# A Transient Model Approach to Improve On-Farm Irrigation and Drainage in Semi-Arid Zones

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# A Transient Model Approach to Improve On-Farm Irrigation and Drainage in Semi-Arid Zones

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Dr. Ir. L. Speelman,
in het openbaar te verdedigen
op woensdag 27 September 2000
des namiddags te 16.00 uur in de Aula

The research reported in this thesis was supported by the Wageningen University and Research Center (WUR) through a 'sandwich' PhD fellowship. The field work was carried out in Pakistan with the financial and technical support of the Netherlands Research Assistance Project (NRAP), a joint project of the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands, and the International Waterlogging and Salinity Research Institute (IWASRI), Lahore, Pakistan. Part of the research was also supported by the International Water Management Institute (IWMI), Lahore, Pakistan. The financial and technical support of all these organizations is gratefully acknowledged. The printing cost of this thesis was shared by the ILRI, Wageningen and the National Drainage Program (NDP), WAPDA, Lahore, Pakistan.

ISBN 90-5808-258-X

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Asad Sarwar, 2000

A transient model approach to improve on-farm irrigation and drainage in semi-arid zones/ Sarwar, A. Ph.D. Thesis, Wageningen University and Research Center -With references-with summaries in English and Dutch.

# PROPOSITIONS

1. Drainage systems are no guarantee for sustainable water management if the irrigation planning is not adjusted. *(This thesis)*

2. The selection of drain depth is more critical than drain spacing in semi-arid climates. *(This thesis)*

3. Adaptation of water conservation strategies is a better option than recommending farmers to irrigate with poor quality tubewell water. *(This thesis)*

4. In shallow groundwater table areas, irrigation water supplies on the basis of potential evapotranspiration is wrong. *(This thesis)*

5. Under *un-restricted* water supply conditions, the flexibility in irrigation water distribution has a considerable positive impact on the *productivity* of water. *(This thesis)*

6. In the present water deficient environment of the Indus basin, introduction of the *on-demand* irrigation water distribution system is not a viable option. *(This thesis)*

7. We never know the worth of water till the well is dry. *(English proverb)*

8. Modelers and model users should have one step in the field.

9. The scientist is not a person who gives the right answers, he is one who asks the right questions. *(Claude Levi-Strauss)*

10. Ability will enable a man to get to the top, but it takes character to keep him there.

Asad Sarwar
"A Transient Model Approach to Improve On-Farm Irrigation and Drainage in Semi-Arid Zones." (September 27, 2000).

*This work is dedicated to my father,*
*Ghulam Sarwar, who did not live long*
*to see the fruits of his hard work.*

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# ACKNOWLEDGEMENTS

This work would never have materialized without the contribution of many people to whom I have the pleasure of expressing my appreciation and gratitude.

First and foremost, my deepest gratefulness is due to my promotor, Prof. R.A. Feddes, whose intellectual inspiration, guidance, encouragement and regular lengthy discussions have been invaluable to me. He made me determined to continue, to revise, and strive for improvement. His continual willingness to listen, discuss and render critical judgements helped me to produce this dissertation in its present shape.

I acknowledge my indebtedness to my co-promotor, Prof. W.G.M. Bastiaanssen for his endless help in this study. His periodical presence in IWMI-Pakistan provided me the opportunity to seek his valuable guidance in data collection and analysis. I am indebted for his expert advises and the time he spared me, irrespective of the hour. I appreciate him for his critical reading and comments on the drafts of different papers included in this thesis.

I extend my deepest gratitude to my second co-promotor, Dr. Th.M. Boers for providing financial and technical support during my field work in the Fourth Drainage Project (FDP), Pakistan. I am especially thankful to Dr. Boers for taking keen interest in my personal and educational matters during all this period. His critical reading, suggestions and editing of manuscripts are highly appreciated.

I gratefully acknowledge the support of the present Director of International Water Management Institute (IWMI), Lahore, Pakistan, Dr. S.A. Prathapar, for allowing me to complete this research during my job at IWMI. I am thankful for the moral, financial and scientific support that I got from him at any time. This support has been essential to me and I acknowledge its value. I am also thankful to all my colleagues in IWMI for their friendly treatment.

I would like to express my special gratitude to Dr. W. Wolters of ILRI, for his efforts in getting PhD fellowship from the Wageningen University. As Team Leader, NRAP-Pakistan, his generous financial support made it possible to install costly equipments like TDR, tensiometer recorders and drainage pumps, which provided important data for this study. I also express my especial gratitude to Ir. Jos Van Dam for his valuable contribution in all stages of this study. His help in solving the SWAP model problems both in Pakistan (through e-mail messages) and in Wageningen through discussions is highly appreciated.

I am extremely grateful to Dr. M.N. Bhutta, Director General, International Waterlogging and Salinity Research Institute (IWASRI), Lahore for providing technical facilities to carry out this research in IWASRI. I also offer my thanks to Dr. M.R. Choudhry, Director, Salinity and Environment section of IWASRI, for his support during the field work. My special thanks are to all IWASRI staff for their assistance during my work at IWASRI. I am grateful to my friends Syed Asher Hussain, Shamshad Ahmad, Talat Mehmood, Ittfaq Ahmad and Raza Chohan for creating friendly environment during my stay at IWASRI. I would like to express my sense of indebtedness to the staff of the FDP-area who was always ready to work. They helped me in installing and calibrating instruments in the experimental fields and were always standing by me to take readings in the hot sunny days of summer and cold wet mornings of winter. They are too many to mention each by name, but I will especially mention Mr. Arshad, without him this work would have been difficult.

During my both stays in Wageningen, I enjoyed the friendly atmosphere in the Sub-department of Water Resources. I like to acknowledge the pleasant company of my friends Dr. Mehdi Homaee, Ms. Robina Wahaj and Mr. Mobin-ud-din. Many thanks are due to the secretarial section of the Department, Mrs. H. Van Werven and Mrs. Annamerie Hofs for their help.

I am grateful to Mr. J. van Manen of ILRI, for his help in the finalization of some figures presented in this thesis. I am extremely thankful to Mr. Michael Davlin and Sarah Carriger of the International Water Management Institute (IWMI), Colombo, Sri Lanka, for the quick and careful English editing of this thesis. I am extremely grateful to Mr. Stan van Heijst of the Wageningen University for providing additional financial support, which made it possible to complete this study on time.

I express my deepest appreciation to my parents, brothers and sisters for remembering me in their prayers and for believing in me. Their moral support was always a continuous source of inspiration for me. I could not have attained my desires without their kindness and help. I am also thankful to my parents-in-law for their love and affection during all this period. Lastly, I express my gratefulness to my wife and daughter. I express my appreciation to my wife who patiently took more responsibility of managing household activities and taking care of our daughter during my long absence from home.

# LIST OF FREQUENTLY USED SYMBOLS

| Symbol | Representation | Dimensions |
|---|---|---|
| $a$ | Geometry factor for radial resistance | L |
| $C$ | Differential soil water capacity | $L^{-1}$ |
| $c$ | Solute concentration | $ML^{-3}$ |
| $c_{gr}$ | Average solute concenration of the groundwater | $ML^{-3}$ |
| $c_i$ | Solute concentration of soil water | $ML^{-3}$ |
| $c_n$ | Solute concentration of the lowest compartment | $ML^{-3}$ |
| $c_{irr}$ | Solute concentration of irrigation water | $ML^{-3}$ |
| $c_{prec}$ | Solute concentration of the rainfall | $ML^{-3}$ |
| $D$ | Depth of impervious layer below drain level | L |
| $D_h$ | Thickness of layer in which horizontal flow is considered | L |
| $D_v$ | Thickness of layer in which vertical flow is considered | L |
| $D_r$ | Thickness of layer in which radial flow is considered | L |
| $D_{dif}$ | Solute diffusion coefficient | $L^2T^{-1}$ |
| $D_{dis}$ | Solute dispersion coefficient | $L^2T^{-1}$ |
| $D_{root}$ | Rooting depth | L |
| $D_w$ | Solute diffusion coefficient in free water | $L^2T^{-1}$ |
| $d$ | Equivalent depth to impervious layer below drain level | L |
| $EC$ | Electrical conductivity | $L^{-3}M^{-1}T^3I^2$ |
| $EC_e^*$ | Electrical conductivity of soil saturation extract at which yield begins to decrease | $L^{-3}M^{-1}T^3I^2$ |
| $EC_a$ | Apparent electrical conductivity of a bulk soil volume | $L^{-3}M^{-1}T^3I^2$ |
| $EC_e$ | Electrical conductivity of soil saturation extract | $L^{-3}M^{-1}T^3I^2$ |
| $EC_e^{0-1}$ | Average electrical conductivity of soil saturation extract taken from 0-1.0 m depth | $L^{-3}M^{-1}T^3I^2$ |
| $EC_e^{min}$ | Permissible electrical conductivity of soil saturation extract for 100% crop yield | $L^{-3}M^{-1}T^3I^2$ |
| $EC_e^{max}$ | Permissible electrical conductivity of soil saturation extract for 0% crop yield | $L^{-3}M^{-1}T^3I^2$ |
| $E_{act}$ | Actual soil evaporation rate | $LT^{-1}$ |

| Symbol | Representation | Dimensions |
|---|---|---|
| $E_{pot}$ | Potential soil evaporation rate | $LT^{-1}$ |
| $ET_o$ | Reference evapotranspiration rate | $LT^{-1}$ |
| $ET_{act}$ | Actual evapotranspiration rate | $LT^{-1}$ |
| $ET_{pot}$ | Potential evapotranspiration rate | $LT^{-1}$ |
| $H$ | Design groundwater table depth from soil surface (Fig. 3.4) | L |
| $h$ | Soil water pressure head | L |
| $\Delta h$ | Difference in hydraulic head between drain level and the phreatic level at mid point | L |
| $I_{rr}$ | Depth of irrigation water supply | $L^3L^{-2}$ |
| $J$ | Solute flux density | $ML^{-2}T^{-1}$ |
| $J_{drain}$ | Solute flux density during drainage | $ML^{-2}T^{-1}$ |
| $J_{bot}$ | Solute flux density during bottom flux | $ML^{-2}T^{-1}$ |
| $K$ | Hydraulic conductivity | $LT^{-1}$ |
| $K_{sat}$ | Saturated hydraulic conductivity | $LT^{-1}$ |
| $K_h$ | Horizontal hydraulic conductivity | $LT^{-1}$ |
| $K_v$ | Vertical hydraulic conductivity | $LT^{-1}$ |
| $K^h_{sat}$ | Saturated horizontal hydraulic conductivity | $LT^{-1}$ |
| $K^v_{sat}$ | Saturated vertical hydraulic conductivity | $LT^{-1}$ |
| $K^r_{sat}$ | Saturated radial hydraulic conductivity | $LT^{-1}$ |
| $k_r$ | Root water uptake preference factor | - |
| $K_y$ | Yield response factor | - |
| $k_c$ | Crop factor | - |
| $L$ | Drain spacing | L |
| $LAI$ | Leaf area index | $L^2L^{-2}$ |
| $L_{dis}$ | Dispersion Length | L |
| $l_{root}$ | Root length density | $LL^{-3}$ |
| $m$ | Shape factor in Mualem-Van Genuchten functions | - |
| $n$ | Shape factor in Mualem-Van Genuchten functions | - |
| $Q$ | Solute fraction adsorbed to soil particles | $MM^{-1}$ |
| $Q$ | Soil water flux density (positive upward) | $LT^{-1}$ |
| $q_{drain}$ | Drain discharge rate | $LT^{-1}$ |
| $q_{bot}$ | Bottom flux density | $LT^{-1}$ |

| Symbol | Representation | Dimensions |
|---|---|---|
| $q_{250}$ | Flux density at 250 cm depth of the soil profile | $LT^{-1}$ |
| $r_o$ | Outer radius of the drain | L |
| $S$ | Root water extraction rate | $L^3L^{-3}T^{-1}$ |
| $S_{pot}$ | Potential root water extraction rate | $L^3L^{-3}T^{-1}$ |
| $S_{act}$ | Actual root water extraction rate | $L^3L^{-3}T^{-1}$ |
| $SC$ | Soil cover fraction | $L^2L^{-2}$ |
| $S_s$ | Solute sink term | $ML^{-3}T^{-1}$ |
| $T_{act}$ | Actual transpiration rate | $LT^{-1}$ |
| $T_{pot}$ | Potential transpiration rate | $LT^{-1}$ |
| $v$ | Pore water velocity | $LT^{-1}$ |
| $X$ | Total solute concentration in the soil water system | $ML^{-3}$ |
| $Y_{act}$ | Actual crop yield | $ML^{-2}$ |
| $Y_{pot}$ | Potential crop yield | $ML^{-2}$ |
| $z$ | Vertical coordinate, positive upward, zero at soil surface | L |
| $\alpha$ | Shape factor in Mualem Van-Genuchten functions | $L^{-1}$ |
| $\alpha_{rw}$ | Reduction factor for root water uptake due to water stress | - |
| $\alpha_{rs}$ | Reduction factor for root water uptake due to salinity stress | - |
| $\gamma_{drain}$ | Drainage resistance | T |
| $\theta$ | Volumetric soil water content | $L^3L^{-3}$ |
| $\theta_{res}$ | Residual volumetric soil water content | $L^3L^{-3}$ |
| $\theta_{sat}$ | Saturated volumetric soil water content | $L^3L^{-3}$ |
| $\lambda$ | Shape factor in Mualem-Van Genuchten functions | - |
| $\mu$ | First order rate coefficient of transformation | $JM^{-1}$ |
| $\rho_b$ | Dry soil bulk density | $ML^{-3}$ |
| $\phi_{por}$ | Soil porosity | $L^3L^{-3}$ |
| $\pi$ | Osmotic head | L |

# ABSTRACT

Sarwar, A. **A transient model approach to improve on-farm irrigation and drainage in semi-arid zones.** Ph.D. thesis, Wageningen University and Research Center, Wageningen, The Netherlands.

A transient model approach is introduced to improve design procedures for subsurface drainage systems in relation to different irrigation management strategies to increase crop *productivity* and environmental *sustainability* in the water scarce environment of Pakistan. The water flow and solute transport model, SWAP, is used to evaluate the impact of irrigation and drainage on crop transpiration, soil salinity and groundwater table behavior taking 15 years of actual weather data. Model calibration improves considerably when field determined soil water retention curves were used. The reference evapotranspiration calculated by the Priestly-Taylor method appears to be physically more realistic than the Penman-Monteith method because the latter ignores the feed-back mechanism of vapor pressure deficit on stomatal closure. For the Fourth Drainage Project (FDP) conditions, a zero flux at the bottom of the soil profile was found to be a suitable bottom boundary for further model simulations.

For semi-arid areas, the selection of a proper drain depth is more critical than drain spacing. A drain depth of 2.2 m is found to be optimal for the *multiple cropping system* of the FDP-area. This drain depth gave the best results with regard to crop yields, soil salinity and groundwater table control at rather low drainage intensity ($q_{drain}/\Delta h$), resulting from a drain spacing of 500 m. Long-term model simulations covering a period of 15 years show that the present FDP drainage system has been designed at too high drainage intensity. If no operational and maintenance constraints are present, the FDP-area could be drained with 25 percent less drainage intensity.

Under shallow groundwater table conditions, reduced irrigation applications can save up to 25 percent of the canal water each year. This strategy will produce reasonably high crop yields (relative transpiration $T_{act}/T_{pot} > 0.90$) and limit field percolation losses. For either conjunctive use or use of tubewell water alone, reduced irrigation applications will not be sufficient and additional supplies would be required for leaching the salts from the root zone. It must be recognized that during relatively dry years drainage is not a guaranteed success. In the *absence* of a drainage system, leaching of salts by means of poor quality irrigation water will not be suitable. For these areas other options like growing more salt tolerant crops should be considered. Reduced irrigation inputs is a proper short-term solution, however, in the long run drainage systems associated with adjusted irrigation planning seems necessary.

Under average conditions, the effect of irrigation schedule flexibility on crop yields is insignificant. However, compared to a *fixed* schedule and when *un-restricted* water supplies would be available, the *productivity* of water ($Y_{act}/I_{rr}$) for the *on-demand* schedule would be up to 30 percent higher, but at the cost of salinity build up. The average annual water use by the *on-demand* schedule is 20 percent lower than the *fixed* schedule, which would result in 30 percent lower drainage volumes and 15 percent lower recharge to the groundwater. In the *absence* of sufficient canal supplies, necessary infrastructure and management facilities in the Indus basin, moving towards a demand-based system would neither be economically feasible nor socially acceptable. Therefore the emphasis should be on reducing irrigation water application and constructing drainage in conjunctive water use areas.

***Key-words:*** drainage design, irrigation, crop *productivity*, soil salinity, *sustainability*, integrated water management, transient modeling, semi-arid zones, Pakistan.

# 1 INTRODUCTION

## 1.1 Water for food

The world's population is increasing at a rate of 1.5 percent per year. According to the United Nations, the world population will reach eight billion by the year 2025. Because of this population growth, the average annual per capita availability of renewable water resources is projected to fall from 6600 cubic meters today to 4800 cubic meters in 2025 (Cosgrove and Rijsberman, 2000). Current fresh water use is not sustainable as many countries are entering an era of severe water shortages. Given the uneven distribution of these resources, some 3 billion people (about 40 percent of total world population) will live in arid or semi-arid countries by the year 2025, having less than 1700 cubic meters per capita per year. This is the quantity below which people start to suffer from water stress (Falkenmark et al., 1989).

Irrigated agriculture produces about 40 percent of the agricultural outputs and 60 percent of the world's grain production. To meet the increasing demand for food, irrigated agriculture will have to keep pace and therefore expand by 20 to 30 percent in area by 2025. However, it is perceived that due to decreased investments in irrigation sector combined with environmental and ecological threats, the expansion in irrigated area will be limited to the 5 to 10 percent range only. This strong reduction in irrigation expansion will lead to serious food shortages and rising food prices. As opportunities for development of new water resources diminish and costs rise, increasing the *productivity* of existing water resources becomes a more attractive alternative. Therefore there is every motivation to designate more capital and efforts to increase the *productivity* of water and the *sustainability* of water resources management[1].

Increasing the *productivity* of existing water resources is central to produce more food, to fight poverty, to reduce competition for water and to ensure that there is enough water for nature. The *productivity* of irrigation water can be increased in essentially four ways: (i) increasing the *productivity* per unit of evapotranspiration (or, more precisely, transpiration) by reducing evaporation losses; (ii) reducing flows of usable waters to sinks; (iii) controlling salinity, sodicity and pollution; and (iv)

---

[1] *Productivity* of water (kg $m^{-3}$) is expressed in terms of yield (kg $ha^{-1}$) produced per unit evapotranspiration (m). *Sustainability* refers to management of water systems which does not lead to environmental degradation (waterlogging, salinization and desertification).

reallocating water from lower-valued crops to higher-valued crops (IWMI, 2000). Achieving the greater *productivity* is possible, especially in developing countries, where water *productivity* is far below potential. For cereal grains, for example, the range is between 0.2 and 1.5 kg $m^{-3}$. Even though production depends on conditions of the environment, the market, the soil and other factors not equal across sites, there appears to be a scope to manage resources for higher *productivity*.

Pakistan is also one of the countries who could face severe food and water crises in the 21st century. Continuous population growth with limited land and water resources has put an enormous pressure on the economy of the country. The population is increasing at a rate of 3.0 percent per year and has reached about 140 million. Considering the reduction in present storage capacities and non-availability of additional storage facilities, the shortfall of water requirements would be about 50 percent by the year 2025 (Alam and Bhutta, 1996). This shortfall of water would impact on the agricultural production. Because of continuous rise in population, water demand for domestic, industrial and non-agricultural uses will increase by about eight percent and is expected to reach to ten percent of the total available water resources by the year 2025. Water availability per capita will reduce to less than 600 cubic meters per capita in year 2025 (Figure 1.1). This is roughly the value below which water availability becomes a primary constraint to life (Engelman and Leroy, 1993). Availabe land per person for cultivation is also decreasing. Moreover, agriculture is threatened by severe waterlogging and salinity due to lack of drainage facilities and good quality irrigation water. Therefore a multi-dimensional approach needs to be applied for sustainable development of land and water resources.

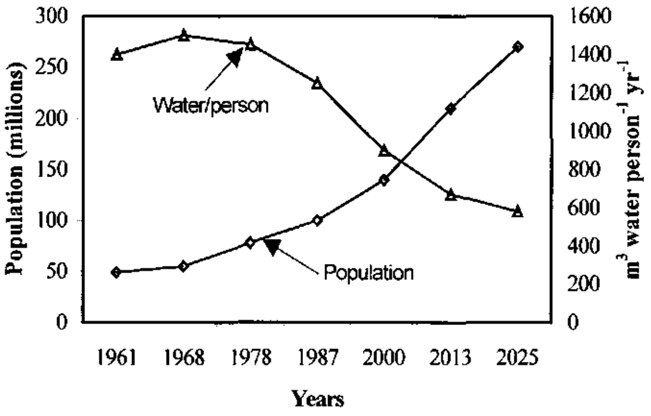

**Figure 1.1.** Population growth and water availability per capita per year in Pakistan (after Alam and Bhutta, 1996).

## 1.2 Irrigation and drainage in the Indus basin

Irrigated agriculture in Pakistan is mainly confined to the Indus plains where it has been developed by harnessing principal water resources available to the country. Without assured irrigation supplies, these arid and semi-arid areas of Pakistan can not support any agriculture, as the evapotranspiration demand is high and rainfall is either meager or unreliable. The contiguous Indus basin irrigation system irrigates an area of about 16 million ha, diverting annually about 131 billion $m^3$ of surface water to 43 main canal systems (Badruddin, 1996). Figure 1.2 shows some features of Indus basin irrigation system. About a century ago, the system was originally designed for an annual cropping intensity (i.e. yearly cropped area) of about 75 percent with the intention to spread the irrigation water over as large an area as possible to expand the settlement opportunities. The major objective of irrigation development at that time was to prevent crop failure and avoid famine (Jurriens and Mollinga, 1996). Another design feature was the low management and operational requirements, which is an advantage, with an inherent disadvantage of inflexibility. Increasing demand for food to cope with the ever-increasing population has caused the annual cropping intensities to rise to about 150 percent. Moreover, many canals can even no longer convey their official design capacity, due to siltation and erosion of banks. From the scarcity by design and the intensified farmer practices, over time canal water availability per unit of irrigated land has become even more limited.

The irrigation system typically consists of the main canals from which the water is distributed to branch canals. Secondary channels, called distributaries, take off from the branch canals. The distributaries and their branches, called minors are the main arteries for releasing water through outlets to small irrigation service areas (averaging 160 ha) called 'chaks'. The outlets are free draining structures, which have a capacity fixed in proportion to the service area. The outlet discharge is a function of water level elevation in the supply canal. Due to the variations in the main canal discharges and the changes in the channel regime caused by siltation, it becomes difficult to achieve equity in water distribution. In times of water shortage, the water has to be rotated between secondary canals, the distributaries and minors.

The operation of the Indus basin irrigation system is based on a continuous water supply and is not related to actual crop water requirements. Irrigation canals are usually not allocated more than their design capacity, of which a typical value is about 2 mm $d^{-1}$. Despite significant increase in storage capacities, it is essentially a supply-based system. Hence, it can not adequately accommodate changing water demands uring the crop season. The distribution of water from the canal outlets having mostly

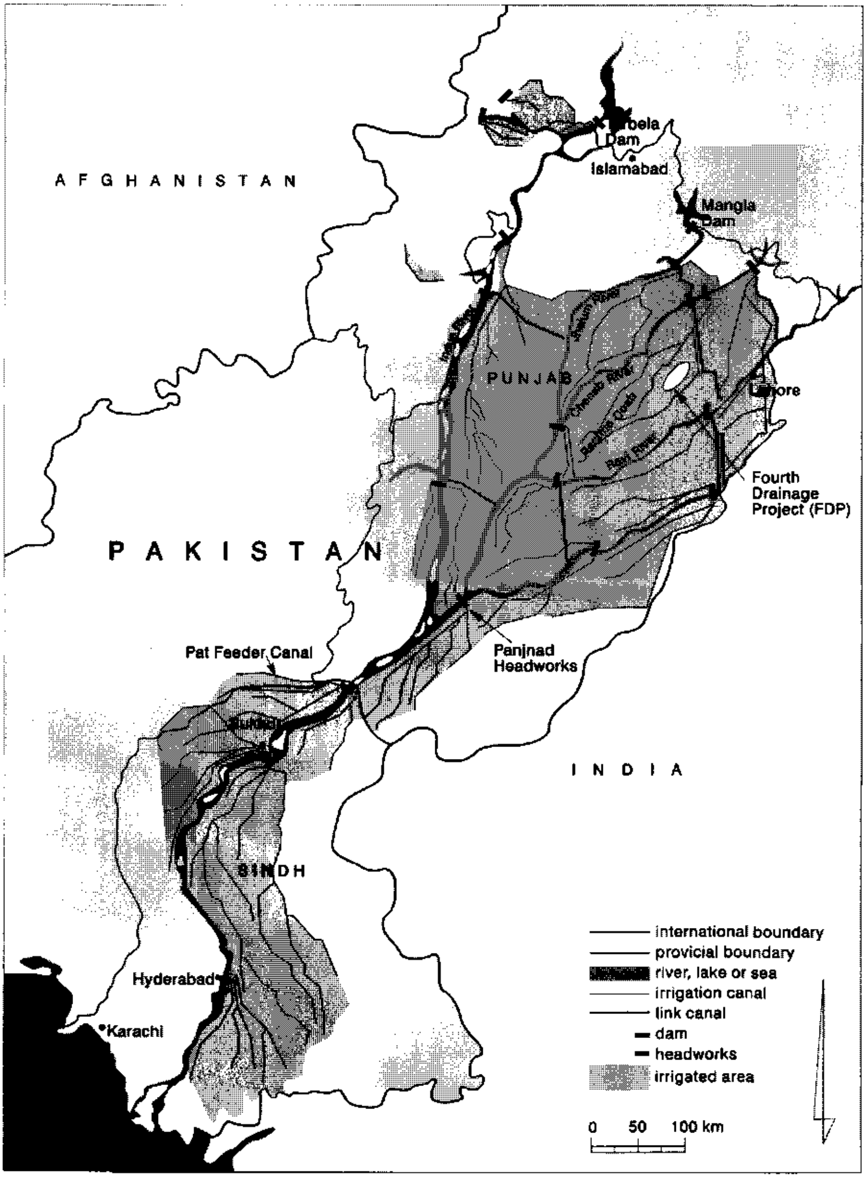

Figure 1.2. Some features of the Indus basin irrigation system of Pakistan.

a capacity of 30 to 90 l $s^{-1}$, to the group of farmers (in 'chaks') is done on a fixed rotational system called '*warabandi*' being generally a seven days cycle. This means that each farmer is allowed to take an entire flow of the outlet once in seven days and for a period proportional to the size of his land holding. The water duty is insufficient to irrigate the entire farm in one irrigation turn, and the farmer can decide whether to under-irrigate all land or leave a fraction unirrigated and bring irrigation water to a smaller fraction of his land holding. Due to age and poor maintenance, the delivery efficiency of irrigation system is low, ranging from 35 to 40 percent from canal head to the crop root zone (Tarar, 1995). In practical terms, therefore, much surface water is currently lost enroute, which, if salvaged, could be profitably used by the farmers.

Due to the inadequacy, variability and unreliability of the surface irrigation supplies, the farmers have turned more and more to the use of groundwater without a full awareness of the hazard represented by groundwater quality. The Indus basin is underlain by an extensive groundwater aquifer covering about 16 million ha, of which 6 million ha are fresh and the remaining 10 million ha are saline (Haider et al., 1999). The massive development of groundwater from the Indus basin aquifer started about 30 years ago. At present, total groundwater contribution is estimated as approximately 30 to 40 percent of the total irrigation water available at the farm gate. This source is exploited by the use of 20,000 public and about 450,000 private tubewells (Nespak/SGI, 1991). About 70 percent of the private tubewells are located in the canal command areas while the rest provides irrigation based on groundwater alone. The quality of groundwater is highly variable ranging from fresh ($EC \leq 1.5$ dS $m^{-1}$) to extremely saline ($EC \geq 4.5$ dS $m^{-1}$) and is a main factor of salinity development in the root zone.

The Indus plain is characterized by a lack of any well-defined natural surface drainage and differences in micro-relief define the pathways for surface run-off during the monsoon season. The surface drainage problems are further aggravated by the construction of infrastructures like roads, railways, flood embankments and the irrigation system. Due to the flat nature of the Indus basin, natural subsurface drainage through down-valley movement of groundwater is also restricted. Therefore, ponding of agricultural lands following intense rainstorms, with consequent crop and property damages, has become a recurrent phenomenon in many parts of the Indus plains. The need for surface drainage of agricultural lands has long been recognized and measures were taken to construct surface drains in areas prone to severe damage. Even though about 15,000 kilometers of surface drains have been constructed to-date, crop losses because of rain flooding remain excessive, especially in the Punjab and Sindh provinces (Afzal, 1992).

## 1.3 Waterlogging and salinity in the Indus basin

### *Waterlogging*

The introduction of large-scale irrigation without adequate drainage altered the hydrological balance in the Indus basin. At the time of construction of irrigation canals about a century ago, the groundwater table depth in different canal command areas ranged between 20 to 30 m below the soil surface. Therefore the need for provision of subsurface drainage as a part of irrigation system was not felt. Persistent seepage over the years from unlined earthen canals and from a large network of distributing channels and percolation losses from irrigated fields, increased the groundwater recharge substantially. In the absence of drainage in the canal command areas, the groundwater table rose rapidly in vast irrigated areas to within 1.5 m of the soil surface. This created waterlogging and, consequently, soil salinity. These problems are more serious in areas where groundwater is saline. As a typical example, the rise of the groundwater table after the introduction of the irrigation system in the Punjab is shown in Figure 1.3.

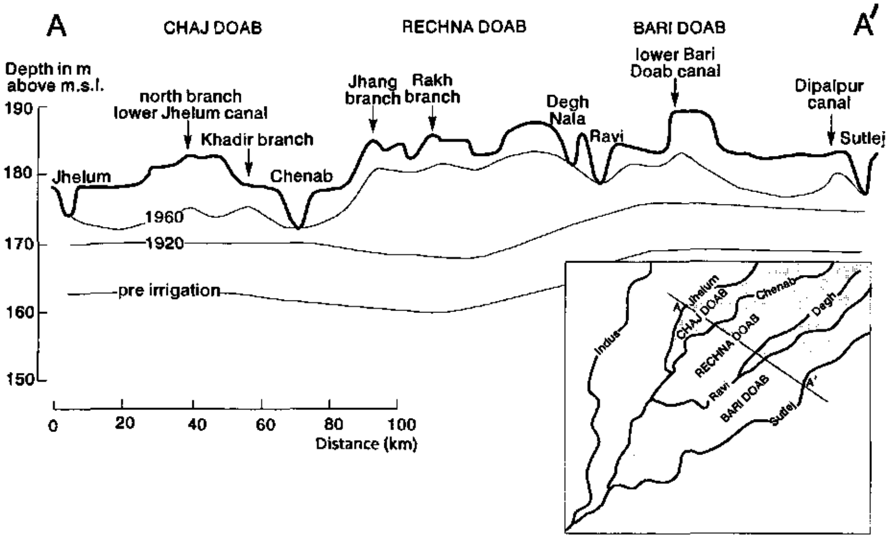

**Figure 1.3.** Rise of the groundwater table after the introduction of canal irrigation in the Punjab, Pakistan (after Wolters and Bhutta, 1997). The groundwater profiles are shown for the years 1920 and 1960.

The groundwater table in the Indus basin fluctuates seasonally. In general, groundwater tables are deepest at the end of the dry season (May-June) and shallowest immediately after the wet season (September). It is presently estimated that after the monsoon season, about 4.7 million ha (30 percent of the irrigated area) have a groundwater table within 1.5 m of the soil surface (severely waterlogged). Prior to monsoon, this area is reduced to about 2 million ha i.e. 13 percent of the irrigated area (Tarar, 1995). The Punjab Province has about 25 percent of its irrigated area severely waterlogged and Sindh has about 60 percent in the same category. Due to the presence of this shallow and saline groundwater, about 40,000 ha are annually abandoned within the Indus basin due to secondary salinization (WAPDA, 1989). Figure 1.4 shows that about 46 percent of the irrigated land have groundwater tables deeper than 3 m and this proportion is not affected by the season.

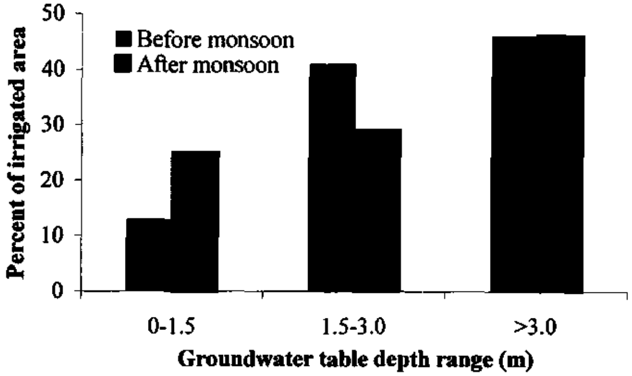

**Figure 1.4.** Seasonal effects on groundwater table depths in the Indus basin.

***Soil salinization***

The Indus basin is faced with a considerable salt balance problem. The salts are brought in by the rivers and their tributaries. The average annual salt inflow by the Indus river water, is estimated to be 33 million tons while the outflow to the sea is only 16.4 million tons. This means an annual average addition of some 16.6 million tons to the salt storage in the Indus basin. Out of this only 2.2 million tons is deposited in a series of evaporation ponds and the remainder of salts accumulates in the soil profiles in the irrigated lands and its underlying strata and aquifer (Nespak/MMI, 1993). This implies that, annually, an average of one ton of salts is added to each hectare of irrigated land. This salt accumulation is mainly causing salinization of the land. Therefore about 35 to 40 percent of the irrigated areas are affected by salinity. Out of this, eight percent is severely affected and six percent moderately affected by salinity. Of course, the scale of the problem of salt accumulation in the root zone is even greater if saline groundwater is used for irrigation.

Most of the soil salinity in the Indus basin is inherent, as it was produced during the process of soil formation. The secondary salinization associated with the shallow groundwater tables and use of poor quality groundwater for irrigation has further compounded the problem. Therefore salt-affected soils have become an important ecological entity in the Indus basin of Pakistan. It is estimated that nearly six million ha are already afflicted with this menace, of which about half is in irrigated areas (WAPDA, 1989). An estimated two million ha are abandoned due to severe salinity (Wolters and Bhutta, 1997). The extent keeps on changing due to dynamic nature of the problem.

The problems of soils in the Indus basin are not only of salinity but also of sodicity. About 70 percent of the tubewells in the Indus basin pump sodic water, which contain high concentrations of carbonate and bicarbonate. Application of this quality of water for irrigation turn the soils to saline-sodic affecting soil structure and infiltration rates thereby restricting the growth of conventional crops. Salt-affected soils of the Indus basin are usually classified into four types (Qureshi and Barret-Lennard, 1998). The area affected and the characteristics of these four soil types are given in Table 1.1.

**Table 1.1.** Classification of salt-affected soils in the Indus basin (after Qureshi and Barret-Lennard, 1998).

| Classification of salt-affected soils | Area affected (million ha) | Characteristics |
|---|---|---|
| Slightly saline-sodic | 0.7 | Slight salinity-sodicity problem, occurring as patches (about 20% of the area) in cultivated fields. |
| Porous saline-sodic | 1.9 | Saline-sodic throughout the root zone, porous and pervious to water. |
| Severely saline-sodic | 1.1 | Have high groundwater tables, dense and nearly impervious to water. |
| Soils with sodic tubewell water | 2.3 | Severely sodic due to application of sodic tubewell water. Contain high concentrations of carbonates and bicarbonates. Almost impervious. |

The above facts indicate that the agricultural sector suffers deeply from both waterlogging and salinity. About 75 percent of the population and about half of the Gross National Product (GNP) are directly or indirectly related to the agricultural sector. This shows that the problems of waterlogging and salinity are not just agricultural problems, but that they do affect the country as a whole and ultimately the social fabric of Pakistani society. Waterlogging and salinity have very adverse social and economical effects on communities in Pakistan, causing poor living standards in affected areas and health problems for humans and animals. This situation has forced the local population to migrate to other areas.

*In conclusion, waterlogging and salinity remain a hazard for the Indus basin and threaten the livelihood of farmers, especially the smaller-scale ones. Therefore, in future, drainage rather than additional water continue to be a top priority for the sustainability of the system.*

## 1.4 Measures taken to control waterlogging and salinity

The threat of waterlogging was recognized soon after the introduction of irrigation in the Indus basin. The first observation wells to monitor the effect of irrigation on the groundwater table depth were installed as early as in 1870. Based on these studies, various remedial measures were tried. These measures were largely focused on controlling the groundwater table depth with the idea to contain the capillary salinization process. These measures included closure of canals in the monsoon season, construction of surface drains in waterlogged areas and lowering of full supply levels of canals (Ahmad and Choudhry, 1988). However, none of these measures provided more than a local or temporary relief and the regional problem of waterlogging and salinity continued to increase in severity. In 1958, the Water and Power Development Authority (WAPDA) was created to tackle the problems of waterlogging and salinity in the Indus basin, notably through large-scale vertical and horizontal drainage projects. These projects are briefly discussed below.

***Vertical (tubewell) drainage***

The first detailed surveys of groundwater table depth and salinity conducted in the 1950s with the collaboration of the US Geological Survey Department formed the basis for the SCARP (Salinity Control And Reclamation Project) program and the decision to go ahead with vertical drainage (public tubewell program). As a result, in fresh groundwater areas, about 14,000 tubewells (covering about 2.6 million ha of irrigated land) with an average capacity of approximately 80 $l\ s^{-1}$ were constructed in the 1960s and 1970s. The main aims of the SCARP projects were to combat waterlogging and salinity through lowering of the groundwater table and increase the irrigation supplies at the farm gate by using the pumped groundwater directly or mixed with canal water. This demonstration also led to a proliferation of private tubewells with a capacity of about 28 l $s^{-1}$ and less by farmers in the 1970s and 1980s. Since then number of private tubewells are increasing with an average annual growth rate of about 9.6 percent (Badruddin et al., 1999). Implementation of SCARPs was moderately successful and initially the problems of waterlogging and salinity were somewhat arrested and reversed.

The exploitation of useable groundwater provided an opportunity for the farmers of these areas to supplement their irrigation supplies and to cope with the vagaries of the surface supplies. However, the present uncontrolled and unregulated use of groundwater is replete with serious consequences as it is depleting the fresh groundwater (Bhatti and Kijne, 1992). This may lead to excessive lowering of groundwater and intrusion of saline groundwater into fresh groundwater aquifers. This will not only deteriorate the quality of groundwater but also increase the pumping cost. This means more expensive and poor quality groundwater will have to be used for irrigation in future.

### *Horizontal (tile) drainage*

In the mid-seventies, it was realized that circulating salt-contaminated water through vertical drainage only serves to aggravate the problem. Therefore thinking shifted towards horizontal (pipe) drainage systems particularly in saline groundwater areas. Under Pakistani conditions, pipe drainage systems are some 10 times more expensive than tubewell systems (roughly US$ 1000 $ha^{-1}$ compared to US$ 100 $ha^{-1}$). The main reasons to introduce pipe drains in saline groundwater areas, despite the high costs, were the assumptions that the long-term drainage water quality would be better with pipe drains than with tubewells and a small volume of saline effluent will be produced (Bhatti, 1987). Better drainage water quality will reduce the disposal problems and increase the possibility of using drainage water for irrigation.

In Pakistan, the horizontal subsurface drainage for waterlogging and salinity control was first introduced in the East-Khairpur project. The project was constructed between 1977 and 1985. After this, pipe drains were installed in the Mardan SCARP project and the Fourth Drainage Project (FDP). At the time of construction of these projects, no guidelines were available for the planning and design of subsurface drainage systems for the (semi-) arid conditions of Pakistan. Therefore these projects were designed by applying the drainage design criteria as used for humid areas. These criteria are mostly based on the steady-state equations of Hooghoudt and Ernst (see

Ritzema, 1994), which assume steady-state moisture and solute fluxes occurring in the unsaturated zone i.e. the design of drain depth and drain spacing for a *priori* chosen drain discharge rate and permissible depth to groundwater table.

The drain discharge rate for the above-mentioned drainage projects was calculated using simple steady-state water balance approach. For the East-Khairpur drainage project, recharge to the groundwater was mainly estimated from seepage of irrigation canals and on-farm irrigation losses, which resulted in a steady recharge to the groundwater of 3.5 mm $d^{-1}$ (van Someren and Boers, 1978). The main objective of the design was to maintain an acceptable groundwater table depth rather than rapidly preventing excessive groundwater rises due to monsoon showers. For the Mardan SCARP project, recharge to the groundwater was calculated considering on-farm irrigation components, 5-year return period rainfall and reduced irrigation during the monsoon and recharge to groundwater was found to be 3.2 mm $d^{-1}$. At the Fourth Drainage Project (FDP), the highest mean annual rainfall in the area was used while the root zone was considered fully saturated before the design rainfall occurred. This resulted in a recharge to groundwater of 2.44 mm $d^{-1}$.

These estimated drain discharge rates were then used to calculate the required lateral spacings using steady-state equations of Hooghoudt and Ernst. The average drain depths of these three projects range from 1.95 m for East-Khairpur to 2.44 m for the FDP and were mainly selected on the basis of minimum costs (Smedema et al., 1992). The comparative studies of the above three completed projects have shown that all three designs are rather conservative with high drainage intensities. Discussions with farmers at Mardan and FDP projects confirmed that in the areas already drained the demand for surface irrigation has increased (Vlotman et al., 1990).

Since the completion of the East-Khairpur drainage project, nine more pipe drainage projects have been designed, of which several have been completed and others are in various stages of completion. Since the design of the first drainage project, the value of design drain discharge rate has gradually reduced from 3.5 mm $d^{-1}$ at East-Khairpur to 1.3 mm $d^{-1}$ at Khushab Project (Figure 1.5). Although local conditions such as annual rainfall or seepage loss from canals influence the drain discharge rates, the general trend towards lower drain discharge rates can be explained by the experience designers have built up over the years who now feel more confident to design for lower drain discharge rates (Boers and Zuberi, 1995). Above discussion reveals that after 25-years of experience in the field of drainage, Pakistan is still struggling to find, through trial and error, the suitable drainage design criteria for its conditions. Experience has shown (Smedema, 1990) that drainage systems functioning in (semi-)

arid zones for salinity control typically have a drain discharge rate of 2 mm $d^{-1}$. From the Figure 1.5 it can be seen that this single value of 2 mm $d^{-1}$ does not satisfy local field conditions of different drainage projects installed in Pakistan. The drain discharge rate used for the design has a large influence on the drain spacing and hence on the project costs. Therefore, it is logical to develop the best methodology for the design of drainage systems under the conditions prevailing in Pakistan.

