Irrigation management strategies

for improved

salinity and sodicity control

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ABSTRACT

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An integrated approach is developed to assess *a priori* the effects of irrigation management interventions on soil salinity, sodicity and transpiration. The approach is tested for a 75,000 ha irrigation system in Pakistan, where canal and groundwater are used conjunctively. The main hypothesis is that by reallocating good quality canal water, the use of poor quality groundwater can be restricted, thus combating salinity and sodicity and mitigating their effects on crops. The study has three components. Firstly, interventions in canal water deliveries to tertiary units are analyzed using an unsteady state hydraulic model, based on the St. Venant equations, and linked with a regulation module, which captures the operational decisions of the irrigation agency. By changing the operational rules at the main canal, and by redimensioning the outlets in secondary canals, the water can be distributed equitably to tertiary units or delivered to those units that require it for salinity control. Secondly, the impact of irrigation on salinity, sodicity and transpiration is assessed for farmers' fields, using a combined soil water flow and solute transport model, based on Richard's equation and the convection-dispersion equation, and a regression equation, based on the irrigation quality and soil texture. A curvilinear relationship with a decreasing tangent was found between the irrigation quantity and soil salinity. Increases in the *EC* of the irrigation water result in a parallel curve with higher salinity levels. Adapting the irrigation quantity and quality to the existing soil types and depth to groundwater table can, therefore, reduce salinity and sodicity, thus avoiding soil degradation, which already occurs at an *ESP* of 4%. Thirdly, both components are combined with a parallel, socio-economic study, where farmers' decisions related to the crop portfolio and acquisition/application of water, were captured in Linear Programming models. The individual models of both studies are interfaced to develop a tool, capable of quantifying the effect of irrigation management interventions. For a secondary canal serving 14,000 ha, it is shown that the area threatened by sodicity is reduced by 40% by reallocating canal water, without affecting the agricultural production. The results of the developed tool should not be taken as accurate predictions, as there are likely to be unforeseen events due to the complexity of irrigation systems. Instead, the approach should be evaluated for its effectiveness in supporting actors' decisions in irrigation system management, by enhancing their understanding of the effects of interventions on salinity, sodicity and agricultural production. The application of the approach, in two case studies, shows that it allows the investigation of a wide range of policy and management interventions, and captures adequately the complexity of an irrigation system, thus providing indications about its transferability. However, the tools should be applied as part of an integrated concept, which includes phases of diagnosis, identification of relevant processes and parameters, and discussions with actors.

Keywords: irrigation management, integrated approach, canal regulation, soil salinity, sodicity, soil degradation, modelling

PREFACE

One cannot but feel priviliged for having had the opportunity of working and living in Pakistan. Working in the irrigation systems stretching the plains of the Indus and its tributaries, where efforts of many focus on the use of that precious resource water, is exciting. Perhaps, the strongest sensation one feels is the presence of the past, with the rich tradition of irrigation in the Indus Basin. This sensation is apparent when visiting the remains of Moenjodaro or Harappa, but is also never very far away in discussions with irrigation engineers, who relate to the concepts of Kennedy, Lacey and others. A careful reading of the not so recent publications, e.g. those published by the Punjab Engineering Congress at the beginning of the century, frequently showed that contemporary issues were not new and had been extensively discussed in the past[1].

Working in an environment with such a rich history offers great opportunities to learn, many a time leading to long discussions about the concepts of irrigation. The ingenuity of solutions that have been discussed, developed, implemented and adapted to problems associated with irrigation in the Indus Basin, is amazing. An obvious example is the empirical design of channels to minimize the silt deposition. At the same time, a historical perspective can be a handicap, when the irrigation sector remains static and the associated paradigms constrain people in developing new concepts. It provided in any case an extra challenge to develop an innovative approach that makes sense to all concerned.

Irrigation cannot be separated from society and living in Pakistan has been enriching. It appeared at times to be a three-dimensional experience. The third dimension was not only attained when leaving the flat irrigated plains for the Karakoram mountains, but was also obvious in daily interactions outside the scope of irrigation management. Looking at it from the outside, irrigation became one of the pieces of a larger puzzle. Whether or not I have been able to structure these pieces into something more coherent is perhaps not very important, as the puzzle should keep some of its surprises.

I wish to dedicate this thesis to Zaigham Habib and Mushtaq Ahmed Khan.

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1 A completely different example was shown to me by Fawzi Khawaja after our establishment of the Lahore Rugby Football Club in 1992. According to newspaper clippings, rugby had been established in Pakistan in 1928, 1953 and again in 1992....

Stellingen/Propositions

Behorend bij het proefschrift "Irrigation management strategies for improved salinity and sodicity control" door Marcel Kuper.

1. The combined use of the terms waterlogging and salinity and their qualification as a twin menace is misleading.
   Mehta (1940); Choudry (1979); Kijne and VanderVelde (1992); This thesis

2. A model representing a complex system, e.g. an irrigation system, should be evaluated for the insights it provides in the functioning of the system and in the comparative effect of policy and management interventions, and not for the accurateness of its predictions.
   This thesis

3. If one is interested in improving the performance of an irrigation system, the analysis of physical processes, assuming ideal human management, or the analysis of human behaviour, considering the physical environment as an external factor, is not sufficient. In addition, a common platform should be developed, quantifying the physical impact of human interventions.
   Strosser (1997); This thesis

4. In continuation of the economic principles related to the functioning of markets, the spatial heterogeneity of physical parameters can be considered an important asset in the management of an irrigation system, allowing a more innovative allocation of irrigation water.
   Peasant economics, Ellis (1988); This thesis

5. Archaeologists today in Mohenjodaro are fighting a similar battle that farmers were 4000 years ago in keeping soil salinity within acceptable limits.
   Mohenjodaro and the Indus civilization, Marshall (1973)

6. L'objet de la vérification d'une proposition n'est pas la proposition elle-même, mais sa valeur de vérité.
   Encyclopaedia universalis (1985); Konikow and Bredehoeft (1992)

7. C'est trop facile, de faire semblant
   Grand Jacques, Jacques Brel (1955)

8. Een proefschrift, ook één in de exacte wetenschappen, moet naast een wetenschappelijke ook een literaire waarde hebben.

