95	18
FD/62-R	8.27	9.51	9.14	9.11	2.75	2.59	2.12	2.11	9.01	2.40	17
FD/130-R	8.29	8.85	11.58	9.96	1.68	1.67	1.99	2.02	9.67	1.84	33
Averages:	7.84	7.99	8.51	8.30	2.47	2.32	2.26	2.17	8.16	2.31	285

Average Ec_e and SAR values are non-weighed.