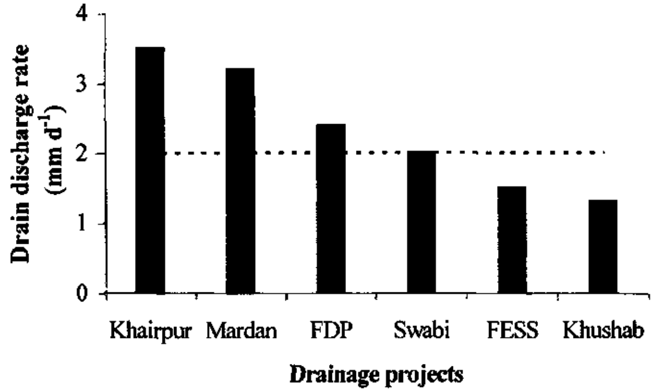

**Figure 1.5.** Drain discharge rates used for different drainage projects in Pakistan. (derived from data of Bhutta et al., 1994). The dotted line represents the value proposed by Smedema (1990) for semi-arid regions. FESS represents Fordwah Eastern Sadiqia South drainage project.

### *On-farm water management measures*

To prevent further deterioration of agricultural lands from the twin menace of waterlogging and salinity, a number of on-farm water management measures were also tried. These included lining of watercourses to reduce seepage losses, adaptation of proper irrigation schedules for different crops and climatic conditions. Considerable work was also done to develop guidelines for the safe use of different quality waters for irrigation and to reclaim salt-affected soils through biotic, physical and chemical measures (Ahmad et al. 1990). However, these efforts remained confined to the farm and field level, and no serious attempt was made to translate the implications of these findings to a larger, system level. On the other hand, farmers continue their efforts to reclaim large tracts of irrigated lands affected by salinity and/or sodicity. Their measures are mostly related to water management, crop choices, cultural practices and the application of chemical and biotic amendments. Kielen (1996) has listed a number of measures adopted by farmers to cope with the problems of waterlogging and soil salinity in the Indus basin of Pakistan.

Despite all these efforts, problems still widely persist in vast tracts of irrigated areas. A total of 40 percent of irrigation losses takes place in the watercourse only (Aziz et al., 1992). Farmers generally lack knowledge of important aspects of plant-soil-climate relationships and proper management of different quality waters for irrigation.

## 1.5 Problem statement

Continuous population growth with limited land and water resources has put an enormous pressure on the economy of Pakistan. Pakistan is turning to a water scarce country in the near future. It is estimated that to feed the increasing population, 40 percent more food would be required by the year 2025 (Alam and Bhutta, 1996). Due to lack of compatible development of water resources, water availability per capita per year will be reduced to 580 $m^3$ by that time (Figure 1.1). The scope of expansion of irrigated area will also be limited due to shortage of good quality canal water. This stresses the need to increase the *productivity* of available limited water resources.

The average yields in Pakistan are low for wheat and rice, being 2276 kg $ha^{-1}$ and 1756 kg $ha^{-1}$, respectively. There is a great variability in crop yields with some farmers achieving yields of 3874 kg $ha^{-1}$ for wheat and 3545 kg $ha^{-1}$ for rice. The *productivity* of water in Pakistan is among the lowest in the world. For wheat, for example it is 0.5 kg $m^{-3}$ as compared to 1.0 kg $m^{-3}$ in India (IWMI, 2000). Maize reveals even a factor nine between lowest in Pakistan (0.3 kg $m^{-3}$) and highest (2.7 kg $m^{-3}$) in Argentina (Bastiaanssen, 2000). This reveals that there is a substantial potential for increasing the *productivity* of water.

Large tracts of irrigated lands are already salinized or under threat. Areas with proper drainage facilities are rare. Due to an overall shortage of canal water to irrigate all the agricultural lands, use of poor quality groundwater as a supplementary source of irrigation has become a routine practice, which is adding huge amount of salts in the root zone thus aggravating the problem of soil salinity. On the other hand, losses from the main irrigation canals and irrigated fields are resulting in a rapid rise of the groundwater tables. Due to lack of drainage facilities, shallow groundwater tables are becoming an inevitable feature contributing to secondary salinization.

Over the past three decades, numerous efforts have been made to solve the problems of waterlogging and salinity and to improve water use efficiency at the farm level. In spite of huge investments the success has been limited. The reasons are that the installed drainage systems had not been operated as intended. The research conducted to advise farmers on appropriate irrigation methods, water use practices with tubewell waters of different qualities and methods for reclaiming salt affected soils was generally based on field scale experiments and was not tested for their long-term consequences on crop production and environmental degradation. The results were therefore regarded as local and short-term solutions and could not get the attention of farming community. Moreover, no concrete efforts were made for the dissemination of this knowledge.

The above discussion revealed that problems are very complex and a straightforward solution seems impossible. An integrated water management approach could be useful to manage available surface and subsurface water resources with respect to quality and quantity in view of increasing demands, limited resources, rising groundwater tables and soil salinization. In order to increase *productivity* and *sustainability* of the irrigation and drainage systems, the following potential solutions can be suggested:

- Improve irrigation efficiencies (save irrigation water);
- Conserve water at all levels (increase *productivity* of water);
- Minimize drainage requirements (improve drainage design);
- Evacuate salts from the root zone (arrest soil salinization);
- Manage water quality (maintain salt balance);
- Improve irrigation water distribution (improve reliability).

To address the above-mentioned issues, integration of irrigation and drainage is very necessary because irrigation management and drainage problems are closely inter-linked through: (i) irrigation as a cause of waterlogging, and (ii) relationship between irrigation management and effluent disposal. In the past, no tools were available for these integrated analysis therefore there was no other way except to simplify the problem by concentrating upon the factors which have more direct bearing upon the system. Although increased understanding of the soil-water-crop relationships and concurrent development of new experimental and computational techniques provided more opportunities for addressing these problems, their practical utility remained limited due to time, money and labor constraints.

The complexity in analyzing irrigation and drainage systems together is that there are many combinations of irrigation management and drainage design that could be investigated. The simulation models are the best tools to describe these complex soil-water-crop-climate interactions. The simulation models provide a more direct link between design parameters and objectives of drainage and water management systems. Besides giving water and salt balance terms, simulation models can also help to find the variables necessary for the calculations of crop water requirements (infiltration, capillary contribution, leaching requirements). This data can be used to study the long-term effects of different water management interventions on groundwater table, soil, environment and crop growth for which field data is not available or field trials could not be conducted. Since models answer easily and quickly 'what if' questions, they can help in organizing thoughts and in executing systematic and efficient research.

For the large projects, it is time consuming, difficult and expensive to conduct such detailed investigations. Therefore it is advantageous to do this research in pilot areas where soil and hydrological conditions are similar to the project areas. For the same reasons, data from Drainage Unit No. 9 (referred to as S1B9) of the Fourth Drainage Project (FDP), Punjab, Pakistan, has been used in this study. The S1B9 area was selected because its land use and intensity of cultivation is typical for the FDP-area. The study approach involves the use of a soil water simulation model, SWAP. This is a one-dimensional hydrological model, which produces daily water and salt balance components as an output. The model is capable of simulating long-term impacts of different irrigation management strategies on water and salt movement through the root zone to the drains, considering temporal variations in weather.

## 1.6 Outline of the thesis

*The main objective of this study is to develop a transient model approach to improve design procedures for subsurface drainage systems in relation to adapted irrigation techniques for improving crop yields without further detriment to waterlogging and soil salinity in the (semi-) arid zones.*

The specific objectives of this study are:

- To demonstrate a methodology for the calibration of a transient-state soil water simulation model in an irrigated and drained environment;
- To improve design procedures for subsurface drainage systems for the semi-arid conditions of Pakistan;
- To revise irrigation planning for the shallow groundwater table areas for both drained and un-drained conditions based on maximum irrigation water savings and to study the long-term impacts of this water conservation strategy on crop transpiration, soil salinity, drainage requirements and groundwater table behavior as influenced by different irrigation water qualities;

- To evaluate the impact of flexibility in irrigation water distribution on overall crop *productivity*, water savings, soil salinization, drainage requirements and groundwater table behavior.

Chapter 2 describes some important features of the Fourth Drainage Project (FDP) and S1B9 pilot area along with the details of data collection for this study. Chapter 3 describes the brief theory of the SWAP model including the root water uptake as a function of soil water pressure head and soil water electrical conductivity, top and bottom boundary conditions, flow to the drains, different options to calculate irrigation schedules and solute transport.

Chapter 4 deals with the calibration of the SWAP model for the physical conditions prevailing in the FDP-area, experimental set up and methods of data collection. The discrepancies between laboratory and field determined soil water retention curves $\theta(h)$ and initial and boundary conditions for SWAP will be discussed. Classical misconceptions about the calculations of reference evapotranspiration ($ET_o$) for semi-arid conditions will also be highlighted by comparing $ET_o$ values calculated with the Penman-Monteith method as well as the Priestly-Taylor method. As the field sizes in the FDP-area are considerably smaller than the distance between the lateral drains, the resulting lateral discharge is the cumulative drainage from all these fields. A methodology to estimate the contribution of sample field to the lateral drainage in this heterogeneously irrigated and drained environment will be introduced. A simple but suitable bottom boundary condition will be determined for further applications of the SWAP model in the FDP-area.

Chapter 5 deals with the re-evaluation of the existing drainage design criteria and determination of an optimal drainage design criteria for the FDP-area. The effects of twelve different drainage combinations (drain depth and drain spacing) on crop transpiration, soil salinization and groundwater table behavior will be evaluated using the calibrated SWAP model. Based on these analyses, an optimal drainage design for the *multiple cropping system* of the FDP-area is presented. The performance of this optimal drainage design will be compared with the present FDP design and the design proposed by Smedema (1990) for the semi-arid conditions of Pakistan.

Chapter 6 presents water conservation strategies for a wheat-cotton cropping rotation for the shallow groundwater table conditions of the FDP-area. The conservation strategies will be compared with the farmers' present irrigation practices to evaluate their long-term (15-years) impact on crop transpiration, soil salinity, drainage requirements and groundwater table behavior. The FDP-area represents a conjunctive use environment and only one-fourth of the project area is equipped with subsurface drainage system. Therefore long-term simulations will be performed for both drained and un-drained conditions considering three different irrigation water qualities.

Chapter 7 evaluates the impact of flexibility in irrigation water distribution on crop *productivity* and environmental *sustainability*. Three water delivery schedules, representing different levels of flexibility, will be studied under three conditions of water supply. The long-term (15-year) simulations will be performed for drained, un-drained and deep groundwater table conditions to evaluate the impact of various water delivery schedules on overall crop *productivity*, water savings, soil salinization, drainage requirements and groundwater table behavior.

Finally Chapter 8 summarizes the findings of this study.

# 2 DESCRIPTION OF THE STUDY AREA

## 2.1 Location and climate

The study area i.e. Fourth Drainage Project (FDP) is located in the Rechna Doab, an alluvial plain between the rivers Ravi and Chenab. It is situated north-east of Faisalabad city in the Punjab Province of Pakistan. The area has a longitude of 73°E and latitude of 31°N. The location of the FDP-area is shown in Figure 1.2. The area is sub-tropical, continental low-land, characterized as semi-arid with large seasonal fluctuations in temperature and rainfall. Summers are long and hot, lasting from April through September, with maximum day time temperature varying between 27 °C and 43 °C, while in winter, it varies between 4°C and 24°C. The average annual rainfall is about 360 mm. The monsoon, or rainy season, occurs from July to September and accounts for about two-third of the total annual rainfall. One-third falls in winter from January to March as low intensity frontal rains. A comparison of rainfall and annual potential evapotranspiration calculated with the Priestly-Taylor (1972) method for a period of 15 years (1980-94) is shown in Figure 2.1.

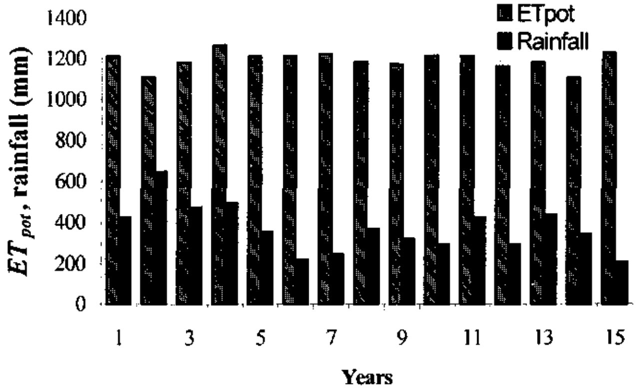

**Figure 2.1.** Comparison of annual potential evapotranspiration ($ET_{pot}$) and rainfall for a period of 15 years (1980-94).

## 2.2 Soils and soil salinity

The study area consists of a vast stretch of alluvial deposits, mainly unconsolidated sand and silt with major amounts of clay and gravel. Clay is generally found in lenses. Most soils in the area have a wide range of coarse to medium textured material. Surface soils in the area range from sandy loam to silty clay loam, with marked dominance of loam to silt loam soils. These surface soils are underlain by loamy sand to sandy loam sublayers. The soils are rapid to moderately permeable with a small water holding capacity and generally low in organic matter. The dry bulk density varies from 1.5 to 1.7 g $cm^{-3}$. The area is underlain by a highly conductive and deep aquifer of loamy sand to sandy loam. Estimates of the depth of the aquifer range from 100 to 300 m. The depth of the basement rock which forms the lower boundary of the aquifer varies throughout the Rechna Doab. However, for the FDP design the general aquifer depth was taken as 76 m (USBR, 1989).

Soil salinity in the FDP-area is highly variable. This is mainly due to inequity in the canal water supplies, which limit the chances of proper leaching at all fields. The distribution of irrigation water in the fields is also not uniform due to inadequate land leveling and irrigation application practices. This uneven distribution of water produces patches of low and high infiltration rates, which in turn produces patches of low and high salinity within the same field. Detailed profile salinity surveys conducted by the Soil Survey of Pakistan (IWASRI, 1990) show that the problem is not only of salinity but also of sodicity as a result of poor quality groundwater used for irrigation. About 35 to 40 percent farmers of the FDP-area are confronted with this problem to various degrees.

Three surface salinity surveys were conducted in the FDP-area during the period of 1983 to 1992 with a gap of about four years (SMO, 1994). The results of these surveys show that there is a gradual decrease in the area affected by salinity. This can be attributed to the groundwater tables decline in large parts of the FDP-area as a result of surface and subsurface drainage improvements. This slowed down the process of soil salinization. Another reason is that farmers have reclaimed large tracts of land over the years. The results of the surveys of 1983 and 1992 are compared in Table 2.1. The salinity was determined by visual observations. *Table 2.1 shows that despite all efforts to eliminate the problem of salinity, about 30 percent of the FDP-area is still suffering from different levels of soil salinity.*

**Table 2.1.** Percentage of FDP-area in different salinity classes determined through visual observations during surveys of 1983 and 1992 (SMO, 1994).

| Salinity class | Salinity level | Area affected (%) 1983 | Area affected (%) 1992 |
|---|---|---|---|
| S1 | Non-saline | 55 | 68 |
| S2 | Slightly saline | 20 | 17 |
| S3 | Moderately saline | 15 | 7 |
| S4 | Severely saline | 10 | 7 |

## 2.3 Groundwater table depth and groundwater quality

The groundwater table depths in the FDP-area are generally shallow: about 70 percent of the total area has a groundwater table between 1.5 to 2.5 m (Moghal et al., 1992). The groundwater table depth varies considerably before and after the monsoon season. Before monsoon, about 10 percent of the area has groundwater table depth between 0-150 cm. After the monsoon, the area with groundwater table depth between 0-150 cm increases to 40 percent (Table 2.2). The percentage of area with groundwater table depth below 300 cm remained unchanged before and after the monsoon season. The presence of this shallow groundwater is a continuous source of capillary salinization.

**Table 2.2.** Percentage of FDP-area under different groundwater table depths before and after the monsoon season.

| Groundwater table depth (cm) | Before monsoon (%) | After monsoon (%) |
|---|---|---|
| 0-150 | 10 | 40 |
| 150-300 | 70 | 40 |
| >300 | 20 | 20 |

The groundwater quality in the area is highly variable, reflecting the heterogeneity in the materials of the area. Groundwater is often saline and contains relatively high amounts of sodium and bi-carbonates. Groundwater EC ranges from 2 to 4 dS $m^{-1}$, which makes it generally unsuitable for irrigation. The water quality is usually categorized according to the standards adopted by WAPDA (Beg and Lone, 1992) as presented in Table 2.3. Apart from the total salt concentration, expressed by the electrical conductivity EC, the sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) are also used as indicators. The SAR presents the ratio of the $Na^+$ concentration over $Ca^{2+}$ and $Mg^{2+}$ concentration $(mmol\ l^{-1})^{0.5}$, while the RSC gives the concentration of $CO_3^-$ and $HCO_3^-$ minus those of $Ca^{2+}$ and $Mg^{2+}$. The percentage of FDP-area under different groundwater quality categories is presented in Table 2.3.

**Table 2.3.** Water quality standards (Beg and Lone, 1992) and percentage of FDP-area in each category.

| EC (dS $m^{-1}$) | SAR (mmol $l^{-1})^{0.5}$ | RSC (meq $l^{-1}$) | Category | Percentage of FDP-area |
|---|---|---|---|---|
| 0-1.5 | 0-10 | 0-2.5 | Useable | 40 |
| 1.5-2.7 | 10-18 | 2.5-5.0 | Marginal | 20 |
| > 2.7 | > 18 | > 5.0 | Hazardous | 40 |

## 2.4 Irrigation system and irrigation schedules

The irrigation water in the FDP-area is transported to the farmer fields through an extensive system of unlined canals and small watercourses. The delivery of water in the tertiary unit is based on seven day fixed rotational system called '*warabandi*'. The farmers then distribute their water turn on their fields. The amount of water applied to each field entirely depends on the wish of the farmer. Mostly, farmers use basin-flooding method to spread water over their fields. Farmers usually formulate the roster of water rotation. The operation of this system is based on a continuous (but not necessarily constant) supply, which is not related to the crop water requirements. A considerable variability in the canal supplies occurs due to unforeseen irregularities in upstream water off takes at watercourse level.

The sanctioned water supply to the FDP-area is 0.2 l $s^{-1}$ $ha^{-1}$, which is equivalent to 1.7 mm $d^{-1}$, almost half of the crop water requirements (WAPDA, 1988). The canal water quality is excellent with an EC of 0.3 dS $m^{-1}$. The conveyance losses in the FDP-area ranged from 25 to 40 percent of the discharge at the outlet (Brussel, 1990). Due to these conveyance losses, the delivery rate at the fields might be even lower. Therefore not all fields can be cropped with this amount of water. As a result, about 12 percent of the total FDP-area is abandoned. In winter, an additional 13 percent of the fields are kept fallow. In summer, this area increases to an additional 24 percent (SMO, 1994). Due to limited canal water supplies, farmers are prompted to use more and more tubewell water to supplement their irrigation requirements. This is evident from the increasing number of private tubewells in the FDP-area during the period 1983-92 (Figure 2.2). The quality of private tubewell water ranged from marginal to hazardous (EC = 2-4 $dSm^{-1}$; SAR = 13-17; RSC = 4-7) (Table 2.2) and is considered injurious for both crops and soils.

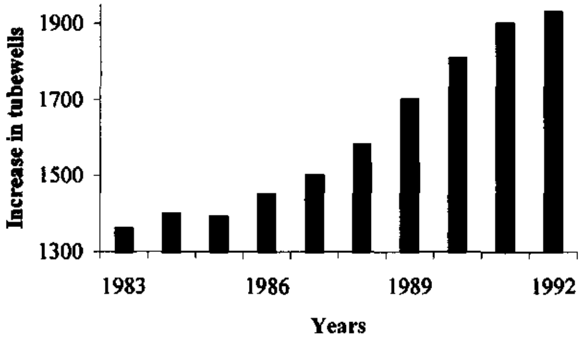

**Figure 2.2.** Growth in number of private tubewells in the FDP-area from 1983 to 1992.

Because of the poor quality, groundwater is usually applied in conjunction with canal water. By mixing tubewell water with the good quality canal water, farmers tend to decrease the salinity of the irrigation water in order to reduce the risk of soil salinization. Although evidences exist that blending of saline and non-saline irrigation water is less effective in keeping soil salinity levels lower than applying alternate irrigations (e.g. Hussain et al., 1990; Shalhevet, 1994; Kumar, 1995), this strategy is widely practised in the FDP-area.

In extreme downstream areas where canal water supplies are even more limited, groundwater is used as the only source of irrigation. Farmers who do not have their own tubewell, usually buy tubewell water from their neighbors in periods of acute water shortage. Trading of tubewell water is a more common practice in those areas where only tubewell water is available for irrigation (Vlotman et al., 1994).

Farmers having access to groundwater in addition to canal water tend to apply more water compared to those who are fully dependent on canal water, which aggravates waterlogging conditions. The irrigation schedules in the FDP-area vary a lot. Due to uncertainties in the canal water supplies, farmers usually do not plan their irrigations in advance. Their decision to irrigate mainly depends upon the crop water need and availability of water in the canal system. The studies carried out in the FDP-area (Vlotman et al., 1994; Raza and Choudhry, 1998) have shown that the number of irrigations applied to a wheat crop varies from 3 to 6, to cotton from 4 to 6, to maize from 4 to 7 and to sugarcane from 10 to 14. The depth of individual irrigation applications has been subject of many research studies in the FDP-area. According to Willardson (1992), the depth of water applied per irrigation is about 50 mm. Vehmeyer (1992) found that it ranged from 60 to 70 mm. Vlotman and Latif (1993) determined the average depth applied per irrigation between 70 and 80 mm. On the basis of field measurements, Raza and Choudhry (1998) reached a value of 50 to 75 mm with an average of about 65 mm per irrigation.

## 2.5 Crops and cropping patterns

The climate of the study area allows for two cropping seasons in a year: the winter growing season called Rabi, which lasts from November to April, and the summer growing season called Kharif, which lasts from May to October. Wheat, sugarcane, cotton and fodder are principle crops in the area. Next in importance are maize and vegetables. The most dominant cropping patterns are wheat-cotton, and year long sugarcane crop with cropping intensity (i.e. yearly cropped area) of about 120 percent. The average farm size in the area is about 3.75 ha compared to the national average of five ha and a decrease in farm sizes is still continuing (Bhatti and Kijne, 1992). More than 80 percent of the farms are either owner operated or owner-cum-tenant operated. The crops are selected, to a small degree, to serve the farmer's own household consumption and for livestock. The crop yields in the area are generally below the national average yields in Pakistan.

## 2.6 Subsurface drainage system

The FDP-area occupies 120,000 ha of irrigated land. The area has long been suffering from waterlogging and salinity. The detailed survey conducted in 1983 shows that about 77 percent of the project area is suffering from extremely high groundwater tables (less than 1.5 m from soil surface), while about 45 percent of the area was affected by salinity/sodicity (Table 2.1). Considering this alarming situation, it was decided to control waterlogging and salinity by improving surface drainage systems in the entire project area and by installing a horizontal subsurface pipe drainage system in an area of about 30,000 ha.

The subsurface drainage system was designed on the recommendations of the United States Bureau of Reclamation (USBR, 1989). Based on their studies, the most economical drainage design was one with the drain pipes at an average depth of 2.44 m. Drain spacings vary considerably from 100 to 610 m. The corrugated PVC pipes, ranging in diameter from 10 to 30 cm have been used for both laterals and collectors. Both laterals and collectors are perforated, and are surrounded by a gravel envelope. The drainage water is discharged into a sump at a depth of 3 to 4 m below the soil surface. From the sump the water is pumped into the surface drains which convey the water to the rivers Ravi and Chenab. The Fourth Drainage Project includes two separate areas, Schedule I and II. The total area of these two schedules was divided into 79 small drainage units. A typical drainage unit in the FDP-area usually covers between 200 and 400 ha. Generally, it consists of subsurface laterals that discharge in a sump through a subsurface collector. Each drainage unit has its own sump-pump arrangement and access to the surface drain.

## 2.7 Site for data collection

The data for this study was collected from a 225 ha drainage unit (called S1B9) of the FDP-area. The acronym S1B9 stands for the ninth sump unit of Schedule 1-B of the Fourth Drainage Project. Schedule 1-B borders on the Lower Gugera Branch Canal in the north, on the Burala Branch Canal in the south, on the town of Satiana in the east and on the Maduana Branch Drain in the west. To alleviate waterlogging and salinity in the area, eleven sump units with collectors and field drains were installed (Figure 2.3). The S1B9 area was selected for this study because its land use, intensity of cultivation and hydro-geological conditions were found fairly representative of the FDP-area. Moreover, this area was extensively monitored after the completion of the Fourth Drainage Project and sufficient data was available for this study.

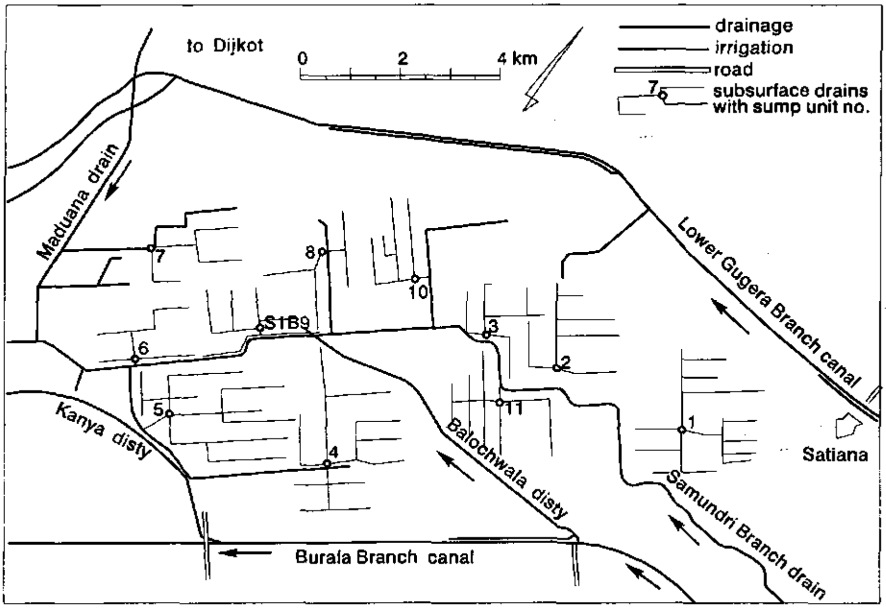

**Figure 2.3**. Schedule 1-B of the Fourth Drainage Project with the location and layout of subsurface drainage systems at the 11 sump units. The location of the S1B9 area is also shown.

Soil investigations have shown that the S1B9 area has two distinct soil layers. The upper layer up to 2.5 m depth has a low permeability. The deeper layer has a relatively high permeability. The surface soils in the S1B9 area range from mainly loam to silt loam. The loamy sand to sandy loam sublayers start at about 2.5 m depth (IWASRI, 1990). The area is under perennial canal[1] irrigation and is located at the end of the Balochwala distributory. Canal water supplies are usually irregular and well below the design value. As a result, use of poor quality groundwater is a common practice to meet crop water requirements. The main crops in the area are wheat, cotton, sugarcane and fodder. About 75 percent of the area is under cultivation while the remaining 25 percent is abandoned mainly due to lack of irrigation water and due to waterlogging and salinity. A summary of general characteristics of the S1B9 area is given in Table 2.4.

**Table 2.4.** General characteristics of the S1B9 area of the Fourth Drainage Project (FDP).

| | | | |
|---|---|---|---|
| **Total area** | **225 ha** | | |
| **Climate** | | | **Irrigation system** |
| Mean annual rainfall = 360 mm | | | Sanctioned irrigation water supply: 0.2 l $s^{-1}$ $ha^{-1}$ = 1.7 mm $d^{-1}$ |
| Mean annual evaporation = 1500 mm | | | Warabandi rotation: 7 days |
| **Land use** | **Kharif (%)** | **Rabi (%)** | **Drainage system** |
| Cultivated | 45 | 61 | Design drain discharge = 2.44 mm $d^{-1}$ |
| Abandoned | 25 | 25 | Drain spacings = 460 – 515 m |
| Fallow | 25 | 9 | Three parallel laterals depths = 1.64 - 3.2 m |
| Municipal | 5 | 5 | Length of each lateral = 840 m |

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[1] Perennial canals are those designed to receive water throughout the year, with exception of the annual maintenance period. Non-perennial canals receive water only during the kharif (monsoon season) period.

# 3 THEORY OF THE SWAP MODEL

Feddes et al. (1978) developed the one-dimensional model SWATR to describe transient water flow in a heterogeneous soil-root system, which can be under the influence of groundwater. This model was further developed by Belmans et al. (1983), Wesseling et al. (1991), Van den Broek et al. (1994) and Van Dam et al. (1997) and is now referred to as SWAP. The model aims at simulation of unsaturated flow, solute transport, heat flow and crop growth in the atmosphere-plant-soil environment at field scale level (Figure 3.1). The model offers a wide range of possibilities to address practical questions in the field of agriculture, water management and environmental protection. Previous versions of this model have successfully been applied in many hydrological studies for a variety of climatic and agricultural conditions (Bastiaanssen et al., 1996). Options exist for irrigation scheduling, drainage design, prediction of depth to groundwater table, soil salinity and leaching of nitrogen and pesticides.

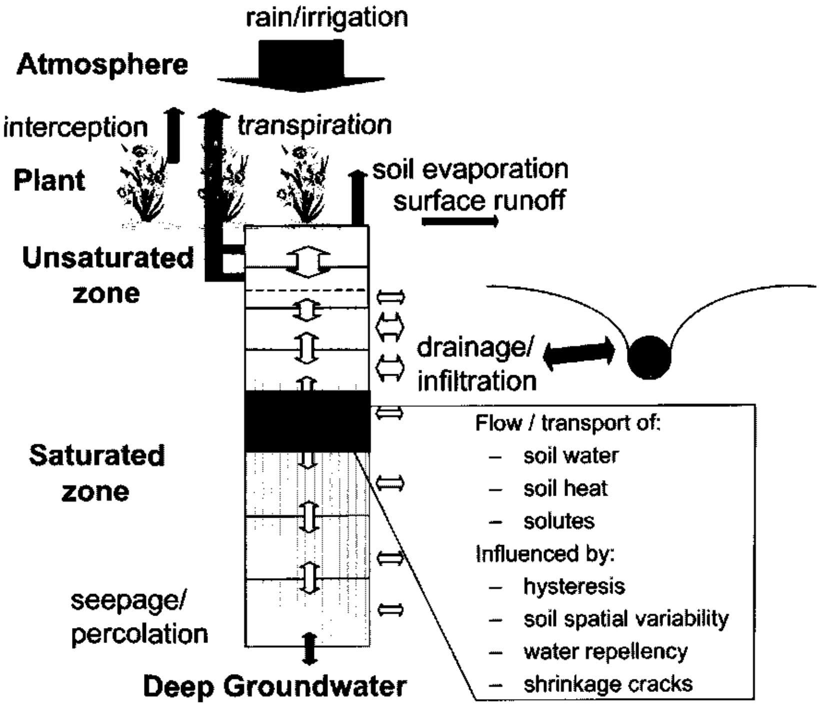

**Figure 3.1.** Processes incorporated in the SWAP model.

## 3.1 Soil water flow

SWAP employs Richards' equation for soil water flow in the soil matrix. Richards' equation is a combination of Darcy's law and the classical continuity equation (conservation of mass). For vertical flow , the equation reads:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[\ K(h)\left(\frac{\partial h}{\partial z}+1\right)\ \right] - S(h) \tag{3.1}$$

where $h$ (cm) is soil water pressure head, $K$ (cm $d^{-1}$) is hydraulic conductivity, $C$ ($d\theta/dh$) ($cm^{-1}$) is the differential soil water capacity, $S$ ($cm^3$ $cm^{-3}$ $d^{-1}$) is soil water extraction rate by plant roots, $z$ (cm) is the vertical coordinate positive in the upward direction and $t$ (d) is time. Richards' equation is solved through an implicit finite difference scheme as described by Van Dam and Feddes (2000).

Richards' equation has a clear physical basis at a scale where the soil can be considered as a continuum of soil, air and water. SWAP solves Eq. 3.1 numerically for both the unsaturated and saturated zone, subject to specified initial and boundary conditions and with known relations between soil water content ($\theta$), soil water pressure head ($h$) and unsaturated hydraulic conductivity ($K$). These relationships, which are generally called the soil hydraulic functions, can be measured directly in the soil, or might be obtained from basic soil data. The soil hydraulic functions are described by the Van Genuchten (1980) and Mualem (1976) model or by tabular values. Hysteresis of the water retention function can be taken into account with the scaling model of Scott et al. (1983).

The analytical soil water retention, $\theta(h)$ function proposed by Van Genuchten reads:

$$\theta = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{(1+|\alpha h|^{n})^{m}} \tag{3.2}$$

where $\theta_{sat}$ ($cm^3$ $cm^{-3}$) is the saturated water content, $\theta_{res}$ ($cm^3$ $cm^{-3}$) is the residual water content in the very dry range and $\alpha$ ($cm^{-1}$), $n$ (-) and $m$ (-) are empirical shape factors. Without loosing much flexibility, $m$ can be taken equal to:

$$m = 1 - \frac{1}{n} \tag{3.3}$$

Using the above $\theta(h)$ relation and applying the theory on unsaturated hydraulic conductivity by Mualem (1976), the following $K(\theta)$ function results:

$$K = K_{sat} S_e^{\lambda} \left[ 1 - \left( 1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \qquad (3.4)$$

where $K_{sat}$ (cm $d^{-1}$) is the saturated hydraulic conductivity, $\lambda$ is a shape parameter depending on $dK/dh$, and $S_e$ is the relative saturation defined as:

$$S_e = \frac{\theta - \theta_{res}}{\theta_{sat} - \theta_{res}} \qquad (3.5)$$

### 3.2 Soil water extraction by roots

The potential root water extraction rate ($S_{pot}$), integrated over the rooting depth ($D_{root}$), is equal to the potential transpiration rate, $T_{pot}$, which is governed by atmospheric conditions. The potential root water extraction rate at a certain depth, $S_{pot}$ $(z)$ ($d^{-1}$), may be determined by the root length density, $l_{root}$ $(z)$ (cm $cm^{-3}$), at this depth as fraction of the integrated root length density (e.g. Bouten, 1992):

$$S_{pot}(z) = \frac{l_{root}(z)}{\int_{-D_{root}}^{0} l_{root}(z)dz} T_{pot} \qquad (3.6)$$

where $D_{root}$ is the root zone depth (cm).

SWAP can handle every distribution of root length density. In practice however precise data on root length density distribution is often not available. Therefore in this thesis, a uniform root length density distribution is assumed, which leads to a simplified form of the Eq. 3.6 (Feddes et al., 1978).

$$S_{pot}(z) = \frac{T_{pot}}{D_{root}} \qquad (3.7)$$

Stresses due to dry or wet conditions and/or high salinity concentrations may reduce $S_{pot}$ $(z)$. Water stress in SWAP is described by the function proposed by Feddes et al. (1978).

$$S(h,z) = \alpha_{rw}(h)S_{pot}(z) \tag{3.8}$$

where $\alpha_{rw}(h)$ is a dimensionless function of soil water pressure head ($h$) (see Figure 3.2). The value of $\alpha_{rw}$ varies between 0 and 1. When $\alpha_{rw}$ is 1, water extraction by roots is equal to potential. If $0 < \alpha_{rw} < 1$, the soil water status in the root zone becomes important. Above $h_1$ no water uptake takes place due to oxygen deficiency, while below the wilting point, $h_4$, the plant is not able to extract water due to 'too dry' conditions. Between $h_2$ and $h_3$, water uptake remains optimal. Critical pressure head values of this sink term function for a variety of crops can be obtained from Taylor and Ashcroft (1972), Wesseling et al. (1991) and can also be derived from the soil and crop data given in FAO Publications (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Smith, 1995).

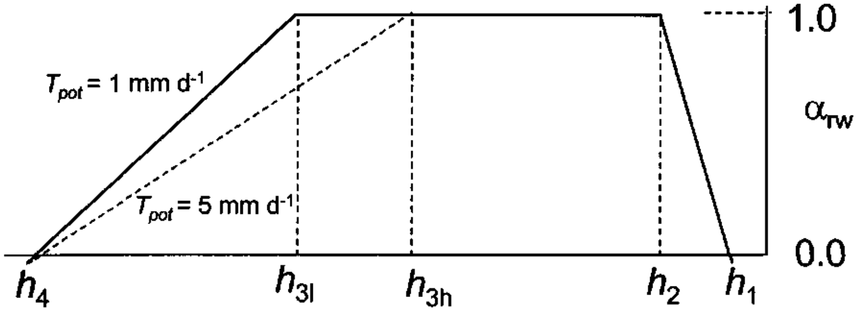

**Figure 3.2.** Dimensionless sink term variable, $\alpha_{rw}$, as function of soil water pressure head $h$ and potential transpiration rate, $T_{pot}$ (after Feddes et al., 1978).

For salinity stress the response function of Maas and Hoffman (1977) is used. They found that the reduction in crop yield due to salinity can be linearly related to the soil solution electrical conductivity. Crops can tolerate increases in soil salinity up to a threshold value, after which yield reduces linearly with increasing salt concentration (Figure 3.3a).

$$\frac{Y_{act}}{Y_{pot}} = 1 \qquad \text{for} \qquad 0 \le EC_e \ge EC_e^* \tag{3.9}$$

$$\frac{Y_{act}}{Y_{pot}} = 1 - a(EC_e - EC_e^*) \qquad \text{for} \qquad EC_e > EC_e^* \tag{3.10}$$

where $EC_e$ is the electrical conductivity of the soil saturation extract (dS $m^{-1}$), $EC_e^*$ is the electrical conductivity of the soil saturation extract at which yield begins to decrease (dS $m^{-1}$) and $a$ is the slope which equals the fraction yield decrease per unit of electrical conductivity increase. Salt tolerance data according to Eq. (3.9 and 3.10) have been listed for a number of crops by Maas (1990).

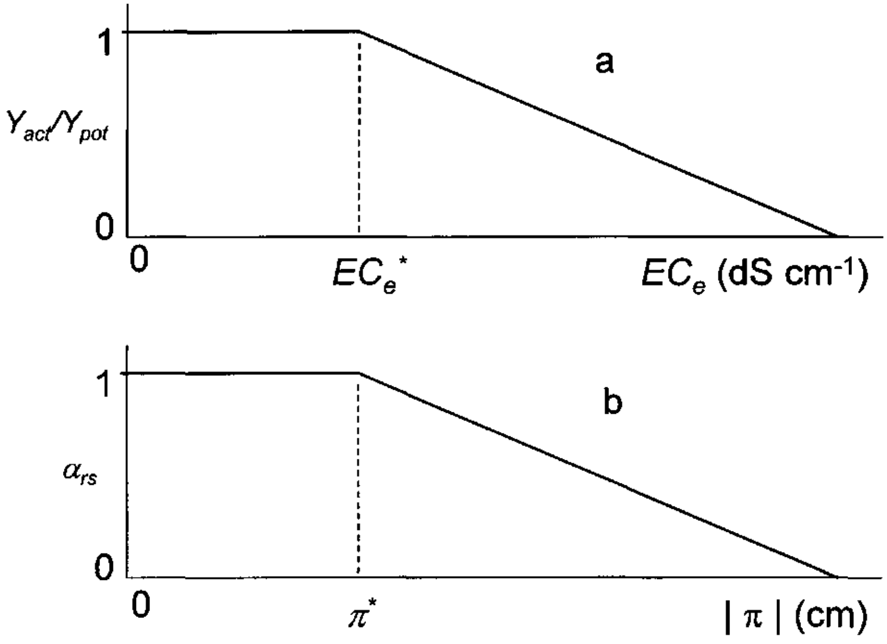

**Figure 3.3.** a: Relative yield $Y_{act}/Y_{pot}$ versus the electrical conductivity of the soil saturation extract $EC_e$. b: Root water uptake reduction function $\alpha_{rs}$ versus osmotic head π.

Assuming that relative yield ($Y_{act}/Y_{pot}$) has a one to one relationship with relative transpiration ($T_{act}/T_{pot}$) and thus with relative root water water uptake ($S_{act}/S_{pot}$) over the entire root zone, we can write that under saline conditions:

$$\frac{Y_{act}}{Y_{pot}} = \frac{T_{act}}{T_{pot}} = \frac{\int_{-D_{root}}^{0} S_{act}\,dz}{\int_{-D_{root}}^{0} S_{pot}\,dz} = f(EC_e) = \alpha_{rs}(\pi) \qquad (3.11)$$

where $\alpha_{rs}(\pi)$ is the root water reduction function due to salinity, written in terms of osmotic head. To convert the electrical conductivity based slope $a$ into an osmotic head based slope, one may use a factor of 360 (US Salinity Lab., 1954): $\pi = -360\,EC_e$. Hence

$$\alpha_{rs}(\pi) = 1 \qquad \text{for} \qquad 0 \leq \pi \leq \pi^*$$

$$\alpha_{rs}(\pi) = 1 - \frac{a}{360}(\pi - \pi^*) \qquad \text{for} \qquad \pi > \pi^*$$

where $\pi^*$ is the osmotic threshold value (Figure 3.3b).

For the root water uptake at depth $z$ the effect of salinity stress can then similar to water stress, be expressed as:

$$S(\pi, z) = \alpha_{rs}(\pi)\, S_{pot}(z) \tag{3.12}$$

It is still not clear if under the conditions where both stresses apply, the stresses are additive or multiplicative (Van Genuchten, 1987; Dirksen et al., 1993; Shalhevet, 1994) or neither of them (Homaee, 1999). In order to simplify parameter calibration and data retrieval, the parametrization of water and salinity stresses in SWAP is multiplicative. This means that the actual root water flux, $S_{act}(z)$ ($\mathrm{d}^{-1}$), is calculated from:

$$S_{act}(h, \pi, z) = \alpha_{rw}(h)\alpha_{rs}(\pi)S_{pot}(z) \tag{3.13}$$

Integration of $S_{act}(z)$ over the root zone yields the actual transpiration rate, $T_{act}$ (cm $\mathrm{d}^{-1}$).

$$T_{act} = \int_{-D_{root}}^{0} S_{act}\, dz \tag{3.14}$$

### 3.3 Solute transport

Solute transport in SWAP is calculated according to the convection-dispersion-diffusion equation:

$$J = qc - \theta\left(D_{dif} + D_{dis}\right)\frac{\partial c}{\partial z} \tag{3.15}$$

where $J$ (g cm$^{-2}$ d$^{-1}$) is the total solute flux density, $D_{dif}$ (cm$^2$ d$^{-1}$) is the solute diffusion coefficient, $D_{dis}$ (cm$^2$ d$^{-1}$) is the solute dispersion coefficient and $\partial c/\partial z$ is the solute concentration gradient. The solute diffusion coefficient is very sensitive to the actual water content, as it strongly affects the solute transport path and the effective cross-sectional transport area. In SWAP, the relation proposed by Millington and Quirk (1961) is used to describe flow path tortuosity and $D_{dif}$ is equal to:

$$D_{dif} = D_w \frac{\theta^{7/3}}{\phi_{por}^2} \tag{3.16}$$

where $D_w$ (cm$^2$ d$^{-1}$) is the solute diffusion coefficient in free water and $\phi_{por}$ (cm$^3$ cm$^{-3}$) is the soil porosity. Under laminar conditions, $D_{dis}$ is proportional to the pore velocity $v$ (cm d$^{-1}$) (Bolt, 1979):

$$D_{dis} = L_{dis} v \tag{3.17}$$

where $L_{dis}$ (cm) is the dispersion length, which depends on the scale over which the water flux and solute convection are averaged.