9. Rugby maakt meer kapot dan drank goed kan maken
   pers. meded. J. Wijdeven (1987)

10. Θαλασσα, θαλασσα
    Anabasis, Xenophon (4e eeuw voor Christus)

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Salinity and sodicity in the Indus Basin

The Indus Basin: a conjunctive use environment

The contiguous Indus Basin irrigation system irrigates an area of about 16 million ha, diverting annually about 128 billion m^3 of surface water to 43 canal systems (Badruddin, 1996). It is only in the last 30 years that extensive public development of Pakistan's groundwater resources has taken place through vertical drainage schemes, entailing the installation of about 16,000 public tube wells, serving also to increase irrigation supplies. Increased cropping intensities, government subsidies and the example of the public tube wells, have prompted farmers to install a large number of private tube wells. These wells are generally shallow (20-50 m deep) and have a capacity of about 30 l s^{-1}. Presently, an estimated number of 500,000 tube wells[1] are providing approximately 30-40 % of the irrigation water at the farm gate (Nespak/SGI, 1991). A recent survey showed that out of 1200 farms, 90% had access to tube well water, either through ownership or through water markets (PERI, 1990). The fact that the Indus Basin is a conjunctive use environment is not a new phenomenon. At the turn of the century, an estimated number of 350,000 hand- and dug wells existed in the Punjab (including what is now Indian Punjab) and the North-West Frontier Province, contributing supposedly about 40% of the total irrigation supplies (Indian Irrigation Commission, 1903). Ironically, it was the development of large-scale canal irrigation in the beginning of this century that made these irrigation wells superfluous.

Salinity: from single to multiple cause

Traditionally, salinity has been associated with irrigated agriculture in the Indus Basin (Framji et al., 1984, Ahmed and Chaudry, 1988). Often salinity was considered to be linked with waterlogging and the

[1] According to the Agricultural Census of 1991, a total number of 375,000 tube wells are present in the Indus Basin. However, only diesel and electric tube wells have been counted, neglecting the tractor operated tube wells. About a third of the private tube wells is estimated to be tractor driven (Malik and Strosser, 1993).

rise of the groundwater table, which occurred due to the introduction of large-scale perennial irrigation in the Indus Basin. However, the Soil Survey of Pakistan (SSP) demonstrated in the 1970s that the causes of salinity were much more diverse[2]. Basically, three main causes were identified. Genetic salinity, due to weathering of parent material, was thought to affect some 4.8 million ha of land under command (Choudry, 1979). A second source of salinization was shown to be the rise in groundwater tables in the *doabs*, which displaces salts and brings them into the root zone through capillary rise. Finally, the Soil Survey of Pakistan warned about the imminent threat of salinization through the use of poor quality groundwater by public and private tube wells. The often doubtful quality of groundwater was known for much longer (e.g. Council of the Bahawalpur State, 1900), but became an important issue due to the massive deployment of tube wells in the Indus Basin.

Sodicity

Another important issue that was brought to the fore was the distinction that was made between salinity and sodicity (Choudry, 1979). SSP argued that instead of looking only at the total number of dissolved salts, it would be better to look at the *composition of the salts*. This was further substantiated by a large-scale survey undertaken by WAPDA, which demonstrated that out of a total number of 63,866 samples 10.7 % was saline, 23.6 % saline-sodic and 3.5 % sodic (Ghassemi et al., 1995).

Measures taken

Measures that have been taken in Pakistan by the Government to control salinity have largely focused on controlling the groundwater table with the idea to contain the salinization process. These measures included the prevention of seepage through canal lining (from 1895 onwards), tree plantations, surface and interceptor drains (from 1930 onwards), irrigation management (lowering of Full Supply Levels, canal closures from 1930 onwards) and vertical drainage through tube wells from 1940 onwards (Ahmed and Chaudry, 1988). Vertical drainage was considered to be the most effective measure and the implementation gathered momentum, particularly after partition with India in 1947 with the Rasul Tube Well Project.

The Water and Power Development Authority (WAPDA), created in 1958, was entrusted with the responsibility to tackle problems of waterlogging and salinity in the Indus Basin, notably through large-scale vertical and horizontal drainage schemes. These schemes, referred to as SCARPs - Salinity Control And Reclamation Projects - had a dual aim of lowering groundwater tables through the installation of public tube wells and increased cropping intensities, and of making additional irrigation supplies available at the farm gate.

In the seventies, researchers recognized the existence of sodic soils, as evidenced in the surveys of WAPDA and SSP, but more importantly they realized the adverse effects of (bi) carbonates and sodium in irrigation water hailing from the aquifer. A number of research institutes and universities studied on-farm salinity control as part of a larger USAID funded On-Farm research project with the technical support of Colorado State University. Certain recommendations have been made regarding safe limits

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2 There have been earlier papers emphasizing the fact that waterlogging was not the only cause for soil salinity and sodicity. Mehta (1940), for instance, provided evidence for the existence of "alkalinity" in irrigated areas with deep groundwater tables.

of irrigation water incorporating the effect of (bi-)carbonates and sodium, gypsum application, salinity-tolerant crops (e.g. Ahmad and Majeed, 1975; Bakhsh and Hussain, 1975; Muhammed, 1975). However, their work remained confined to the farm and field level, and no attempt was made to translate the implications of their findings to a larger, system level. Their recommendations went largely unheeded in the large scale development projects in the country, which continued to focus on the prevention of seepage through the lining of thousands of tertiary canals and on the implementation of large-scale drainage projects on the assumed link between *waterlogging and salinity* (Muhammed, 1978). This signalled the inception of a dispute between researchers who understood the complexity of the salinity issue and engineers who had to come up with practical solutions for a problem affecting millions of hectares.

The Directorate for Land Reclamation (DLR) of the Punjab Irrigation & Power Department (PID) has been conducting a yearly visual salinity survey, *Thur Girdawari*, since 1943 (Muhammed, 1978). On the basis of this survey, DLR advises the irrigation agency, PID, on the installation of *reclamation shoots*, pipes that offtake from irrigation channels for a period of 3 months in the flood season, kharif. Thus, extra water is provided to those areas affected by salinity. In recent years, due to the tremendous pressure on canal water, hardly any reclamation shoots have been sanctioned by PID.

Interestingly, farmers have been much more diverse in their measures to bring large areas under cultivation that were hithertofore affected by (genetic) salinity. These range from the application of good quality irrigation water and taking various biotic, mechanical and chemical reclamation measures. Farmers are also unremittingly mitigating the effects of high groundwater tables and poor quality irrigation water in order not to have their soils and crop yields affected. Kielen (1996a) lists a number of measures, related mainly to changes in the quantity, frequency and ratio of application of canal and tube well water, to the crop choice and the application of chemical amendments.