By considering conservation of mass in an elementary volume, the continuity equation for solute transport is expressed as:

$$\frac{\partial X}{\partial t} = -\frac{\partial J}{\partial z} - S_s \tag{3.18}$$

where $X$ (g cm$^{-3}$) is the total solute concentration in the soil system and $S_s$ (g cm$^{-3}$ d$^{-1}$) is the solute sink term accounting for decomposition and uptake by roots.

The solutes may be dissolved in the soil water and/or may be adsorbed to organic matter or to clay minerals:

$$X = \theta c + \rho_b Q \tag{3.19}$$

where $\rho_b$ (g cm$^{-3}$) is the dry soil bulk density and $Q$ (g g$^{-1}$) is the solute fraction adsorbed to soil particles. The solute sink term $S_s$ can be written as:

$$S_s = \mu(\theta c + \rho_b Q) + k_r S c \tag{3.20}$$

where $\mu$ (d$^{-1}$) is the first order rate coefficient of transformation, $k_r$ is the root water uptake preference factor (-) and $S$ is the root water extraction rate (d$^{-1}$).

Combination of Eq. 3.15, 3.18, 3.19 and 3.20, yields the transport equation applied in SWAP which is valid for dynamic, one-dimensional, convective-dispersive mass transport, including non-linear first order decomposition and root water uptake (Boesten and Van der Linden, 1991). Eq. 3.21 permits the simulation of salt transport, including the effect of salinity on root water uptake.

$$\frac{\partial(\theta c + \rho_b Q)}{\partial t} = -\frac{\partial qc}{\partial z} + \frac{\partial}{\partial z}(\theta(D_{dif} + D_{dis})\frac{\partial c}{\partial z}) - \mu(\theta c + \rho_b Q) - k_r Sc \tag{3.21}$$

As initial condition, the solute concentration, $c_i$ (g cm$^{-3}$) in the soil water and the average solute concentration in the groundwater, $c_{gr}$ (g cm$^{-3}$) need to be specified. For the upper boundary condition, the solute concentrations of irrigation water, $c_{irr}$ (g cm$^{-3}$), and rain water, $c_{prec}$ (g cm$^{-3}$), need to be specified. For the drainage boundary conditions, SWAP assumes that the lateral drainage flux leaves the soil profile laterally at the lowest compartment. During drainage ($q_{drain} > 0$), the solute flux density, $J_{drain}$ (g cm$^{-2}$) that leaves the one-dimensional soil profile is calculated as:

$$J_{drain} = q_{drain} c_n \tag{3.22}$$

where $c_n$ is the solute concentration (g cm$^{-3}$) in the lowest compartment. During infiltration ($q_{drain} < 0$), $J_{drain}$ follows from:

$$J_{drain} = q_{drain} c_{gr} \tag{3.23}$$

where $c_{gr}$ is the average solute concentration in the groundwater (g cm$^{-3}$).

From the bottom boundary condition, SWAP uses the flux through the bottom of the soil profile ($q_{bot}$). In case of upward flow ($q_{bot} > 0$), the solute flux density, $J_{bot}$ (g cm$^{-2}$), positive upward) equals:

$$J_{bot} = q_{bot} c_{gr} \tag{3.24}$$

If $q_{bot}$ is directed downwards ($q_{bot} < 0$), the solute flux density, $J_{bot}$ (g cm$^{-2}$) equals:

$$J_{bot} = q_{bot} c_n \tag{3.25}$$

## 3.4 Boundary conditions

The wide range of upper and lower boundary conditions being offered in SWAP is one of the key advantages of the model. The upper boundary conditions of the system are described by potential evapotranspiration rate, $ET_{pot}$ (cm d$^{-1}$), irrigation and precipitation. SWAP uses daily meteorological data to calculate daily $ET_{pot}$ according to Penman-Monteith (Smith, 1995). If necessary meteorological data are not available, SWAP opts for alternative procedures and $ET_{pot}$ or reference evapotranspiration rate, $ET_o$ (cm d$^{-1}$) can directly be used as input. Precipitation may be provided either on a daily basis or as actual intensities. Short-term rainfall data allow the calculation of runoff and preferential flow.

$ET_{pot}$ is divided into potential transpiration rate, $T_{pot}$ (cm d$^{-1}$) and potential soil evaporation rate, $E_{pot}$ (cm d$^{-1}$) based either on the leaf area index, $LAI$ (m$^2$ m$^{-2}$) or the soil cover fraction, $SC$ (-), both as a function of crop development. Reduction of the potential soil evaporation rate into actual soil evaporation rate, $E_{act}$ (cm d$^{-1}$) depends on the maximum soil water flux in the top soil according to Darcy's law or is calculated by an empirical function following either Black et al. (1969) or Boesten and Stroosnijder (1986). For this study, reference evapotranspiration rate calculated by the Priestly-Taylor (1972) method was directly used as input. Soil cover fraction was used to partition $ET_{pot}$ into $E_{pot}$ and $T_{pot}$, while the empirical function of Boesten and Stroosnijder was used for the reduction of $E_{pot}$ into $E_{act}$.

The bottom of the flow system may be situated either in the unsaturated zone or in the saturated zone. At this lower boundary, one can specify a pressure head, a flux or a relation between the two. With the lower boundary conditions the connection with the saturated zone can be established. In this way effects of surface water management influencing the groundwater depth upon, for instance, crop transpiration can be simulated. The coupling between the two systems is possible by considering the phreatic surface as an internal moving boundary.

At the bottom of the system, the boundary conditions can be described with various options. These include groundwater level as a function of time, flux to/from semi-confined aquifers, flux to/from open surface drains, an exponential relationship between bottom flux and groundwater table or zero flux, free drainage and free outflow (Van Dam et al., 1997). In this study, for the calibration of the model daily measured groundwater levels were used as bottom boundary condition. For model simulations, zero flux at the bottom of the soil profile was applied.

## 3.5 Field drainage

SWAP makes a distinction between lateral and vertical outflow, the former is the local flow to drains ('drain discharge rate'), $q_{drain}$ (cm $d^{-1}$), and the later regional groundwater flux at the bottom of the simulated soil profile, $q_{bot}$ (cm $d^{-1}$). The drain discharge rate depends on the simulated groundwater level midway between the drains. In order to calculate correct residence time for solutes, SWAP assumes that $q_{drain}$ is extracted laterally in the saturated zone of the soil profile. So the bottom flux, $q_{bot}$, excludes the $q_{drain}$. Three options are available for the calculation of the drain discharge rate. These include a flux-groundwater level relationship, a tabular flux-groundwater relationship or drainage equations of Hooghoudt and Ernst (see Ritzema, 1994). The difference in hydraulic properties of the layered soil profile determines whether the Hooghoudt or Ernst equation should be chosen. For the FDP-area, the drainage situation is described by a homogeneous soil profile with drains above the impervious layer as shown in Figure 3.4.

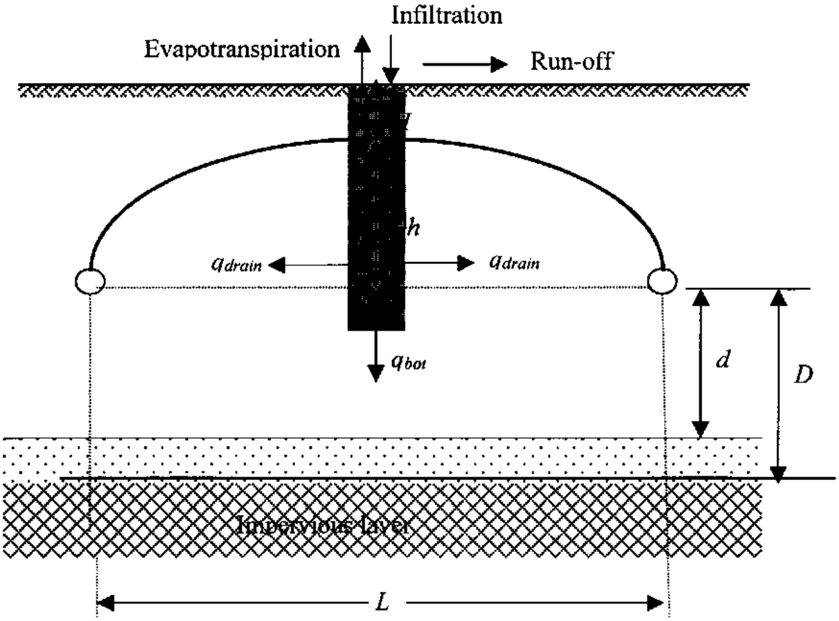

**Figure 3.4.** Schematization of flow in the SWAP column in relation to the location of the subsurface drains for the FDP-area. $q_{drain}$ = drain discharge rate, $d$ = equivalent depth which is a reduced value of the depth of impervious layer below drain level, $D$, $\Delta h$ = total hydraulic head difference between the drain level and the phreatic level at midpoint, $L$ = drain spacing and $H$ = groundwater table depth below the soil surface.

The drain discharge rate ($q_{drain}$) was calculated using the Hooghoudt drainage equation. These equations allow studying the effect of given drain spacings and drain depths on drain discharge rates and groundwater table fluctuations by simulating the water and solute transport in the unsaturated zone. This opens the possibilities for the design or evaluation of drainage systems. The Hooghoudt equation reads as:

$$q_{drain} = \frac{8K_{sat}^{h} d\Delta h \ + 4K_{sat}^{h} \Delta h^2}{L^2} \tag{3.26}$$

where $q_{drain}$ (cm $d^{-1}$) is the drain discharge rate, $K_{sat}{}^{h}$ (cm $d^{-1}$) is the horizontal saturated hydraulic conductivity, $d$ (cm) is the equivalent depth which is a reduced depth of the impervious layer below drain level, $D$ (m), $\Delta h$ (cm) is the hydraulic head difference between the drain level and the phreatic level at midpoint and $L$ (cm) is the drain spacing. Parameter $d$ is a function of $L$, $D$ and the radius of the drain $r_o$ and needs an iterative procedure to be solved. The value of $d$ was calculated using the relationship of $L$, $D$ and $r_o$ as given below (see Ritzema, 1994).

$$d = \frac{\frac{\pi L}{8}}{\frac{\pi L}{8D} + \ln(\frac{D}{L}) + \ln(\frac{L}{\pi r_o})} \tag{3.27}$$

## 3.6 Irrigation scheduling

Irrigations in SWAP may be prescribed at fixed times or scheduled according to a number of criteria. Also a combination of irrigation prescription and scheduling is possible. The scheduling criteria define the time and depth of irrigation application. Both depth and timing criteria may be dynamic i.e. defined as a function of crop development stage. The scheduling options allow the evaluation of alternative application strategies, which can be used to support the design of a combined irrigation and drainage system.

Two irrigation depth criteria can be specified: a constant application depth, a volume of water needed to fill the root zone back to field capacity. According to the rate of depletion through evapotranspiration and percolation, timing of the next irrigation will be automatically calculated taking actual weather, groundwater conditions, root water uptake and capillary water flow into account. Five different timing criteria can be selected to generate an irrigation schedule. These include allowable daily stress, allowable depletion of readily available water in the root zone, allowable depletion of totally available water in the root zone, allowable depletion amount of water in the root zone and critical pressure head or water content at a certain depth.

## 3.7 Crop growth

Effects of water on crop production in irrigation design and management are paramount. Plants consume water essentially for the process of photosynthesis and transpiration. Water is transported to the roots of a plant and then removed from the leaf surface via transpiration. Transpiration is controlled by the stomatal aperture and by the vapor pressure gradient from the leaf to the atmosphere. Since stomata acts as regulators for $CO_2$ exchange and water loss, water stress sufficient to close stomata depresses photosynthesis and ultimately crop yield.

The amount of water required by the plants for their growth depends on a number of factors including the type of plant, its growth stage, soil properties and meteorological conditions. Under water limiting conditions, it is important to know what is the minimum amount of irrigation water needed to ensure a maximum production of a certain crop.

Doorenbos and Kassam (1979) suggested that when the full crop water requirements are not met, the effect of water stress on crop production can be quantified by deriving a relationship between relative yield decrease and relative evapotranspiration deficit given by the empirically-derived yield response factor ($K_y$):

$$1-\frac{Y_{act}}{Y_{pot}}=K_y\left(1-\frac{ET_{act}}{ET_{pot}}\right) \tag{3.28}$$

where $Y_{act}$ (kg ha$^{-1}$) is the actual crop yield, $Y_{pot}$ (kg ha$^{-1}$) is the potential crop yield, $ET_{act}$ (cm d$^{-1}$) is the actual evapotranspiration rate and $ET_{pot}$ (cm d$^{-1}$) is the potential evapotranspiration rate. The value of $K_y$ is based on a wide range of growing conditions.

For the determination of water use efficiency at crop production level, a distinction should be made between evapotranspiration of soil and crop and transpiration. Evaporation is the water loss to the atmosphere from bare soil and transpiration is the loss of water vapor to the atmosphere through plant surfaces. Evaporation from bare soil should therefore be considered a loss, only transpiration reveals crop water use. Therefore when considering *production/water use* relationships one should infact not consider the water use by soil plus crop i.e. evapotranspiration, but the water use by the crop itself i.e. transpiration. This because photosynthesis/dry matter production and transpiration are directly related through the processes of diffusion of carbon dioxide and water vapor through the stomata of leaves (Feddes, 1985; Feddes and Koopmans, 1997).

De Wit (1958) pointed out that under high radiation conditions not restricting transpiration, the water requirements of plants are more or less proportional to the level of radiation expressed as evaporation from a free water surface, $E_o$. He concluded that the relationship between actual crop yield ($Y_{act}$) and actual transpiration ($T_{act}$) for arid and semi-arid regions is linear in the following form:

$$Y_{act} = f\left(\frac{T_{act}}{E_o}\right) \tag{3.29}$$

where $f$ is a crop parameter. De Wit also indicated that this relationship is hardly affected by small variations in water and nutrient availability.

For a given crop and year for which $f$ and $E_o$ are constant, a simplified relationship between relative yield $Y_{act}/Y_{pot}$ and relative transpiration $T_{act}/T_{pot}$ applies:

$$\frac{Y_{act}}{Y_{pot}} = \frac{T_{act}}{T_{pot}} \tag{3.30}$$

The validity of De Wit's linear relationship in field experiments was confirmed by several researchers in different climates (Hanks, 1974, 1983; Stewart et al., 1977; Feddes, 1985). Eq. 3.30 does not include the occurrence of drought sensitive periods, however the use of a more complicated expression including drought sensitive stages does not seem to improve the results (Stewart et al., 1977). Hanks (1983) correctly remarked that Eq. 3.30 is more suitable to compare treatments within a given year, because $Y_{pot}$ may vary from year to year. Since under arid and semi-arid conditions of Pakistan variations in solar radiations (i.e. evapotranspiration) over the different years are relatively small (Figure 2.1), Eq. 3.30 can be used as a general expression for the estimation of actual crop yields. Other non-water factors such as nutrient availability, pest, weed and disease control and farm management are considered to be optimal. Further details of SWAP are described by Van Dam et al. (1997) and the program use is documented by Kroes et al. (1999).

# 4 CALIBRATION OF THE SWAP MODEL[1]

## Abstract

This Chapter deals with the calibration and verification of the transient state water flow and solute transport model, SWAP, for the physical conditions prevailing in the Fourth Drainage Project (FDP), Punjab, Pakistan. The calibration was performed for a period of about 14 months using data from two sample fields located in the S1B9 drainage unit of the FDP-area. During the calibration process, emphasis was given to the accurate determination of soil hydraulic parameters, reference evapotranspiration, drainage from sample fields, and bottom boundary condition. Laboratory determined soil hydraulic parameters were found non-representative of the field conditions. Difference between laboratory and field determined soil water retention curves were found significant.The pressure heads and soil water contents measured in depth increments of 15 cm were in good agreement with the simulated values after applying a field measured retention curve. A close proximity was also found between measured and simulated average root zone salinity at 0 to 1.0 m depth. The reference evapotranspiration calculated by the Priestly-Taylor (PT-$ET_o$) method was found physically more realistic than the Penman-Monteith (PM-$ET_o$) method due to ignorance of the feed back mechanism of vapor pressure deficit on stomatal closure. The simulated cumulative drainage from two sample fields was comparable with the field determined values. The analysis of piezometer data shows that there is a negligible water exchange between the deep aquifer and the unsaturated zone. Therefore for scenario analysis, no flow conditions at the bottom of the soil profile can be applied as a bottom boundary.

## 4.1 Introduction

In semi-arid areas, the purpose of a drainage system is to keep the water table deep enough to allow adequate aeration in the active root zone, to meet leaching requirements, and to minimize capillary salinization during fallow periods. On the other hand, watertable should be high enough to maximize the contribution of soil water replenishment through capillary rise (Feddes, 1990). These objectives have made the drainage design more difficult and complex. In the absence of a specific drainage design criteria for the semi-arid conditions, the drainage systems in Pakistan were designed using steady-state equations of Hooghoudt and Ernst (See Ritzema, 1994, for review). Different drainage projects installed in Pakistan have failed to generate enough agricultural benefits to justify their construction. One of the reasons of this low efficiency was that the steady-state approach does not allow to study the

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[1] Adapted version of Sarwar, A., Th.M. Boers and J.C. Van Dam, 2000. Evaluating drainage design parameters for the Fourth Drainage Project, Pakistan by using SWAP model: Part I-Calibration. *Irrigation and Drainage Systems (in press).*

impact of different hydrological conditions on the necessary drainage capacity. Therefore, it did not yield satisfactory results to achieve a multi-objective drainage design criteria needed for the semi-arid conditions.

In reality, the recharge to the groundwater varies with time according to fluctuations in rainfall, irrigation, evapotranspiration and seepage. In order to solve these unsteady-state problems, various approaches have been developed. They include Glover-Dumm (1960), De Zeeuw-Hellinga (1958), and Krayenhoff van der Leur-Maasland (Krayenhoff van der Leur, 1958, 1962; Maasland, 1959). The unsteady-state approach offers major advantages compared with the steady-state approach, but various assumptions restrict the use of these unsteady-state equations. Firstly, these equations can be applied in soils with a homogeneous profile only. Secondly, they do not consider moisture transfer dynamics in the unsaturated zone: only fluxes are made variable as a function of the depth of the watertable. Introducing a constant value for the drainable pore space in unsteady state equations could result in considerable errors (see Ritzema, 1994).

Drain spacing and drain depth are not independent but should in combination be capable to discharge excess soil water and salts. The transient simulation models are powerful tools to describe these interactions. They provide an opportunity to capture the full range of all influencing parameters, many of which vary during the crop season and interact with each other. The greatest limitation of these models is the lack of reliable input data for practical applications and a standard protocol to calibrate these models. One such transient simulation model is SWAP (Van Dam et al., 1997). SWAP is a one-dimensional model, which can simulate the effects of certain drainage designs on soil water and salinity dynamics in the unsaturated zone. Previous versions of this model have been successfully applied to design criteria for drainage dimensions in relation to actual transpiration and crop yields (Feddes, 1988; Van Wijk and Feddes, 1990; Skaggs, 1999) and for the interaction between irrigation, drainage and crop yields (Bastiaanssen et al., 1996).

The SWAP model has also been applied in Pakistan to simulate irrigation and drainage conditions (Sarwar, 1993; Kelleners, 1994; Beekma et al., 1995; Van Dam and Feddes, 1996; Smets et al., 1997). In these studies, many assumptions regarding the model-input data were made. Moreover, the model was mainly calibrated for conditions in the unsaturated zone and no emphasis was given on the evaluation of the drainage component and the bottom boundary conditions. Therefore there is a need to perform profound analysis of the different model input parameters and their influence on model results.

The objective of this study is to demonstrate that by putting specific effort on the collection of required input data, the transient state models can be calibrated against local field data. This Chapter presents the methodology used to calibrate the model, and the results of model calibration. Special emphasize will be given to:

- Compare laboratory and field measured soil hydraulic parameters.
- Emphasize classical misconceptions about the calculations of reference evapotranspiration for semi-arid conditions.
- Estimate drainage from sample fields in a heterogenously irrigated and drained environment.
- Determine a suitable bottom boundary condition for further model simulations.

## 4.2 Material and methods

The data for this study was collected from drainage unit no. 9 (called S1B9) of the FDP-area (see Chapter 2). The S1B9 area has its own field drainage system with sump and pump. The schematic view of the drainage system at S1B9 area is shown in Figure 4.1. The spacing of laterals varies from 460 to 515 m with an average slope of 0.05 percent. Drain depths varies from 1.64 m to 3.20 m below the soil surface. The depth of the collector is 3.05 m. The collector of S1B9 area is perforated to provide additional drainage. The design drain discharge rate was 2.44 mm $d^{-1}$. Subsurface drainage water generally originates from excess irrigation and rainfall percolating below the root zone. A parallel system with a single sided entry into the collector was installed. Manholes have been provided at the junction of each lateral and collector. A subsurface interceptor drain was constructed to increase stability of side slopes of the surface drains and to prevent seepage from the surface drain back to the drained area.

For the calibration of the SWAP model, two farmer fields of 0.2 ha each were selected and extensively monitored from December '95 to April '97 (Figure 4.1). Field 1 represents the silt loam terrace and belongs to the Faisalabad soil series. Field 2 also represents a silt loam terrace but belongs to the Jaranwala soil series due to the presence of small stones at depths of 60 cm and below (IWASRI, 1990). The soil analysis of both fields shows that textural differences in horizontal direction are very small. In vertical direction, there is a tendency towards a somewhat coarser texture with increasing depth. The average dry bulk density from 0 to 1.20 m is 1.67 g $cm^{-3}$ for Field 1, and 1.55 g $cm^{-3}$ for Field 2. Both fields are under basin irrigation. The crops grown during the calibration period were sugarcane (Field 1) and sugarcane-wheat (Field 2) with intermittent short fallow periods.

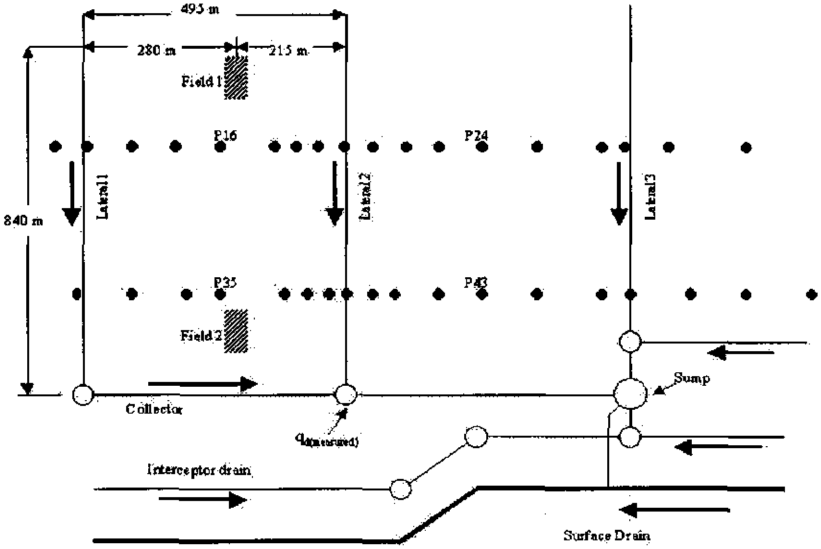

**Figure 4.1**. Layout of the drainage system at the S1B9 area along with the location of the two monitoring fields. The dots represent the position of the piezometers.

Input data relate mainly to the water and salt balance and to characterization of the soils. The meteorological data were collected from a weather station installed in the study area. The data includes daily values of maximum and minimum air temperatures, wind speed, rainfall, wet and dry bulb temperatures to calculate the relative humidity and daily sunshine hours. The meteorological data for the calibration period of 420 days (16.2.96 to 22.4.97) is shown in Figure 4.2.

In each field, tensiometers were installed at eight different depths (at 15, 30, 45, 60, 90, 120, 150, 200 cm) and were read weekly. For the determination of soil water content, Time Domain Reflectometery (TDR) (Topp et al., 1980) tubes were installed in both fields. TDR readings are sensitive to soil type, soil density, temperature and salinity. Therefore for accurate results, soil specific calibration is necessary (Dirksen, 1999). TDR readings collected from two sample fields were calibrated by comparing them with the soil water data obtained by the gravimetric method. The soil water contents were also measured weekly, from the same depths as that of tensiometers, which allows for determination of the soil water retention characteristics under field conditions.

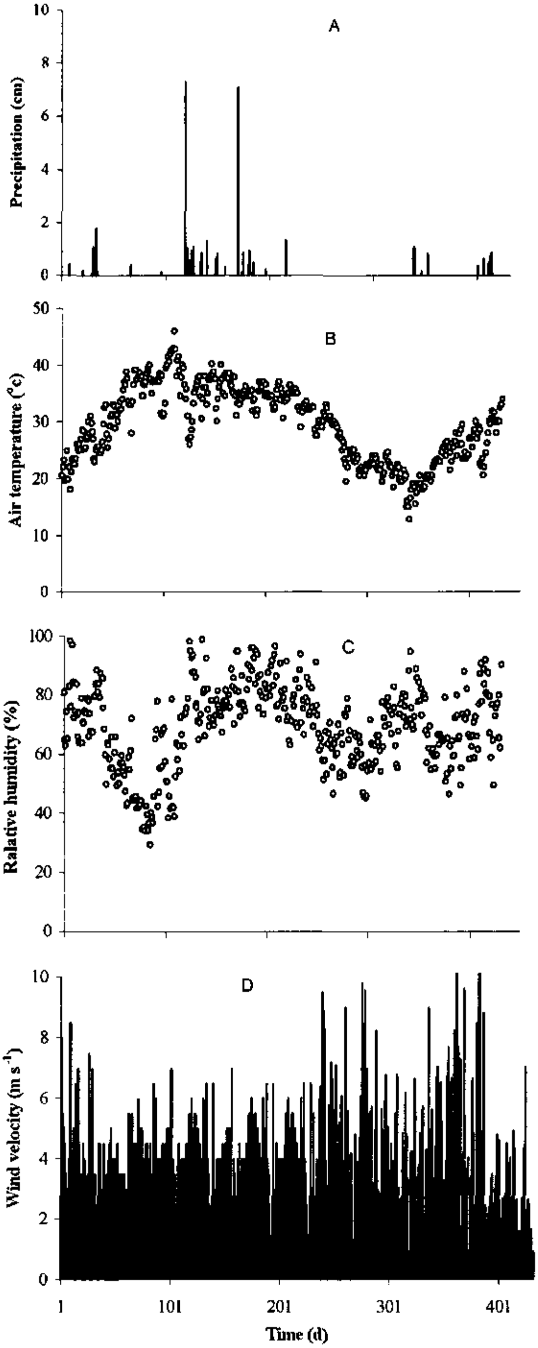

**Figure 4.2.** Meteorological measurements conducted at the S1B9 area from 16.2.96 (Day 1) to 22.4.97 (Day 420). (Part A) Precipitation, (Part B) Air temperature (Part C) Relative humidity, and (Part D) Wind velocity.

The soil hydraulic parameters describing the relationship between hydraulic conductivity ($K$), soil water pressure head ($h$) and soil water content ($\theta$) for the surface soils of the monitoring fields were also determined by taking undisturbed soil samples at different depths and analyzing them in the laboratory with the laboratory outflow method (Van Dam et al., 1990). With the laboratory outflow method, a wet soil sample is put on a perforated ceramic plate in a pressure cell and subjected to a number of increasing pressures. This induces unsaturated flow, with the ceramic plate remaining saturated. Cumulative outflow from the sample between successive pressure increments is measured at different times. The measured cumulative outflow was used to determine the parameters of the Van Genuchten-Mualem model (Van Genuchten, 1980) using an optimization model called MULSTP (Van Dam et al., 1990). A detailed description of these experiments is given in Beekma (1993).

Piezometers were installed in both sample fields and across the laterals to monitor the depth to groundwater table (Figure 4.1). The piezometers installed in the sample fields were read on daily basis while the others on bi-weekly basis. Drain discharges were measured by two methods. The first method was based on PVC sharp-crested weirs installed in the manholes at the end of each lateral. Stilling wells were used to measure the upstream heads. Drain discharges were determined by using the discharge-head relationships developed with the computer program FLUME (Brussel, 1990). Drain discharges were also measured at the manholes with a bucket and a stopwatch. The measurements were made on daily basis except for the period when laterals were dry due to dry weather conditions or when no irrigation activities occurred.

The depth of all irrigations applied to the sample fields was measured. The inflow to each sample field was measured with a cut-throat flume and the duration of each application was registered. From this, the depth of each irrigation application was calculated. Salinity measurements of the sample fields were taken at the beginning and end of each growing season by electromagnetic induction with EM38 equipment (McNeill, 1986). Measurements were taken at 40 different locations from each sample field. The EM38 readings were corrected for differences in soil temperature that occur within a year. With the EM38, apparent electrical conductivity ($EC_a$) of a bulk soil volume was measured. These $EC_a$ values were then converted into $EC_e$ values using the equations developed by Beekma et al. (1994) for the S1B9 area. At the end of each growing season, eight soil samples were taken at different depths in each field and analyzed in the laboratory for soil texture, soil water content and $EC_e$ values.

Data on crop development, crop height, sowing and harvesting dates and crop yields was recorded on continuous basis. The data collected for the calibration of the SWAP model are listed in Table 4.1.

**Table 4.1.** Data collected for the calibration and validation of the SWAP model in the S1B9 drainage unit of the FDP-area.

| Type of data | Collection method | Frequency |
|---|---|---|
| Soil characteristics | Undisturbed samples-Laboratory outflow method | Once |
| Soil water content | Time Domain Reflectometery (TDR) | Weekly |
| Soil water pressure head | Tensiometers | Weekly |
| Meteorological data | Weather station at S1B9 area | Daily |
| Soil salinity | EM38-surveys | Seasonal |
|  | Disturbed samples | Seasonal |
| Irrigation regime | Field observations | When applied |
| Drain discharges | PVC sharp-crested weirs | Daily |
|  | Bucket and stop watch | Daily |
| Groundwater levels sample fields | Piezometers | Daily |
| Groundwater levels in area | Piezometers | Bi-weekly |
| Agronomic data | Field surveys | Continuous |

## 4.3 Calibration of model input parameters

### *Top boundary conditions*

The upper boundary of the soil profile was described on daily basis by potential evapotranspiration rate ($ET_{pot}$), actual rainfall, and irrigation. $ET_{pot}$ was obtained by multiplying the reference evapotranspiration rate ($ET_o$) with the crop factors ($k_c$). The maximum rooting depth for sugarcane and wheat were taken as 160 and 110 cm, respectively. The crop factors ($k_c$) and rooting depths for both wheat and sugarcane crops were taken from the studies of Pakistan Agricultural Research Council (PARC, 1982). Root length density distribution was considered to decline linearly with depth. The Boesten model (Boesten and Stroosnijder, 1986) was used for the reduction of the potential soil evaporation rate ($E_{pot}$) into actual soil evaporation rate ($E_{act}$). The calibrated value of Boesten factor was 0.63. The values of pressure heads for regulating root water uptake were taken from Taylor and Ashcroft (1972). These crop parameters are summarized in Table 4.2.

**Table 4.2.** Input parameters used in the SWAP model. The $h_1$ to $h_4$ values refer to the sink term theory of Feddes et al. (1978).

| Input parameters | Wheat | Cotton | Sugar cane |
|---|---|---|---|
| Boesten parameter, $\beta$ ($cm^{1/2}$) | 0.63 | 0.63 | 0.63 |
| $k_c$-value for full crop cover | 1.15 | 1.15 | 1.15 |
| Maximum rooting depth (cm) | 110 | 160 | 160 |
| Limiting pressure heads (cm) | $h_1$= -0.1; $h_2$= -1.0;<br>$h_3$= -500; $h_3'$= -900;<br>$h_4$= -16000 | $h_1$= -0.1; $h_2$= -1.0;<br>$h_3$= -500; $h_3'$= -900;<br>$h_4$= -16000 | $h_1$= -15; $h_2$= -30;<br>$h_3$= -325; $h_3'$= -600;<br>$h_4$= -8000 |

Reference evpotranspiration rate ($ET_o$) was determined by the Priestly-Taylor (PT) method (Priestly and Taylor, 1972), although FAO has recommended the use of the physically based Penman-Monteith (PM) surface energy balance equation (Smith et al., 1990; Allen et al., 1994). The PT method was preferred because it relies more on radiation rather than on the turbulent momentum, heat and vapor transport mechanisms, and the results are therefore less sensitive to non-representative relative humidity and temperature measurements (only the slope of the saturated vapour pressure deficit is affected). The famous 'well supplied by water' restriction for the measurement site is a pre-condition to a successful application of the PM equation. Paw U and Gao (1988) also stressed that the PM equation should be applied under conditions where the difference in surface and air temperatures is minimal i.e. when sensible heat flux is low and latent heat flux is high. McAneney and Itier (1996) have also shown that the PM is often impractical beause of uncertainities about stomatal behavior and turbulant transport under high saturation deficits. Using similar arguments, Kumar and Bastiaanssen (1993) advised the use of the PT method instead of the PM for the irrigated areas in Pakistan and India.

Figure 4.3 (Part A) shows a one to one line comparison of PT-$ET_o$ and PM-$ET_o$. A distinction has been made between the values below and above the vapor pressure deficit (vpd) of 20 mbar. The results show that $ET_o$ values calculated by two methods are in good agreement below vpd value of 20 mbar. Above this threshold vpd, PM-$ET_o$ values are consistently higher than PT-$ET_o$ values. Figure 4.3 (Part B) shows that PM-$ET_o$ values exceed the net radiation values ($R_n$) above a vpd of 20 mbar leading to PM-$ET_o$/Rn > 1.3, which is physically unlikely. However, a good correlation with net radiation is present for a vpd of less than 20 mbar. This shows that under dry and hot climatic conditions, $ET_o$ values are overestimated by PM. However, $ET_o$ values calculated by PT are consistent with the net radiation values for both, below and above the 20 mbar vpd conditions. Therefore, $ET_o$ calculated by the PT method was used in the model as input.

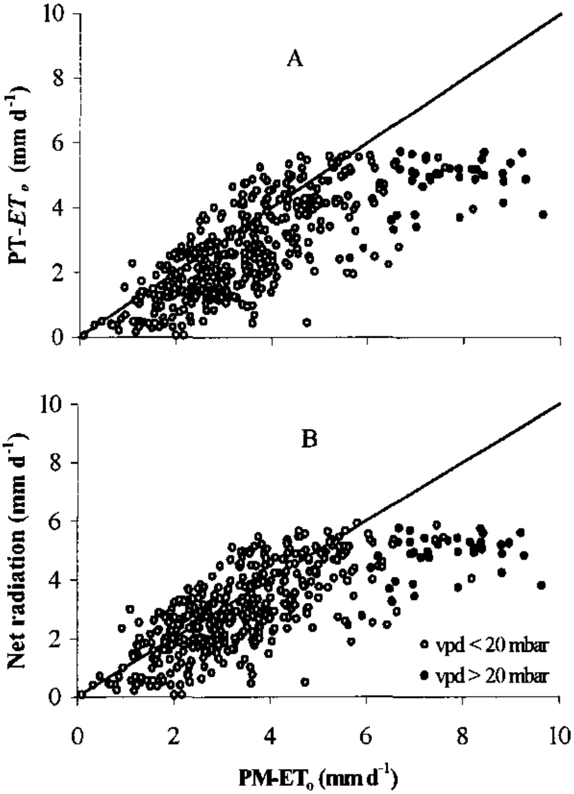

**Figure 4.3.** Comparison of PM-$ET_o$ with PT-$ET_o$ (Part A) and PM-$ET_o$ with Net radiation (Part B) with one to one line.

### *Soil hydraulic properties*

For both fields, a 480 cm soil profile was divided into three layers, each of them having different physical properties. The first layer is from 0-30 cm, the second from 30-280 cm, and the third beyond 280 cm. The soil water retention curves $\theta(h)$ for the first two layers of both fields were derived from the field measurements of pressure heads and soil water contents and were also determined in the laboratory using a pressure outflow method (Van Dam et al. 1994). The comparison of laboratory and field measured $\theta(h)$ relationships for the first two layers of both fields is shown in Figure 4.4.

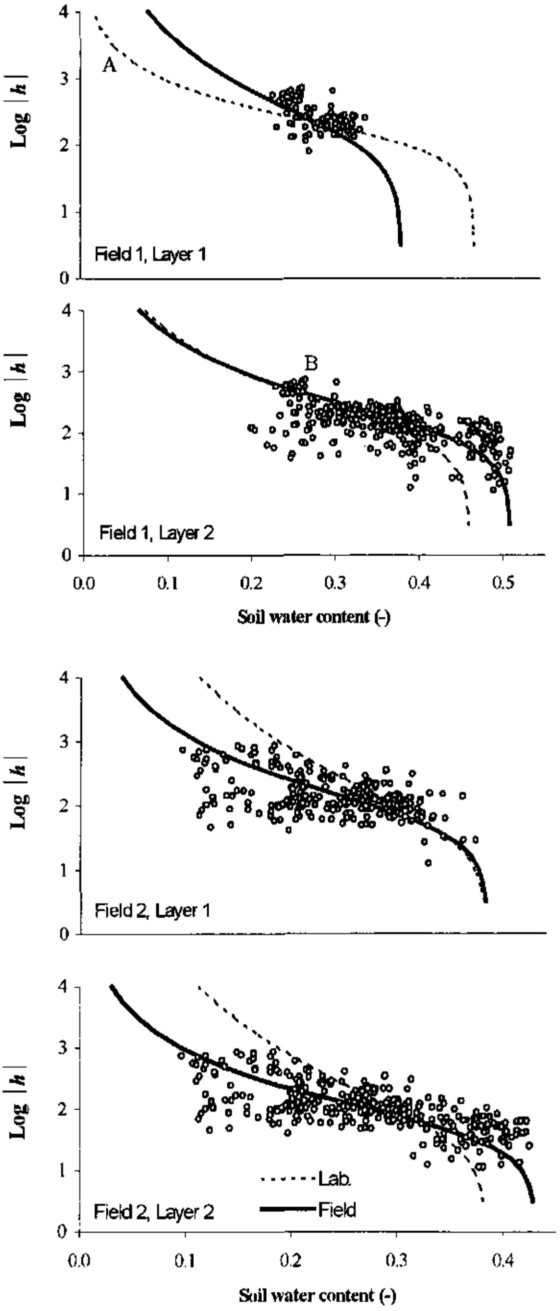

**Figure 4.4.** Comparison of laboratory and field measured soil water retention curves for Field 1 and Field 2. Dots represent field measurements. Soil water pressure head *h* is expressed in cm.

The deviations of laboratory parameters from the field determined parameters were substantial, which is likely to be related to the sample size and unavoidable disturbances during the experimental procedure. The laboratory parameters gave unrealistic simulation results, which shows their uncertainty to describe the soil-water relationship. Bastiaanssen et al. (1996) have also stressed the need to give more attention to the field determination of soil hydraulic properties rather than getting them from laboratory measurements or other sources like pedo-transfer functions. They obtained ill-affected water balances of the irrigated fields in Egypt and Argentina by applying laboratory determined soil hydraulic properties. During the calibration process, field-determined soil water retention parameters $(\theta_r, \theta_s, \alpha, n)$ were kept constant. The parameters to describe unsaturated hydraulic conductivity $(K_{sat}, \lambda)$ for these two layers were taken from the studies conducted by Beekma (1993) for the S1B9 area. These parameters were slightly adjusted in a 'trial and error' process to obtain optimal calibration results against $\theta(z)$ and $h(z)$ profiles. The calibrated hydraulic conductivity curves of both sample fields are shown in Figure 4.5.

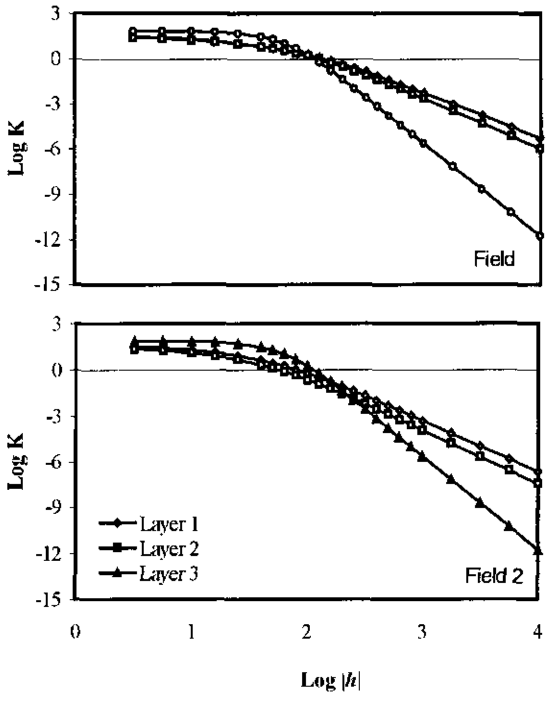

**Figure 4.5.** Calibrated hydraulic conductivity curves for the three different layers of Field 1 and Field 2. $K$ is expressed in cm d$^{-1}$ and $h$ in cm.

The parameters to describe *θ(h)* and *K(h)* relationships for the third layer were also taken from Beekma (1993) as they could not be measured in the field due to presence of groundwater table. The calibrated Van Genuchten-Mualem (VGM) parameters for Fields 1 and 2 are given in Table 4.3.

**Table 4.3.** Calibrated Van Genuchten-Mualem (VGM) parameters used to describe soil hydraulic properties in the SWAP model.

| Parameters | Field 1 | | | Field 2 | | |
|---|---|---|---|---|---|---|
| | Layer 1 | Layer 2 | Layer 3 | Layer 1 | Layer 2 | Layer 3 |
| Depth of Layer (cm) | 0-30 | 30-280 | >280 | 0-30 | 30-280 | >280 |
| Soil Texture | loam | silt loam | loamy sand | silt loam | silt loam | loamy sand |
| Residual water content $\theta_{res}$ | 0.0 | 0.0 | 0.028 | 0.0 | 0.0 | 0.028 |
| Sat. water content $\theta_{sat}$ | 0.384 | 0.509 | 0.40 | 0.384 | 0.43 | 0.40 |
| Sat. hyd. cond. $K_{sat}$ (cm $d^{-1}$) | 60 | 40 | 72 | 60 | 40 | 72 |
| Shape parameter $\alpha$ ($cm^{-1}$) | 0.0085 | 0.0090 | 0.014 | 0.016 | 0.020 | 0.014 |
| Shape parameter $n$ (-) | 1.35 | 1.45 | 2.663 | 1.45 | 1.50 | 2.663 |
| Shape parameter $\lambda$ (-) | 1.0 | 1.0 | 0.5 | 1.0 | 1.0 | 0.5 |

***Bottom boundary conditions***

The daily measured groundwater table depths and the characteristics of the drainage system were used to describe the bottom boundary of the soil profile. The soil hydraulic parameters given in Table 4.3 only describe the vertical hydraulic conductivity ($K_v$). The lateral flow to drains is mainly driven by the horizontal hydraulic conductivity ($K_h$). In alluvial deposits, the $K_h$ is often higher than the $K_v$. In SWAP, this can be expressed as an anistropy-factor ($K_h/K_v$). The $K_h$ for the surface soils of the S1B9 area was determined by WAPDA (1983) and USBR (1989). Based on their data, the anistropy factors for layers 1 and 2 were taken as 1 and 2, respectively. The anistropy factor for the third layer was calculated using the measured field data. The procedure used is as follows.

The measured data on drain discharge rates and groundwater table depths midway between drains was used to calculate the drainage resistance for the entire area surrounding Lateral 2 (Figure 4.1). The average groundwater table depth mid way between the drains was determined using piezometers P16, P24, P35, and P43 (Figure 4.1). Figure 4.6 shows the relationship between drain discharge rate ($q_{drain}$) and the total hydraulic head difference between drain level and phreatic level at mid point ($\Delta h$). The slope of this curve determines the drainage resistance ($\gamma_{drain}$), which can be calculated as being 616 days. The designed drainage resistance for this project was 500 days. Earlier studies in the area have also shown that the actual drainage resistance is higher than the designed value. This is mainly due to lower field permeabilities (IWASRI, 1994). As the depth of impervious layer below the drain level is very large, the second term in the numerator of Eq. 3.26 can be neglected. The horizontal hydraulic conductivity was therefore calculated by using the simplified relationship as given below.

$$\gamma_{drain} = \frac{\Delta h}{q_{drain}} = \frac{L^2}{8K_{sat}^{h} d} \tag{4.1}$$

The value of equivalent depth, *d*, was calculated using Eq. 3.27 and was found to be 23.97 m. Putting this value in equation (1), the horizontal hydraulic conductivity was calculated as 188 cm $d^{-1}$. The vertical hydraulic conductivity for the bottom layer was 72 cm $d^{-1}$ (Table 4.2), which yielded an anistropy factor of 2.6.

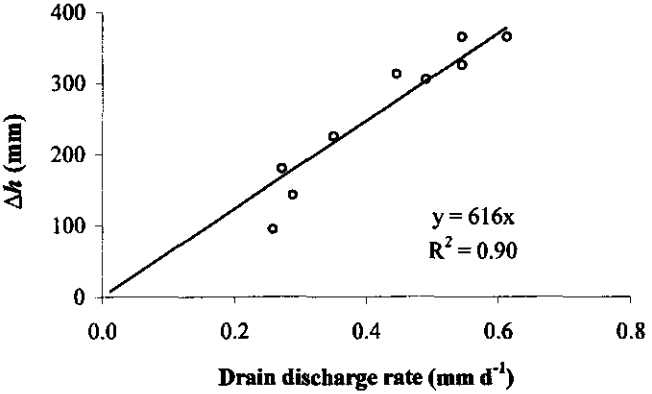

**Figure 4.6.** Relationship between drain discharge rate and the hydraulic head difference between the drain and phreatic level at mid point (*Δh*) for the S1B9 area based on field data.

### *Salinity parameters*

The salinity parameters in the classical convection-dispersion equation that describe salt transport are the dispersivity, $L_{dis}$ (cm), and the diffusion, $D_{dif}$ ($cm^2$ $d^{-1}$). Under field conditions with irrigation, solute spreading due to dispersion is much more pronounced than solute spreading due to diffusion. The value of $L_{dis}$ typically ranges from 0.5 cm, or less, for laboratory scale experiments involving disturbed soils, to about 10 cm or more for field scale experiments (Nielsen et al., 1986). The values for $L_{dis}$ and $D_{dif}$ that gave best results of simulated profiles $EC_e(z)$, were 15 cm and 0.48 $cm^2$ $d^{-1}$, respectively.

## 4.4 Verification of model input parameters

The calibration period for Field 1 was from 16.2.96 to 22.4.97 covering two cropping seasons i.e. sugarcane and wheat. The calibration period for Field 2 was from 8.3.96 to 6.3.97 covering year long sugarcane crop. Measured field data regarding soil water pressure heads, soil water contents and drain discharge rate were compared with simulated results. For these simulations, measured daily groundwater table depths were used as input data and both pressure heads $h(z)$ and soil water profiles $\theta(z)$ and the fluxes $q_{drain}$ and $q_{bot}$ were computed. Agreement between simulated and measured values was quantified by the root mean square error ($RMSE$). The $RMSE$ represents how much the simulation overestimate or underestimate the actual field measurements.

$$RMSE = \left[ \frac{\sum_{i=1}^{n} (M_i - S_i)^2}{n} \right]^{1/2} \tag{4.2}$$

where $M_i$ and $S_i$ are the measured and simulated values at the end of day $i$ and $n$ is the number of days of observation.

***Pressure heads***

As a typical example, the measured and simulated pressure heads at depths of 30 cm and 90 cm for both fields are illustrated in Figure 4.7. The simulated pressure heads match quite well with the measured data for all depths. The root mean square error for the pressure heads of all depths was 29 cm (n = 88) for Field 1 and 24 cm (n = 93) for Field 2. Some discrepancies were found in the top layer of 15 cm where the model simulated more dry conditions than the measured values (not shown here). This was mainly due to the limitation of tensiometers to read the pressure heads below -600 cm.

***Soil water content***

Figure 4.8 shows a typical example of measured and simulated soil water contents at two different depths for Fields 1 and 2. The graph shows that the soil water trend simulated by the model for both fields is in good agreement with the measured data. The root mean square error for the volumetric soil water content of all depths for Field 1 was 0.020 $cm^3cm^{-3}$ (n = 170) and for Field 2, it was 0.018 $cm^3cm^{-3}$ (n = 113). The root mean square error values show a very good matching between measured and simulated values.

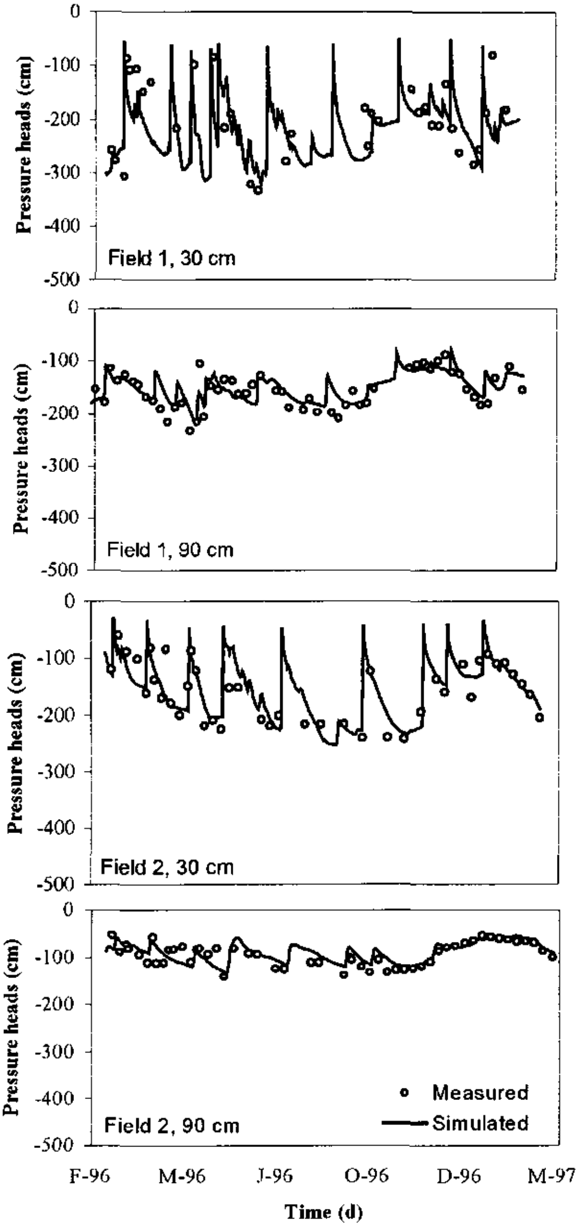

**Figure 4.7.** Comparison of measured and simulated pressure heads for Field 1 and Field 2 at 30 cm and 90 cm depths.

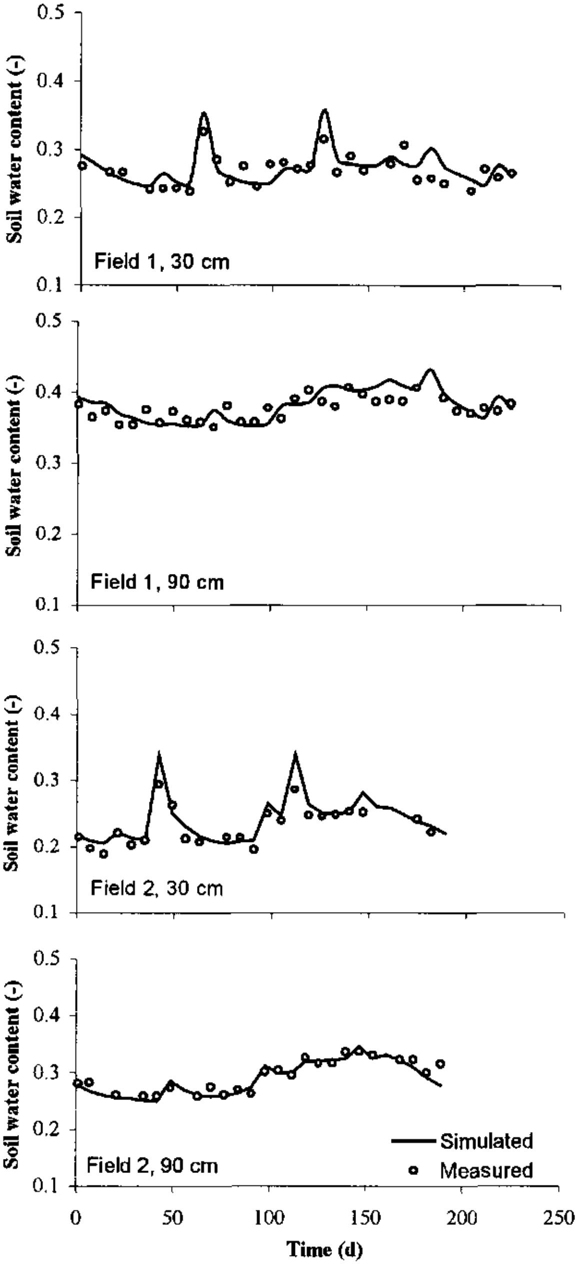

**Figure 4.8.** Comparison of measured and simulated soil water contents for Field 1 and Field 2 at 30 cm and 90 cm depths.

***Soil salinity***

The measured $EC_e$ values from the sample fields were available for a limited number of days. Therefore a comparison could only be accomplished for these days (Figure 4.9). The root mean square error (*RMSE*) for $EC_e$ was 0.15 dS m$^{-1}$ (n = 5) for Field 1, which shows a close proximity between measured and simulated values. The measured data for Field 2 was available for two days during the calibration period. Although not shown, measured and simulated $EC_e$ values for Field 2 were in good agreement for both days.

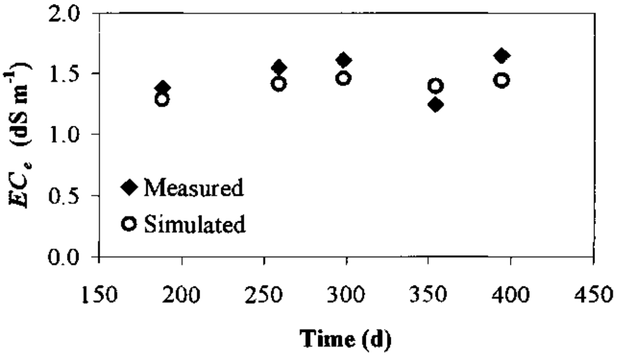

**Figure 4.9.** Comparison of measured and simulated $EC_e$ values (0-1.0 m depth) for Field 1.

***Bottom flux***

During the calibration process, daily groundwater table depths were used as bottom boundary and the bottom flux has been computed as the water balance residual. The variations in the bottom flux over the calibrated period for both fields are shown in Figure 4.10. The positive and negative bottom flux shows upward and downward movement of water at the bottom of the soil profile, respectively. The graphs show that there are fluctuations in the bottom flux after an irrigation or rainfall event. However, the cumulative bottom flux for both fields was within five percent of the total applied water, which means that overall effect of bottom flux was not very significant. This implies that at the bottom of the soil profile almost no flow conditions occur.

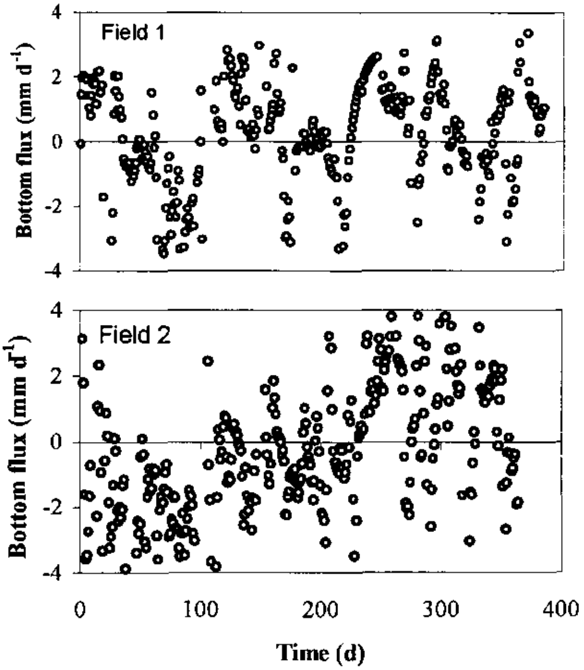

**Figure 4.10.** Fluctuations in the bottom flux at 480 cm depth during the calibration period for Field 1 and Field 2.

This situation was confirmed by installing three piezometers in the S1B9 area at depths of 4 m, 5 m, and 6 m with a distance of 1.0 m between each. A deep piezometer was also installed at a depth of about 200 m. These piezometers were read simultaneously on daily basis for a period of about three months. The data shows that they all read about the same water levels, which means that changes in the hydraulic head due to seepage are almost negligible. This hypothesis of zero flux at the bottom was further verified by giving it as bottom boundary in the SWAP and model was run to simulate groundwater tables. The comparison of measured and simulated groundwater tables is shown in Figure 4.11.

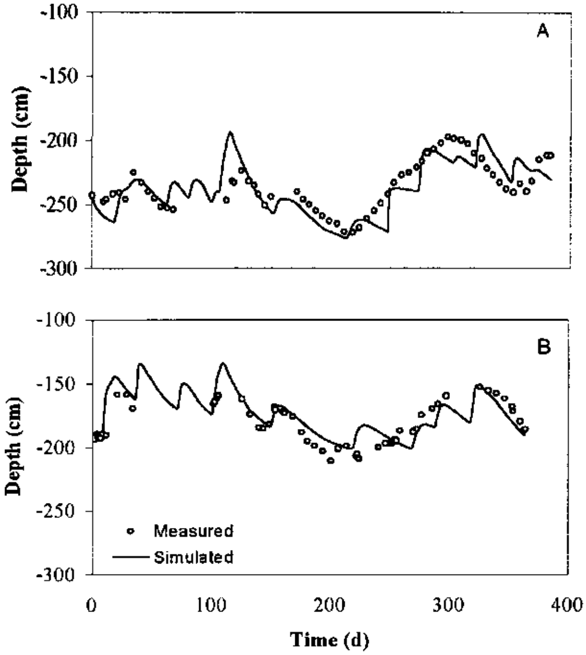

**Figure 4.11.** Comparison of measured and simulated groundwater table depths using zero flux as a bottom boundary for Field 1(Part A) and Field 2 (Part B).

The comparison shows that the discrepancies in the measured and simulated groundwater table depths were small with a root mean square error (*RMSE*) of 15 cm for Field 1 and 19 cm for Field 2. Considering that piezometer observations reflect a larger area than that of the investigated field and the limited possibility to describe field heterogeneity in the theoretical simulation models, the results are encouraging. This means that under the prevailing aquifer conditions of the area, zero flux at the bottom of the soil profile could be used as bottom boundary for scenario analysis. However, other areas where irrigation schedules and hydrogeological conditions are different, may result in considerable amounts of bottom flux. In such conditions, the net bottom flux as calculated during the model calibration (using groundwater table depths as bottom boundary condition), can be used as bottom boundary condition during scenario analysis.

***Drain discharge rate***

As the field sizes (0.2-0.4 ha) in the S1B9 area are considerably smaller than the distance between the lateral drains, the measured lateral discharge is the cumulative drainage from all these fields. As the model could be applied on one field with one crop at a time, the simulated drainage could not be compared directly with the measured drain discharges from the laterals. In order to compare the simulated drainage, the contribution of sample fields to the lateral drainage must be calculated separately. This was done in the following way.

The two sample fields are not located exactly in the middle of the two lateral drains. Therefore drainage resistance and hence amount of drainage from these two fields will be different than those fields which are located in the middle of the drains. Both sample fields are located at a distance of 215 m from Lateral 2 (see Figure 4.1). Therefore this distance was considered equal to the half of drain spacing (*L/2*). This means that a drain spacing (*L*) of 430 m is valid for the two sample fields. This drain spacing was used to calculate equivalent resistance ($\gamma_{drain}$) for the sample fields. Daily measured groundwater levels were used to calculate drainage from the sample fields using Eq. (4.3). This is referred as calculated drainage.

$$q_{drain} = \frac{\Delta h'}{\gamma'_{drain}} \tag{4.3}$$

where $q_{drain}$ is the drain discharge rate from the sample field, $\Delta h'$ is the total hydraulic head difference between the drain and phreatic levels in the sample field, and $\gamma'_{drain}$ is the drainage resistance of the sample field (518 days, calculated with $L$ = 430 m and $K_{sat}^{h}$ = 1.88 m d$^{-1}$ and $d$ = 23.74). For drainage calculations, daily measured groundwater levels were used.

For model simulations, a drain spacing of 430 m and zero flux as bottom boundary was specified to simulate groundwater levels. These simulated groundwater levels were then used to calculate drainage according to the Eq. 4.3. This is referred as simulated drainage. Figure 4.12 shows that the simulated cumulative drainage is in good agreement with the calculated cumulative drainage. The root mean square error (*RMSE*) was 0.009 mm d$^{-1}$ (n = 430) and 0.018 mm d$^{-1}$ (n = 250) for Fields 1 and 2, respectively.

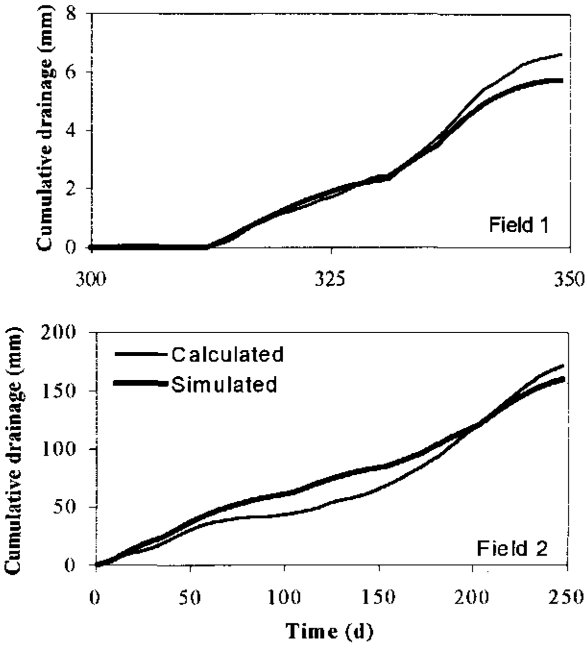

**Figure 4.12.** Comparison of calculated and simulated cumulative drainage for Field 1 and Field 2. For the calculated drainage, daily measured groundwater table depths were used to determine $\Delta h'$ for Eq. 4.3. For the simulated drainage, groundwater table depths obtained from model simulations using zero flux as bottom boundary condition were used to determine $\Delta h'$.

The simulation results also show that the drain discharge rate is not constant over time, but fluctuates according to the percolating moisture flux in the unsaturated zone. Figure 4.13 shows the fluctuations in the flux below the root zone for both the sample fields during the calibration period. The depth of root zone for wheat crop is taken as 110 cm whereas for sugarcane and cotton it is 160 cm (see Table 4.2). The graphs show that considerable fluctutaions in the flux after an irrigation or a heavy rainfall event can be expected, but generally it is less than the designed value of 2.44 mm $d^{-1}$. Earlier studies have also shown that the drain discharge rate at the S1B9 is far less than the design value (IWASRI, 1994).

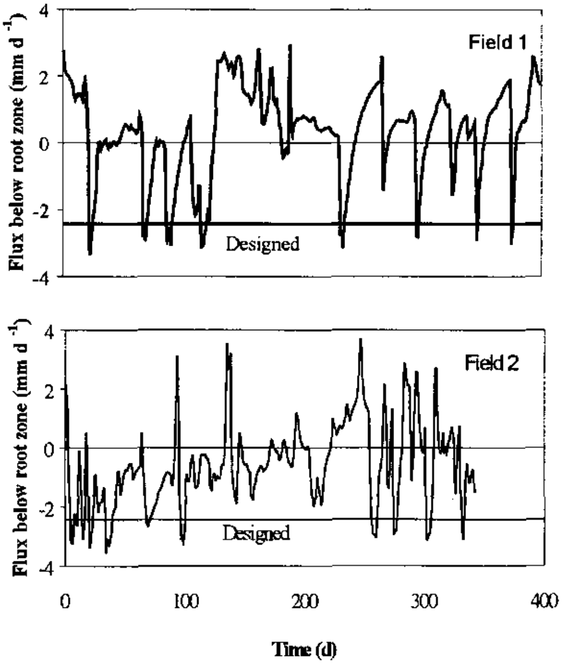

**Figure 4.13.** Flux at the bottom of the root zone for Field 1 and Field 2 during the calibration period.

## 4.5 Conclusions

- The difference between laboratory and field measured soil water retention curves *θ(h)* were found significant. Laboratory determined *θ(h)* relationships were found to be non-representative of field conditions for irrigation and drainage modeling. Therefore more efforts should be dedicated to the field determination of these parameters.

- For arid and semi-arid conditions, the Priestly-Taylor method for the determination of reference evapotranspiration was found more realistic than the Penman-Monteith method due to ignorance of vapor pressure deficit feed back mechanism on stomatal aperture.

- The strategy adopted to calculate drainage from sample fields in a heterogeneously irrigated and drained environment seems successful. A close proximity in the calculated and simulated cumulative drainage shows that the calibrated drainage system characteristics are reliable.

- Analysis of piezometer data shows that under the prevailing aquifer conditions of the FDP-area, no flow conditions at the bottom of the soil profile could be applied as a bottom boundary for further model simulations, and this was confirmed from the simulated groundwater fluctuations.
- The calibration results show that the SWAP model can be applied to obtain water and salt balance terms to analyze water efficiency and drainage system performance.

# 5 RE-EVALUATION OF DRAINAGE DESIGN CRITERIA FOR THE FOURTH DRAINAGE PROJECT[1]

## Abstract

This Chapter presents the results of model simulations to re-evaluate drainage design criteria for the Fourth Drainage Project (FDP). The SWAP model was applied to compute the effects of land drainage (twelve combinations of drain depth and spacing) on soil water conditions in the root zone and their effect on crop yield and soil salinization. The results indicate that the selection of drain depth in semi-arid areas is more important than drain spacing. Deeper drains perform technically better in relation to crop growth and soil salinization. The optimum drain depth for the multiple cropping system of the FDP-area was found to be 2.2 m. This drain depth produced reasonably good crop yields at rather low drainage intensity (drain spacing of 500 m) while keeping the root zone salinity within acceptable limits. This drainage design also maintained the groundwater table depth below the root zone throughout the growing season. The outcome of this study also revealed that the present drainage design criteria of the FDP is rather conservative with high drainage intensity. The model simulations show that the FDP-area can effectively be drained with a 25 percent lower drainage intensity ($q_{drain}/\Delta h$) provided no operational or maintenance constraints are present. However, the final decision on the optimum combination of drain depth and drain spacing would require a thorough economic analysis. The non-steady state approach proved successful in analyzing the complex interactions between irrigation and drainage components. It is a valuable tool to optimize the design of drainage systems against crop yields and soil salinization.

## 5.1 Introduction

The specific objective of a drainage system for (semi-) arid area is to protect crops from excess soil water conditions (waterlogging) and to prevent soil salinity. Since drainage needs of these areas are heavily dependent on the irrigation component, additional constraints include minimizing drainage effluent and the amount of irrigation water required (Skaggs, 1990). Environmental considerations also impose severe constraints on the design and operation of drainage and related water management systems (Tanji, 1990). Another factor of critical importance is the control of groundwater table, which should be lower than the so-called critical depth. In (semi-) arid areas, soil salinity caused by shallow groundwater tables is often the main limiting factor to crop production. The depth of the groundwater table during the

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[1] Adapted version of Sarwar, A. and R.A. Feddes, 2000. Evaluating drainage design parameters for the Fourth Drainage Project, Pakistan by using SWAP model: Part II-Modeling results. *Irrigation and Drainage Systems (in press)*

dry spell when land is fallow is of critical importance for capillary rise and secondary soil salinisation (Prathapar and Sarwar, 1999). The reason for this is that, by maintaining a deep groundwater table, the drainage system can intercept the seepage water and hence reduce the capillary rise and soil salinisation. Therefore the optimum watertable depth will be the one, leading to maximum crop yield and reducing or maintaining soil salinization at an acceptable level.

Evapotranspiration during the warm growing periods is considerable and contributes significantly to depletion of soil moisture, thus creating storage for subsequent rainfall. But at the same time, solute concentration increases due to the lesser amount of water available. Drainage requirements during these periods are rather small, except for occasional (monsoon) rains, which can create periods of excess water in the root zone. Under such conditions, drainage aims primarily at a rapid restoration of the upper root zone aeration, following a heavy rainfall.

The depth at which drains should be installed is a design decision and the drain spacing is derived from it. Drains are generally placed as deep as economically feasible. Advantages of deeper drains are a greater watertable head and more water storage capacity in the soil, both resulting in a large spacing and less length of drains per unit area (Feddes, 1990). The drain depth affects the depth of groundwater table and the depth can be optimized such that the groundwater contribution to the crops through capillary rise is maximum, without permanently accumulating salts in the root zone (Hendrickx et al., 1990). Wider drains also reduce drainage volume and installation costs. However, higher salt concentrations may be found in drainage effluent as leaching occurs within a deeper soil profile.

The success of a drainage system depends on its proper design and installation. For irrigated lands in (semi-) arid regions, no specific drainage design criteria are available. It has therefore become a common practice to apply the design criteria of the type used for humid areas. These criteria are mostly based on the steady-state equations of Hooghoudt and Ernst (see Ritzema, 1994), which assume steady-state moisture and solute fluxes occurring in the unsaturated zone, being independent of soil and crop. One such steady-state criteria usually used for drainage design in (semi-) arid conditions in general and for Pakistan in particular is given in Table 5.1 (Smedema, 1990).

**Table 5.1.** Drainage design criteria *(independent of soil and crop!)* applied for different water control objectives for *semi-arid* regions in Pakistan (after Smedema, 1990).

| Objectives | Drain discharge rate $q_{drain}$ (m d$^{-1}$) | Design groundwater table depth $H$ (m) | Drain depth $D$ (m) | Groundwater table head midway drains $\Delta h = D\text{-}H$ (m) | Drainage intensity $q_{drain}/\Delta h$ (d$^{-1}$) |
|---|---|---|---|---|---|
| Aeration | 0.0070 | 0.50 | 1.2 | 0.70 | 0.010 |
| Sub-irrigation | - | 1.00 | 1.0 | - | - |
| Capillary salinization | 0.0005 | 1.75 | 2.5 | 0.75 | 0.0007 |
| Leaching | 0.0020 | 1.00 | 2.5 | 1.50 | 0.0013 |
| **Compromise** | **0.0020** | **1.00** | **2.0** | **1.00** | **0.0020** |

In Table 5.1, separate criteria for different processes are given, because in the past irrigation and drainage systems were mostly planned and designed separately. For aeration, the high criteria as used in moderate climates is used. For sub-irrigation, design groundwater table depth is based on the controlled field experiments conducted in Pakistan. For leaching and capillary salinization, the criterion is based on a typical case where there is a small seepage load (coming from canal leakage) and soil has a fine sandy/silty subsoil with high capillarity found in many alluvial river plains in semi-arid regions. The drain depth $D$ has been taken as the least cost depth. It is clear from the Table 5.1 that highest drainage intensity is required for aeration control as the crops can stand only a limited period of waterlogging. For capillary salinization control about 15 times lower drainage intensity is reuired.

Different drainage projects installed in Pakistan using these steady-state design criteria have failed to reach the designed objectives. Because the impact of irrigation management on a drainage system and vice versa, has been difficult to evaluate and at times impossible. For practical purposes, a unique criterion needs to be developed taking into account the effects of all the processes involved in an integrated way. For this purpose, determination of water and salt balances in the unsaturated zone is absolutely necessary.

The strong and complex interaction between irrigation and drainage components can be better described by the use of simulation models, which can accurately simulate irrigation requirements, crop production, water and salt movement through the root zone and flow to the drains on a day-to-day basis, considering variations in the rainfall and evaporative demand of the atmosphere. This integrated irrigation and drainage modeling will be very useful to evaluate the impact of alternative drainage designs on crop growth and soil salinisation.

The main objective of this study is to analyze the drainage design criteria of the Fourth Drainage Project (FDP), and to improve the drainage design procedures for subsurface drainage systems in Pakistan. The effects of drainage system design on the yields of dominant crops grown in FDP-area are evaluated with the calibrated SWAP model. The basic features of the model and, the results of calibration and field validation are presented in Chapters 3 and 4. This Chapter presents the results of model simulations for obtaining an optimum drainage design for the FDP-area. It also includes a comparison of optimum design with the present United States Bureau of Reclamation (USBR) and Smedema design parameters (Table 5.1).

## 5.2 Input data and model application

Simulations were performed for a period of 15-years (1980-94) as the daily climatic data (rainfall, sunshine hours, wind speed, maximum and minimum temperatures) for this period were available from the Fourth Drainage Project (FDP). Model simulations were performed both for the wheat-cotton and sugarcane crop rotation. Wheat-cotton is by far the largest crop rotation system in the Indus basin comprising over 4.5 million hectares (Mulk, 1993) and sugarcane is the major cash crop of the area.

***Irrigation schedules***

In the heterogenous cropped and irrigation environment of the FDP-area, it was difficult to translate the behaviour of individual farmers into an average condition. Therefore, for this study, on average twelve irrigations in a growing year are assumed. This means five irrigations to wheat and five to cotton crop along with two pre-sowing irrigations and twelve irrigations (including pre-sowing) to the sugarcane crop. The depth of each irrigation was taken as equivalent to a normal irrigation of an upland crop in Pakistan i.e. 65 mm (OFWM, 1980). The amount and number of irrigations were kept constant for the years of simulation. For all irrigations in a year, canal water of very good quality (EC = 0.3 dS $m^{-1}$) was used. The groundwater salinity in the FDP-area varies between 3 to 4 dS $m^{-1}$, therefore an average value of 3.5 dS $m^{-1}$ was taken for these simulations. A zero flux at the bottom of the soil profile was taken as bottom boundary condition (see Chapter 4).

***Drainage combinations tested***

The model was applied to compute the effect of land drainage (12 combinations of drain depth and drain spacing) on the yields of wheat, cotton and sugarcane. The drain depths chosen were 1.0, 1.5, 2.0 and 2.5 m below the soil surface. Each of these drain depths were combined with three different drain spacings ranging from narrow (125 m), medium (250 m) to wide (500 m). These drain spacing correspond with high, medium and low drainage intensities, respectively, in a ratio of 4:2:1. For each drainage combination (drain depth and drain intensity), simulations were performed for a period of 15-years under the prevailing climatic conditions.

### *Initial conditions*

In order to achieve zero change in the water storage over the year for each drainage combination, initial soil profile was generated by changing the initial soil water contents. The initial salinity concentrations were derived from current field measurements. Salinity surveys conducted in the FDP-area during 1990-96 show that the average $EC_e$ of the soil profile up to a depth of 2.0 m varies between 1.5 and 2.6 dS $m^{-1}$ with an average value of about 2.0 dS $m^{-1}$ (Raza and Choudhry, 1998). As the depth-wise salinity data were not available, this average value was used as an initial condition for salt balance simulations. For salinity stress the response function of Maas and Hoffman (1977) and for water stress the function proposed by Feddes et al. (1978) were used (see Chapters 3 and 4).

## 5.3 Results and discussion

Crop growth rate and actual crop transpiration rate ($T_{act}$) are linked. Transpiration and crop growth can be adversely influenced by the soil being either 'too wet' or 'too dry' (Feddes and van Wijk, 1990). Salinity also retards crop transpiration by reducing root water uptake. Therefore, relative transpiration ($T_{act}/T_{pot}$) is a good indicator to evaluate the effect of different drainage designs on soil moisture and salinity and their effect on crop growth. $T_{pot}$ is the potential crop transpiration rate. Relative transpiration is further considered equivalent to relative crop yield (see Chapter 3).

### *Effect of land drainage on crop transpiration rate*

The SWAP model simulations were carried out to compute the effects of land drainage (12 combinations of drain depth and spacing) on the relative transpiration ($T_{act}/T_{pot}$) of three major crops grown in the FDP-area. In Figure 5.1, relative transpiration of wheat, cotton and sugarcane is shown as a function of four drain depths at three different drainage intensities. The values of $T_{act}/T_{pot}$ are based on 15 year averages.

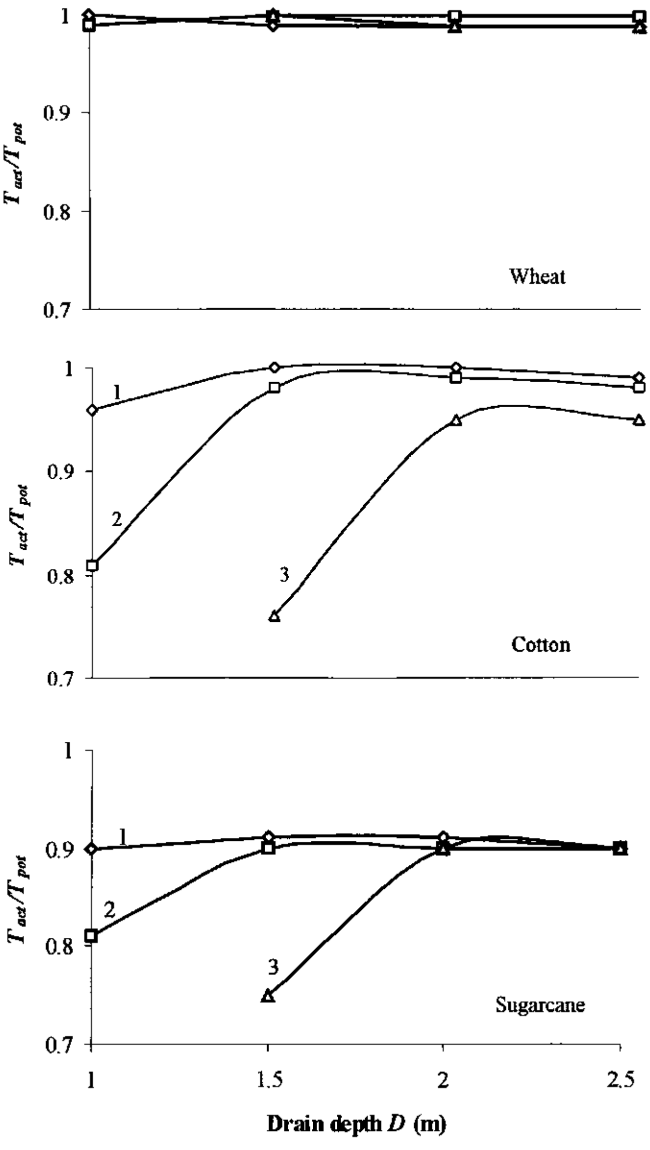

**Figure 5.1.** Relative transpiration ($T_{act}/T_{pot}$) of *wheat, cotton and sugarcane* as a function of drain depth $D$ at three drainage intensities ($q_{drain}/\Delta h$) based on 15 year (1980-94) averages as calculated with SWAP. 1, high drainage intensity; 2, medium drainage intensity; 3, low drainage intensity.

Figure 5.1 shows that there is a clear effect of drain depth (*D*) and drainage intensity ($q_{drain}/\Delta h$) on crop yields. The values of $T_{act}/T_{pot}$ for wheat were optimal for all drainage combinations, which means that both moisture and salinity conditions remained favourable during the growing season. The wheat crop is usually grown in winter (Dec.-Apr.) when evapotranspiration demand is relatively low. Therefore water applied through irrigation and rainfall kept the root zone sufficiently wet to maximize crop transpiration and to maintain a downward flux for the leaching of salts.

Cotton being a summer crop is usually subjected to heavy monsoon rains. Therefore risk of damage due to 'too wet' conditions for cotton is much higher. Figure 5.1 shows that for all drain depths, the maximum yield of cotton is obtained at high drainage intensity. At 1.0 m drain depth, the relative crop yield obtained at this high drainage intensity is about three percent smaller than the yields obtained at the drain depths of 1.5, 2.0 and 2.5 m. This was due to excessive soil water conditions after heavy monsoon rains, which reduced the capacity of roots to extract water from the soil and negatively affected the crop transpiration.

For medium drainage intensity, excessive soil water conditions persist much longer causing a further 15 percent reduction in the relative crop yield at a drain depth of 1.0 m. At low drainage intensity, the cotton crop completely failed due to submerged conditions after the monsoon season. With drains at 1.5 m depth, the highest cotton yields were obtained at high and medium drainage intensities. However, at the low drainage intensity, considerable reduction in cotton yield occurred mainly due to waterlogged conditions. At deeper drain depths, 95 percent of the potential yield was obtained at the low drainage intensity. This yield was only three percent smaller than the yield obtained at the (four times) high drainage intensity.

The maximum yield of sugarcane is obtained at high drainage intensity for all drainage combinations. This is due to the fast removal of excess water by closely spaced drainage system thereby reducing the time for which the soil conditions are anaerobic. At the 1.0 m drain depth, yield obtained at the medium drainage intensity is nine percent lower than the yield obtained at the high drainage intensity. This reduction is mainly due to excessive soil water conditions. For shallow drains (1.0 m) together with the low drainage intensity, the groundwater table reached to the soil surface after the first year of simulations, resulting in a complete failure of the sugarcane crop. At 1.5 m drain depth, sugarcane crop do survive but yields are about 16 percent lower as compared to high and medium drainage intensity. However, this is not the case when drains are installed at deeper depths: reasonably good yields are obtained even at the low drainage intensity.

Figure 5.1 also shows that the maximum achievable yields of sugarcane under all drainage combinations were only up to 90 percent of the potential yield. Because of its longer growing season and the high demand of the atmosphere, sugarcane needs considerably more water than the wheat-cotton crop rotation. The average actual transpiration of sugarcane (1050 mm) is about 250 mm higher than wheat-cotton (800 mm) rotation. This means that the considered irrigation regime (780 mm of irrigation water) was not sufficient to satisfy the transpiration demand of the sugarcane. This created deficit soil water conditions and hence relative yield was reduced.

In an attempt to reduce drought stress, additional simulations were performed with an increased amount of irrigation water, which was obtained by maintaining the same irrigation frequency at twelve irrigations per year but increasing the depth of each irrigation from 65 mm to 90 mm. This increases the total amount of irrigation water from 780 to 1080 mm per year. This irrigation strategy nearly eliminated the drought stress at all drainage intensities and increased maximum yield of sugarcane to about 98 percent for drain depths of 2.0 m and 2.5 m. However, this strategy raised the groundwater table and reduced yields due to excessive soil water conditions at shallow drain depths.

In the Fourth Drainage Project (FDP), agricultural field sizes are considerably smaller than the average distance between two laterals. The catchment area of each lateral usually comprises several individual fields, each with a different crop and water requirement. Therefore the drainage system for this area should be able to fulfill the requirements of this *multiple cropping system*. For this purpose, effects of different drainage combinations on the relative transpiration of multiple crops was investigated, and the results are presented in Figure 5.2.

The optimum drain depth for the soil, crop and climatic conditions prevailing in the FDP-area is about 2.2 m. The maximum relative yields are obtained at the high drainage intensity. The yield obtained at the low drainage intensity for $D$ = 2.2 m, however, is only one percent smaller, despite the fourfold difference in the drainage intensity. At the optimum drain depth, the groundwater table remained below the root zone throughout the growing season, thereby eliminating the chances of any yield reductions due to excessive soil water conditions. Figure 5.2 shows that the drains shallower than $D$ = 2.2 m can cause severe yield reductions due to excessive soil moisture conditions. The situation may become more worse during relatively wet years. Further increase in drain depth will increase the costs without any additional benefits.

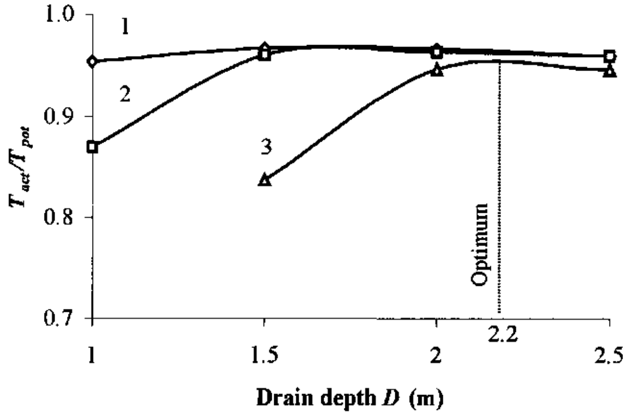

**Figure 5.2.** Relative transpiration ($T_{act}/T_{pot}$) for the *multiple cropping system* as a function of drain depth $D$ at three different drainage intensities ($q_{drain}/\Delta h$) based on 15 year averages (1980-94) as calculated with SWAP. 1, high drainage intensity; 2, medium drainage intensity; 3, low drainage intensity.