Pakistan's efforts for an integrated approach in salinity control

Large-scale surveys undertaken in the seventies such as the WAPDA Master Planning Survey and the Soil Reconnaissance Survey by SSP, emphasized the complexity of the nature and the causes of salt-affected soils in the Indus Basin. In the past many efforts to improve the salinity control were undertaken in isolation, either through a series of measures at the field level (e.g. Niazi et al., 1989; Siddiq, 1995), or through large-scale drainage projects. Recently, there has been a growing recognition by policy makers and scientists in the country that much is to be gained by developing an integrated approach, which would enable to identify appropriate government interventions by testing and comparing several interventions at different levels of the agricultural sector.

Limited efforts were made through the Command Water Management projects in the eighties, which emphasized the integration of activities of specialized agencies, but ended up carrying out separate infrastructural works, such as the lining of channels and installation of tube wells. At the moment a large World Bank funded project is underway in the Fordwah/Eastern Sadiqia (South) area which aims to reduce problems of salinity through a set of irrigation and drainage works and management interventions. To prepare for this project a research project is currently underway, in which 13 national organizations take part, to come up with a set of recommendations for irrigation and drainage measures

(Water and Power Development Authority, 1993). The underlying idea of the research is that a set of interventions in irrigation management targeted towards salinity can minimize the costs of drainage.

In anticipation, the International Irrigation Management Institute (IIMI) in Pakistan has initiated the development and field application of an integrated approach in a 75,000 ha irrigation system in south-east Punjab, the Chishtian Sub-division, to assess the effect of policy and management interventions on agricultural production and on salinity and sodicity. Thus, experience can be obtained in integrating research activities carried out by different disciplines. This study is part of that integrated approach.

1.2 Statement of the problem

Farmers have managed to bring large areas affected by genetic salinity and/or sodicity under the plough. At the same time, groundwater tables are declining in large parts of the Punjab, which makes the issue of waterlogging in relation to salinity control less urgent. However, increased cropping intensities have induced farmers to tap groundwater resources on a very large scale, threatening to degrade soils through a sodification process as a result of irrigation with poor quality water (Kijne and Kuper, 1995). This relatively recent threat has not received much attention, yet, and research is needed to provide guidelines for future projects.

Canal water is of excellent quality, and has, obviously, tremendous value for farmers who are dealing with salinity and/or sodicity. When dealing with genetic salinity, they use canal water for reclamation purposes, while they mitigate the effect of poor quality tube well water by applying it in conjunction with canal water. The importance of canal water for farmers was substantiated in a survey conducted by Kielen (1996a), where farmers singled out canal water as the most important factor for salinity management. In a modelling exercise, the importance of canal water was further confirmed in ensuring a long term salinity equilibrium at reasonable levels (Condom, 1996; Smets et al., 1997). Making more canal water available to farmers would, therefore, help them in their salinity management.

The amount of canal water available is limited and not all crops in the Indus Basin can be fed by this water alone. However, not all farmers are faced with the same problem due to an inequitable distribution of canal water and due to differences in environmental parameters, such as groundwater quality, soils, etc. In addition, not all farmers have the same opportunities to deal with salinity. This leads to the assertion that *a redistribution of canal water, making it available to those farmers who really need the water for salinity control, will contribute to minimizing salinity and sodicity, and to mitigating the effects of salts on crop production.* At present, no tools are available to carry out a comparison of various measures intended to enhance the capability of farmers to deal with salinity. There is an urgent need for the development of tools and methodologies that would help policy makers and irrigation managers in assessing the impacts of various measures and to evaluate whether a better irrigation management could reduce the need for implementation of high cost infrastructural works.

The development of these tools is all the more urgent, because several proposals have been made recently for tackling the financial and efficiency issues of the irrigation sector in Pakistan by the World Bank (1994). This includes privatization, improved management, involvement of the irrigators, and a more market-oriented approach to water, which would increase the awareness of water as a scarce (and valuable) good. Follow-up discussions with various actors at the provincial and federal levels have led to an intermediate solution currently endorsed by the Government of Pakistan, i.e. decentralization of irrigation management with the formation of public authorities, so-called Provincial Irrigation & Drainage Authorities (PIDAs) that would be financially autonomous. Involvement of farmers in the management of parts of the irrigation system is considered and pilot tested in some secondary canals. Finally, the development of water markets where farmers of groups of farmers could trade water is considered. These proposed interventions have not been assessed yet for their supposed impact and debates on the advantages and disadvantages remain at best ambiguous due to the lack of data to quantify this impact. This underscores the importance to further analyse the functioning of the present irrigation systems, to clearly identify factors and constraints that explain its current level of performance and its potential for change.

The objectives of the present study can thus be formulated as follows:
- To define the scope for canal irrigation management interventions and assess the impact on canal water distribution;
- To assess the impact of canal irrigation supplies at the farm and field level on soil salinity and sodicity and the likely effect on crop production; and
- To develop and apply an integrated approach to assess the impact of canal irrigation management interventions on salinity and sodicity and on crop production, in the context of an irrigation system.

1.3 Outline of the study

There are two principal research axes in this study, an intervention-oriented analysis of canal irrigation system management, and a process-oriented study of salinity and sodicity at the farm and field levels. These studies are then combined by developing and operationalizing an integrated approach which translates the effect of changes in canal irrigation management on the evolution of soil salinity and sodicity. The approach is tested in a 75,000 ha irrigation system in south-east Punjab, Pakistan.

The studies are preceded by a description of the irrigation system, to which the analyses are applied, in *Chapter 2*.

Canal irrigation management

In *Chapter 3*, the hydraulics of canal irrigation are modelled using a hydro-dynamic model, to assess the effect of hydraulic characteristics on canal water levels and discharges. The model is calibrated/validated for the present physical conditions. Then, the decision-making process of water distribution, in an interaction between the system manager and operational staff, is analyzed and the operational rules governing water distribution are determined. These decision rules are then captured in a regulation module that is linked to the hydro-dynamic model. This composite model is used to identify existing physical and managerial bottlenecks in water deliveries, and assess the comparative benefits of main and secondary canal management interventions, on the water distribution to tertiary units. This leads to the formulation of alternative operational rules and maintenance measures, captured in a number of operational scenarios. These scenarios are simulated and the results are evaluated using performance indicators.

Salinity and sodicity

In *Chapter 4*, salinization is studied at the field level, using a soil water-solute transfer model. After calibration/validation, the model is used to assess the effect of the irrigation regime of farmers on salinity, sodicity and on crop transpiration, for a range of soils. The sodification process is studied and a relationship is developed to quantify the risk of sodification as a function of the irrigation regime for different soil types. Both models are then verified at the level of the tertiary unit, in order to enable the integration of the analyses with those on irrigation system management, which were treated in Chapter 3. A study is made of the farmers' salinity management to verify the utility of making more canal water available for salinity control.

Towards an integrated approach

In *Chapter 5*, an integration of analyses of canal irrigation management interventions at the system level, and field level studies of salinity and sodicity, is undertaken by developing a common platform in which physical processes and human decisions that are governing these processes are quantified. This integrated framework is developed jointly with Strosser (1997), who in a parallel study, studied the decision-making process of farmers with respect to irrigation water distribution, groundwater use and crop choice as a function of the farm strategy, farmers' constraints, the physical and irrigation environment. A common tool is developed, which is applied to two case studies. The first case study is described by Strosser (1997), who tests the feasibility of developing water markets and their impact on agricultural production. The second case study, described here, relates to the assessment of the effect of canal irrigation management interventions on salinity and sodicity. Scale issues will be addressed in operationalizing this tool. The application of the tool to an irrigation system, will quantify the comparative advantage of proposed management interventions, but will also enable an assessment of the utility of the tool.

The thesis is summarized and concluded in *Chapter 6*.

1.4 Limitations of the study

The study takes place in the 75,000 ha Chishtian Sub-division, an irrigation system that forms part of the Fordwah/Eastern Sadiqia area in south-east Punjab. The study area is quite representative as far as the complexity of an irrigation system is concerned, and offers ample opportunity for irrigation management interventions. Also, irrigation-induced salinity and sodicity, the focus of this study, is a real concern for farmers in the area. Present practices, and their impact, can thus be studied and evaluated. The choice of the study area, however, also brings with it certain limitations. Probably, the biggest limitation is that the groundwater table is fairly deep, and no detailed study of the aquifer was made. The groundwater is taken into account only in as far as it contributes water (capillary rise) to the unsaturated zone and is further taken to be a reservoir which is tapped through shallow tube wells. This means that the study of the interaction between groundwater and the unsaturated zone is not complete. A second limitation is that the study was confined to an irrigation system of 75,000 ha. Since the irrigation systems in the Indus plains are inter-connected, the irrigation management upstream of the study area places certain constraints on the study area. In this study, the inflow of the study area is considered as a given.

An integrated approach has a few known limitations. The complexity of an irrigation system makes it difficult to develop an integrated model that has accurate predictive capability. This is due to the interaction of human and physical processes and the large variability over time and space of the different characteristics of an irrigation system. It is, therefore, better to focus the overall approach *more towards creating an understanding of the impact of management interventions on salinity and agricultural production than on an accurate prediction*. The results of simulations can help actors prepare for the future and enables a comparative analysis, but should not be evaluated for the absolute values.

The integrated approach touches on bio-physical as well as human or behavioural processes. While the former are modelled, even though often much simplified, the latter can only be described and captured in decisional rules. The complexity of the mixture of these processes makes that validation of the outcomes in the traditional sense of the word is not possible. Results that seem numerical in the outcome of models become fuzzy in reality as people have a tendency to adapt/react to changes in the bio-physical environment, thereby changing the nature and format of relationships that were assumed in the approach. However, the validity of the integrated approach can be verified by analyzing the existing situation, and by verifying the plausibility of the outcomes with the actors concerned. The criterion then becomes whether the tool is useful for an improved management of water resources in order to better tackle salinity and sodicity.

CHAPTER 2

RESEARCH LOCALE

2.1 Description of the Chishtian Sub-division

The location of the study area, the Chishtian Sub-division is shown in Figure 2.1.

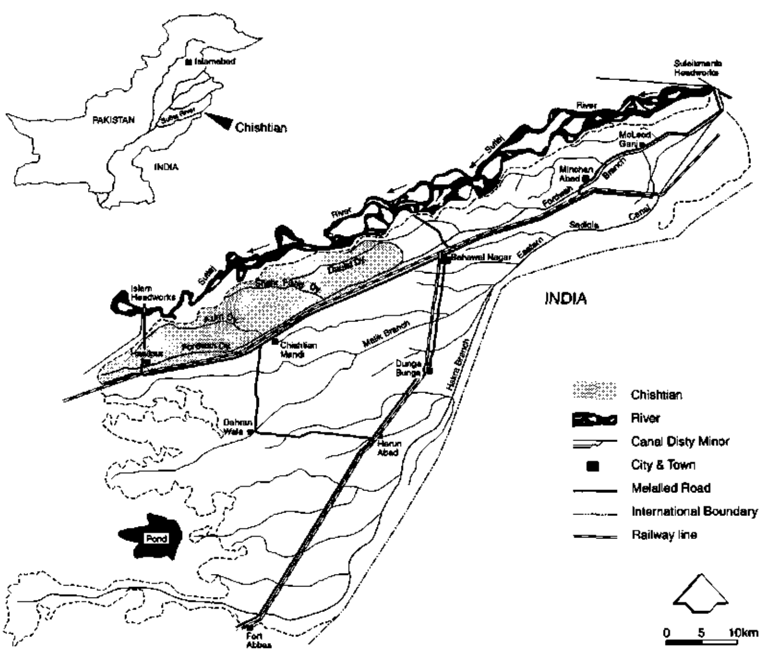

Figure 2.1: Location map of the Chishtian sub-division, Punjab, Pakistan.

The Chishtian Sub-division covers 75,000 ha of irrigated land. It forms part of the Fordwah/Eastern Sadiqia irrigation system, which consists of the riparian tract along the river Sutlej, the flood plains of the ancient Hakra river and reclaimed desert area of the lesser Cholistan desert. The Fordwah/Eastern Sadiqia area is located in the south-east of Pakistan's Punjab and is confined by the Sutlej river in the north-west, the Indian border in the east and by the Cholistan desert in the south-east, see Figure 2.1. The Fordwah and Eastern Sadiqia canals command a gross area of 684,985 ha, out of which 593,100 ha is officially irrigated (CCA-Culturable Commandable Area).