### *Effect of land drainage on soil salinity*

Salinity control is a major concern for the soils of the semi-arid areas, therefore to maintain long-term *sustainability*, the effect of different drainage designs on the soil salinization also needs serious consideration. Long-term (15-year) model simulations were performed to determine the effects of drainage on the root zone salinity, and the results are presented in Figure 5.3. The $EC_e$ values represent the average salinity calculated over a 2.0 m deep root zone based on 15-year averages.

Figure 5.3 shows that soil salinization is closely related to drain depth. The salinity of the root zone decreases with the increasing drain depth. This is because of increased effective leaching of salts by deeper drains. However, for a particular drain depth, salinity changes are relatively independent of the drainage intensity. The average root zone salinity never exceeded the threshold values at which crop yield reduction starts e.g. for wheat at 6.0 dS $m^{-1}$, cotton at 7.7 dS $m^{-1}$ and sugarcane at 1.7 dS $m^{-1}$ (after Maas, 1990). This implies that yield reductions for different drain depths were mainly due to either excessive or deficient soil water conditions. The low salinity values can be explained by the good quality canal water (EC = 0.3 dS $m^{-1}$) used for all irrigations.

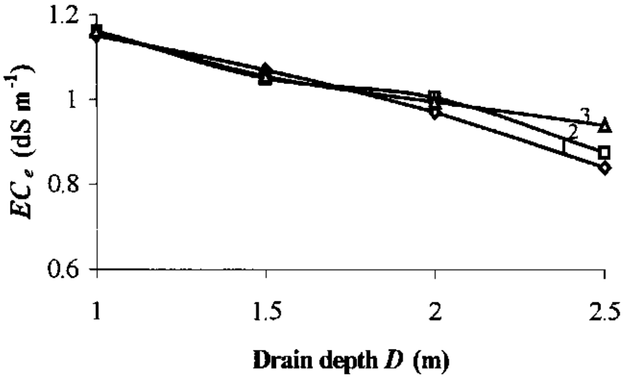

**Figure 5.3.** Average root zone salinity ($EC_e$) for the *multiple cropping system* as a function of drain depth $D$ at three drainage intensities ($q_{drain}/\Delta h$) based on 15 year averages (1980-94) as calculated with SWAP. 1, high drainage intensity; 2, medium drainage intensity; 3, low drainage intensity.

In conclusion, selection of the proper drain depth for semi-arid regions seems more critical than the drain spacing. For the conditions considered, deeper drains perform better than shallow drains with regard to crop growth and soil salinisation. Bastiaanssen et al. (1996) also found deeper drains more feasible for semi-arid areas. Their findings were based on detailed analysis of integrated on-farm water management in Haryana, India. However, the final decision on the optimum combination of drain depth and drainage intensity would require thorough economical analysis.

## 5.4 Comparison of present USBR, Smedema and SWAP drainage design parameters

The present drainage design of FDP was based on the estimates of United States Bureau of Reclamation (USBR, 1989). The USBR design was based on a 5 year return period monsoon (June-Sept.) rainfall. However, they did not mention the amount of design rainfall. The analysis of Boonstra (1991) shows that 5 year return period monsoon rainfall for the FDP-area is 347 mm. The root zone was considered fully saturated before the design rainfall occurred. The drain discharge rate was calculated considering conveyence losses from irrigation canals and watercourses. excess irrigation deliveries and infiltration from the excess rainfall. The drain discharge rate estimated by this method was further increased to account for possible power failures, but by how much is not mentioned. It was assumed that 16 out of 24 hours will be available to pump out the daily design rainfall. The designed drain discharge rate was 2.44 mm $d^{-1}$. This drain discharge rate was also considered adequate to satisfy the leaching requirements and maintain a favourable salt balance in the root zone. The designed groundwater table depth midway between the drains was 1.2 m below the soil surface, which resulted in a drainage intensity ($q_{drain}/\Delta h$) of 0.0020 $d^{-1}$. Drains are, on average, installed at a depths of 2.4 m with a range between 1.8 to 3.8 m, mainly selected on low cost basis. The drain spacing varies considerably in the area from 100 to 750 m with an average of 495 m. A comparison of present USBR, Smedema and SWAP drainage design parameters is given in Table 5.2.

**Table 5.2.** Comparison of the present ***USBR***, ***Smedema*** and ***SWAP*** drainage design parameters.

| Drainage designs | Drain discharge $q_{drain}$ (mm $d^{-1}$) | Drain depth $D$ (m) | Groundwater table head midway drains $\Delta h = D-H$ (m) | Drainage intensity $q_{drain}/\Delta h$ ($d^{-1}$) | Drainage spacing $L$ (m) |
|---|---|---|---|---|---|
| USBR | 2.44 | 2.44 (1.8-3.8) | 1.22 | 0.0020 | 495 (100-750) |
| Smedema | 2.0 | 2.0 | 1.00 | 0.0020 | 450 |
| SWAP | - | 2.2 | - | 0.0015 | 525 |

Table 5.2 shows that the drainage intensities of the present USBR as well as the Smedema design are about 25 percent higher than the SWAP design. The optimum drain depth determined by SWAP model is shallower than the USBR but higher than the Smedema design. The SWAP design also advocates a larger drain spacing. The present USBR and Smedema designs are rather conservative with high drainage intensities. From the SWAP simulations it appears that drain discharge rate is not constant but fluctuates over time according to the percolating moisture flux in the unsaturated zone and an average value of 1.5 mm $d^{-1}$ is sufficient to drain the area.

The post project (1990-97) monitoring of the FDP (Figure 5.4) shows that the actual drain discharge rates are far less than the SWAP value of 1.5 mm $d^{-1}$, and even most of the maximum observed values are substantially lower than the USBR designed value of 2.4 mm $d^{-1}$. Bhutta et al. (1992) and Kelleners and Choudhry (1998) have also shown that the maximum measured drain discharge rates for the FDP-area are of the order of 1.2 to 1.5 mm $d^{-1}$. This gives confidence on the drain discharge rates as predicted by SWAP. The low drain discharge rates measured during 1990-97 could be due to the fact that the designed monsoon rainfall (347 mm) did not occur during this period. The monsoon rainfall during the year 1992 was 270 mm, being close to the designed rainfall. Even then the drain discharge rates are considerably lower than the designed value (see Figure 5.4). This implies that either the USBR over-estimated irrigation system and field percolation losses or the margin of safety was kept too high.

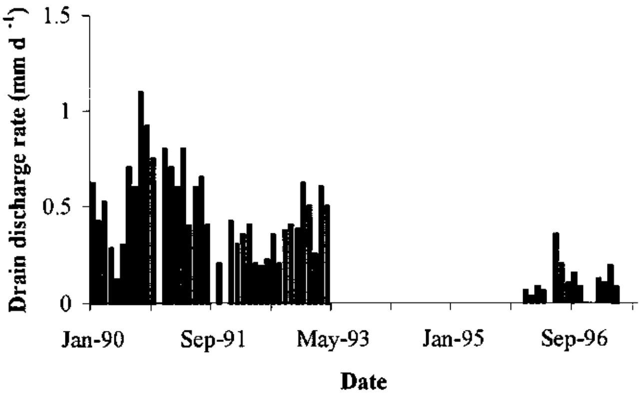

**Figure 5.4.** Measured mean daily drain discharge rates of the FDP-area on monthly basis during 1990-97. The gaps in the graph indicate missing data.

The performance of these three drainage designs was also evaluated by comparing their effects on crop transpiration, groundwater table fluctuations and root zone salinity. For this purpose, simulations were carried out with the SWAP model for a period of 15-years (1980-94) using the drainage design parameters as given in Table 5.2.

***Relative transpiration***

Figure 5.5 shows that the relative transpiration of wheat, cotton and sugarcane predicted by the three sets of design parameters are comparable. The relative transpiration of all crops predicted by the SWAP design parameters is in good agreement with the other two sets of parameters. The slightly lower relative transpiration values of the present USBR design can be explained by the deficit soil water conditions due to the applied deeper drain depth.

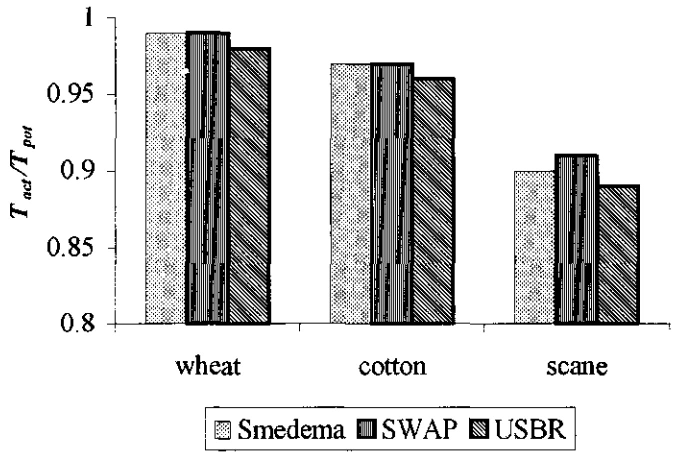

**Figure 5.5.** Relative transpiration ($T_{act}/T_{pot}$) of wheat, cotton and sugarcane for the present USBR, Smedema and SWAP drainage design parameters based on 15 year averages (1980-94) as calculated with SWAP.

***Groundwater table fluctuations***

The groundwater table depth is the most important design parameter in the practice of drainage. Because of inefficient drainage systems, the groundwater table may rise into the root zone resulting in an increase in capillary salinization. The situation becomes even more critical when groundwater is of poor quality as in the FDP-area. Therefore the groundwater table is usually kept lower than the so-called critical depth. The critical groundwater table depth for most of the soils is in the range of 1.0 to 1.5 m and rising to 2.0 m in very fine sandy or silty profiles according to Smedema and Rycroft (1988). Agronomic surveys have indicated that most of the crops grown in Pakistan decrease their production when the groundwater table rises above 1.5 m below soil surface (Harza/Nespak, 1984).

Figure 5.6 presents the relationship between the average highest groundwater table depth and the drainage intensity for four different drain depths based on 15-year averages. On a semi-logrithmic scale there is a linear relationship. The points on the lines refer to the drainage intensities applied in the model study. The dotted lines show the predicted highest groundwater table depths for three drainage designs at their respective drainage intensities. Figure 5.6 implies that by installing deeper drains, the groundwater table depth can effectively be controlled at relatively low drainage intensities. For shallow drains, however, considerably higher drainage intensities will be needed to ensure fast removal of the excess water from the root zone.

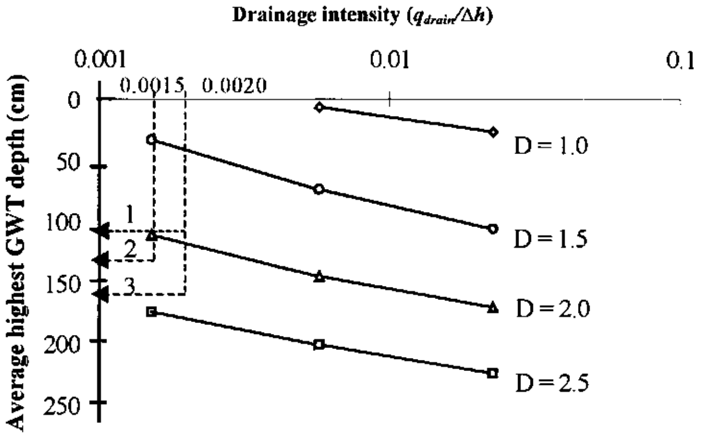

**Figure 5.6.** Relationship between average highest Groundwater Table (GWT) depth and drainage intensity ($q_{drain}/\Delta h$) for four drain depths $D$ based on 15 year averages (1980-94) as calculated with SWAP. 1, Smedema design; 2, SWAP design; 3, present USBR design.

The average highest predicted groundwater table depth for the Smedema design is around 100 cm below the soil surface. Because of the high potential of capillary rise in silt loam soils, this shallow groundwater table depth might increase the salinity of the soil profile due to capillary rise. The highest predicted groundwater table depth with the SWAP design will be around 140 cm, which is roughly the depth considered to be optimal for Pakistani conditions. The present USBR design will maintain the groundwater table at deeper depths. This is favorable for both average and wet conditions. However, in relatively dry years, the groundwater table might drop to much deeper depths creating soil water deficit conditions in the root zone. This will then require additional surface irrigation to supplement the depleted moisture profile, ultimately requiring more drainage effluent to be disposed of. This situation already occurred during the post project monitoring of the FDP-area when the deepest groundwater tables during dry periods were found more than 3.0 m deep below the soil surface (IWASRI, 1994).

### *Soil salinization*

Long-term (15-years) salinity trends for the *multiple cropping system* for three drainage designs are illustrated in Figure 5.7, where the $EC_e$ values represent the average root zone salinity calculated over a root zone depth of 2.0 m based on 15 year averages. For all three drainage designs, salinity reduces, as compared to the initial value of 2.0 dS m$^{-1}$. The SWAP drainage design proves to be equally good in keeping the root zone salinity within acceptable limits. The $EC_e$ values up to a depth of 1.5 m are around 1.0 dS $m^{-1}$, but below that there is an increase and maximum salinity is found at the drain depths. This is due to the fact that the salinity concentrations near the drain depths do not depend on the percolation and groundwater salinity only, but also on the build-up of salts during wet/dry years. Therefore salinity values around 2.0 m depth are indicative rather than conclusive.

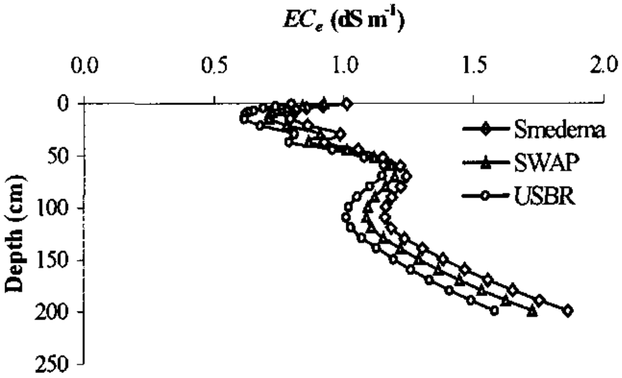

**Figure 5.7.** Comparison of simulated average root zone salinity ($EC_e$) for the *multiple cropping system* for the present ***USBR***, ***Smedema*** and ***SWAP*** drainage designs based on 15 year averages (1980-940 as calculated with SWAP.

## 5.5 Conclusions

The premise of this study was that the drainage systems designed by using the steady-state methods did not yield satisfactory results because the relationship between rainfall, irrigation and drainage are complex and dynamic in nature. Therefore these designs need to be re-evaluated and improved. In this study, present drainage design of the FDP-area has been checked using a transient modeling approach that accounts for soil moisture and root water uptake dynamics. The model simulations lead to the following conclusions.

- In semi-arid areas, the selection of a proper drain depth is more critical than that of drain spacing. For the conditions considered, deeper drains perform better with regard to crop growth, soil salinization and groundwater table depth.

- The optimum drain depth from an agro-hydrological perspective for the *multiple cropping system* of the FDP-area is about 2.2 m. This drain depth will produce reasonably high crop yields ($T_{act}/T_{pot} > 0.90$) at a rather low drainage intensity and maintains the root zone salinity within acceptable limits. Drains shallower than this depth can cause severe yield reductions due to excessive soil water conditions particularly during relatively wet years. Drains deeper than this will increase the costs without any additional benefits.

- The present USBR and Smedema designs are rather conservative with high drainage intensities. The SWAP simulations show that the FDP-area can effectively be drained with 25 percent less drainage intensity ($q_{drain}/\Delta h$) than the other two drainage designs provided no operational or maintenance constraints are present. This design may also reduce the costs considerably.

- These findings are based on a fixed irrigation schedule (12 irrigations or 780 mm of irrigation water per year) and the assumption that a sufficient amount of good quality canal water is available for irrigation. However, under the circumstances, when quality and/or quantity of irrigation water is not optimal, irrigation schedules should be adjusted accordingly. These aspects of water management will be discussed in detail in Chapter 6.

- Drainage needs of irrigated areas are much dependent on the irrigation component. Therefore drainage systems in these areas should be designed taking into account the interactions between irrigation and drainage. Non steady-state approaches like SWAP make it possible to study the complex soil-crop-climate interactions and to predict the effect of different drainage designs on water and salt movement in the root zone and their ultimate effect on crop yields.

# 6 EFFECTS OF IRRIGATION WATER CONSERVATION ON CROP PRODUCTION AND ENVIRONMENT[1]

## Abstract

As water is becoming a scarcer commodity, savings in the irrigation sector could enhance water development in areas currently not being irrigated, and arrest the rapid environmental degradation due to waterlogging in arid zones. This Chapter investigates possible water reductions for wheat and cotton crops under shallow groundwater table conditions prevailing in the Fourth Drainage Project (FDP). The simulations are performed for both drained and un-drained conditions considering three different irrigation water qualities. The results indicate that as far as good quality canal water is available, a reduced application to wheat (195 mm) and cotton (260 mm) will maintain the soil sustainability under both drained and un-drained conditions. When farmers have no option other than conjunctive use or using tubewell water, they should apply more water (wheat 325 mm; cotton 325 mm). However, this will only be applicable to the areas where proper subsurface drainage systems are present. For un-drained areas, this strategy will not be suitable therefore other options such as growing more salt tolerant crops should be encouraged. Drainage can not solve the salinity build up problem under all circumstances because relatively dry monsoons provide insufficient leaching water, and salts added by tubewell irrigation can only be evacuated from the soil profile if the drainage system is very intense. Reduced irrigation inputs is a proper short-term solution, although the wheat production tends to decline in all areas without a drainage system, even when irrigated with the canal water. Large scale drainage investments associated with adjusted irrigation planning seem unavoidable in the long run.

## 6.1 Introduction

In the (semi-) arid climates, irrigation is often essential to achieve economically viable crop productions. Benefits from irrigation may be partially offset by detrimental effects of rising groundwater tables and soil salinization. Inefficient water delivery systems and poor on-farm irrigation techniques can waste a fair amount of water as deep percolation. This not only reduces the water availability to other crops but also increases the drainage requirements, which can be an economical burden and an environmental problem for disposing of effluent, especially when there is no outlet to the sea such as in the Punjab. A fragile equilibrium between leaching, root water uptake and groundwater interactions exists in (semi-) arid climates and salinized soils.

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[1] Adapted version of Sarwar, A. and W.G.M. Bastiaanssen, 2000. Long-term effects of irrigation water conservation on crop production and environment in semi-arid areas. *ASCE Irrigation and Drainage Engineering (Submitted)*.

This makes the irrigation management more complex and important than in other irrigation conditions. It necessitates precise calculations of irrigation and leaching processes to halt environmental degradation and foster crop production.

Irrigation scheduling is one of the important tools to achieve efficient use of water on the farm. It is defined as the process of forecasting the optimum amount and the optimum time of irrigation application (Fereres, 1996). The concept of irrigation scheduling received widespread emphasis some three decades ago. Initially, it was defined as a method of measuring soil water status for deciding when to irrigate. The amount of water applied was generally determined by the method of irrigation and the soil water holding capacity. At that time, water resources availablility was high and groundwater tables were deep. Jensen (1969, 1975) proposed to accomplish irrigation scheduling by using computers. Since then considerable progress has been made to refine irrigation planning and investigate the role of drainage systems, as irrigation and drainage issues can not be separated.

Despite all scientific progress, scheduling practices witnessed in the field are based on maximum water holding capacity or, worse, on the maximum amount of water a farmer can capture. Farmers around the world commonly use plant symptoms as an indicator of when to irrigate (Clyma, 1996). Hill and Allen (1995) found that farmers in Pakistan usually do not plan their irrigations in advance. Their decision mainly depends upon the visual plant stress indicators and the instant availability of water in the canal system being related to the reliability of the irrigation service. Trimmer (1990) concluded that farmers in Pakistan do not have sufficient knowledge of irrigation scheduling. Therefore present irrigation practices of farmers include a tendency to over-irrigate, whereas the opposite should be accomplished. These farm management practices have also been noticed in similar field conditions in Haryana, India (Jacobs et al., 1997).

Recommended irrigation schedules from the educated community are mainly based on the guidelines recommended by FAO (Smith, 1995) and field experiments conducted by local Agricultural Departments. These guidelines are very generic, and do not take into account the groundwater contribution to crop evapotranspiration, and consider irrigation and precipitation as the only source of water in the calculation of irrigation water requirement for crops. Drainage systems are–no–doubt required to control rising groundwater tables, but have the drawback of being expensive to install and producing highly saline effluents, which must be properly disposed of. The need for installing drainage systems may be avoided by reducing the irrigation water applications and allowing the crop to draw maximum water from the groundwater (Singh and Singh, 1997).

Dynamic simulation models that can calculate soil water and solute transfer originating from all water resources in combination with crop growth, are useful tools to provide a rapid, flexible and relatively inexpensive means of estimating the effects of various irrigation management practices on crop production under a variety of climatic and physical conditions (Bradford and Letey, 1992; Teixeira et al., 1995). These tools can be used to derive guidelines and examples, which could be transferred to farmers through extension workers. The main objective of this study was to revise irrigation planning based on maximum irrigation water savings for wheat and cotton crops for the shallow groundwater table conditions prevailing in the Fourth Drainage Project (FDP) within the context of the present rotational irrigation system. The calibrated model SWAP (Chapter 4) was used to determine water conservation strategies. The best irrigation water conservation practices were compared with the farmers' present irrigation practices to evaluate the long-term consequences of water conservation on crop transpiration, soil salinity, depth to groundwater table and the drainage requirements.

## 6.2 Modeling farmers present irrigation practices

Studies conducted in the FDP-area have shown that the average number of irrigations for wheat ranged between three to six and four to six for cotton (Raza and Choudhry, 1998). These irrigations are in addition to one pre-sowing irrigation, which most of the farmers apply to ensure favourable moisture conditions for seed germination. To simulate farmers irrigation practices, five irrigations for wheat as well as for cotton are schematized in addition to one pre-sowing irrigation for each crop. Farmers apply more water (80 mm) during pre-sowing irrigation to reduce root zone salinity. All together, twelve irrigations totalling 810 mm in a growing year are applied independent of water quality as to demonstrate the effects of canal and tubewell water. The first irrigation to wheat was applied three weeks after sowing, and to cotton, six weeks after sowing. As the behaviour of individual farmers is difficult to translate into an average condition, subsequent irrigations to wheat and cotton were distributed uniformly over the growing season.

SWAP offers different options for the irrigation timing and application depth criteria. In this study, a fixed interval of one week in between consecutive irrigation applications and a fixed depth of 65 mm were taken to comply with the rotational *warabandi* system characteristics. The initial soil water profile was adapted to each scenario by achieving zero annual change in water storage. The initial soil salinity concentrations were derived from field measurements. The average electrical conductivity ($EC_e$) of the soil profile was taken as 2 dS $m^{-1}$ or 2700 g $m^{-3}$ (Raza and Choudhry, 1998).

## 6.3 Performance indicators

As our ultimate objective is to maximize crop yields with a minimum of canal water resources, maintaining an acceptable relative transpiration ($T_{act}/T_{pot}$), is mandatory. Since $T_{act}/T_{pot}$ takes into account the effect of both soil water and salinity, it was used as an indicator to reflect the overall conditions in the unsaturated zone and their effect on crop yield. The effects of soil salinization on the relative transpiration are not immediately apparent because of their different time scales: Salinization is a gradual process whereas crop transpiration varies from day-to-day with state variables. To ensure long-term sustainability of irrigated agriculture, salt build up in the root zone should be kept within tolerable limits. To quantify the impact of different irrigation schedules on root zone salinity, two different indicators were identified (Bastiaanssen et al., 1996). The threshold values of different performance indicators used for this study are given below.

- *Relative transpiration* ($T_{act}/T_{pot}$) is considered equivalent to relative crop yields (see Chapter 3). Because the FDP-area has a water scarce environment, a limited water stress may be allowed. For these simulations, it has been assumed that $T_{act}/T_{pot} \geq 0.90$ is acceptable for both cotton and wheat crops. It is certain that crop yield is not affected by the water factor alone, but inclusion of other factors (i.e. crop varieties, fertilisers, disease and pest management) is beyond the scope of this study. Therefore these non-water factors are considered to be optimal.
- *Salt Storage Change* ($SSC = \Delta C/C_{initial}$) helps in estimating whether the considered irrigation schedules are increasing or decreasing the salt storage in the root zone. The salt storage change over a certain period is $\Delta C$ and $C_{initial}$ is the salt storage at the onset of the time frame considered. The value of $SSC$ is determined for 1.0 m soil layer below the soil surface. Ideally, $SSC$ should be zero, however, in view of saline groundwater conditions, a small build up of salts is tolerable. It is assumed that $SSC \leq 0.05$ (5% increase in salt storage from the initial value) over a period of 15-years is acceptable.
- *Salinity Hazard Index* ($SHI$) defined as $(EC_e^{0-1}-EC_e^{min})/(EC_e^{max}-EC_e^{min})$ is used to quantify the harmful effects of different salinity levels in the root zone on crop yield. Where $EC_e^{0-1}$ is the average salinity calculated over a 1.0 m depth of root

zone, $EC_e^{min}$ is the permissible electrical conductivity of soil saturation extract for 100 percent crop yield and $EC_e^{max}$ is the permissible electrical conductivity of soil saturation extract for zero percent crop yield. The value of *SHI* varies between 0 to 1. Negative values are taken equal to zero. For this study, $SHI \leq 0.10$, which corresponds to 10% yield reduction due to build up of root zone salinity is considered acceptable. $EC_e^{min}$ values for wheat and cotton were taken as 6.0 and 7.7 dS $m^{-1}$, respectively, whereas $EC_e^{max}$ values for wheat and cotton were taken as 20 dS $m^{-1}$ and 27 dS $m^{-1}$, respectively (after Doorenbos and Pruitt, 1977).

## 6.4 Determining water conservation schedules

***Irrigation planning of the average year***

The irrigation schedules for reduced water application were determined first for an *average year* to comply with the rigid water application characteristic of the *warabandi* system. The *average year* was selected on the basis of annual rainfall data of 15-years (1980-94). The average annual rainfall of this series was 375 mm. Rainfall for 1987 with 363 mm was the closest (45 percent probability of exceedance with a return period of 2.5 years). The daily weather data (i.e. maximum and minimum temperatures, wind speed, sunshine hours) of 1987 were taken to get a matching reference evapotranspiration ($ET_o$) using the Priestly and Taylor (1972) method. The $ET_o$ is substantially smaller (1110 mm) and more realistic than the 2000 mm resulting from Pan evaporation measurements. The average monthly rainfall and $ET_o$ for the *average year* are shown in Figure 6.1.

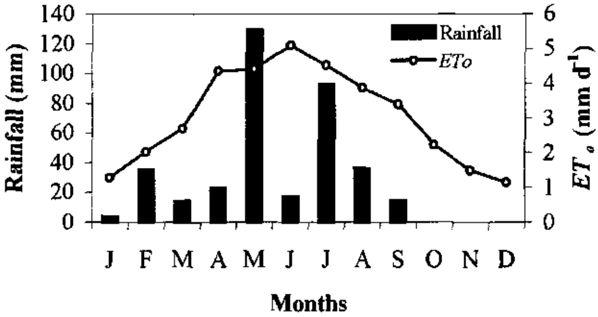

**Figure 6.1.** Average monthly rainfall and Priestly-Taylor $ET_o$ for the *average* year of 1987.

For simulations of the average year, the SWAP irrigation schedule found that three irrigations (195 mm) for wheat and four (260 mm) for cotton are sufficient to obtain $T_{act}/T_{pot}$ values higher than 0.90. This irrigation schedule was also successful in maintaining the salt storage change and salinity hazard index values within acceptable limits. A comparison between reduced water application and the present farmers' irrigation practices is presented in Table 6.1. The irrigation amounts shown in Table 6.1 are in addition to rainfall and pre-sowing irrigations.

**Table 6.1.** Comparison of water conservation schedules ('reduced') and the farmers' present irrigation practices.

| Parameters | Wheat | | Cotton | |
|---|---|---|---|---|
| | Reduced | Farmers' practices | Reduced | Farmers' practices |
| No. of irrigations | 3 | 5 | 4 | 5 |
| Total irrigation water applied (mm) | 195 | 325 | 260 | 325 |
| Actual evapotranspiration (mm) | 396 | - | 610 | - |
| Average irrigation interval (days) | 50 | 30 | 46 | 30 |
| Days of first irrigation after sowing | 45 | 21 | 40 | 45 |

Table 6.1 shows that farmers in the FDP-area are applying higher irrigation amounts to wheat and cotton crops as compared to what is theoretically necessary to meet the crop and environmental conditions described before. The difference is more pronounced for wheat than for cotton. The conservation technique - applied to the *warabandi* context - suggests an average irrigation interval of about six weeks for wheat and cotton as compared to four weeks presently practised by farmers. Table 6.1 shows that farmers are applying the first irrigation to wheat 24 days earlier and for cotton five days later than under the water conservation schedule. The simulation results show that the first irrigation to wheat crop can be delayed because the winter period from December to January has low evapotranspiration. In this way farmers can save a considerable amount of water, which is otherwise not used for root water uptake, but which pushes the groundwater table upwards.

## 6.5 Long-term evaluation of irrigation schedules

Long-term (1980-94) simulations were performed in order to predict the effect of irrigation schedules identified in Table 6.1 on crop transpiration, soil salinity, groundwater table behaviour and drainage requirements. Variations in water quality on the irrigated crops were incorporated. As farmers of the FDP-area are using tubewell water for irrigation, three different irrigation water qualities were considered: Irrigation with the good quality canal water (EC = 0.3 dS m$^{-1}$), irrigation with the blended canal and tubewell water (EC = 1.5 dS m$^{-1}$) and irrigation with tubewell water only (EC = 3.0 dS m$^{-1}$). Two conditions related to groundwater table depths prevailing in the FDP-area were considered:

- The first condition represents the area where an adequate sub-surface drainage system is present, which keeps the groundwater table at desired depths. The characteristics of this adequate drainage design are taken as a drain depth of 2.2 m with a drain spacing of 500 m (see Chapter 5), which approximately coincide with the present drainage design of the Fourth Drainage Project i.e. a drain depth of 2.4 m and a drain spacing of 495 m.

- The second condition is related to the areas where no drainage system is present and the groundwater is shallow and saline. For this situation, the groundwater table was initially assumed at a depth of 2.0 m and was allowed to fluctuate over the growing season depending upon the amount of irrigation, the irrigation water quality and rainfall. The electrical conductivity (EC) of the groundwater was taken as 3.5 dS m$^{-1}$ or 4700 g m$^{-3}$.

A summary of different water management scenarios simulated is given in Table 6.2.

**Table 6.2.** Description of different water management scenarios used for the long-term analysis with the SWAP model. CW = Canal Water, CTW = Canal + Tubewell Water and TW = Tubewell Water.

| Irrigation applications | With drainage | Without drainage | Irrigation water qualities | | |
|---|---|---|---|---|---|
| | | | CW | CTW | TW |
| Water conservation schedule | ✓ | | ✓ | ✓ | ✓ |
| | | ✓ | ✓ | ✓ | ✓ |
| Farmers irrigation practices | ✓ | | ✓ | ✓ | ✓ |
| | | ✓ | ✓ | ✓ | ✓ |

## 6.6 Results and discussion

***Water conservation schedule-with drainage***

The relative transpiration of wheat and cotton as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system are illustrated in Figure 6.2. The simulations were performed for a continuous period of 15 wheat-cotton crop rotations. Afterwards, the results of wheat and cotton crops were presented separately to quantify the effect of different irrigation management strategies on relative transpiration of wheat and cotton individually.

Figure 6.2 shows that there is a clear effect of different irrigation water qualities on crop transpiration. When good quality canal water is used for irrigation, relative transpiration higher than 0.90 can often be maintained both for wheat and cotton crops during 15 years. However, when canal water is used in conjunction with the tubewell water (1.5 dS $m^{-1}$), acceptable crop transpiration for cotton can be obtained, but not for wheat (7 out of 15 years has $T_{act}/T_{pot} < 0.90$). The simulation results show that the use of poor quality tubewell water (3.0 dS $m^{-1}$) for irrigation will lead to a considerable reduction in crop yield with $T_{act}/T_{pot}$ values as low as 0.60, both for wheat and cotton.

The decrease in relative transpiration due to poor quality tubewell water is approximately 13 percent if good quality canal water is taken as reference. The reductions are more for wheat than for cotton. Two factors cause cotton crop to suffer less under these conditions: Firstly, cotton is more salt tolerant than wheat and secondly salinity levels in the wet cotton season are generally lower due to monsoon rains. The temporal variations in $T_{act}/T_{pot}$ over the simulation period can be ascribed to differences in annual precipitation. The year 1985 with 217-mm precipitation introduced a significant drop in $T_{act}/T_{pot}$. *This reveals that years with a below-average precipitation enhance soil salinization in the root zone immediately, which affects water uptake by roots.*

The considerable reductions in the relative transpiration for the poor quality (1.5 and 3.0 dS $m^{-1}$) irrigation waters are mainly due to increases in the root zone salinity. This implies that less irrigation water is used for crop transpiration and indicates that salts are building up. The average annual amount of drainage water produced under optimized irrigation schedules with the canal water irrigation is only 20 mm, which did not provide enough leaching ($SSC = +0.03$). The simulated average annual water and salt balances for wheat-cotton rotation for three different irrigation water qualities are presented in Table 6.3.

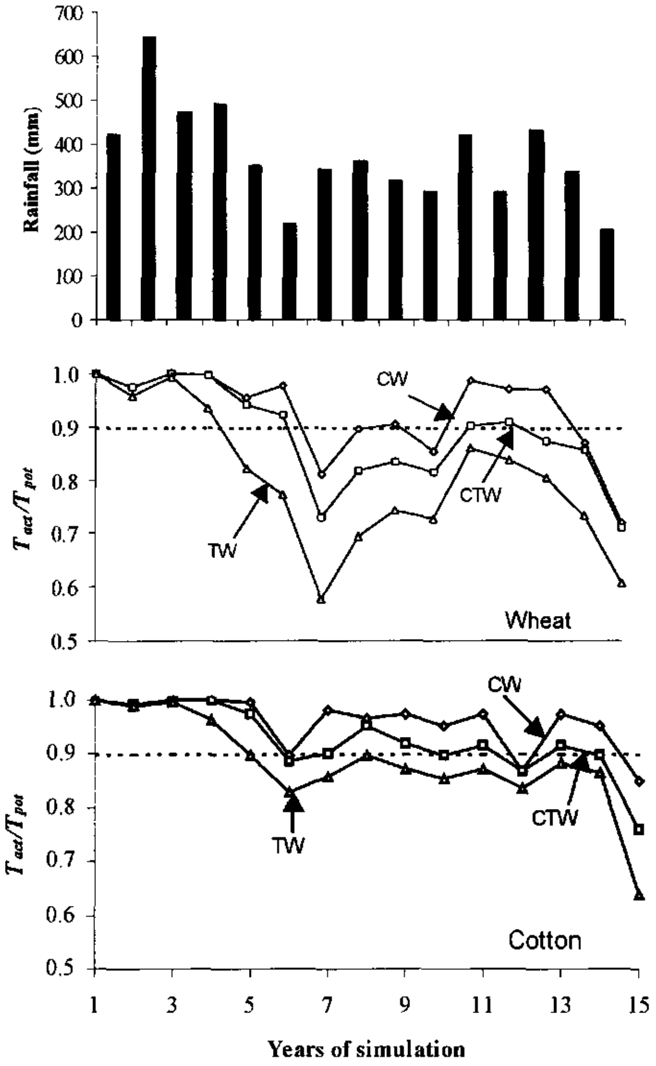

**Figure 6.2.** Rainfall and relative transpiration ($T_{act}/T_{pot}$) of wheat and cotton based on the water conservation schedule as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system for a period of 15 years (1980-94). CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. Dotted line indicates the acceptable threshold value.

**Table 6.3.** Simulated average annual water and salt balances for wheat-cotton rotation based on the water conservation schedule as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system. CW = Canal Water; CTW=Canal+Tubewell Water; TW = Tubewell Water. The $T_{pot}$ is 901 mm and the $E_{pot}$ is 367 mm.

| Treatment | *Rainfall* (mm) | *Irrigation* (mm) | $T_{act}$ (cm) | $E_{act}$ (mm) | *Drainage* (mm) | $\Delta W$ (mm) | *SSC* (-) |
|---|---|---|---|---|---|---|---|
| CW | 375 | 615 | 851 | 159 | 20.0 | -52.1 | +0.03 |
| CTW | 375 | 615 | 837 | 162 | 20.5 | -22.9 | +4.53 |
| TW | 375 | 615 | 811 | 165 | 30.8 | +9.6 | +6.81 |

Table 6.3 shows that the solutes, supplied through the irrigation water are seen to suppress the crop transpiration (by 2 to 5 percent) and enhance the soil evaporation rate, $E_{act}$, by (2 to 4 percent) since the surface remains wet for longer periods as compared to the CW scenario. The change in soil water storage, $\Delta W$, reflects the net wetting/drying effects. For TW scenarios, $\Delta W$ is positive due to increased soil salinity and reduced transpiration rates. The value of *SSC* for CW treatment was 0.03 (3 percent increase in salt storage) over the simulation period of 15-years, which is acceptable. However, for CTW and TW treatments, *SSC* values are extremely high and show severe environmental destructions, even if a drainage system is present. *This shows that drainage systems are no guarantee for success if the irrigation component is not properly adjusted.*

Figure 6.3 presents the trends of root zone salinity. The $EC_e$ values represent the average root zone salinity calculated over a 1.0 m deep root zone at the end of each simulation year. Irrigations with the canal water maintain the root zone salinity below a threshold value of 4.0 dS $m^{-1}$ although a slightly increasing trend may be witnessed (*SSC* = +0.03). A value of 4.0 dS $m^{-1}$ is usually considered for non-saline soils in Pakistan (Mulk, 1993). For the poor quality (1.5 and 3.0 dS $m^{-1}$) irrigation waters, the root zone salinity increases sharply in the first six years and then this salinization process reaches to a certain equilibrium state with more or less a constant salt storage.

The temporal development of *salinity hazard index* (*SHI*) for wheat-cotton rotation for three different irrigation water treatments is shown in Figure 6.4. As wheat and cotton crops respond differently to the increased root zone salinity due to their salt tolerance characteristics, the *SHI* was first calculated separately for wheat and cotton crops and then averaged to show the overall effect of salinity build up on crop yield. Although *SSC* for CW treatment was slightly positive (Table 6.3), *SHI* remained zero. The CTW and TW treatments, will result in an increase in *SHI* with the superiority of TW. Remarkable are the step changes occurring during elongated dry spells.

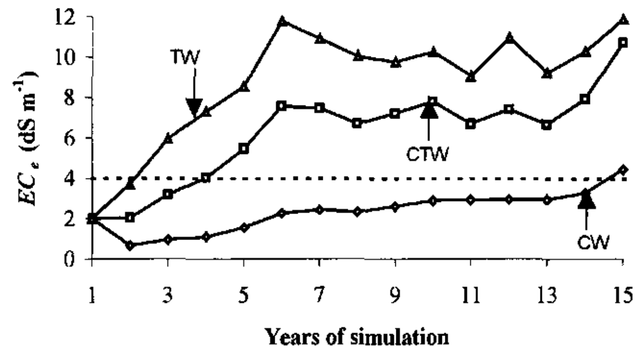

**Figure 6.3.** Temporal development of average root zone salinity ($EC_e$) based on the water conservation schedule as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system. CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. Dotted line indicates the acceptable threshold value.

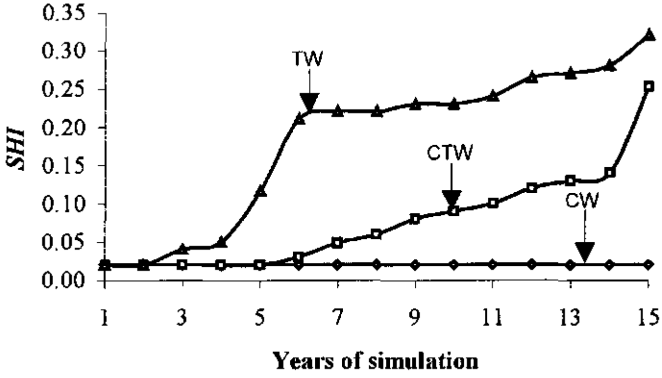

**Figure 6.4.** Temporal development of the *salinity hazard index* (*SHI*) for wheat-cotton rotation based on the water conservation schedule as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system. CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water.

### *Water conservation schedule-without drainage*

Figure 6.5 illustrates the relative transpiration ($T_{act}/T_{pot}$) of wheat and cotton based on the water conservation schedule as influenced by three different irrigation water qualities (Table 6.2) in the *absence* of a subsurface drainage system. This combination represents the majority in the Punjab, besides the fact that farmers irrigate more than the annual 615 mm applicable to water conservation.

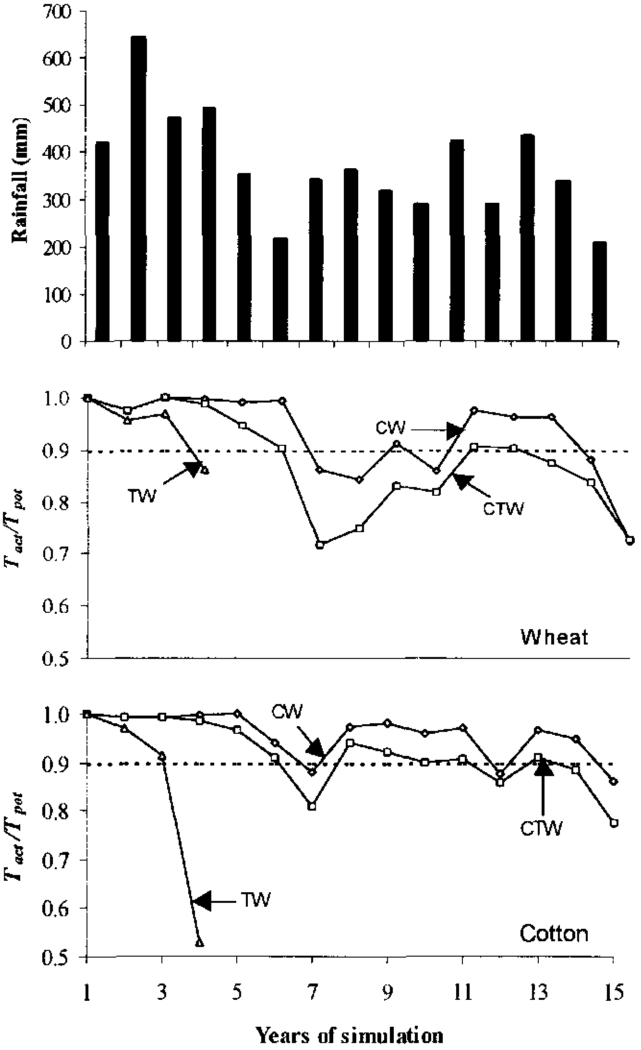

**Figure 6.5.** Rainfall and relative transpiration ($T_{act}/T_{pot}$) of wheat and cotton based on the water conservation schedule as influenced by three different irrigation water qualities in the *absence* of a subsurface drainage system for a period of 15 years (1980-94). CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. Dotted line indicates the acceptable threshold value.