2.1.1 Physical environment

Climate

The climate is semi-arid continental with annual potential evaporation (class A pan) at 2400 mm far exceeding the annual rainfall of 200 mm, see Figure 2.2. The data presented in Figure 2.2 were obtained from Bahawalpur, located about 80 km to the west of the Chishtian Sub-division, and from Bahawalnagar, located at the extreme east of the Chishtian Sub-division. Two thirds of the rainfall is received during the monsoon period from July to September, while the remainder falls in mild showers during the winter. The monsoon is preceded by an extremely dry period, characterized by hot winds from the adjoining desert and mean maximum air temperatures reaching 44 °C. The winter season lasts only from December to mid-February with mean minimum air temperatures of 4.4 °C. The area is part of the cotton-wheat agro-climatic zone of the Punjab with cotton, forage and rice crops dominating in the summer season *kharif* and wheat and forage the principal crops in the winter season *rabi*.

Surface water resources

The area is served by two large main canals, Fordwah Canal and Eastern Sadiqia Canal, off-taking from the left abutment of Suleimanki Headworks on the Sutlej river. They were constructed as part of the Sutlej Valley Project, which was commissioned in 1926. This project was launched to increase the reliability of (flood) water supplies to the riparian tract of the Sutlej already irrigated through inundation canals and small wells, and to supply water to lands in hithertofore unirrigated lands at the fringes of the Cholistan desert. The present irrigation network thus partly overlays an old irrigation system developed and operated by the rulers of the former Bahawalpur state.

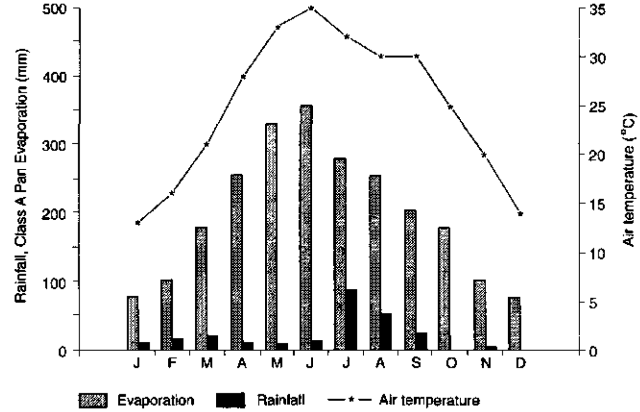

Figure 2.2: Mean monthly potential evaporation, rainfall and temperatures. These are 30 year averages of Bahawalpur and Bahawalnagar weather stations (Punjab Meteorological Department).

Groundwater resources

Groundwater tables in the study area are generally more than 2 metres below the soil surface, except in the north-western portion and along Fordwah Branch. About 10% of the area has groundwater tables within 2.5 m of the surface. In addition, the groundwater table is going down in some parts of the Chishtian Sub-division, as a consequence of groundwater exploitation. Only in a limited part of the area, therefore, salinization occurs through capillary rise.

The groundwater quality in the area is highly variable, reflecting the heterogeneity in materials of the area, from marine and alluvial origin. Groundwater is often saline and contains relatively high amounts of sodium and bi-carbonates. The quality range, measured for a sample of 500 tube wells, is summarized in Table 2.1. Apart from the total salt concentration, approximated by the *electrical conductivity* EC, the *sodium adsorption ratio* (SAR) and the *residual sodium carbonates* value (RSC) are used as indicators. The SAR presents the ratio of the Na^+ concentration over Ca^{2+} and Mg^{2+} concentrations (in mmol l^{-1}), while the RSC gives the concentrations of CO_3^- and HCO_3^- minus those of Ca^{2+} and Mg^{2+}.

Table 2.1: Quality of irrigation waters pumped through shallow tube wells in the Chishtian Sub-division, data collected by IIMI and analyzed by DLR and SSP in 1995/1996.

	EC (dS m^{-1})	SAR (mmol l^{-1})$^{0.5}$	RSC (meq l^{-1})
Average	1.1	3.8	0.4
Minimum	0.3	0.0	-24.0
Maximum	4.8	20.9	13.2
CV	0.5	1.0	6.6

Soils

The soils in the Chishtian Sub-Division have been mostly developed in mixed calcareous recent and sub-recent river terraces and are underlain by thick marine sediments. Close to the river Sutlej recent alluvium is found, referred to as Shahdara terrace, covering about 5 % of the area. South of this terrace two sub-recent terraces indicate that the river Sutlej has had a much more southern course in the past. The terrace located furthest north is referred to as a Sultanpur sub-recent river terrace with soils of moderately coarse to moderately fine texture. Further south is the Rasulpur sub-recent terrace, comprising soils which developed in subrecent river alluvium mixed with aeolian Pleistocene deposits from the adjacent Cholistan desert. Collectively, these two terraces cover about 90 % of the area. In the south-west corner of the area a Pleistocene aeolian terrace is found. The physiographic units that are encountered in the Chishtian Sub-division are listed in Table 2.2 (Soil Survey of Pakistan, 1996).

Table 2.2: Physiographic units in the Chishtian Sub-division (source: Soil Survey of Pakistan,1996)

Units	Location	Soils
Basins	Lowest part of the flood plains	Fine and moderately fine textured
Level plains	Level parts of the flood plains	Moderately coarse to moderately fine textured
Levees	Low ridges parallel to an ancient rivercourse	Moderately coarse textured
Sand bars	Formed by deposition of sand on the inner side of a meandering river	Coarse textured

The finer textured soils are found in the basins and are generally associated with genetic salinity and sodicity. Especially the soils formed in those parts of the basin where water was stagnant during soil formation are very dense and highly sodic. These soils are referred to as the Satgara soil series in Pakistan. Other soils in this physiographic unit that are associated with salinity and sodicity are the Adilpur soil series. Even today these soils are generally not cultivated. In addition to that, some soils located in other physiographic units have a saline-sodic variant depending on the water-related transport processes during soil formation and thereafter.

Salinity and sodicity

A number of salinity surveys have been undertaken in the Chishtian Sub-division, employing different techniques and sampling frames, rendering it difficult to make a comparison. The main surveys that have been undertaken are listed in Table 2.3. The surveys of WASID and WAPDA were part of a larger salinity survey of the Indus Plains, while the survey of NESPAK was done for the Fordwah/Eastern Sadiqia irrigation and drainage improvement project, which is currently underway in the area (Water and Power Development Authority, 1993). The surveys carried out by IIMI and its partners were undertaken to develop an effective methodology to assess the salinity and sodicity status in large areas.

Table 2.3: Inventory of salinity surveys undertaken in the study area.

Organizations	Year	Methods
WASID	1960	Visual observations, aerial photographs
WAPDA Master Planning	1978	Sampling, visual observations
NESPAK	1986	Sampling
Cemagref/IIMI	1995	Remote sensing (Tabet, 1996; Tabet et al., 1997)
SSP/IIMI	1996	Sampling (Soil Survey of Pakistan, 1997)
DLR/IIMI	1996	Visual observations (Asif et al., 1996)

It is interesting to compare the results of the earlier surveys with more recent information. There has been a gradual decrease in the area affected by salinity and sodicity. This can be attributed to the fact that farmers have reclaimed large tracts of land, made possible by the canal water supplies available to farmers. This decrease concerns mainly the areas affected by genetic salinity (Soil Survey of Pakistan, 1997). The results of the surveys of 1960 and 1978 were digitized, which allowed a quantification of this decrease, see Table 2.4.

Table 2.4: Status of salinity in the study area, determined during surveys in 1960 by WASID and 1978 by WAPDA. The salinity was determined through visual observations, where S0 stands for no salinity, S2 for slightly saline, S3 for moderately saline and S4 for severely saline.

Salinity level	Area affected (%) 1960	Area affected (%) 1978
S1	55.1	83.1
S2	22.4	3.3
S3	6.5	9.4
S4	16.1	4.3

An important decrease in the area moderately and severely affected by salinity and sodicity (S3, S4) can be observed, i.e. from 22.6 to 13.7% of the total area. This is an area of almost 7000 ha that has been reclaimed Also, the area slightly affected by salinity has decreased tremendously. The total area that was found non-saline in 1978 had increased to more than 80% of the area.

A relatively recent phenomenon concerns the sodification as a result of groundwater application (Soil Survey of Pakistan, 1997). In quite a few areas surface crusts were observed, while in some areas the effects were noticeable up to a depth of 1 m. The area affected by groundwater induced sodicity is difficult to estimate, and is mitigated by farmers. About 40-50% of the farmers are confronted with this problem in various degrees. This estimate is based on the area underlain by groundwater of doubtful quality and the fact that surveys have shown that almost all farmers use groundwater in the study area (e.g. Rinaudo, 1994).

2.1.2 Irrigation system

Canal irrigation system

Two large canals, offtaking at Suleimanki Headworks on the Sutlej river, feed the study area, i.e. the Fordwah Canal and the Eastern Sadiqia Canal. The Fordwah Canal is fairly short and splits into two branch canals after 14.6 km. The larger of the two, Fordwah Branch supplies the Chishtian Sub-division. Because of limited supplies outside the flood season, it was decided to feed Fordwah Canal only during kharif (non-perennial) while Eastern Sadiqia would be entitled to all year round supplies (perennial). However, five secondary canals at the tail of the Fordwah system are perennial canals and are supplied during rabi, when Fordwah Canal is closed, through the Sadiq-Ford Feeder, see Figure 2.3.

Originally, the system derived its water from the Sutlej and its tributary the Beas, but since the Indus Water Accord of 1960, this water is at the disposal of India. Upon conclusion of the accord, a series of link canals was constructed to convey water from the western rivers, Indus, Jhelum and Chenab, to the irrigation systems located on the Ravi and Sutlej rivers. Thus in the flood season, July to September, the water at Suleimanki Headworks is mainly derived from the Chenab river, while in the winter the water is tapped from the Mangla reservoir on the Jhelum river.

The Chishtian Sub-Division is a 75,000 ha hydraulic unit situated at the lower end of the Fordwah Canal Command. It starts at km 75 (RD[1] 245) of Fordwah Branch, which itself offtakes at the tail of Fordwah Canal, but places its demand (indent) at km 61 (RD 199) of Fordwah Branch. It comprises the administrative units of Hasilpur and Chishtian towns and falls in Bahawalpur and Bahawalnagar districts.

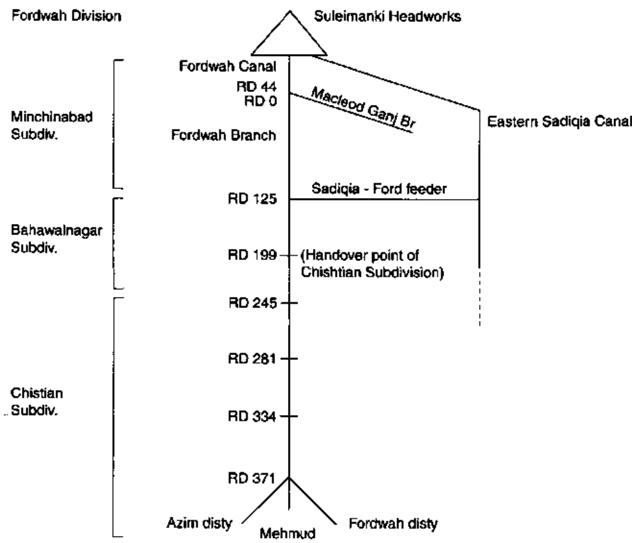

Figure 2.3: Schematic overview of the hydraulic network of the Fordwah/Eastern Sadiqia irrigation systems (source: Litrico, 1995).

Organizational set-up

The Punjab Irrigation & Power Department (PID) is responsable for the operation and maintenance of the system from the headworks up to the outlet of the tertiary unit (*mogha*). Below the mogha, farmers share the water and maintain the tertiary canals. PID is reponsable for assessment of water charges on the basis of the area and the type of crop that is cultivated. It is a large bureaucracy employing about 57,000 people, of which some 300 are qualified engineers. The basic hydraulic unit in the Indus Basin is considered to be the canal command or division under the responsability of Executive Engineers (XEN). There are 43 canal commands in Pakistan, out of which 21 are located in the Punjab. These canal commands are grouped in canal circles, directed by Superintending Engineers, which fall in 5 irrigation zones that are administered by Chief Engineers. Responsability for day-to-day operating and maintaining the irrigation system lies with the XENs, who can delegate some responsabilities to sub-ordinate Sub-Divisional Officers (SDO), who are generally qualified engineers. The Chief and Superintending engineers have mainly controlling and supervisory responsabilities.