The results indicate that the relative transpiration for wheat collapsed after a few years with below average precipitation in the middle of the eighties. The reductions in $T_{act}/T_{pot}$ values during the years six to ten are mainly due to increasing soil salinity in the root zone (Figure 6.6). The groundwater table started declining for CW and CTW (Figure 6.7) as a result of capillary rise to supplement the low precipitation. It is apparent that the crop *productivity* reduces with time, even when good quality water irrigations are supplied. The cotton crop seems less affected under these conditions as was observed under drained conditions.

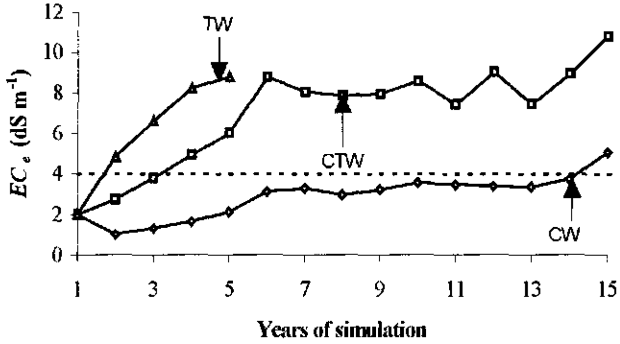

**Figure 6.6.** Temporal development of average root zone salinity ($EC_e$) based on the water conservation schedule as influenced by three different irrigation water qualities in the *absence* of a subsurface drainage system. CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. Dotted line indicates the acceptable threshold value.

The long-term simulations revealed that for tubewell water irrigations, the effect of a shallow groundwater table is very pronounced. Salts are added by capillary rise as well as through tubewell irrigations. As plants are constrained in their root water uptake under highly saline conditions, infiltrated water pushes the groundwater table up. This phenomenon not only increased the root zone salinity (Figure 6.6) but also created waterlogged conditions (Figure 6.7). For these shallow saline groundwater table areas, leaching of salts by means of poor quality irrigation water will not be suitable and the lands will go out of production even faster. Therefore, other options like growing more salt tolerant crops, eucalyptus or phreophytes should be adapted.

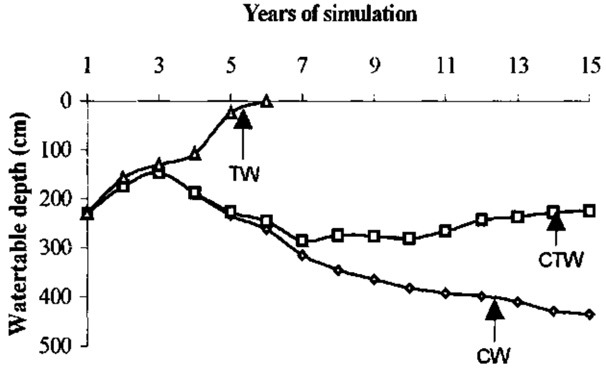

**Figure 6.7.** Temporal development of groundwater tables based on the water conservation schedule as influenced by three irrigation water qualities in the *absence* of a subsurface drainage system. CW= Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water

***Farmers present irrigation practices-with drainage***

Figure 6.8 shows that with the farmers present irrigation practices, maximum relative transpiration ($T_{act}/T_{pot}$) for both wheat and cotton crops could be obtained irrespective of water quality issues. The total depth of water applied by farmers per year is 810 mm, being 25 percent higher than the water conservation schedule with 615 mm including pre-sowing irrigation.

The increased water application did not result in a proportionate increase in $T_{act}/T_{pot}$ values. The relative transpiration is five percent higher for wheat and only three percent for cotton as compared to the values obtained by water conservation schedule. However, it did result in increased drainage requirements (130 mm) (Table 6.4) as compared to 20 mm for the water conservation strategy (Table 6.3) causing inefficient use of irrigation water. However, this extra amount of water provides sufficient leaching to maintain root zone salinity below 4.0 dS m$^{-1}$ (Figure 6.9) as far as canal water is used for irrigation. For CTW and TW treatments, only a slight reduction in $T_{act}/T_{pot}$ values occurred due to increased root zone salinity. The simulated cumulative average annual water and salt balances for wheat-cotton rotation for three different irrigation water are given in Table 6.4.

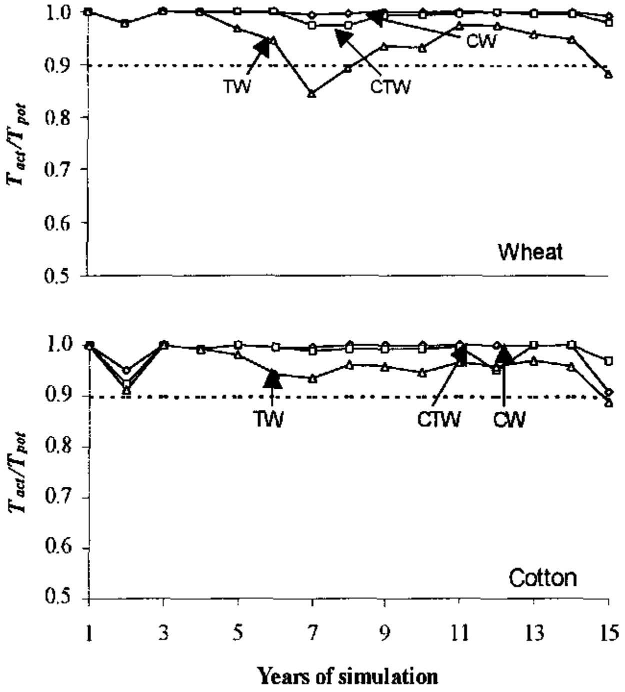

**Figure 6.8.** Relative transpiration ($T_{act}/T_{pot}$) of wheat and cotton based on the farmers present irrigation practices as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system for a period of 15 years (1980-94). CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. Dotted line indicates the acceptable threshold value.

**Table 6.4.** Simulated average annual water and salt balances for wheat and cotton based on the farmers present irrigation practices as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system. CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. The $T_{pot}$ is 910 and $E_{pot}$ is 367 mm.

| Treatment | *Rainfall* (mm) | *Irrigation* (mm) | $T_{act}$ (mm) | $E_{act}$ (mm) | *Drainage* (mm) | $\Delta W$ (mm) | *SSC* (-) |
|---|---|---|---|---|---|---|---|
| CW | 375 | 810 | 894 | 177 | 129 | -7.6 | -0.26 |
| CTW | 375 | 810 | 891 | 178 | 130 | -6.2 | +2.78 |
| TW | 375 | 810 | 859 | 180 | 156 | -0.9 | +5.15 |

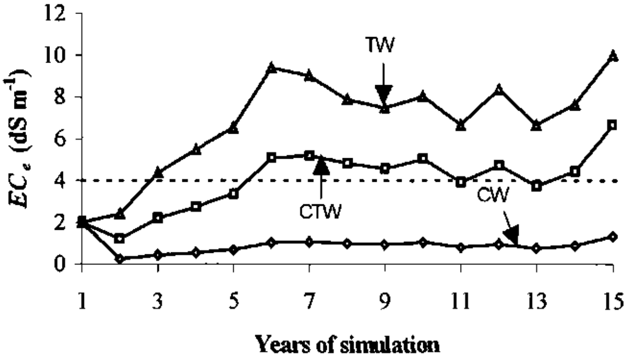

**Figure 6.9.** Temporal development of average root zone salinity ($EC_e$) based on the farmers present irrigation practices as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system. CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water. Dotted line indicates the acceptable threshold value.

Table 6.4 shows that tubewell water depressed the crop transpiration by about five percent as compared to canal water irrigation. Interesting to note is that the *salt storage change* becomes negative only in the case of CW, while for the other two treatments it remained positive despite about six times more leaching through drainage as compared to the water conservation scenario. This shows that salts added by poor quality irrigation water were in excess of the amount of salts removed through drainage. *This implies that applying more frequent irrigations with saline water does not help in taking away the salts from the crop roots and that this scenario is not sustainable*. The *SHI* for CW remained zero (not shown), while for other two treatments a slightly increasing trend was observed with TW leading CTW.

### *Farmers present irrigation practices-without drainage*

The long-term simulations show that the farmers present irrigation practices are not suitable for adaptation in the areas where no drainage system is present and groundwater is shallow and saline. *Application of five irrigations for wheat and five for cotton will raise the groundwater table to the surface level in just two to three years, making crop production very difficult.* Therefore results of these simulations are not presented here.

For sustainable crop production in these areas without installing a drainage system, irrigation applications should be substantially reduced to minimize percolation losses and to enhance capillary drying of the soil. The best irrigation strategy under shallow water table conditions could be to irrigate at relatively high stress levels and the most critical growth stages that do not reduce yields. Prathapar and Sarwar (1999) have shown that in areas where no drainage systems are present and groundwater is shallow and saline, the quantities of irrigation water can be reduced to meet 80 percent of the crop evapotranspiration without reducing crop yields and without increasing soil salinization.

***Productivity of water***

Where water is a constraining resource, yield per unit of water becomes more important. Different indicators to relate crop production per unit of water exist. Most commonly used are 'yield per unit of water evapotranspired ($Y_{act}/ET_{act}$)' and 'yield per unit of irrigation water supply ($Y_{act}/I_{rr}$) (Molden et al., 1998). Droogers and Kite (1999) expressed the *productivity* of water per unit 1) evapotranspiration ($Y_{act}/ET_{act}$), 2) transpiration ($Y_{act}/T_{act}$), 3) irrigation water supply ($Y_{act}/I_{rr}$) and 4) depletion using the concept of relative transpiration for estimating crop yields ($Y_{act}/(ET_{act} + D_r)$. In our case, depletion is defined as the sum of actual evapotranspiration ($ET_{act}$) and amount of drainage ($D_r$). The maximum attainable yields in the FDP-area for wheat and cotton are taken as 3350 kg ha$^{-1}$ and 1950 kg ha$^{-1}$, respectively (Bastiaanssen and Ali, 2000). Table 6.5 shows the comparison of different productivities of water for wheat and cotton crops for water conservation schedule and farmers present irrigation practices.

**Table 6.5.** Comparison of different productivities of water for water conservation schedule and farmers present irrigation practices in the *presence* of a subsurface drainage system.

| | Water conservation scenario | | Farmers present irrigation practices | |
|---|---|---|---|---|
| | Wheat | Cotton | Wheat | Cotton |
| Precipitation (mm) | 106 | 270 | 106 | 270 |
| Irrigation, $I_{rr}$ (mm) | 195 | 260 | 325 | 325 |
| Actual transpiration, $T_{act}$ (mm) | 327 | 524 | 353 | 541 |
| Actual evaporation, $E_{act}$ (mm) | 54 | 109 | 50 | 177 |
| Actual evapotranspiration, $ET_{act}$ (mm) | 381 | 633 | 403 | 718 |
| Drainage, $D_r$ (mm) | 5 | 15 | 28 | 126 |
| Actual estimated yield, $Y_{act}$ (kg ha$^{-1}$) | 3070 | 1880 | 3340 | 1940 |
| | | | | |
| $Y_{act}/T_{act}$ (kg m$^{-3}$) | 0.94 | 0.36 | 0.95 | 0.36 |
| $Y_{act}/ET_{act}$ (kg m$^{-3}$) | 0.81 | 0.30 | 0.81 | 0.30 |
| $Y_{act}/I_{rr}$ (kg m$^{-3}$) | 1.57 | 0.72 | 1.03 | 0.60 |
| $Y_{act}/(ET_{act} + D_r)$ (kg m$^{-3}$) | 0.80 | 0.29 | 0.77 | 0.23 |

In general, *productivity* of water is higher in case of water conservation schedule as compared to farmers present irrigation practices. Table 6.5 shows that the actual yields obtained under farmers present irrigation practices are 8 percent higher for wheat and only three percent for cotton as compared to yields obtained under the water conservation schedule. The yield per unit of irrigation water supply for the water conservation schedule is 35 percent higher for wheat and 17 percent for cotton as compared to farmers present irrigation practices. This reflects higher efficiency of canal water use under water conservation schedule. The yield per unit of depletion is also significantly higher (4 percent for wheat and 20 percent for cotton) for water conservation schedule as compared to farmers present irrigation practices under drained conditions.

## 6.7 Conclusions

The farmers present irrigation practices are aimed at applying maximum water for maximum crop production. The law of the increased benefits does not apply to salinized land threatened by a rising groundwater table. The opposite is true: Unplanned irrigation applications can ruin the land resources within a time span of several years. Careful management is therefor a pre-requisite to use the resources in a productive and sustainable way.

Irrigations with good quality canal water shows that three post-sowing irrigations to wheat and four to cotton (with each irrigation application depth being 65 mm) are sufficient to maintain reasonably high relative transpiration ($T_{act}/T_{pot}$) for shallow groundwater table conditions of the FDP-area under both drained and un-drained conditions. Such water conservation schedule will minimize deep percolation and keep the *salt storage change* (*SSC*) and *salinity hazard index* (*SHI*) within acceptable limits. Farmers of the FDP-area can save up to 25 percent of the scarce canal irrigation water each year, water that otherwise will be drained. This saved water can be used for subsequent utilization on the adjoining 24 percent of the un-irrigated FDP-areas (SMO, 1994). For poor quality irrigation waters (mixed or tubewell only), this water conservation schedule will be insufficient. Hence, water savings are applicable to canal water irrigations only. Table 6.6 summarizes the water management performance indicators for different scenarios tested in this study. The values given are only for drained conditions and are based on 15-year averages. The *SSC* values, however, reflect the *salt storage change* over the entire simulation period of 15-years.

**Table 6.6.** Summary of water management performance indicators for the water conservation schedule and the farmers present irrigation practices as influenced by three different irrigation water qualities in the *presence* of a subsurface drainage system based on 15 year averages. CW = Canal Water; CTW = Canal+Tubewell Water; TW = Tubewell Water.

| Performance indicators | Water conservation schedule | | | Farmers present irrigation practices | | |
|---|---|---|---|---|---|---|
| | CW | CTW | TW | CW | CTW | TW |
| Relative transpiration ($T_{act}/T_{pot}$) | 0.94 | 0.93 | 0.90 | 0.99 | 0.99 | 0.95 |
| Salt Storage Change (*SSC*) | +0.03 | +4.53 | +6.81 | -0.26 | +2.78 | +5.15 |
| Salinity Hazard Index (*SHI*) | 0 | 0.08 | 0.08 | 0 | 0.02 | 0.05 |
| Drainage ($D_r$) (mm yr$^{-1}$) | 20 | 21 | 31 | 129 | 130 | 156 |

The model simulations have indicated that for un-drained areas, leaching of salts by means of poor quality irrigation water will not be feasible and the lands will go out of production even at a faster rate due to rising groundwater tables. Therefore, in these areas, other options like growing more salt tolerant crops such as eucalyptus or phreophytes should be considered. The construction of drainage systems is an economical burden for rural communities. It is nevertheless necessary, but not a guarantee for successful water management. The CTW and TW treatments showed an increasing trend in *salt storage change* (*SSC*) and *salinity hazard index* (*SHI*) despite a high leaching induced by drainage systems. This essentially affects wheat with seven out of fifteen years having a production below desired level.

The temporal variations in relative transpiration and root zone salinity revealed that the deviations in annual precipitation from an *average* year are very critical to maintain fragile equilibrium between different water and salt balance components. Ideally, water allocation and distribution should be based on crop evapotranspiration, precipitation and salinity build up and reviewed yearly. However, for the present fixed rotational irrigation system, this will remain a constraint.

Due to the population expansion in Pakistan there exists a need for more food, while the per capita irrigation water availability is diminishing. The fact of having less irrigation water of good quality available by the withdrawal of water resources to urban areas should result in a 25 percent reduction of canal supplies to farmers. Under these conditions, adaptation of water conservation strategies is a better option than recommending farmers to irrigate with tubewell water, unless the groundwater quality is acceptable. Drainage helps long-term solutions but success is not guaranteed and some deviations from the optimum should be accepted.

From the above conclusions, guidelines for the extension workers can be drawn for the safe and sustainable use of different quality irrigation waters (Table 6.7). These guidelines are based on the taken simulation period of 15 years considering wheat-cotton crop rotation. The yield reductions are assumed to be affected only due to excessive moisture and/or salinity conditions. Other non-water factor such as nutrient availability, pests, weeds, disease control and cultural practices are considered as optimal.

**Table 6.7.** Management strategies for the safe and sustainable use of different quality irrigation waters under different groundwater table conditions for the FDP-area based on 15 year simulations with the SWAP model. CW = Canal Water, CTW = Canal + Tubewell Water, TW = Tubewell Water. Irrigation amounts to wheat and cotton crops represent post-sowing water applications (mm) in a growing season.

| Drainage conditions | Management strategies for different quality irrigation waters | | |
|---|---|---|---|
| | CW<br>(EC = 0.3 dS m$^{-1}$) | CTW<br>(EC = 1.5 dS m$^{-1}$) | TW<br>(EC = 3.0 dS m$^{-1}$) |
| Subsurface drainage | Reduced water application | Leaching feasible | Extra leaching not feasible<br>Grow salt tolerant crops |
| | Wheat = 195 mm<br>Cotton = 260 mm | Wheat = 325 mm<br>Cotton = 325 mm | Wheat = 325 mm<br>Cotton = 325 mm |
| No subsurface drainage | Reduced water application | Leaching not feasible<br>Grow salt tolerant crops | Install drainage systems or grow salt tolerant plants for reclamation e.g. eucalyptus |
| | Wheat = 195 mm<br>Cotton = 260 mm | Wheat = 195 mm<br>Cotton = 260 mm | |

# 7 EFFECTS OF IRRIGATION WATER DISTRIBUTION ON CROP PRODUCTION AND ENVIRONMENT[1]

## Abstract

This Chapter examines the response of three water delivery schedules, representing various levels of flexibility, on crop production, water saving, soil salinization, drainage requirements and groundwater table behavior. The calibrated SWAP model has been used as a tool. The evaluations were made for *un-restricted* and *restricted* water supply situations considering three different groundwater table conditions prevailing in the Fourth Drainage Project (FDP) of the Punjab, Pakistan. From the simulation results it is apparent that on average the effect of schedule flexibility on crop yields is not very significant. However, compared to a *fixed* schedule provided *un-restricted* canal water supplies are available, the *productivity* of irrigation water supply ($Y_{act}/I_{rr}$), is up to 30 percent higher for the *on-demand* schedule. The *on-demand* schedule capable of complying with the temporal variations in climate is also more effective in water saving, reducing drainage volumes and controlling rising groundwater tables. In the present water deficient environment of the Indus basin, the benefits of the *on-demand* schedule and a *fixed* schedule are comparable. In the *absence* of sufficient canal water supplies, infrastructure and a well-designed and effective monitoring and communication system, moving towards the *on-demand* system will be un-productive. For the long-term *sustainability* of the irrigation system, improvements in the performance of the present water allocations and on-farm water management practices seems to be more necessary.

## 7.1 Introduction

Increasing demand and decreasing water quality has put enormous pressure on the agriculture sector to use its available water resources more efficiently and to improve the *productivity* of water. These pressures are a result of the increasing demand for food and evermore limited possibilities for extension of irrigation to other areas due to scarcity of land and water resources and costs of development (Shanan, 1992). The growing scarcity of water has also increased the inter-sectoral competition for water, particularly from the municipal and industrial sectors. Thus, in future, irrigation's contribution to food security will have to come from improving existing systems and expanding the area under irrigation. This requires a major effort to improve irrigation management, operation and maintenance, rehabilitation and modernization of existing schemes.

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[1] Adapted version of Sarwar, A., W.G.M. Bastiaanssen and R.A. Feddes. 2000. Irrigation water distribution and long-term effects on crop and environment. *Agricultural Water Management (Submitted)*.

The allocation and distribution of water in an irrigation system are some of the most important activities found in agriculture because they require an understanding of the complex interactions between the physical, technical, socio-economical and organizational factors that uniquely affect each irrigation system. The present process of water allocation and distribution in Pakistan is based on the assumption that irrigation systems are homogenous (Renault and Godaliyada, 1999). This implies that generic rules for operation will lead to equivalent levels of performance whatever systems or subsystems are considered. The characteristics of an irrigation system, however, vary both in time and space (Steiner and Walter, 1993). The greatest challenge often faced by irrigation managers is to cope with the spatial diversity and temporal variability of their irrigation system. The spatial diversity includes cropping patterns, local convective rains, topography and soils, social organizations and management capacity. Temporal variability encompasses short-term changes in agro-climatic conditions, long-term changes in ecological conditions, degradation of hardware and management. Therefore in order to optimize *productivity* of water, a heterogeneous approach to operations is required to deal with the spatial diversity and temporal variability of the irrigation system. The word operation refers to both the manipulations of physical structures in the irrigation system to implement management decisions about water allocation and the schedules of delivery and distribution (Renault and Makin, 1999).

The large scale, low-supply schemes of Indo-Pak (Ganga and Indus) basins are characterized as 'protective irrigation'. This term is more related to water rights and has historically influenced the system's design and canal capacities. The major objective of 'protective irrigation' was to distribute the little water available to the greatest possible number of users to prevent crop failure and avoid famine (Jurriens and Mollinga, 1996). The major concerns regarding performance of irrigated agriculture in Pakistan are low crop yields and low water use efficiency. Among others, inequitable, untimely and non-assured canal water supplies are usually held responsible for this low performance (Shanan, 1992).

It must be realized that it is not just the volume of water delivered, but the way it is delivered controls the effective use of resources. It is generally argued that improvement in *productivity* primarily depends upon better matching irrigation supplies with crop demand. Therefore a more flexible scheduling system capable of distributing water in such a way that it is available in the quantities and at the times it is needed, is necessary for the optimization of crop production. In Pakistan, emphasis is also increasing for a change-over from the present fixed rotational system (based on proportionate division of water over available land) to a more crop demand-based irrigation management to achieve equitable and timely deliveries and efficient use of water (World Bank, 1992).

The discussions on the water division are usually based on the comparison of crop yields, development costs, management and infrastructural constraints and socio-political conditions (Merriam, 1992; Steiner and Walter, 1993; Wolters et al., 1997). However, very little attention is given to the long-term impacts of these proposed interventions on environmental parameters such as soil salinization, drainage requirements and groundwater table behavior. Therefore, the debates on the advantages and disadvantages of this change remain ambiguous due to the lack of necessary data to quantify this impact. In this Chapter the consequences of water delivery at the farm gate on crop production and environment will be evaluated using the calibrated SWAP model. The results of long-term SWAP model simulations to include weather anomalies will be described. Some opportunities and constraints for the introduction of a more flexible irrigation water distribution system in the Indus basin will also be discussed.

To systematically evaluate the impact of different water delivery schedules on crop production and environment, following performance indicators were used.

- *Relative transpiration* ($T_{act}/T_{pot}$) (see Chapter 6).
- *Salt Storage Change* ($SSC = \Delta C/C_{initial}$) (see Chapter 6).
- *Net flux at 250 cm depth leaving or entering the root zone* ($q_{250}$). This flux was considered as deep percolation and capillary rise. The deep percolation is represented by negative values and the capillary rise by positive values.
- *Productivity of irrigation water supply* (yield per unit of irrigation supply, $Y_{act}/I_{rr}$ (kg m$^{-3}$). where $Y_{act}$ (kg ha$^{-1}$) is the estimated actual yield and $I_{rr}$ (m$^{3}$ m$^{-2}$) is the depth of irrigation water applied. The maximum attainable yields in the FDP-area for wheat and cotton are taken as 3350 kg ha$^{-1}$ and 1950 kg ha$^{-1}$, respectively (Bastiaanssen and Ali, 2000).

## 7.2 Water delivery schedules studied

A water delivery schedule during an irrigation period is a sequence of regulations specifying the amount of irrigation water at each point in time for all recipients or groups of recipients in a distribution system. The water delivery schedules differ mainly in time period and flow re-adjustments and are usually based on the type of water allocation. Water allocations to tertiary units can either be supply-based or demand-based. Supply-based water allocations are based on proportional division of water over available land. In the case of demand-based water allocation, the actual or estimated crop water requirements form the basis of water distribution.

Of crucial importance for the establishment of irrigation schedule is the specification of three components of water delivery at the farm outlet: *the rate of water flow ('discharge'), the duration of water delivery and the frequency of water delivery.* Assuming that each of these components can either be constant or variable, a number of different types of irrigation delivery schedules can be distinguished (FAO, 1982; Replogle and Merriam, 1982; World Bank, 1986; Clemmens, 1987; Horst, 1998). For this study, the three most important categories of water delivery schedules, representing different levels of schedule flexibility, were studied. These schedules are briefly discussed below.

- *Fixed schedule:* Water delivery is based on a schedule proportional to land holding or irrigated area. This can be attained either by dividing continuous flows through the system according to the areas served or by delivering the water intermittently on a proportional time basis (*rotation system)*. This schedule is presently being practiced in many irrigated areas of India and Pakistan.
- *Flexible schedule*: Crop water requirement can either be based on the requests of farmers for water ('on-request') or on an assessment by the Central Irrigation Agency of the various crops and their water requirement ('arranged'). In 'on-request' schedule, flows are regularly adjusted (once every 1 or 2 days), for 'arranged' schedule, re-adjustments are usually made once every 7, 10 or 14 days.
- *On-demand schedule*: Individual farmers decide when and how much irrigation water is needed. The system is designed in such a way that each farmer is able to draw any quantity of water at any time he wishes. With this type of scheduling, some form of automatic control in which the system responds automatically to withdrawal of water is needed.

To achieve desired targets, the abundance and shortage of water supplies can make a significant difference in the performance of an irrigation system. The selection of a water delivery schedule can not be made freely without testing it in terms of demand-supply considerations. The above-mentioned three water delivery schedules were tested for two water supply situations: *un-restricted* water supplies throughout the year and *restricted* water supplies (considered equivalent to the sanctioned canal water supply to the FDP-area i.e. 600 mm $yr^{-1}$).

***Un-restricted water supply***

*Fixed schedule*: These schedules have their conditions fixed at the beginning of the irrigation season as to frequency, rate and duration. The behavior of individual farmers in the *fixed* schedule is difficult to translate into an average condition. Therefore we adapted the irrigation schedule recommended by the Punjab Agricultural Department (PAD) for wheat-cotton agro-climatic zone of the Punjab (OFWM, 1980) usually being followed by farmers. The first irrigation was applied to wheat, three weeks after sowing, and to cotton, five weeks after sowing. In addition to the pre-sowing irrigations, subsequent irrigations were applied to wheat and cotton at three-week intervals. Irrigations of wheat and cotton were stopped three weeks and five weeks before harvesting, respectively. The depth of each individual irrigation was taken as 65 mm whereas for pre-sowing irrigation 80 mm was taken (Sarwar and Bastiaanssen, 2000). This rotation represents a '*fixed*' schedule since all three delivery components i.e. frequency, rate and duration of flow are fixed.

*Flexible schedule*: Water is delivered by the Central Agency according to crop water requirements. The interval of water supply was taken as 7 days and the irrigation requirement for each interval was calculated by subtracting cumulative effective rainfall from the cumulative potential evapotranspiration ($ET_{pot}$) during that period. Daily $ET_{pot}$ values were calculated by multiplying reference evapotranspiration ($ET_o$) with the crop factors ($k_c$) for wheat and cotton crops. To obtain effective rainfall, a fixed factor of 0.85 (Smith, 1995) was used. The irrigation requirements were calculated for an *average year*. The *average year* was determined on the basis of annual rainfall and $ET_{pot}$ data of 15 years (1980-94). The average annual rainfall of this series was 375 mm and average annual $ET_{pot}$ 1180 mm. The net irrigation requirement for each week was calculated according to $0.9*(ET_{pot}-0.85*P)$, where P is the rainfall. The factor 0.9 was used to account for the unavoidable field losses due to unequal water distribution within a field. This represents a more '*flexible*' schedule since the actual crop water requirements are used to vary the depth of irrigation application.

*On-demand schedule*: This irrigation schedule allows the farmers to control the frequency, rate and duration of flow at his outlet. This situation was modelled by filling the root zone to field capacity whenever relative transpiration ratio ($T_{act}/T_{pot}$) dropped below a value of 1.0. A value of 1.0 for $T_{act}/T_{pot}$ represents maximum attainable crop yields. This criterion was used to optimize timing and amount of irrigation using SWAP model. This represents the '*on-demand*' schedule since all three water delivery components i.e. frequency, rate and duration of flow are variable.

***Restricted water supplies***

The total canal water available for crop growth in the FDP-area is about 600 mm $yr^{-1}$ (WAPDA, 1989). Irrigations were adjusted to three water delivery schedules in such a way that the total amount of water applied in a year does not exceed 600 mm. For a *fixed* schedule, in addition to one pre-sowing irrigation of 80 mm to each crop, application of this criterion resulted in three post-sowing irrigations to wheat and four to cotton with depth of each individual irrigation equivalent to 65 mm. For the *flexible* schedule, this amount of water could only meet 60 percent of the total irrigation water requirements, in addition to two pre-sowing irrigations. Irrigations were applied with the same 7-day interval. For the *on-demand* schedule, the best irrigation schedule for wheat and cotton crops that fits within 600 mm $yr^{-1}$ of water, was optimized using the SWAP model. It was found that filling the soil profile back to field capacity whenever $T_{act}/T_{pot}$ value dropped below 0.85, would be the best strategy under the *restricted* water supply conditions. SWAP uses this criterion ($T_{act}/T_{pot} = 0.85$) on daily basis to calculate irrigation requirements. However, cumulative relative transpiration at the end of the growing season could be higher than this value.

The long-term (15 year) simulations were performed for three groundwater table conditions prevailing in the FDP-area. In addition to the 'drained' and 'un-drained' situations as defined in Chapter 6, simulations were also performed for the deep groundwater table (DWT) conditions. For this situation, a soil column of 10 m was considered for which an initial groundwater table depth of 10 m below soil surface was assumed. Zero flux at the bottom of the soil profile was used as bottom boundary condition.

## 7.3 Results and discussion

***Un-restricted water supplies***

Figure 7.1 shows the response curve illustrating the effect of increasing schedule flexibility on relative crop yields and *salt storage change* (*SSC*) under drained, un-drained and deep groundwater table (DWT) conditions for *un-restricted* canal water supplies. The presented results are based on 15 year averages considering wheat-cotton crop rotation as calculated with the SWAP model.

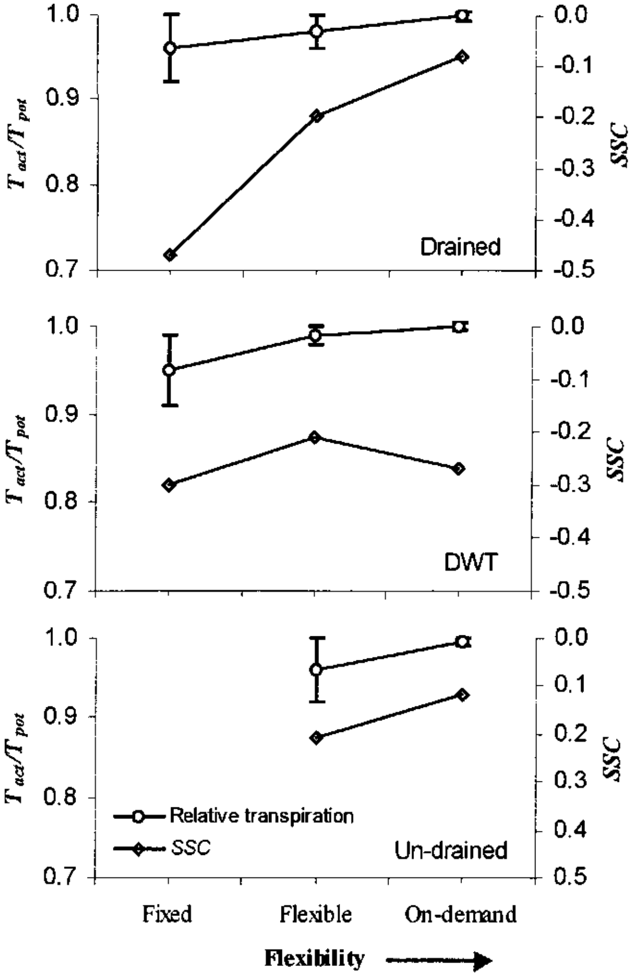

**Figure 7.1.** Relative transpiration ($T_{act}/T_{pot}$) and *salt storage change (SSC* = $\Delta C/C_{initial}$) as influenced by a *fixed*, *flexible* and *on-demand* schedule for *un-restricted* canal water supplies under drained, deep groundwater table (DWT) and un-drained conditions as calculated with SWAP based on 15 year averages (1980-94). The values for the *fixed* schedule under DWT conditions are based on 11 year averages. Note that *SSC* values for un-drained conditions are positive indicating an increase in *SSC*. I = standard deviations.

Increasing the schedule flexibility by moving from a fixed application of 65 mm at constant intervals to filling the soil profile back to field capacity whenever relative transpiration dropped below 1.0, crop yields under drained conditions increased by 4 percent. The small reduction in yields for a *fixed* schedule is due to constant irrigation supplies without considering temporal variations in climate. Due to the restricted capacity of the drainage system, during high rainfall years excessive soil moisture conditions in the root zone persists for relatively longer periods. This reduces the capacity of roots to extract water and negatively affected crop transpiration. For relatively dry years, a *fixed* schedule was sufficient to maintain maximum crop yields under variable climatic conditions. The slightly reduced relative yields in case of a *flexible* schedule are attributed to variations in the hydrological conditions of different simulation years from an *average* year. The *on-demand* schedule maintained maximum yields under all climatic conditions as the timing and amount of irrigations could be adjusted according to variations in rainfall and evaporative demand of the atmosphere. As would be expected, the more flexible the schedule was, the lower the standard deviation in crop productivity. This is logical since the added flexibility in water delivery allows it to respond better to crop stress and thus minimize variability.

The percolation losses under deep groundwater table conditions triggered the groundwater table rise, which exacerbates the damage potential of waterlogging and increases the need for subsurface drainage. The irrigations according to a *fixed* schedule raises the groundwater table to soil surface levels in the 11th year of simulations (Figure 7.2), making the crop production very difficult. Therefore relative transpiration values for a *fixed* schedule under deep groundwater table conditions are based on 11 year averages rather than 15 years.

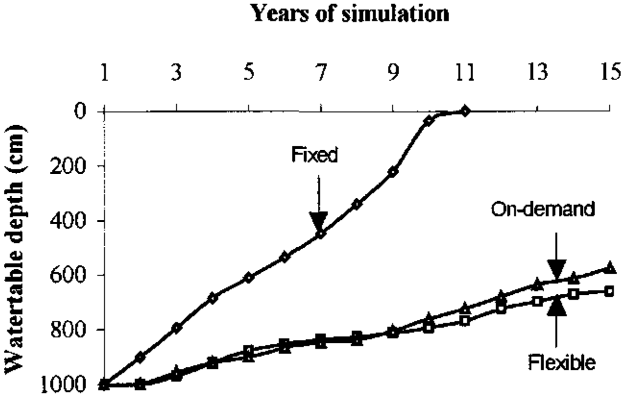

**Figure 7.2.** Groundwater table rise as influenced by *a fixed*, *flexible* and *on-demand* schedule under deep groundwater table conditions for *un-restricted* canal water supplies over a period of 15 years (1980-94).

The groundwater table rise for the other two schedules was less steep and follows a more or less similar trend (Figure 7.2). Here the groundwater table rise over the simulation period of 15-years was about 3.5 m. *This implies that distributing canal water based on the temporal variable crop water requirements (flexible or on-demand schedules), recharge to the groundwater can be reduced and the process of waterlogging can be delayed if not avoided. This is advantageous for the long-term sustainability of crop production and environment.*

Under un-drained conditions, a *fixed* schedule was a complete failure as the groundwater table rises to the soil surface level in just two years, creating severe waterlogged conditions (not shown here). For these areas, the *flexible* and the *on-demand* schedules perform better as the irrigation amounts could be matched to the actual crop water requirements, avoiding excessive deep percolation losses and consequently rising groundwater tables.

Under drained and deep groundwater table conditions, soil desalinisation took place for all three water delivery schedules. For a *fixed* schedule, the *salt storage change* (*SSC*) was more negative (i.e. decreased) mainly due to high amounts of irrigation water application. Under drained conditions, the lower *SSC* values for the *on-demand* schedule indicates that applied water was efficiently used for crop transpiration therefore very little leaching occurred. However, leaching of salts was sufficiently enough to keep the *SSC* desirably negative. The substantial amount of deep percolation under deep groundwater table conditions removed a significant amount of salts from the root zone, making *SSC* values considerably negative. Under un-drained conditions, the *SSC* values remained positive (i.e. increased) for all three water delivery schedules. This is attributed to inflow of salts from the bottom of the soil profile through capillary rise.

The simulated water and salt balances for the local hydrological conditions computed over a period of 15-years are presented in Table 7.1. In general, a *fixed* schedule used more irrigation water than the other two schedules. Under drained conditions, the total average annual water used by the *on-demand* schedule (680 mm) was 20 percent lower than the total annual water used by a *fixed* schedule (845 mm). The less amount of water used by the *on-demand* schedule was mainly due to the presence of shallow groundwater table, which contributed positively to the crop transpiration. However, in terms of total average water used, the *on-demand* schedule was often comparable to the *flexible* schedule, especially when one standard deviation was taken into account.

Under deep groundwater table conditions, for the 15-years of model simulations, the total average annual water used for the *on-demand* schedule amounts 780 mm. This amount remained 13 percent higher than the total average annual water used under drained conditions.

Under un-drained conditions, the total average annual water used for the *on-demand* schedule was 620 mm. This amount was 8 percent and 20 percent lower than the total average annual water used under drained and DWT conditions, respectively. The total average water used for the *flexible* schedule was 30 percent lower than the total average annual water used under drained and DWT conditions. However, the yield reductions due to this reduced water application were only three to five percent. *This implies that in shallow groundwater table areas, water supplies on the basis of potential evapotranspiration is not feasible and corrections for capillary contribution should be made more effectively.*

**Table 7.1.** Simulated cumulative average annual water and salt balance components as influenced by a *fixed*, *flexible* and *on-demand* schedule for *un-restricted* canal water supplies under drained, deep groundwater table (DWT) and un-drained conditions. The values for the *fixed* schedule under DWT conditions are based on 11 year averages. The numbers between parentheses show the standarad deviation. Fxd. = *Fixed* schedule, Flex. = *Flexible* schedule, Odm. = *On-demand* schedule. The $T_{pot}$ = 901 mm.

| Water balance | Drained conditions | | | DWT conditions | | | Un-drained conditions | | |
|---|---|---|---|---|---|---|---|---|---|
| components | Fxd. | Flex. | Odm. | Fxd. | Flex. | Odm. | Fxd. | Flex. | Odm. |
| Irrigation (mm) | 845 | 760 | 680<br>(85) | 845 | 760 | 780<br>(83) | 845 | 520 | 620<br>(133) |
| $T_{act}$ (mm) | 868 | 885 | 893 | 854 | 895 | 900 | - | 858 | 895 |
| Drainage (mm) | 300 | 104 | 20 | - | - | - | - | - | - |
| $q_{250}$ (mm) | - | - | - | -246 | -94 | -110 | - | +18 | +8 |
| $T_{act}/T_{pot}$ | 0.96 | 0.98 | 1.0 | 0.95 | 1.0 | 1.0 | - | 0.95 | 1.0 |
| *SSC* | -0.47 | -0.20 | -0.08 | -0.30 | -0.21 | -0.27 | - | +0.21 | +0.12 |
| $Y_{act}/I_{rr}$ (kg m$^{-3}$) | 0.63 | 0.71 | 0.93 | 0.61 | 0.72 | 0.74 | - | 0.88 | 0.87 |

The *productivity* of irrigation water supply ($Y_{act}/I_{rr}$) for different combinations is presented in Table 7.1. As the simulations were made for two crops (i.e. wheat-cotton) in a growing year, $Y_{act}/I_{rr}$ was first calculated for each crop separately and then averaged to demonstrate the overall effect of irrigation water applied in a growing year. In general, $Y_{act}/I_{rr}$ values for wheat were higher than cotton (not shown here). Table 7.1 shows that although for the *on-demand* schedule, relative crop yields are four to five percent higher as compared to a *fixed schedule*, the increase in $Y_{act}/I_{rr}$ is 15 percent for DWT and 30 percent for drained conditions. The lower values of $Y_{act}/I_{rr}$ for DWT conditions are attributed to high percolation losses. However, $Y_{act}/I_{rr}$ values for the *flexible* schedule are comparable to the *on-demand* schedule. The lower $Y_{act}/I_{rr}$ values for a *fixed* schedule can be explained by the large amount of water lost through drainage and deep percolation. *This illustrates that under un-restricted water supply conditions, the flexibility in irrigation scheduling has a considerable positive impact on the productivity of irrigation water supply.*

The average drainage requirements for the *on-demand* schedule were only 3 percent of the total canal water applied as compared to 36 percent for a *fixed* schedule and 14 percent for the *flexible* schedule. The drainage requirements for a *fixed* schedule also showed large fluctuations over the simulated period of 15-years. They varied from 137 to 590 mm yr$^{-1}$ (Figure 7.3). These fluctuations were primarily related to the variations in rainfall amounts, as the irrigation gifts were kept constant for a *fixed* schedule. The variations in drainage requirements were 20 to 280 mm yr$^{-1}$ for the *flexible* schedule and 0-128 mm yr$^{-1}$ for the *on-demand* schedule.

The average deep percolation losses for a *fixed* schedule accounted for about 29 percent of the total canal water applied as compared to 13 percent for the *flexible* and 14 percent for the *on-demand* schedules (Table 7.1). The annual fluctuations varied from 47 to 550 mm yr$^{-1}$ for a *fixed* schedule as compared to 25 to 246 mm yr$^{-1}$ for the *flexible* schedule and 20 to 230 mm yr$^{-1}$ for the *on-demand* schedule (Figure 7.3). This shows that with increasing schedule flexibility, water losses both through drainage as well as deep percolation tend to be reduced. The positive $q_{250}$ values under un-drained conditions indicate that shallow groundwater table contributed positively to crop transpiration through capillary rise.

The above discussion revealed that compared to a *fixed* schedule, the *on-demand* schedule is more effective not only in increasing crop yields and *productivity* of irrigation water supply but also in saving precious canal water, reducing drainage volumes and controlling rising groundwater tables. These are important parameters from the *sustainability* point of view and provide enough incentives to advocate a shift from a *fixed* to a more *flexible* water distribution system provided *un-restricted* water supplies are available.