The Fordwah Canal Division is divided into three Canal Sub-Divisions, each headed by an SDO. The SDO is assisted for technical matters by Sub Engineers (SBE) looking after a *section* and for revenue matters by revenue staff. Worth mentioning are the *gauge readers* or gate keepers, who are generally

[1] RD stands for reduced distance from the head of a canal in 1000 feet; RD 199 is therefore located at 199,000 feet from the head of Fordwah Branch.

stationed at important regulation points in the system (cross-regulators, large distributaries) and are operating the structures under their control.

The SDO decides on the opening and closing of the larger distributaries, based on the rotational plan and based on operational preferences, which are influenced by farmers. His instructions are conveyed to gate keepers, who implement these instructions by manipulating the gated structures. For the smaller distributaries, gate keepers are generally independently deciding on opening or closing the head regulator. Their operations for both the larger and the small distributaries as well as cross-regulators are based on maintaining an upstream *full supply level* (FSL) in order to be able to feed the required discharge to the distributaries as well as to the downstream parent channel. A major concern of gate keepers is the safety of the main/branch canal. The communication between SDO and gate keepers is depicted in Figure 2.4.

The telegraph communication system between gate operators and the irrigation manager and between gate operators themselves is in a dismal condition. This means that in practice gate operators have been given a great deal of responsability in operating the system. Instructions from the irrigation manager relate mainly to the definition of target discharges for certain distributaries, opening/closing of distributaries and target discharges for cross-regulators. The positive impact of a communication network on the discharge variability was evaluated by Litrico (1995), showing that gate keepers are much better able to attenuate the discharge fluctuations if a communication network is provided.

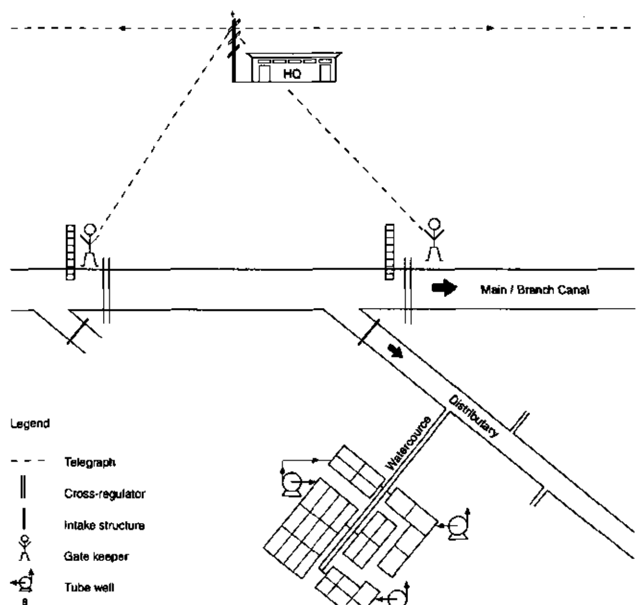

Figure 2.4: Communication system between the irrigation manager and the gate keepers.

The Chishtian Sub-division is considered to be difficult with substantial political interference and managers tend to minimize their tenure. From 1993 to 1996 there have been 5 different SDOs, while their normal tenure is in the range of 2-3 years. The farmers in the riparian tract constitute a feudal inegalitarian society, characterized by a large number of schisms and conflicts concerning amongst others water, which tend to aggravate the work of PID. Much less problems are reported about the settlers who have arrived in the area in the 1930s (e.g. Fordwah distributary command) and whose landholdings are much more equal. A more detailed study on the relationships between farmers in the riparian tract has been undertaken in the same area by Carbonnell and Micheau (1996).

Beyond the mogha, farmers are responsable for sharing the water through a traditional system of *warabandi*. A roster of turns is formulated by farmers on the basis of which each farmer is entitled to the entire flow delivered to a mogha for a specified period of time. PID will only intervene in this roster in case of a dispute between farmers. Generally, a warabandi roster is frequently updated by farmers (Bandaragoda and Rehman, 1995). Maintenance of the tertiary canal is also the responsability of the farmers and is generally carried out jointly (Malik et al., 1996). In every village a few farmers have been appointed by the government to collect the water charges and forward them to the Revenue Department, for which they are paid a fixed percentage of the collected money.

Water entitlements

Farmers in the study area had some historical water rights prior to implementation of the present irrigation system. On top of that, the system was designed by the British colonial government as part of a larger project, while the command area was located in the independent state of Bahawalpur. These socio-political complexities at the time of design of the irrigation system, have resulted in an odd mixture of perennial and non-perennial canals within the same system, thereby imposing a build-in inequity in water allocation. The water allocation to distributary commands ranges from 0.25 for perennial to 0.49 $ls^{-1}ha^{-1}$ for non-perennial canals. Irrigation intensities are in the order of 70 % for non-perennial distributaries (35/35 in Kharif and Rabi, respectively) and 80 % for the perennial distributaries (32/48 in Kharif and Rabi, respectively). This means that when farmers stick to the design cropping intensities, they have 0.8 to 1.4 $ls^{-1}ha^{-1}$ to their disposal, which covers adequately the crop water requirements.

Infrastructure: canals and structures

Punjab irrigation canals are typically earthen, gravity flow canals. They have a trapezoidal inner prism, and a berm formed inside this prism by sediment deposition, which strengthens the banks. The canals were designed based on the theories of famous British engineers working in the sub-continent, like Kennedy, Lindley and Lacey (Ali, 1993). The main characteristics of these "regime canals" are that they are designed to maintain a critical flow velocity, based on the hydraulic mean depth and a sediment factor, in order to be 'non-silting, non-scouring', and that they are fairly wide and shallow, which was found to be more conducive for sediment transport. The width of Fordwah Branch at RD 199 is 35 m and is 15 m at the tail (RD 371). The average slope of Fordwah Branch is 1:5000 and the seepage was established at 3.2 $m^3 s^{-1}$ with an inflow of 25.5 $m^3 s^{-1}$, which corresponds to 12.5 % or 60 $l s^{-1} km^{-1}$. Seepage in the secondary canals is much lower and is on average 5% (Tareen et al., 1996). The total length of main and secondary canals in the Chishtian Sub-division is a little over 300 km, which is 4.3 m per ha of commanded land.

The fact that the system combines perennial and non-perennial distributaries, has necessitated a relatively large number of gated structures as compared to other systems in Pakistan. In the Chishtian Sub-Division, five gated cross-regulators and nine gated off-takes are daily operated in order to meet operational targets, see Figure 2.5. The cross-regulators are orifices provided with flat sliding gates, while the distributary intakes are a mixture of gated orifices, weirs and culverts. In order to regulate the inflow into distributaries that do not have gated structures, wooden stoplogs (*karrees*) are used.