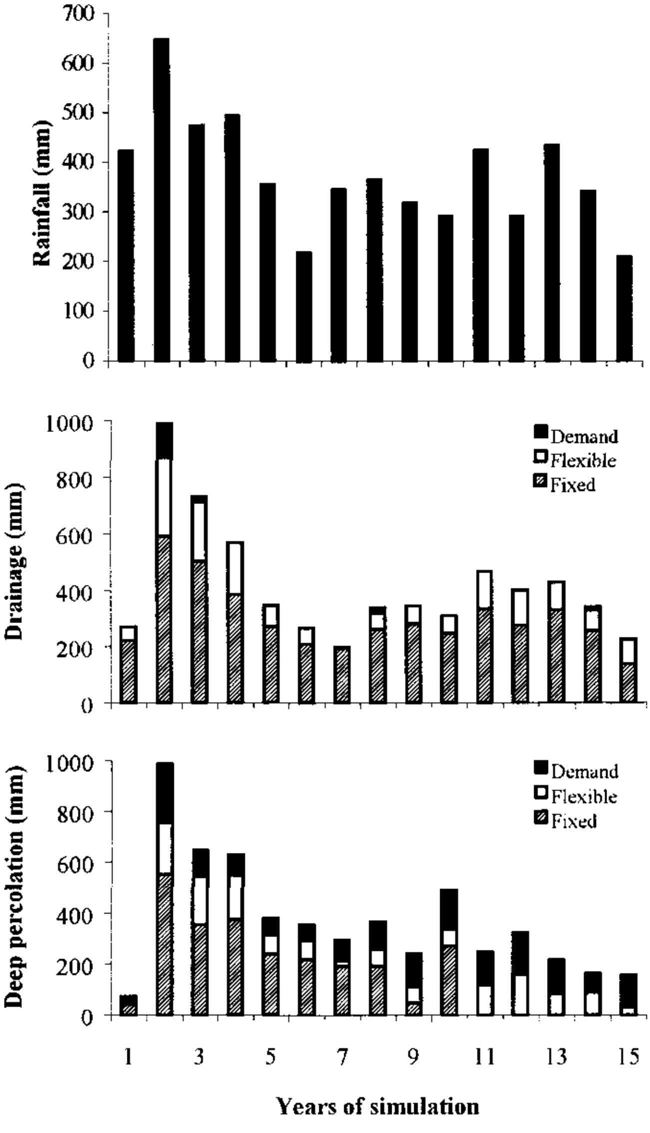

**Figure 7.3.** Average annual amounts of drainage and deep percolation as influenced by *fixed*, *flexible* and *on-demand* schedule for *un-restricted* canal water supplies as calculated with SWAP for a period of 15 years (1980-94). Drainage and deep percolation refer to drained and deep groundwater table conditions, respectively. The amount of capillary rise under un-drained conditions is not shown.

While comparing the results it must be kept in mind that model simulations assume that the *on-demand* schedule can or will be perfectly carried out by the irrigation organization-an assumption that is often not valid. At some level of flexibility, most organizations will have limited capital or capacity to implement the *on-demand* schedule and ultimately the performance will suffer. Thus, instead of standard deviations decreasing as flexibility increases, the standard deviations will increase. Clearly during schedule selection, the management capacity of an irrigation organization must be taken into account. Due to high management capacity with associated high costs required for the *on-demand* schedule, the general practice is a more *fixed* schedule.

***Restricted water supplies***

When the same amount of irrigation water (600 mm $yr^{-1}$) is applied, water distribution according to the *on-demand* schedule increases the average crop yields by two to three percent as compared to a *fixed* and the *flexible* schedule under drained, DWT and un-drained conditions. This implies that under *restricted* canal water supplies, deviations in crop yields due to temporal variability in the climate can to some extent be compensated by increasing the flexibility of water distribution (Figure 7.4).

The average yields under drained and un-drained conditions for all water delivery schedules were about four percent higher than DWT conditions. This increase in yield under shallow groundwater table conditions can be attributed to the contribution of capillary rise from the shallow groundwater table to crop evapotranspiration. Under DWT conditions, the standard deviation in relative crop yields was also larger. Under all conditions, the standard deviation in relative crop yields decreases with the increase in schedule flexibility.

The drainage requirements and deep percolation for all three water delivery schedules are within three percent of the total canal water applied (Table 7.2). Under drained conditions, these amounts were just sufficient to keep the *SSC* within acceptable limits ($\leq 0.05$). However, this was not the case under DWT conditions and the leaching was insufficient to push the salts below the root zone, which makes the *SSC* values considerably positive irrespective of water delivery schedule. Under un-drained conditions, the capillary rise from the groundwater table contributes positively to crop transpiration ($T_{act}/T_{pot}$ is higher than under DWT conditions) but increases the *SSC* for all three water delivery schedules. However, differences in *SSC* values within three water delivery schedules are comparable. Due to low percolation losses under DWT conditions, the recharge to the groundwater was very low and the rise in the groundwater table over the 15-year simulation period was only 50 cm.

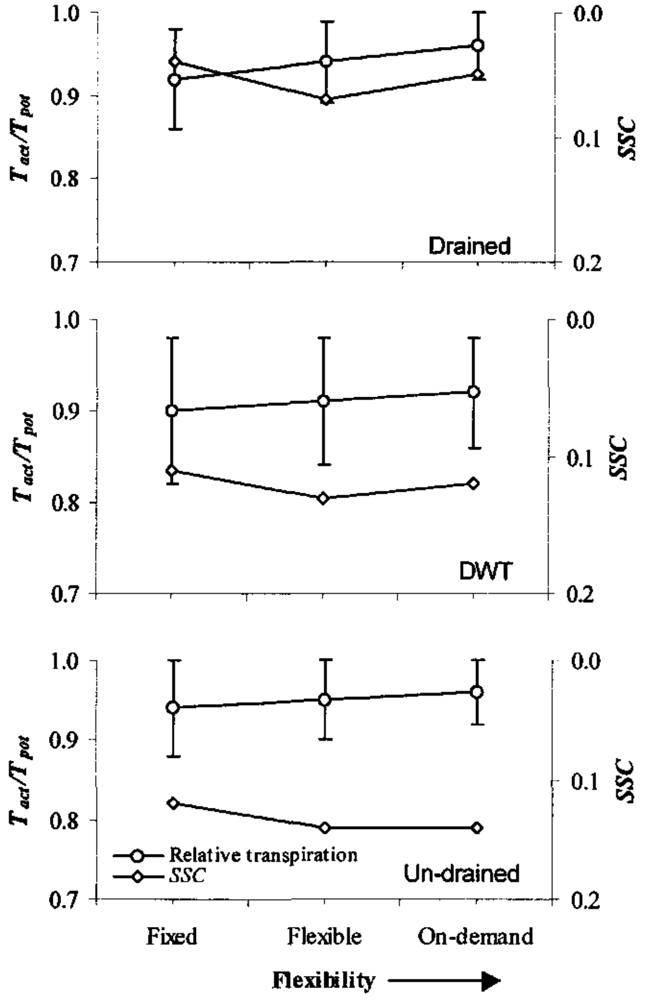

**Figure 7.4.** Relative transpiration ($T_{act}/T_{pot}$) and *salt storage change* ($SSC = \Delta C/C_{initial}$) as influenced by a *fixed*, *flexible* and *on-demand* schedule for *restricted* canal water supplies under drained, deep groundwater table (DWT) and un-drained conditions as calculated with SWAP based on 15 year averages (1980-94). Note that *SSC* values for un-drained and DWT conditions are positive indicating an increase in salt storage change. I = standard deviations.

**Table 7.2.** Simulated cumulative average annual water and salt balance components as influenced by a *fixed, flexible* and *on-demand* schedule for *restricted* canal water supplies under drained, deep groundwater table (DWT) and un-drained conditions. Fxd. = *Fixed* schedule, Flex. = *Flexible* schedule, Odm. = *On-demand* schedule. The $T_{pot}$ = 901 mm.

| Water balance components | Drained conditions | | | DWT conditions | | | Un-drained conditions | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fxd. | Flex. | Odm. | Fxd. | Flex. | Odm. | Fxd. | Flex. | Odm. |
| Irrigation (mm) | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 | 600 |
| $T_{act}$ (mm) | 830 | 843 | 861 | 810 | 816 | 824 | 850 | 822 | 861 |
| Drainage (mm) | -15 | 7 | 6 | - | - | - | - | - | - |
| $q_{250}$ (mm) | - | - | - | -20 | -5 | -15 | +18 | +22 | +20 |
| $T_{act}/T_{pot}$ | 0.92 | 0.94 | 0.96 | 0.90 | 0.91 | 0.92 | 0.94 | 0.91 | 0.95 |
| *SSC* | +0.04 | +0.07 | +0.05 | +0.11 | +0.13 | +0.12 | +0.12 | +0.14 | +0.14 |
| $Y_{act}/I_{rr}$ (kg m$^{-3}$) | 1.14 | 1.13 | 1.17 | 1.11 | 1.09 | 1.12 | 1.15 | 1.12 | 1.16 |

Table 7.2 shows that *productivity* of irrigation water supply ($Y_{act}/I_{rr}$) is, as expected, higher for the *restricted* water supply as compared to *un-restricted* water supply conditions (Table 7.1). Under *restricted* water supply conditions, the limited amount of water applied was fully utilized for crop transpiration and losses through drainage or deep percolation were almost nil (Table 7.2). This seems to be a justification for applying deficit irrigation: lower irrigation inputs increase the *productivity* of water. Contrary to *un-restricted* canal water supplies, the $Y_{act}/I_{rr}$ values are comparable for all three water delivery schedules under drained, un-drained and DWT conditions. *This implies that under restricted water supply conditions, impact of schedule flexibility on productivity of irrigation water supply is not very substantial.*

A close review of presented results indicate that under *restricted* canal water supplies, the advantage of shifting from a *fixed* to the *on-demand* water distribution system is only a small increase in crop yields. The effects of the *on-demand* schedule on *productivity* of water, soil salinization, drainage requirements and groundwater table behaviour are comparable with the *fixed* and the *flexible* schedules.

## 7.4 Constraints and opportunities for improved water distribution in the Indus basin

The advantages of the *on-demand* schedule are obvious when *un-resricted* canal water supplies are available and the objective is to maximize crop production and minimize environmental degradation. However, the most basic requirement for the *on-demand* supply system is the availability of variable amounts of water during cropping seasons. The cropping patterns and intensities also need to be more consistent. In the present circumstances, both these conditions are not fulfilled in Pakistan. The actual crop calendars often deviate strongly from those assumed in the design. The present cropping intensities are around 150 percent as compared to the design value of 75 percent. The existing experiences show that it is not possible to control the cropping patterns and intensities so as to keep maximum crop water requirement within the water allowance and supply range (based upon the original calculations for crop water requirement). Farmers plan according to the maximum available water for all periods. Economic incentives have urged them to grow more cash crops (i.e. rice and sugarcane). These crops often require much more water, rendering it impossible to meet water delivery requirements.

The water availability in the main irrigation network is limited and present canal supplies are about 50 percent of the total crop water requirements (WADPA, 1989). The existing capacity of the reservoirs is fully utilized and no run-off occurs from the Indus basin during seven months of the year. In Kharif, a substantial amount of water flows into the sea, which could partly be used if new storage facilities could be developed. The only possibility to increase water supplies is the exploitation of usable groundwater. This resource is being extensively used in Pakistan and presently about 30 to 40 percent of the irrigation water available at the farm gate is provided by groundwater through tubewells (Nespak/SGI, 1991). However, the un-regulated pumping of groundwater often causes secondary salinization, land degradation, as well as rapid depletion and quality changes in groundwater. Hence, the surface water supply is the major resource base to be used for irrigation planning.

The successful operation of the *on-demand* supply system requires a differentiated allocation and distribution of canal water, hence the present system of distribution based on equity has to be abandoned. Furthermore, an institutional structure and a large and intensive monitoring system would be required to assess and communicate crop water requirements for each time step or period. The necessary requirements for the *on-demand* supply system include large investments in the hardware (structures as regulators, spillways, etc and communication system) and software (institutions, management and training). This is a cumbersome and costly affair as the present capacity and design of canals is fixed to spread the available water on land and has no relationship whatsoever with the irrigation water requirements of crops.

In a situation where periodic water shortages are experienced as in case of the Indus basin, the decision of which schedule to choose should not be a question of which schedule will maximize crop production, but rather of which one will optimize crop production in a sustainable way within the available water supply and management capacity. The simulation results show that in the present water deficient environment of the Indus basin, the benefits of the *on-demand* schedule over a *fixed* schedule are only a small increase in crop yields. If these benefits are greater than the added management cost of moving to the *on-demand* schedule from a *fixed* schedule then the *on-demand* schedule is probably the most productive and cost effective. Given the high cost of management and infrastructure, it is unlikely, however that this the case. Moreover, a shift from a *fixed* to the *on-demand* schedule will imply more water rights to individual farmers within the same command area. This might be justified from an economical point of view, but is socially unacceptable. Therefore emphasize should be on improvement of the current water allocations and on-farm water management practices.

In Chapter 6 it has already been shown that by adapting water conservation strategies, in shallow groundwater table areas because of supplemental irrigation supply through capillary rise, about 25 percent of canal water can be saved. Furthermore, there is still room for improvements in water supply and crop yields. For example, crop yields are largely influenced by sowing and planting dates. If the present water supplies can be made more reliable, farmers could adjust their farming operations and plan their irrigations in most critical stages of the crop growth thus ensuring maximum crop yields within the available water resources.

## 7.5 Conclusions

The process of choosing an appropriate schedule for an irrigation system must take into account temporal variability of its climate and water supply along with the spatial diversity of soils and crops. Additional improvements of water use efficiency can be obtained by adjusting the canal water supplies according to the temporal variability of the crop water requirements of the irrigated crops, provided *un-restricted* canal water supplies are available. Besides increased yields with the *on-demand* schedule, the deviations from average yields were minimal as a factor of over- or under-supply can be included in order to deal with variations in rainfall amounts and evaporative demand of the atmosphere. The *productivity* of irrigation water supply with the *on-demand* schedule was substantially higher as compared to a *fixed* schedule. The *on-demand* schedule was also effective in irrigation water saving, reducing drainage volumes, and deep percolation. Although a complete solution of the rising groundwater tables can not be achieved, the *on-demand* schedule was found effective in delaying the process of waterlogging and soil salinization leading to a positive effect on the environment.

The advantages of the *on-demand* schedule are obvious when *un-restricted* water supplies are available and the objective is to ensure maximum crop production and minimize environmental degradation. However, the successful operation of the *on-demand* system requires variable amounts of water during cropping seasons, consistent cropping patterns and a well-designed and effective monitoring and communication system to assess and communicate crop water requirements for each time step or period. In the absence of these basic requirements, moving towards the *on-demand* system is beset with social and management problems.

In the present water deficient environment, the *on-demand* water distribution system is no clear option for the Indus basin. Therefore emphasize should be on the improvement of the present supply-based water distribution system. There is still room for improvements in water supply and crop yields. The management options like reducing canal water supplies to areas with fresh shallow groundwater could save a considerable amount of canal water, which can be used in other water deficient areas. If the present water supplies can be made more reliable, farmers could adjust their operations and plan their irrigations in the most critical stages of the crop growth to maximize their crop yields.

# 8 SUMMARY AND CONCLUSIONS

The viability of irrigated agriculture in the Indus basin is threatened by waterlogging and soil salinization. These problems are the result of a multitude of factors, including seepage from unlined earthen canals system, inadequate provision of surface and subsurface drainage, poor water management practices, insufficient water supplies and use of poor quality groundwater for irrigation. Optimal management of available surface and groundwater resources with respect to quantity and quality in view of rapidly diminishing land and water resources per capita is necessary.

The study was conducted in the Fourth Drainage Project (FDP), Punjab, Pakistan. FDP covers about 120, 000 ha irrigated land, of which about 30,000 ha is equipped with a subsurface tile drainage system. The climate is semi-arid with annual evaportranspiration far exceeding the annual rainfall, which necessitates irrigation for crop production. Wheat and cotton are the main crops in winter and summer, respectively. Canal water supplies are limited by design and siltation in the canal system, besides cropping intensities being doubled over the past 50 years. Groundwater tables are generally shallow and groundwater quality is injurious to both crops and soils. Conjunctive use of canal and groundwater is very common.

The problems are complex because good quality water resources are diminishing and the demand for food is increasing, which means that the *productivity* of water must go up. Reduced irrigation applications can increase the risk of soil salinization due to insufficient leaching. Drainage systems have the drawbacks of being expensive to install and operate and to produce highly saline effluent, which is a problem for downstream users. Therefore the challenge is to utilize canal water and groundwater (extracted from tubewells) optimally for crop production while keeping groundwater table fluctuations and salinity build up within the acceptable limits. Improve irrigation water distribution with regard to crop water requirements and restrict the installation of drainage systems to the most deserving areas.

These complex interactions between the irrigation, drainage, weather, groundwater table and salinity can be properly described by the use of simulation models. The transient-state water flow and solute transport model, SWAP was used due to its capability to handle highly dynamic processes such as irrigation, precipitation and drainage. SWAP is a one-dimensional hydrological model, which produces daily water and salt balance components as an output, besides crop growth and environmental conditions in terms of soil moisture, groundwater table and soil salinity fluctuations. Before its application to actual field problems, the model was calibrated and validated for the physical conditions of the FDP-area. During the calibration process, special emphasis was given to accurate determination of soil hydraulic parameters, reference evapotranspiration, drainage from the sample fields and a suitable bottom boundary condition.

In Chapter 4 the calibration of SWAP model has been discussed. The soil water retention curves determined from the laboratory experiments were found to be non-representative for field conditions. Model simulation was significantly improved after applying field determined soil water retention curves and calibration of soil hydraulic properties. The results indicate that applying soil physical laboratory measurements or pedo-transfer functions can cause considerable errors in the calculations of water and salt balance components. For successful application of simulation models in irrigation and drainage studies, more attention should be given to the field determination and calibration of soil hydraulic parameters.

The reference evapotranspiration ($ET_o$) values calculated by the Priestly-Taylor (PT) method were found to be physically more realistic than the values calculated by the Penman-Monteith (PM) method. The latter method assumes stomata to be open due to well-regulated soil moisture conditions. However, biophysical research elsewhere has shown that stomata close to avoid cell water depletion if vapor pressure deficit (vpd) increases beyond a certain level. The $ET_o$ values calculated by the PM and PT methods were in good agreement below a vpd of 20 mbar. Above this threshold value, PM- $ET_o$ values were consistently higher than PT- $ET_o$ values (Figure 4.3). PM- $ET_o$ values exceed the net radiation ($R_n$) values above a vpd of 20 mbar leading to PM-$ET_o/R_n > 1.3$, which is physically unlikely. This implies that for hot and dry climates (i.e. vpd > 20 mbar), the Priestly-Taylor method is more robust to calculate reference evapotranspiration, because it relies on radiation fluxes rather than on turbulent momentum, heat and vapor transport mechanisms inside and above plants, which are very intricate in arid climates with irrigated lands.

The simulated drainage from the sample fields calculated with an equivalent drainage resistance ($\gamma_{drain}$) pertaining to the geometry of that particular field, compares well with the measured drainage. The analysis of piezometer data complemented by the model simulations showed that there is a negligible water exchange between the deep aquifer and unsaturated zone. Therefore zero flow conditions at a depth of 5 m can be assumed for the scenario analysis. This result was further confirmed by comparing measured groundwater tables with simulated groundwater tables using zero flux as bottom boundary in the model. A close match between measured and simulated soil water pressure heads, soil water contents and soil salinity gave confidence on the calibrated parameters. After satisfactory calibration and validation, SWAP was used for the determination of optimal drainage design criteria for the FDP-area. In addition model was used to study the impact of different irrigation management strategies on crop production, drainage requirements, soil salinity and groundwater table behavior for different hydrological conditions prevailing in the FDP-area.

Chapter 5 deals with the re-evaluation of present drainage design criteria and determination of an optimal drainage design criteria for the FDP-area. In Pakistan, drainage systems have been designed using steady-state drainage equations of Hooghoudt and Ernst. These equations assume steady-state moisture and solute fluxes occurring in the unsaturated zone. Classical steady-state drainage design criteria also describe the relationship between drain discharge rate ($q_{drain}$) and the hydraulic head difference between drain level and phreatic level at mid point ($\Delta h$), independent of soil and underground conditions. The ratio $q_{drain}/\Delta h$ is also called 'drainage intensity' and is the inverse of drainage resistance, $\gamma_{drain}$ ($\Delta h/q_{drain}$). In reality, however, moisture and solute fluxes in the unstaurated zone are not steady but vary with time according to fluctuations in rainfall, irrigation and evapotranspiration. This implies that drainage systems should be designed using a transient state approach that accounts for soil water and root water uptake dynamics.

To determine an optimal drainage design for the FDP-area, simulations were conducted for a period of 15 years to examine the long-term effects of land drainage (twelve combinations of drain depth and drainage spacing) on crop transpiration, soil salinization and groundwater table behavior. As the FDP-area represents a *multiple cropping system*, the simulations were carried out for three dominant crops of the area i.e. wheat, cotton and sugarcane with considering the drainage conditions of fields midway between two drains. As these fields have a groundwater table being likely more shallow than at fields located closer to the drains, the worst conditions were considered. The drain depths chosen were 1.0, 1.5, 2.0 and 2.5 m below the soil surface. Each of these drain depths was combined with three different drain spacings ranging from narrow (125 m), medium (250 m) and wide (500 m). These drain spacings correspond to high, medium and low drainage intensities, respectively.

For the (semi-) arid zones, selection of the proper drain depth was critical than the drain spacing. For the conditions considered, deeper drains perform better with regard to crop growth, soil salinization and groundwater table control. The optimum drain depth from an agro-hydrological perspective for the *multiple cropping system* of the FDP-area was found to be 2.20 m (Figure 5.2). This drain depth was successful in producing reasonably high crop yields ($T_{act}/T_{pot}$ > 0.90) at rather low drainage intensities (spacing of 500 m). This drainage design maintained the groundwater table below the root zone throughout the growing year, thereby eliminating the chances of any yield reductions due to excessive soil moisture conditions. Drains shallower than 2.20 m were found to cause severe yield reductions due to excessive soil moisture conditions particularly during relatively wet years. Drains deeper than these were found to increase the costs without any additional benefits. Soil salinization was also more closely related to drain depth than to drain spacing. The salinity of the root zone decreases with increasing drain depth. This can be attributed to the increased effectiveness of salt leaching through deeper drains.

The drain discharge rate was not constant but fluctuates over time according to the percolating moisture flux in the unsaturated zone. The present FDP design based on the recommendations of the United States Bureau of Reclamation (USBR) and the design proposed by Smedema for the (semi-) arid conditions of Pakistan (Table 5.1) were found to be rather conservative i.e. with high drainage intensities. The SWAP simulations show that the FDP-area can effectively be drained with 25 percent less drainage intensity than the USBR and Smedema drainage designs provided operational and/or maintenance constraints are not present. This implies two advantages: less drainage effluent volume and less canal water requirements. However, the final decision on the optimum combination of drain depth and drain intensity would require a thorough economical analysis.

High installation, operational and maintenance costs and saline effluent disposal problems associated with drainage systems stress the need to find alternate solutions to control rising groundwater tables and soil salinization. In shallow groundwater table areas without subsurface drainage systems, reducing irrigation water applications, thereby allowing the crop to draw maximum water from the groundwater, could be a useful strategy to sustain agricultural production. Reduced water application in shallow saline groundwater table conditions has the ultimate goal to prevent water losses and to increase the area that can be brought under irrigation, using the same quantum of surface water resources. One of the objectives of this study was to develop guidelines for sustainable agricultural production in shallow groundwater table areas, avoiding soil salinity problems, under both drained and un-drained conditions.

In Chapter 6 water conservation strategies for the shallow groundwater table conditions of the FDP-area and their long-term affects on crop production and environment have been discussed. To develop these guidelines, the SWAP model was used as a suitable surrogate for otherwise expensive and time-consuming field experiments. Simulations were performed for a period of 15 years to develop water conservation strategies for wheat-cotton crop rotation under the shallow groundwater table conditions of the FDP-area. Due to the fact that farmers in the FDP-area are using more and more groundwater for irrigation, simulations were carried out for three different irrigation water qualities. The developed water conservation strategies were compared with the farmers' present irrigation practices and long-term effects on crop transpiration, root zone salinity, the groundwater table behavior and drainage requirements were evaluated.

A reduced irrigation supply to wheat (195 mm) and to cotton (260 mm) gave the best results in terms of crop production, minimum drainage requirements, soil salinity and groundwater table control under both drained and un-drained conditions, when canal water was used for irrigation. This water conservation strategy saved up to 25 percent of the precious canal water each year as compared to farmers' present irrigation practices. The present irrigation practices of farmers aim at providing maximum water for maximum crop production. The law of increasing benefits does not apply to salinized land threatened by rising groundwater tables. The opposite is true: unplanned irrigation applications could ruin the land resources within a time span of several years. Careful management is therefore a pre-requisite to use the water resources in a productive and sustainable way.

For conjunctive use of canal and tubewell water with an EC value of 1.5 dS $m^{-1}$ or for the use of tubewell water alone with an EC value of 3.0 dS $m^{-1}$, the water conservation strategy was insufficient to maintain soil sustainablility. The average soil salinity, expressed to a critical value in the so-called *salinity hazard index* (*SHI*) increased substantially (Figure 6.4), and the relative transpiration, which gives an indication of relative crop yield, dropped accordingly due to salinity stress. Apparently, irrigation supplies should be enhanced for leaching the salts from the crop root zone. Additional water supply possibilities depend on the drainage system design capacity and on the availability of water. In the absence of a good drainage system, considering the trend in high groundwater tables, soil salinity and crop yield reductions, leaching of salts by means of poor quality irrigation water will not be suitable and lands will go out of production even at a faster rate. Therefore in these areas, other options like growing more salt tolerant crops like eucalyptus or phreophytes should be considered.

Due to decreasing availability of good quality canal water for irrigation, adaptation of water conservation strategies is the best option rather than recommending farmers to use poor quality tubewell water in an attempt to maximize crop production. The simulation results indicate that drainage can not solve the salinity build up problem under all circumstances because relatively dry monsoons provide insufficient leaching water, and salts added by tubewell water irrigation can only be evacuated from the soil profile if the drainage system is very intense and additional water supplies are available. Reduced irrigation applications is a proper short-term solution. However, large-scale drainage investments with adjusted irrigation planning would be necessary in the long run.

The results emanating from the model simulations were used to formulate strategies for the safe and sustainable use of different quality irrigation waters under different groundwater table conditions and are summarized in Table 8.1. These guidelines are restricted to the environmental conditions prevailing in the FDP-area.

**Table 8.1.** Management strategies for the safe and sustainable use of different quality irrigation waters under different groundwater table conditions for the FDP-area based on 15 year simulations with the SWAP model. CW = Canal Water, CTW = Canal + Tubewell Water, TW = Tubewell Water. Irrigation amounts to wheat and cotton crops represent post-sowing water applications (mm) in a growing season.

| Drainage conditions | Management strategies for different quality irrigation waters | | |
|---|---|---|---|
| | CW<br>(EC = 0.3 dS $m^{-1}$) | CTW<br>(EC = 1.5 dS $m^{-1}$) | TW<br>(EC = 3.0 dS $m^{-1}$) |
| Subsurface drainage | Reduced water application | Leaching feasible | Extra leaching not feasible<br>Grow salt tolerant crops |
| | Wheat = 195 mm<br>Cotton = 260 mm | Wheat = 325 mm<br>Cotton = 325 mm | Wheat = 325 mm<br>Cotton = 325 mm |
| No subsurface drainage | Reduced water application | Leaching not feasible<br>Grow salt tolerant crops | Install drainage systems or grow salt tolerant plants for reclamation e.g. eucalyptus |
| | Wheat = 195 mm<br>Cotton = 260 mm | Wheat = 195 mm<br>Cotton = 260 mm | |

In Chapter 7 the effects of irrigation water distribution on crop production and environment were evaluated. In semi-arid areas, the deviations in annual precipitation from an *average year* were found to be critical to maintain a fragile equilibrium between different water and salt balance components (Chapter 6). This implies that for sustainable water and salinity management, the water allocation and distribution should be based on potential evapotranspiration, precipitation as well as salinity build up and being reviewed yearly. This means a change-over from the present fixed rotational system (based on proportionate division of water over available land) to a more flexible irrigation management to provide canal water at the time and location where it is actually required for optimum and efficient field irrigation of crops.

To test the validity of this argument, the impact of flexibility in irrigation water distribution on crop *productivity* and environmental *sustainability* was evaluated. For this purpose, the response of three water delivery schedules, representing various levels of flexibility, on crop production, water saving, soil salinization, drainage requirements and groundwater table behavior was studied. The simulations were carried out for *un-restricted* and *restricted* canal water supply situations considering three groundwater table conditions (drained, deep groundwater table and un-drained) prevailing in the FDP-area. *Un-restricted* supplies are based on ample snowfall and that sufficient storage facilities in Pakistan are being developed. *Restricted* canal water supplies reflects more the current situation.

Although additional water use efficiency improvements were obtained by the *on-demand* schedule, under average conditions the effect of irrigation schedule flexibility on crop yields was not very significant. However, compared to a *fixed* schedule provided *un-restricted* canal water supplies would be available, the *productivity* of irrigation water supply ($Y_{act}/I_{rr}$) for the *on-demand* schedule was up to 30 percent higher (Table 7.1). Besides increased water *productivity* with the *on-demand* schedule, the deviations from average yields were also minimal as the timing and amount of irrigations could be adjusted in order to deal with variations in rainfall amounts and evaporative demand of the atmosphere.

The *on-demand* schedule was also effective in irrigation water saving, reducing drainage volumes, and deep percolation. The average annual water saving of the *on-demand* schedule over a *fixed* schedule was 20 percent, 8 percent and 27 percent for drained, deep groundwater table and un-drained conditions, respectively. The average annual drainage requirements for a *fixed* schedule were more than 30 percent higher as compared to the *on-demand* schedule. The deep percolation losses were 15 percent higher for a *fixed* schedule as compared to the *on-demand* schedule. Although a complete solution for the rising groundwater tables can not be achieved, the *on-demand* schedule was found effective in delaying the process of waterlogging and soil salinization leading to a positive effect on the environment. For the *restricted* canal water supplies, the benefits of the *on-demand* schedule over a *fixed* schedule resulted in only a small increase in crop yields, while the effects on soil salinization, drainage requirements and groundwater table behavior were rather comparable.

The advantages of the *on-demand* schedule are obvious when the *un-restricted* canal water supplies are available and the objective is to ensure maximum crop production and minimize environmental degradation. However, in a situation where periodic water shortages are experienced as is true for the Indus basin, the decision of which schedule to choose should not be a question of which schedule will maximize crop production, but rather of which one will optimize crop production in a sustainable way within the available water supply and management capacity. In the absence of sufficient canal water supplies and a well-designed and effective monitoring and communication system, a shift from a *fixed* to the *on-demand* schedule in the Indus basin will neither be economically feasible nor socially acceptable.

Therefore emphasis should be on improvement of the current supply-based system. There is still room for improvements in water supply and crop yields. Management options like reducing canal water supplies to areas with fresh shallow groundwater could save a considerable amount of canal water, which could be used in other water deficient areas. If the present water supplies can be made more reliable, farmers could adjust their operations and plan their irrigations better in the most critical stages of the crop growth to maximize their crop yields.

The irrigation and drainage planning for different soil and crop conditions in different climatic zones is a difficult proposition and a transient model approach such as SWAP makes it possible to study the complex soil-crop-climate interactions and allows the investigation of long-term effects of a wide range of management interventions on crop production and environment for which experiments could not be conducted. The presented conclusions are based on the climatic, irrigation and agro-hydrological conditions of the FDP-area. However, the developed approach is equally applicable to other areas facing similar problems.

# SAMENVATTING EN CONCLUSIES

De levensvatbaarheid van de geirrigeerde landbouw in de Indus basin wordt bedreigd door hoog grondwater en bodemverzouting. Deze problemen zijn het gevolg van een veelheid van factoren, waaronder lekverliezen uit een niet-bekleed systeem van kanalen, onvoldoende drainage door open drains, buizen en putten, slecht waterbeheer, onvoldoende aanvoer van water en het gebruik van slechte kwaliteit grondwater voor irrigatie. Gezien de snel afnemende voorraden land en water per hoofd van de bevolking, is het noodzakelijk te komen tot optimaal beheer van oppervlaktewater en grondwater, in kwantiteit en in kwaliteit.

Deze studie werd uitgevoerd in het Fourth Drainage Project (FDP) in de Punjab, Pakistan. Het Fourth Drainage Project beslaat ongeveer 120.000 ha geirrigeerd land, waarvan circa 30.000 ha is voorzien van een buisdrainage systeem. Het klimaat in dit gebied is semi-aride met een jaarlijkse evapotranspiratie die ver uitgaat boven de jaarlijkse neerslag, waardoor irrigatie nodig is voor de landbouw. In het winter- en zomerseizoen zijn respectievelijk graan en katoen de voornaamste gewassen. De aanvoer van irrigatiewater is beperkt door het ontwerp en door sedimentafzetting in de kanalen. Bovendien is de intensiteit van het landgebruik in de laatste vijftig jaar verdubbeld. Over het algemeen is de grondwaterstand hoog en de kwaliteit van het grondwater slecht voor gewas en grond. Het naast elkaar gebruiken van kanaalwater en grondwater komt veel voor.

Het probleem wordt gecompliceerd doordat watervoorraden van goede kwaliteit afnemen en tegelijkertijd de vraag naar voedsel toeneemt. Dit betekent dat de *productiviteit* van water moet toenemen. Verminderde irrigatiegiften kunnen het risico doen toenemen van bodemverzouting door onvoldoende afvoer van het zout. Drainagesystemen zijn kostbaar in aanleg en beheer en produceren bovendien zout-effluent, hetgeen een probleem vormt voor de gebruikers benedenstrooms. De uitdaging is om minder kanaalwater te gebruiken en meer grondwater voor het maximaliseren van de gewasopbrengst, terwijl fluctuaties van de grondwaterspiegel en de zoutaccumulatie onder controle blijven. De verdeling van irrigatiewater moet verbeterd worden om te kunnen voldoen aan de waterbehoefte van gewassen en om de aanleg van drainagesystemen te kunnen beperken tot de meeste noodzakelijke gebieden.

De interactie tussen irrigatie, drainage, weersomstandigheden, grondwaterstand en zoutgehalte in de grond kan goed beschreven worden met simulatiemodellen. Het niet-stationaire stromings- en transportmodel Soil Water Atmosfeer Plant (SWAP) werd gebruikt vanwege het modelvermogen om dynamische processen zoals irrigatie, infiltratie en drainage goed te simuleren. SWAP is een 1-D agrohydrologisch model dat naast gewasgroei en milieuomstandigheden uitvoer geeft op dagbasis van de water en zoutbalans componenten in termen van fluctuatie in vochtgehalte, grondwaterstand en bodemzoutgehalte. Voor toepassing werd het model gecalibreerd en gevalideerd met veldgegevens uit het FDP-projectgebied. Het ijkproces werd geconcentreerd op een goede beschrijving van de hydraulische bodemparameters, de referentie-evapotranspiratie, drainage van proefvelden en de meest geschikte onder-randvoorwaarde.

Hoofdstuk 4 beschrijft de ijking van het SWAP-model. De retentiecurven die in het laboratorium werden bepaald bleken niet representatief voor veldomstandigheden. Modelsimulatie verbeterde aanzienlijk toen retentiecurven werden gebruikt die waren gebaseerd op veldgegevens. De resultaten geven aan dat het gebruik van bodemfysische parameters uit het laboratorium of van pedo-transfer functies aanzienlijk fouten kunnen veroorzaken in de berekening van de componenten van de water- en zoutbalans. Voor het succesvol toepassen van simulatiemodellen in irrigatie- en drainagestudies, moet meer aandacht geschonken worden aan de veldbepaling en ijking van hydraulische bodemparameters.

Waarden van de referentie-evapotranspiratie ($ET_o$) berekend met de Priestly-Taylor (PT) methode bleken fysisch meer realistisch dan waarden berekend met de Penman-Monteith (PM) methode. Deze laatste methode veronderstelt dat stomata geopend worden door condities van bodemvocht. Echter, biofysisch onderzoek elders heeft aangetoond dat stomata sluiten om verlies van celvocht te voorkomen wanneer het vochtspanningdeficiet (vpd) boven een bepaalde waarde stijgt. Beneden een vpd van 20 mbar waren de $ET_o$-waarden berekend met de PM en PT methoden in goede overeenstemming met elkaar. Boven deze drempelwaarde waren PM-$ET_o$ hoger dan PT-$ET_o$ waarden (Figuur 4.3) en waren de PM-$ET_o$ waarden hoger dan de netto straling ($R_n$). Dit leidt tot PM-$ET_o/R_n > 1.3$, hetgeen fysisch onwaarschijnlijk is. Dit betekent dat voor hete en droge klimaten, dwz met vpd > 20 mbar, de Priestly-Taylor methode betrouwbaarder is voor het berekenen van de referentie evapotranspiratie. De voornaamste reden is dat deze methode gebaseerd is op stralingsfluxen en niet op de turbulente momentum-, warmte- en damptransport mechanismen in en boven de plant. In aride geirrigeerde gebieden zijn deze mechanismen zeer ingewikkeld.

De drainage van de proefvelden werd gesimuleerdmet een equivalente drainage weerstand ($\gamma_{drain}$'), die een functie is van de geometrie van een bepaald proefveld: de berekende weerstand kwam goed overeen met de gemeten weerstand. Analyse van de piezometerdata aangevuld met modelsimulaties toonden een verwaarloosbaar transport tussen de diepe watervoerende laag en de onverzadigde zone aan. Om deze reden werd als onderrandvoorwaarde op een diepte van vijf meter aangenomen dat de verticale stroming nul was. Dit werd bevestigd door vergelijking tussen gemeten en gesimuleerde grondwaterstanden. Goede overeenstemming tussen gemeten en gesimuleerde drukhoogten, vochtgehalten en zoutgehalten gaf vertrouwen in de gecalibreerde parameterwaarden. Na calibratie en validatie werd het SWAP-model gebruikt voor het bepalen van optimale drainageontwerpcriteria voor het projectgebied. Daarnaast werd het model gebruikt om het effect te bestuderen van verschillende irrigatiestrategieen op gewasproductie, drainagebehoefte, bodemzoutgehalte en grondwaterstand voor verschillende hydrologische omstandigheden in het projectgebied.

Hoofdstuk 5 behandelt de re-evaluatie van het huidige drainageontwerp en de bepaling van optimale ontwerpcriteria voor het projectgebied. In Pakistan zijn drainagesystemen ontworpen met de stationaire modellen van Hooghoudt en Ernst. Deze modellen veronderstellen stationaire vocht- en transportfluxen in de onverzadigde zone. Klassieke stationaire drainage ontwerpcriteria beschrijven de relatie tussen de drainafvoer ($q_{drain}$) en het hydraulische potentiaalverschil tussen drainniveau en phreatisch niveau midden tussen de drains ($\Delta h$) onafhankelijk van de condities beneden maaiveld. De verhouding $q_{drain}/\Delta h$ wordt drainageintensiteit genoemd en is de reciproke van de drainageweerstand $\gamma_{drain}$ ($\Delta h/q_{drain}$). In werkelijkheid echter zijn de onverzadigde vocht- en transportfluxen niet stationair, maar veranderen in de tijd met fluctuaties in neerslag, irrigatie en evapotranspiratie. Dit betekent dat drainagesystemen ontworpen moeten worden met niet-stationaire modellen die gebaseerd zijn op de dynamica van bodemvocht en wateropname door de wortels gedurende het hele jaar.

Voor het maken van een optimaal drainageontwerp voor het projectgebied werden simulaties uitgevoerd over een periode van vijftien jaar om het lange termijneffect te bestuderen van drainage met twaalf combinaties van draindiepte en drainafstand op gewastranspiratie, bodemverzouting en grondwaterstand. Daar het projectgebied een meer-gewas-systeem heeft werden de simulaties voor de drainagecondities midden tussen de drains uitgevoerd voor drie dominante gewassen in het gebied, namelijk graan, katoen en suikerriet. Daar deze velden een grondwaterstand hebben, die waarschijnlijk hoger is dan die van velden dichter bij een drain gelegen, werden in feite de slechtste omstandigheden bestudeerd. De gekozen draindiepten waren 1.0 m, 1.5 m, 2.0 m en 2.5 m beneden maaiveld. Ieder van deze draindiepten werd gecombineerd met drie verschillende drainafstanden varierend van klein (125 m), middengroot (250 m) tot groot (500 m). Deze drainafstanden komen overeen met respectievelijk hoge, middelhoge en lage drainageintensiteiten.

Voor de semi-aride gebieden was de keuze van drain*diepte* meer kritiek dan die van drain*afstand*. Voor de bestudeerde omstandigheden werken diepere drains beter voor de gewasgroei, bodemverzouting en beheer van de grondwaterstand. Vanuit een agrohydrologisch standpunt bezien is de optimum draindiepte 2.20 m voor het meer-gewassen system in het projectgebied (Figuur 5.2). Deze draindiepte bleek succesvol in de productie van redelijk hoge gewasopbrengsten ($T_{act}/T_{pot} > 0.90$) bij tamelijk lage drainage intensiteiten (drainafstand van 500 m). Dit drainageontwerp handhaafde de grondwaterspiegel beneden de wortelzone gedurende het gehele jaar en voorkwam daarbij de kans op opbrengstdalingen als gevolg van te hoge vochtgehalten. Drains die ondieper dan 2.20 m waren gelegd bleken ernstige opbrengstdalingen te veroorzaken door extreem hoge vochtgehalten, in het bijzonder gedurende relatief natte jaren. Dieper geinstalleerde drains bleken de aanlegkosten te verhogen, maar leverden geen additionele baten. Bodemverzouting had ook een nauwere relatie met draindiepte dan met drainafstand. Dit kan worden toegeschreven aan het grotere effect van diepere drains op de zoutuitspoeling.

De drainafvoer was niet constant maar fluctueerde in de tijd als gevolg van de benedenwaartse vochtflux in de onverzadigde zone. Het huidige systeemontwerp in het projectgebied is gebaseerd op aanbevelingen van het United States Bureau of Reclamation (USBR). De ontwerpnormen voorgesteld door Smedema voor de aride en semi-aride condities in Pakistan (Table 5.1) zijn tamelijk conservatief, dwz resulteren in hoge drainageintensiteiten. De SWAP-simulaties laten, onder de aanname dat er geen beperkingen zijn in systeembeheer en onderhoud, zien dat het projectgebied effectief kan worden gedraineerd met een drainageintensiteit die 25 procent lager ligt dan de ontwerpnormen van USBR en Smedema. Dit betekent twee voordelen: een geringer volume draineffluent en minder behoefte aan kanaalwater. Echter, een eindoordeel over de optimale combinatie van draindiepte en drainageintensiteit vereist een degelijke economische analyse.

Hoge kosten van drainagesysteemaanleg, beheer en onderhoud en problemen van de afvoer van zout draineffluent onderstrepen de noodzaak tot het zoeken naar alternatieve oplossingen voor de stijgende grondwaterspiegel en bodemverzouting. In gebieden met een ondiep grondwaterpeil waar geen drainagesysteem wordt geinstalleerd, zou een bruikbare strategie voor duurzame landbouwproductie kunnen bestaan in vermindering van de irrigatiewateraanvoer, waarbij het gewas maximaal grondwater kan opnemen. Verminderde wateraanvoer in gebieden met ondiep zout grondwater heeft tot doel om waterverliezen te voorkomen en om het geirrigeerde areaal te vergroten met dezelfde hoeveelheid irrigatiewater. Een van de doelstellingen van deze studie was het ontwikkelen van aanbevelingen voor duurzame landbouwproductie in gebieden met een ondiep grondwaterpeil, waarbij bodemverzouting wordt voorkomen onder gedraineerde en niet gedraineerde omstandigheden.

Hoofdstuk 6 bevat een discussie over waterconserverende strategieen voor de ondiepe grondwatercondities van het projectgebied en de lange termijneffecten voor gewasproductie en het milieu. Om deze aanbevelingen te ontwikkelen werd het SWAP model gebruikt als een geschikt alternatief voor kostbare en tijdrovende veldproeven. Simulaties werden uitgevoerd voor een periode van vijftien jaar om waterconserverende strategieen te ontwikkelen voor de graan-katoen gewasrotatie bij de voorkomende ondiepe grondwaterstand in het projectgebied. Daar de boeren in het projectgebied steeds meer grondwater gebruiken voor irrigatie, werden de simulaties uitgevoerd voor drie verschillende kwaliteiten irrigatiewater. De resulterende strategieen van waterconservering werden vergeleken met de huidige praktijk van irrigatie door de boeren en een evaluatie werd uitgevoerd van lange termijn effecten op gewastranspiratie, bodemzoutgehalte, grondwaterstand en drainagebehoefte.

Een verminderde irrigatiegift van kanaalwater voor graan van 195 mm en voor katoen van 260 mm gaf het beste resultaat in termen van gewasproductie, minimale drainagebehoefte, bodemzoutgehalte en beheer van het grondwaterpeil voor zowel gedraineerde als ongedraineerde condities. Vergeleken met de huidige irrigatiepraktijk bespaarde deze waterconserveringsstrategie tot 25 procent per jaar van het schaarse kanaalwater. De huidige irrigatiepraktijk is het geven van maximale hoeveelheden water voor maximale gewasproductie. De wet van toenemende meeropbrengsten is echter niet van toepassing op verzout land dat wordt bedreigd door stijgend grondwater. Het tegengestelde is waar. Niet goed geplande irrigatiegiften kunnen het land in enkele jaren ruineren. Nauwkeurig waterbeheer is daarom een voorwaarde voor productief en duurzaam gebruik van watervoorraden.

Voor het gelijktijdig gebruiken van kanaalwater en grondwater met een EC waarde van 1.5 dS $m^{-1}$ of voor het gebruik van grondwater alleen met een EC waarde van 3.0 dS $m^{-1}$ bleek de waterconserveringsstrategie onvoldoende om duurzaam bodemgebruik te handhaven. Het gemiddelde bodemzoutgehalte uitgedrukt in een kritieke waarde als de zogenaamde *Salinity Hazard Index (SHI)* nam substantieel toe (Figuur 6.4). De relatieve transpiratie, die een indicatie geeft voor de relatieve gewasopbrengst, nam af als gevolg van toegenomen bodemzoutgehalte. Kennelijk moet de aanvoer van irrigatiewater vergroot worden om zouten uit de wortelzone te kunnen spoelen. Mogelijkheden voor aanvullende wateraanvoer is een functie van de capaciteit van het drainagesysteem en van de beschikbaarheid van water. Bij een trend van een stijgend grondwaterpeil, toenemend bodemzoutgehalte en reducties in gewasopbrengst en zonder een goed drainagesysteem, is het uitspoelen van zouten met slechte kwaliteit irrigatiewater niet geschikt en zullen deze gronden zelfs sneller uit productie gaan. Daarom moeten voor zulke gebieden andere mogelijkheden overwogen worden zoals het verbouwen van zouttolerante gewassen als eucalyptus of phreatophyten.

Bij de afnemende beschikbaarheid van goede kwaliteit kanaalwater voor irrigatie is de optie van een aanpassing van de waterconserveringsstrategie beter dan het alternatief de boeren aan te raden grondwater van slechte kwaliteit te gebruiken in een poging gewasproductie te maximaliseren. De simulatieresultaten geven aan dat drainage niet onder alle omstandigheden het probleem van zoutopbouw kan oplossen, omdat het relatief droge moessonseizoen niet voldoende water levert voor zoutuitspoeling. Zout dat wordt toegevoegd door irrigatie met zout grondwater kan alleen afgevoerd worden met een intensief drainagesysteem en met aanvullende watervoorraden. Vermindering van irrigatiegiften is een goede korte termijnoplossing. Echter, op lange termijn zullen dan toch grote investeringen noodzakelijk zijn met een aangepast irrigatieplan.

De resultaten van de modelsimulaties werden gebruikt om strategieen te formuleren voor het duurzaam gebruik van verschillende kwaliteiten irrigatiewater bij verschillende omstandigheden van grondwater, zoals samengevat in Tabel 8.1. Deze aanbevelingen zijn beperkt tot de milieuomstandigheden van het projectgebied.

**Table 8.1.** Strategieen voor duurzaam beheer van verschillende kwaliteiten irrigatiewater onder verschillende omstandigheden van de grondwaterstand in het FDP projectgebied gebaseerd op vijftien jaar simulaties met het SWAP model. CW = Canal Water, CTW = Canal + Tubewell Water, TW = Tubewell Water. Hoeveelheden irrigatiewater (mm) voor graan en katoen zijn de irrigatiegiften gedurende het groeiseizoen na het zaaien.

| Drainage condities | Strategieen voor duurzaam beheer van irrigatiewaterkwaliteiten | | |
|---|---|---|---|
| | CW<br>(EC = 0.3 dS $m^{-1}$) | CTW<br>(EC = 1.5 dS $m^{-1}$) | TW<br>(EC = 3.0 dS $m^{-1}$) |
| Met drainage | Verminderde watergiften. | Zoutuitspoeling mogelijk | Extra zoutuitspoeling neit mogelijk.<br>Verbouw van zouttolerante gewassen. |
| | Graan = 195 mm<br>Katoen = 260 mm | Graan = 195 mm<br>Katoen = 260 mm | Graan = 325 mm<br>Katoen = 320 mm |
| Zonder drainage | Verminderde watergiften. | Zoutuitspoeling neit mogelijk.<br>Verbouw van zouttolerante gewassen. | Installeer drainage systeem of verbouw zouttolerante gewassen zoals Eucalyptus. |
| | Graan = 195 mm<br>Katoen = 260 mm | Graan = 195 mm<br>Katoen = 260 mm | |

Hoofdstuk 7 evalueert de effecten van de verdeling van irrigatiewater op gewasproductie en het milieu. In semi-aride gebieden bleken de afwijkingen in jaarlijkse neerslag van een gemiddeld jaar kritiek om een evenwicht te handhaven tussen de verschillende componenten van de water- en zoutbalans (Hoofdstuk 6). Dit betekent dat voor een duurzaam beheer van water en zout de watertoedeling en -verdeling gebaseerd zou moeten zijn op potentiele evapotranspiratie, neerslag en zoutaccumulatie. Dit zou jaarlijks moeten worden herzien. Dit zou een verandering betekenen van het huidige vaste rotatiesysteem, gebaseerd op een proportionele verdeling van water over beschikbaar land, naar een meer flexibel beheer van irrigatiewater om kanaalwater toe te wijzen op tijd en plaats waar het in feite benodigd is voor optimale en efficiente gewasirrigatie.

Om de geldigheid van dit argument te testen, werd het effect geevalueerd van de irrigatiewaterverdeling op basis van gewasproductiviteit en duurzaamheid voor het milieu. Voor dit doel werd het effect bestudeerd van drie waterverdelingsschema's met drie gradaties van flexibiliteit, op gewasproductie, op waterbesparing, op bodemverzouting, op drainagebehoefte en op grondwaterpeil. De simulaties werden uitgevoerd voor een onbeperkte en voor een beperkte aanvoer van kanaalwater, gecombineerd met drie condities van de grondwaterstand (gedraineerd, diep grondwater en ongedraineerd) die in het projectgebied voorkomen. Onbeperkte aanvoer zou betekenen dat er veel sneeuwval is en dat er voldoende voorraden zijn aangelegd. Beperkte aanvoer van kanaalwater komt overeen met de huidige situatie.

Hoewel met het *on-demand* schema additionele verbeteringen werden behaald in efficient watergebruik, was voor gemiddelde condities het effect van irrigatieschema-flexibiliteit op gewasopbrengst niet erg significant. Echter, vergeleken met een *vast schema* en aangenomen dat kanaalwater onbeperkt beschikbaar zou zijn, zou de productiviteit van water ($Y_{act}/I_{rr}$) tot dertig procent hoger zijn voor het *on-demand* schema (Tabel 7.1). Naast verhoogde productiviteit van water met het *on-demand* schema waren afwijkingen van de gemiddelde opbrengst minimaal, daar timing en hoeveelheid irrigaties konden worden aangepast afhankelijk van variaties in neerslag en verdampingsvraag van de atmosfeer.

Het *on-demand* schema was ook effectief in de besparing van irrigatiewater, in de reductie van drainage volumina en diepe percolatie. De gemiddelde jaarlijkse waterbesparing van het *on-demand* schema vergeleken met een *vast schema* was twintig procent, acht procent en zeven-en-twintig procent voor respectievelijk gedraineerde condities, diep grondwater en ongedraineerde condities. De gemiddelde jaarlijkse drainagebehoefte van een *vast schema* was meer dan dertig procent hoger dan van het *on-demand* schema. De diepe percolatieverliezen waren vijftien procent hoger voor een *vast schema* vergeleken met het *on-demand* schema. Hoewel een volledige oplossing van de stijgende grondwaterspiegel niet kon worden bereikt, bleek het *on-demand* schema effectief in het vertragen van het proces van stijgend grondwater en bodemverzouting. Dit gaf een positief milieu-effect. Voor de beperkte aanvoer van kanaalwater waren de baten van het *on-demand* schema vergeleken met een *vast schema* slechts een kleine toename in gewasopbrengst. Het effect op bodemverzouting, drainagebehoefte en grondwaterpeil was vergelijkbaar.

De voordelen van het *on-demand* schema zijn duidelijk wanneer kanaalwater onbeperkt beschikbaar is en wanneer de doelstelling is om maximale gewasproductie te bereiken met minimale milieudegradatie. Maar in een situatie van periodieke watertekorten, zoals in de Indus basin, kan de keuze voor een schema niet alleen een keuze zijn voor maximale gewasproductie. De keuze moet zijn voor een schema dat binnen de gegeven beschikbare wateraanvoer en beheerscapaciteit gewasproductie optimaliseert op een duurzame manier. Zonder voldoende aanvoer van kanaalwater en zonder een effectief monitoring- en communicatiesysteem is de overgang van een *vast* *schema* naar een *on-demand* schema in de Indus basin niet economisch haalbaar en ook niet sociaal acceptabel.

Om deze reden moet het accent liggen op verbetering van het huidige op aanvoer gebaseerde systeem. Er is nog ruimte aanwezig voor verbeteringen in wateraanvoer en gewasopbrengst. Opties voor een beter waterbeheer zoals reductie van kanaalwater-aanvoer naar gebieden met hoog maar zoet grondwater, zou een aanzienlijke besparing van kanaalwater kunnen opleveren. Dit water zou gebruikt kunnen worden in andere gebieden met watertekorten. Indien de huidige wateraanvoer meer betrouwbaar zou kunnen worden gemaakt, zouden boeren om een maximale opbrengst te behalen, hun werkzaamheden kunnen aanpassen en hun irrigatie beter kunnen plannen in de meest kritieke fasen van gewasgroei.

De irrigatie- en drainageplanning voor verschillende bodem- en gewascondities in verschillende klimaatzones is niet eenvoudig. Met een niet-stationair model zoals SWAP kunnen de bodem-gewas-klimaat interacties worden bestudeerd evenals lange termijn effecten van een groot aantal beheersopties op gewasproductie en het milieu, waarvoor veldproeven niet konden worden uitgevoerd. De hier gepresenteerde conclusies zijn gebaseerd op de condities van klimaat, irrigatie en agrohydrologie in het projectgebied. De ontwikkelde aanpak kan echter ook worden toegepast in andere gebieden waar soortgelijke problemen voorkomen.

# REFERENCES

Afzal, M., 1992. Economics of drainage and reclamation measures: a case study from Pakistan. Proceedings of 5th International drainage workshop, Lahore, Pakistan. ICID-CIID, IWASRI, Vol. III, 6.185-6.194.

Ahmad, N., and G. R. Chaudhry, 1988. Irrigated agriculture of Pakistan., Gulberg III, Lahore II.

Ahmad, N., R.H. Qureshi and M. Qadir, 1990. Biotic and chemical reclamation of saline sodic soils. In: Proceedings of the Indo-Pak workshop on soil salinity and water management, volume I:65-72, Pakistan Agricultural Research Council, Islamabad, Pakistan.

Alam, M. and M.N. Bhutta, 1996. Availability of water in Pakistan during 21st century. Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference, Nov. 3-6, San Antonio, Texas.

Allen, R.G., M. Smith, A. Perier and L. S. Pereira, 1994. An update for the definition of reference evapotranspiration. ICID Bulletin, 43(2):1-34.

Aziz, A., Z. Hussain and J.A. Replogle, 1992. Effective water management reinforces land drainage: a case study on alternatives for lining of watercourses. Proceedings of 5th International drainage workshop, Lahore, Pakistan. ICID-CIID, IWASRI, Vol. III, 6.168-6.175

Badruddin, M. 1996. Country profile: Pakistan. Internal report, International Water Management Institute (IWMI), Lahore, Pakistan.

Badruddin, M., M.A. Bhatti, M. Afzal and M.N. Bhutta, 1999. Water and its use in agriculture: a perspective for Pakistan. Paper presented in the Global Water Partnership (GWP) workshop held, on April 11, Islamabad, Pakistan.

Bastiaanssen, W.G.M., K. El-Deen Milad Soliman, C. Mirabile, M. Korani, and S. Abdel Gawad, 1996. Data management related to the application of two crop-water-environment models in Argentina and Egypt. Proceedings of the 16th ICID Congress, Cairo, Egypt. p 54-68.

Bastiaanssen, W.G.M., R. Singh, S. Kumar, J.K. Schakel and R.K. Jhorar, 1996. Analysis and recommendations for integrated on-farm water management in Haryana, India: a model approach. Wageningen (The Netherlands), Winand Staring Centre, Report 118, 152 pp.

Bastiaanssen, W.G.M. and S. Ali, 2000. A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. Agricultural systems (submitted).

Bastiaanssen, W.G.M., 2000. Shared water resources information from space: new management opportunities or unwanted interference? Inaugural address, International institute for aerospace survey and earth sciences, Enschede, The Netherlands. 22 p.

Beekma, J., 1993. Application of soil parameters in land reclamation for balanced agricultural development and environmental management. IWASRI Report 152, Lahore, Pakistan.

Beekma, J., Z.I. Raza, and Th.M. Boers, 1994. Calibration of EM38 for salinity assessment in the Fourth Drainage Project, Pakistan. IWASRI Report 120, Lahore, Pakistan.

Beekma, J., T.J. Kelleners, Th.M. Boers and Z.I. Raza, 1995. Application of SWATRE to evaluate drainage of an irrigated field in the Indus Plain, Pakistan. In: L.S. Pereira et al., (Eds.), Crop-Water-Simulation Models in Practice, Wageningen Press, Wageningen, The Netherlands, pp.141-160.

Beg, A. and M.I. Lone, 1992. Trends of changes in groundwater quality of SCARP-1. Proceedings of 5th International Drainage Workshop, Lahore, Pakistan, ICID-IWASRI, 1992, Vol. II, 3.73-3.85.

Belmans, C., J.G. Wesseling and R.A. Feddes., 1983. Simulation of the waterbalance of a cropped soil: SWATRE. J. Hydrol. 63:217-286.

Bhatti, A.K., 1987. A review of planning strategies of salinity control and reclamation projects in Pakistan. In: Vos, J. (Ed.), Proceedings of Symposium 25th International Course on Land Drainage, Twenty-Five years of Drainage Experience, 24-28 November, 1986, Publ. 42. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, pp 216-226.

Bhatti, M.A. and J.W. Kijne, 1992. Management of groundwater abstraction in Gugera Branch. In: Vlotman, W.F. (Ed.), Proceedings of 5th International Drainage Workshop, Lahore, Pakistan, ICID-IWASRI, 1992, Vol. II, 3.73-3.85.

Bhutta, M.N., W.F. Vlotman and F.A. Zuberi, 1992. Performance of sump-9 Fourth Drainage Project. In: Proceedings of 5th International Drainage Workshop, Lahore, Pakistan, ICID-IWASRI, 1992, Vol. III, 6-139-152.

Bhutta, M.N., T.A. van der Sluis and W. Wolters, 1994. Review of pipe drainage projects in Pakistan. In: Proceedings of national Workshop on Drainage System Performance in Indus Plains and Future Strategies, 28-29 January, Vol. II, Tandojam, Pakistan.

Black, T.A., W.R. Gardner and G.W. Thertell, 1969. The prediction of evaporation, drainage and soil water storage for a bare soil. Soil Sci. Soc. Am.J.33:655-660.

Boers, Th.M.and F.A. Zuberi, 1995. Developing a Drainage Research Strategy for Pakistan. In: Proceedings of national Workshop on Drainage System

Performance in Indus Plains and Future Strategies, 28-29 January, Vol. II, pp 175-190, Tandojam, Pakistan.

Boesten, J.J.T.I. and L. Stroonsnijder, 1986. Simple model for daily evaporation from fallow tilled soil under spring conditions in a temperate climate. Netherlands Journal of Agricultural Science, 4: 75-90.

Boesten, J.J.T.I., and A.M.A van der Linden, 1991. Modeling the influence of sorption and transformation on pesticide leaching and persistence. Journal. Envi. Quality 20:425-435.

Boonstra, J., S. Hamid, A. Moghle and W.F. Vlotman, 1991. Collection, processing and screening of data for the water balance study of S1B9 area of the Fourth Drainage Project, NRAP Report No. 30. Lahore, Pakistan.

Bouten, 1992. Monitoring and modelling forest hydrological processes in support of acidification research. Diss. Univ. of A'dam. 218 pp.

Bradford, S. and J. Letey, 1992. Simulated effects of watertable and irrigation scheduling as factors in cotton production. Irrigation Science, Vol. 13: 101-107.

Brussel, M., 1990. A waterbalance study in the Pakistan Indus Plains. IWASRI Publication N. 52. International Waterlogging and Salinity Research Institute, Lahore, Pakistan.

Clemmens, A.J., 1987. Delivery systems schedules and required capacities. In: Proceedings of symposium on planning, operation, rehabilitation and automation of irrigation water delivery systems. Portland.

Clyma, W., 1996. Irrigation Scheduling Revisited: Historical evaluation and reformulation of the concept. Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference Nov. 3-6, San Antonio, Texas.

Cosgrove, W.J. and F.R. Rijsberman, 2000. World Water Vision, making water everybody's business. World Water Council, Earthscan Publications Ltd., London, UK: 108 pp.

De Wit, C.T., 1958. Transpiration and crop yield. Verslad, van Landbouck, Onderzoek No. 64.6, 88 pp.

De Zeeuw, J.W. and F. Hellinga, 1958. Neerslag en afveer, Landbouwkundig Tijdschrift, 70, pp. 405-422 (in Dutch with English summary).

Dirksen, C., J.B. Kool, P. Koorevaar and Th. M. van Genuchten, 1993. Hyswasor: simulation model of hysteretic water and solute transport in the root zone. In: D. Russo and G. Dagan (Eds.) Water flow and solute transport in soils. Springer-Verlag, Adv. Series in Agric. Sci., 20, 99-122.

Dirksen, C., 1999. Soil physical measurements. Geoscience Publishers, Germany. 154 pp.

Doorenbos, J. and A.H. Kassam, 1977. Yield response to water. Irrigation and Drainage Paper 33, FAO, Rome, Italy.

Doorenbos, J. and W.O. Pruitt, 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24, FAO, Rome, Italy.

Droogers, P. and G. Kite, 1999. Water productivity from integrated basin modeling. Irrigation and Drainage systems, Vol. 13:275-290.

Dumm, L.D., 1960. Validity and use of the transient flow concept in subsurface drainage. Paper presented at ASAE meeting, Memphis, Tenn, Dec. pp. 4-7.

Engelman, R. and L. Peroy, 1993. Sustaining water: Population and future for renewable water supplies. Population and Environment Program. Washington, D.C.: Population Action International.

Falkenmark, M., J. Lundqvist and C. Widstrand, 1989. Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development. Natural Resources Forum 13 (4): 258-267.

FAO, 1982. Organization, operation and maintenance of irrigation schemes. FAO Irrigation and Drainage paper No. 40, Rome, Italy.

Feddes, R.A., P.J. Kawalik, and H. Zaradny, 1978. Simulation of water use and crop yield. Simulation Monogr, PUDOC, Wageningen, 188 pp.

Feddes, R.A., 1985. Crop water use and dry matter production: state of the art. Technical Bulletin No. 63. Institute for Land and Water Management Research (ICW), Wageningen, The Netherlands. 221-234 pp.

Feddes, R.A., 1988. Effects of drainage on crops and farm management. Agricultural Water Management, 14:3-18.

Feddes, R.A. 1990. Proposal on non-steady state water management model for horizontal drainage design. Assistance to IWASRI, Lahore, Pakistan. Mission Report. 31 pp.

Feddes, R.A. and A.L.M. van Wijk, 1990. Dynamic land capability model: a case history. Phil. Trans. R. Soc. Land. B 329:411-419.

Feddes, R.A. and R.W. Koopmans, 1997. Agrohydrology lecture notes. Dept. of Water Resources, Wageningen Agricultural University, The Netherlands.

Fereres, E., 1996. Irrigation scheduling and its impact on 21st century. Evapotranspiration and Irrigation Scheduling. Proceedings of the International Conference, Nov. 3-6, San Antonio, Texas.

Haider, G., S.A. Prathapar, M. Afzal and A.S. Qureshi, 1999. Water for environment in Pakistan. Paper presented in the Global Water Partnership (GWP) workshop held, on April 11, Islamabad, Pakistan.

Hanks, R.J., 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66: 660-665.

Hanks, R.J., 1983. Yield and water use relationships: an overview. In: Limitations to efficient water use in crop production. H.M. Taylor, W.R. Jordan and T.R. Sinclair (Eds.) Amer. Soc. Agron.: 393-411.

Harza/Nespak, 1984. Mardan SCARP subsurface drainage analysis. WAPDA, Pakistan.

Hendrickx, J.M.H., M.A. Choudhry, J.W. Kijne, M. Sadiq and Z.I. Raza., 1990. Soil physical measurements for drainage design in arid regions. Symposium on Land Drainage for Salinity Control in Arid and Semi-Arid Lands. Cairo, Egypt. Vol. 2:121-134.

Hill, R.W. and R.G. Allen, 1995. Developing simple irrigation scheduling calendars. Proceedings of the ICID/FAO Workshop on Irrigation Scheduling: From theory to practice. Rome, Italy, September, 12-13.

Homaee, M., 1999. Root water uptake under non-uniform transient salinity and water stress. Ph.D. thesis, Wageningen University, The Netherlands. 173 pp.

Horst, L., 1998. The dilemmas of water division: Considerations and criteria for irrigation system design. Colombo, Sri Lanka. International Water Management Institute.

Hussain, T., V. Timmer, H. Akram, A. Yaqub, M. Aslam, G. Gilani and M.A. Abbas, 1990. Brackish water management strategies for crop production. In: Proceedings of the Indo-Pak Workshop on soil salinity and water management, Volume II:369-381. Pakistan Agricultural Research Council, Islamabad, Pakistan.

IWASRI, 1990. Detailed soil survey of S1B9 area, Fourth Drainage Project, Faisalabad. Internal Report No. 90/11, IWASRI, Lahore, Pakistan. 28 pp.

IWASRI, 1994. Watertable control in design and practice for pipe drainage systems in Pakistan. Internal Report No. 94/17, IWASRI, Lahore, Pakistan, 106 pp.

IWMI, 2000. Water issues for 2025: A research perspective. Research contribution to the World Water Vision. Colombo, Sri Lanka: International Water Management Institute.

Jacobs, C., J. de Jong, P.P. Mollinga and W.G.M. Bastiaanssen 1997. Constraints and opportunities for improving irrigation management in a water scarce but waterlogged area in Haryana, India. Proceedings of the International Workshop on Sustainable Irrigation in Areas of Water Scarcity and Drought. September 11-12, Oxford, England.

Jensen, M.E., 1969. Scheduling irrigations using computers. J. of Soil and Water Cons. 24(8):193-195.

Jensen, M.E., 1975. Scientific irrigation scheduling for salinity control of irrigation return flows. U.S. EPA Tech. Series EPA-600/2-75-064, Ada, OK 74820, 92 pp.

Jurriens, R., and P.P. Mollinga, 1996. Scarcity by design: protective irrigation in India and Pakistan, ICID Journal 45(2): 31-53.

Kelleners, T.J., 1994. Use of SWATRE to simulate water and salt balance of an irrigated field in the Indus Plain of Pakistan. IWASRI Report 140, Lahore, Pakistan. 42 pp.

Kelleners, T.J., and M.R. Choudhry, 1998. Drainage water salinity of tubewells and pipe drains: A case study from Pakistan. Agric. Water. Manag. Vol. 37:41-53.

Kielen, N., 1996. Farmers' perceptions on salinity and sodicity: a case study into farmers' knowledge of salinity and sodicity. Research Report No. 3. International Irrigation Management Institute (IIMI), Lahore, Pakistan.

Krayenhoff, van de Leur, D.A., 1958. A study of non-steady groundwater flow with special reference to a reservior-coefficient. I. Ingenieur, 70, pp. B87-94.

Krayenhoff, van de Leur, D.A., 1962. A study of non-steady groundwater flow. II. I. Ingenieur, 74, pp. B285-292.

Kroes, J.G., J.C. van Dam, J. Huygen, and R.W. Vervoort, 1999. User's Guide of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Technical Document 53, DLO-Winand Staring Centre, Wageningen, Report 81, Department of Water Resources, Wageningen Agricultural University, the Netherlands.

Kumar, S., and W.G.M. Bastiaanssen, 1993. Simulation of the water balance in relation to crop water requirement in (semi-) arid zones. Question 44, R 28, The Hague, The Netherlands. pp. 349-368.

Kumar, 1995. Suitability of simulation techniques in reuse of drainage water. Proc. National Seminar on Reclamation and Management of Waterlogged Saline Soils, Karnal, India, pp 331-346.

Maas, E.V. & G.J. Hoffman, 1977. Crop salt tolerance-current assessment. J. Irrig. And Drainage Div., ASCE 103, 115-134.

Maas, E.V., 1990. Crop salt tolerance. In: K.K. Tanji (ed.) Agricultural salinity assessment and management. ASAE manuals and reports on engineering practice No. 71. ASCE, New York, USA. p 262-304.

Maasland, M., 1959. Watertable fluctuations induced by intermittent recharge. Journal of Geophysics Research 64, pp. 549-559.

McAneney, K.J., and B. Itier, 1996. Operational limits to the Priestly-Taylor formula. Irrigation Science 17:37-43.

McNeill, J.D., 1986. Geonics EM38 ground conductivity meter. Tech. Note TN-21. Geonics Ltd., Mississauga, Ontario, Canada.

Merriam, J.L., 1992. The need on the farm for flexible water supply schedule. In: Advances in planning, design, and management of irrigation systems as related to sustainable land use. Proceedings of the International conference held in Belgium, September 14-17.

Millington, R.J and J.P. Quirk, 1961. Permeability of porous solids. Trans. Faraday Soc., 57, 1200-1207.

Moghal, A.M., A.S. Hamid and L. Boonstra, 1992. Seasonal net recharge to aquifer underlying the S1B9 area, Fourth Drainage Project. IWASRI Publication No. 106, Lahore, Pakistan. 127 pp.

Molden, D.J., R. Sakthivadivel, C.J. Perry, C. de Fraiture and W.H. Kloezen, 1998. Indicators for comparing performance of irrigated agricultural systems. Research Report 20. Coloumbo, Sri Lanka. International Water Management Institute.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. Vol. 12(3):513-521.

Mulk, S., 1993. Water Resources of Pakistan. Report for World bank, Washington, USA.

Nespak/SGI. 1991. Contribution of private tubewells in the development of water potential. Ministry of Planning and Development, Govt. of Pakistan, Islamabad.

Nespak/MMI, 1993. Feasibility Study National Drainage Program I, Executive Summary, NESPAK and Mott MacDonald, Islamic Republic of Pakistan.

Nielsen, D.R., M.Th. van Genuchten and J.W. Bigger, 1986. Water flow and solute transport in the unsaturated zone. Water Resour. Res., 22, supplement, 89S-108S.

OFWM., 1980. Manual for watercourse monitoring and evaluation. On-Farm Water Management. Ministry of Agriculture, Lahore, Pakistan.

PARC, 1982. Consumptive use of water for crops in Pakistan. Pakistan Agricultural Research Council, Islamabad.

Paw U, K.T. and W. Gao, 1988. Applications of solutions to non-linear energy budget equations. Agr. And Forest Met. 43:121-145.

Prathapar, S.A. and Asad S. Qureshi, 1999. Modeling the Effects of Deficit Irrigation on Soil Salinity, Depth to Water Table and Transpiration in Semi-arid Zones with Monsoonal Rains. Water Resources Development, Vol. 15, Nos. ½:141-159.

Priestley, C.H.B. and R.J. Taylor, 1972. On the assessment of surface flux and evaporation using large-scale parameters. Mon. Weather Rev. 100: 81-92.

Qureshi, R.H. and E.G. Barrett-Lennard, 1998. Saline agriculture for irrigated land in Pakistan: a handbook, ACIAR Monograph No. 50, 142 p.

Raza, Z.I., and M.R. Choudhry., 1998. Soil salinity trends under farmer's management in a pipe drainage project. IWASRI Publication No. 189. Lahore, Pakistan. 88 pp.

Renault, G. & G.G.A. Godaliyadda, 1999. Generic typology for irrigation systems operation. Research Report 29. Colombo, Sri Lanka. International Water Management Institute.

Renault, G. & I.W. Makin, 1999. Modernizing irrigation operations: spatial differentiation resource allocation. Research Report 35, Colombo, Sri Lanka. International Water Management Institute.

Replogle, J.A. and L. Merriam, 1982. Scheduling and management of irrigation water delivery systems. Proceedings of ASAE 2nd irrigation symposium, USA: American Society of Agricultural Engineers.

Ritzema, H.P., (ed.) 1994. Drainage principles and applications. ILRI Publication No. 16, Wageningen, The Netherlands.

SAR, 1992. Staff Appraisal Report. Pakistan. Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project. World Bank, South Asian Region. Country Department III. Agricultural Operations Division.

Sarwar, A., 1993. Application of SWATRE to predict soil water flow in a lysimeter. MSc thesis, Dept. of Water Resources, Wageningen Agricultural University, The Netherlands. 53 pp.

Sarwar, A. and R.A. Feddes, 2000. Re-evaluating drainage design criteria for the Fourth Drainage Project, Pakistan. Part II: Results of model simulations. Irrigation and Drainage Systems. (Submitted)

Sarwar, A. and W.G.M. Bastiaanssen, 2000. Long-term effects of irrigation water conservation on crop production and environment in (semi-) arid areas. ASCE Irrigation and Drainage Engineering. (Submitted)

SCARP Monitoring Organization (SMO), 1994. Annual Report Monitoring and Evaluation Fourth Drainage Project, vol. 1, text. Lahore, Pakistan, 138 pp.

Scott, P.S., G.J. farquhar and N. Kouwen, 1983. Hysteretic effects on net infiltration. In: Advances in infiltration. American Society of Agricultural Engineers, St. Joseph, Mich, P. 163-170.

Shalhevet, J., 1994. Using water of marginal water quality for crop production. Agric. Wat. Manag. 25:233-269.

Shanan, L., 1992. Planning and management of irrigation systems in developing countries. Agric. Wat. Manage. Vol. (1+2). The Netherlands.

Singh, R. and J. Singh, 1997. Irrigation planning in wheat (*Triticum aestivum*) under deep watertable conditions through simulation modelling. Agric. Wat. Manag. Vol. 33: 19-29.

Skaggs, R.W. 1990. Simulation of drainage system performance as affected by irrigation management. Symposium on Land Drainage for Salinity Control in Arid and Semi-Arid Lands. Feb. 25-Mar. 2, Cairo, Egypt. Vol. 1:61-77.

Skaggs, R.W., 1999. Drainage simulation models. In: Agricultural Drainage. R.W. Skaggs and J. van Schilfgaarde (Eds.). American Society of Agronomy Monogram No. 38. Madison, Winconsin, USA.

Smedema, L.K. and D.W. Rycroft, 1988. Land Drainage: Planning and design of irrigation and drainage systems. Anchor Brendon Publishers, London. UK.

Smedema, L.K., 1990. Comparative study of the East Khairpur, Mardan and Drainage IV pipe drainage project. Project: PAK/83/022. Technical Report No. 90/01. IWASRI Publication No. 8, Lahore, Pakistan. 31 pp.

Smedema, L.K. and R.V. Aart, 1992. Subsurface field drainage trials for the Fordwah Eastern Sadiqia (south) Project. NRAP Report No. 38, Lahore, Pakistan.

Smets, S.M.P., M. Kuper, J.C. Van Dam and R.A. Feddes, 1997. Salinization and crop transpiration of irrigated fields in Pakistan's Punjab. Agri. Wat. Manag., 35:43-60.

Smith, M., R.G. Allen, A. Perier and L. Pereira, 1990. Expert consultation on revision of FAO methodologies for crop water requirements. Internal Report FAO: 54 pp.

Smith, M., 1995. CROPWAT: a computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No. 46. Rome, Italy.

Steiner, R.A. & M.F. Walter, 1993. The effect of allocation schedules on the performance of irrigation systems with different levels of spatial diversity and temporal variability. Agric. Wat. Manage. Vol. 23:213-224.

Stewart, J.I., R.H. Cuenca, W.O. Pruitt, R. Hagan and J. Tosso, 1977. Determination and utilization of water production functions for principal California crops. W-67 Calf. Contrib. Proj. Rep. University of California, Davis, USA.

Tanji, K.K., (Eds.), 1990. Agricultural Salinity Assessment and Management, Manual 71, Amer. Soc. Civil Eng., New York, 619 pp.

Tarar, R.N., 1995. Drainage system in Indus plains-An overview. In: Proceedings of national Workshop on Drainage System Performance in Indus Plains and Future Strategies, 28-29 January, Vol. II, pp 1-45, Tandojam, Pakistan.

Taylor, S.A., and G.M. Ashcroft, 1972. Physical Edaphology. W.H. Freeman and Co. San Francisco, 434-435.

Teixeira, J.L., R.M. Fernendo and L.S. Pereira, 1995. Irrigation scheduling alternatives for limited water supply and drought. ICID Journal, Vol. 44, No. 2:73-88.

Topp, G.C., J.L. Davis, and A.P. Annan, 1980. Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. Water. Resour. Res. 16:574.

Trimmer, W.L., 1990. Applying partial irrigation in Pakistan. J. Irrig. And Drain. Div., ASAE. 116 (3);342-353.

U.S. Bureau of Reclamation., 1989. Design memorandum subsurface drainage Fourth Drainage Project, lower remaining Rechna subproject, Faisalabad. U.S. Dept. of Interior, Bureau of Reclamation, and WAPDA, Lahore, Pakistan. 49 pp.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkali soils. Handbook 60, U.S. Government Printing Office, Washington, DC.

Van Dam, J.C., J.N.M. Stricker and P. Droogers, 1990. From one-step to Multi-step determination of soil hydraulic functions by outflow experiments. Report 7. Dept. of Water Resources, Wageningen Agricultural University, The Netherlands. 83 pp.

Van Dam, J.C., J.N.M. Stricker, and P. Droogers., 1994. Inverse method to determine soil hydraulic functions from multi-step outflow experiments. Soil Sci. Soc. Am. J. 58:647-652.

Van Dam, J.C. and R.A. Feddes., 1996. Modeling of water flow and solute transport for irrigation and drainage. In: L.S. Pereira et al., (Eds.), Sustainability of Irrigated Agriculture, Kluwer Academic Publishers, the Netherlands: 211-231.

Van Dam, J.C., J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, and P.E.V.Van Walsum, 1997. Simulation of transport processes in the Soil-Water-Air-Plant environment. SWAP user's manual. DLO-Winand Staring Centre, Wageningen, The Netherlands.

Van Dam, J.C. and R.A.Feddes, 2000. Numerical simulation of infiltration, evaporation and shallow groundwater levels with the Richards' equation. J. Hydro. (in press).

Van den Broek, B.J., J.C. van Dam, J.A. Elbers, R.A. Feddes, J. Huygen, P. Kabat and J.G. Wesseling, 1994. SWAP 1993, input instructions manual. Report 45, Dept. of Water Resources, Wageningen Agricultural University, The Netherlands.

Van Genuchten, M. Th. And R.W. Cleary, 1979. Movement of solutes in soil: computer simulation and laboratory results, In: G.H. Bolt (Ed.), soil Chemistry B, physico-Chemical Models, Elsevier, Amsterdam, pp 349-386.

Van Genuchten, M. Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

Van Genuchten, M. Th. 1987. A numerical model for water and solute movement in and below the root zone. Res. Report. US Salinity Laboratory, Riverside, CA.

van Someren, C.L. and Th.M. Boers, 1978. Preliminary design for tile drainage system and proposal for execution and monitoring in East-Khairpur pilot project, Drainage and Reclamation Institute of Pakistan, Report 2, 32 p.

Vehmeyer, P., 1992. Irrigation management strategies at the farm level in a warabandi schedule. IWASRI Publication No. 122. International Waterlogging and Salinity Research Institute, Lahore, Pakistan. 127 pp.

Vlotman, W.F., A.B. Sufi., and I.A. Sheikh, 1990. Comparison of three subsurface pipe drainage projects in Pakistan. Proceedings of the symposium on land drainage for salinity control in arid and semi-arid regions, Cairo, Egypt.

Vlotman, W.F. and M. Latif, 1993. Present and suggested water management strategies in fixed rotational irrigation system at S1B9 of Fourth Drainage Project, Faisalabad. IWASRI Publication No. 148. International Waterlogging and Salinity Research Institute, Lahore, Pakistan. 90 pp.

Vlotman, W.F. M.N. Bhutta, S.R. Ali and A.K. Bhatti, 1994. Design, Monitoring and Research Fourth Drainage Project, Faisalabad, 1976-1994 (Main Report). IWASRI Publication No. 159. International Waterlogging and Salinity Research Institute, Lahore, Pakistan. 90 pp.

Vlotman, W.F., A. Beg and Z.I. Raza, 1994. Warabandi, Theory and Farmers Practices at S1B9, Fourth Drainage Project, Faisalabad. Working Paper, IWASRI Publication No. 141. Lahore, Pakistan. 281 pp.

Water and Power Development Authority (WAPDA), 1983. Project report Muhajir Branch unit Thal canal SCARP. Publication No. 32, WAPDA, Lahore, Pakistan. 154 pp.

Water and Power Development Authority (WAPDA), 1988. Revised PC-I performa Fourth Drainage Project (Lower Remaining Subproject) Planning and Design Cell, Fourth Drainage Project, Lahore, Pakistan. 89 pp.

Water and Power Development Authority (WAPDA), 1989. PC-II performa for monitoring Salinity Control and Reclamation Projects, SCARPs for the period 1989-93. SMO Publication No. 100. Lahore, Pakistan. 60 pp.

Wesseling, J.G., J.A. Elbers, P. Kabat and B.J. van den Broek, 1991. SWATRE: instructions for input. Internal note, Winand Staring Centre, Wageningen, The Netherlands. International Waterlogging and Salinity Research Institute, Lahore, Pakistan. 29 pp.

Willardsen, L.S., 1992. Drain envelope field testing at S2A8, Backfill procedures, Salinity and Water management at S1B9. Consultancy Report, IWASRI Publication No. 110.

Wolters, W. and M.N. Bhutta, 1997. Need for integrated irrigation and drainage management, example of Pakistan. Proceedings of the ILRI symposium, Towards Integrated Irrigation and Drainage Management, Wageningen, The Netherlands.

Wolters, W., Z. Habib and M.N. Bhutta, 1997. Forget about crop-demand based irrigation canal irrigation in the plains of Pakistan. Proceedings Seminar on On-Farm Salinity, Drainage and Reclamation. May 13-14, Avari, Lahore, Pakistan.

World Bank, 1986. Design and operating guidelines for structured irrigation networks. South Asian Projects department, Washington.

# CURRICULUM VITAE

Asad Sarwar was born on 10 March 1965 in Faisalabad, Pakistan. After secondary school, he studied Agricultural Engineering at the University of Agriculture, Faisalabad, Pakistan, and graduated in 1986. In the same year, he joined the Water Management Research Project (WMRP) in Faisalabad, where he was searching for irrigation techniques to improve water application efficiency and crop yields. At the end of 1988 he joined the International Irrigation Management Institute (IIMI) in Lahore, Pakistan. His specific tasks in IIMI were: organization and implementation of field work and the collection and processing of data related to waterlogging and salinity research.

In 1991, he was awarded a fellowship from The Netherlands' Government to enter the MSc degree program at Wageningen University. In 1993, he obtained his Master's degree in Drainage Engineering with Distinction. On his return to Pakistan, he joined the Netherlands Research Assistance Project (NRAP), a joint project of the International Land Reclamation and Improvement Institute (ILRI), Wageningen, and the International Waterlogging and Salinity Research Institute (IWASRI), Lahore. His main responsibilities were to plan and conduct research to evaluate the performance of drainage systems with regard to irrigation and salinity management.

In 1995, he received a fellowship from Wageningen University to start a 'sandwich' PhD program. Following his 6-month stay in Wageningen he again joined the NRAP-project in October 1995 to collect data for his PhD studies. In July 1997 he again joined IWMI-Pakistan where he worked on irrigation and salinity related studies. His special tasks were to apply numerical and analytical models in unsaturated soils to evaluate agronomic and engineering options to prevent salinization and reclaim saline-sodic soils.

In August 1999, he joined the Water Resources Department of Wageningen University to complete this dissertation. Presently, Asad Sarwar is working as senior irrigation engineer in IWMI-Pakistan.

Mr. Asad is married with Umaira and they have a daughter named Soho.