There are a total of 503 tertiary units served by 14 distributaries and 8 minors (see Table 2.5), while 19 outlets are supplied directly from Fordwah Branch. These tertiary units range in size from less than 10 ha to more than 350 ha. The most common outlet types in the Punjab are (1) the Adjustable Orifice Semi-Module (AOSM), an improved version of Crump's Adjustable Proportional Module, APM (Ali, 1993), (2) the Open Flume with Roof Block, OFRB, (3) the Open Flume, OF, and (4) the Pipe Outlet, PO. All these outlets are ungated.

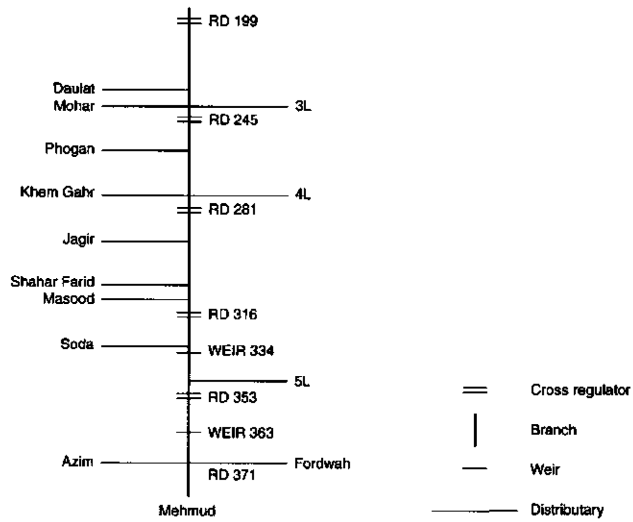

Figure 2.5: Hydraulic network of the Chishtian sub-division (source: Litrico, 1995)

The AOSM and OFRB outlets form an orifice of 15 to 25 cm high, between two masonry walls typically 6 cm apart, a broad crest and a roof block. While the AOSM has a rounded roof block, which lets pass an uncontracted jet of water, the roof block of the OFRB is not rounded, so that contraction of the jet occurs. The OFRBs were originally supposed to function as flumes in normal conditions, while the roof block was to restrict the water delivery to an outlet only when the water level of the channel was above the full supply level. Presently, all OFRBs function as orifices.

Table 2.5: Status, design discharges, length, command area and number of outlets of distributaries and minors of the Chishtian Sub-division. NP is non-perennial, P is perennial

Distributary/Minor	Status	Discharge ($m^3 s^{-1}$)	Length (m)	CCA (ha)	No of outlets
3L	NP	0.51	7040	1200	6
Mohar	NP	1.08	6170	1780	12
Hussainabad minor	NP	0.31	2690	300	3
Daulat	NP	5.92	35100	13230	72
Biluka minor	NP	0.25	3870	530	7
Nakewah minor	NP	1.22	13350	2800	29
Phogan	NP	0.50	2670	890	9
4L	NP	0.40	5290	830	7
Khemgarh	NP	0.68	4720	2040	9
Jagir	P	0.79	4210	1900	9
Shahar Farid	NP	4.33	22820	10070	47
Heerwah minor	NP	1.13	9810	2690	27
Masood	P	1.00	15940	3280	16
Soda	NP	2.18	13320	4090	33
5L	P	0.11	3440	360	3
Fordwah	P	4.47	42600	14840	87
Jiwan minor	P	0.76	10520	2870	23
Mehmud	P	0.23	3610	812	7
Azim	NP	6.91	35970	12330	80
Rathi minor	NP	0.28	3050	560	10
Feroze minor	NP	0.25	2440	500	4
Forest minor	NP	0.25	1010	300	4
Total		29.11	249640	67652	503

The values of design discharges for those distributaries that have minors, are a sum of the authorized discharges of all tertiary units of the parent channel as well as the minors plus the assumed seepage losses. Similarly, the command areas of these distributaries include the command areas of the minors they serve.

Tube wells

A total number of 4450 tube wells were found during a survey in 1996 in the study area, corresponding with a density of 6.4 tube wells per 100 ha. This is a good indication of the importance of groundwater as a source for irrigation. With an average pump capacity of 30 l s^{-1}, the total pumping capacity is more than three times the maximum discharge of the canal irrigation system at the inflow point of the study area. In addition to that non-tube well owners have access to groundwater through water markets, so much so that almost 100% of the farmers use groundwater for irrigation. Assuming a yearly pumpage of 0.15 billion m^3 (Kuper, 1996), groundwater constitutes about 25% of the total irrigation supply (excluding rainfall) with the canal water supplies amounting to 0.51 billion m^3 per year. This percentage increases when the ratio is calculated at the farm gate because of the conveyance losses in the canal system. The number of tube wells in the area has shown a rapid increase from the mid-eighties onwards. Less than 10% of the present number of tube wells existed before 1985. The tube wells in the area are mainly driven by small diesel engines and through the power offtake of tractors. A minority of the tube wells is electrified.

No surface or sub-surface drainage system exists in the study area, although an outfall drain, which is under construction, traverses the area. Excess water in the canal system cannot be diverted and may cause breaches in the downstream part of the system. Often, breaches are created at km 6 of the Azim distributary, diverting water to a low lying area, which is barren and often inundated.

2.1.3 Farming systems

Farm characteristics

Farms in the Chishtian Sub-division are quite diverse in terms of structural characteristics, such as landholding, mechanization and labour, but share on average a market orientation. This market orientation is evidenced by data collected by Rinaudo (1994) on 278 farmers in the command area of the Fordwah and Azim distributaries:
. 30% of the wheat produced is sold
. 37% of the farmers sell livestock products
. 93% of the farmers grow a cash crop (cotton, sugarcane, rice)
. 91% of the farmers grow cotton

Despite the common market orientation of farmers, there is a dramatic range in input use, i.e. seeds, fertilizer and pesticides, and in the agricultural production of farmers. An overview is presented in Table 2.6.

Table 2.6: Area operated, input use and agricultural production of 278 farmers in the Fordwah and Azim distributary commands. In 1994, 30 Pakistan Rupees (Rs) were equivalent to 1 US Dollar

Farm characteristics	Average	Minimum	Maximum
Area operated	6.4 ha	0.4 ha	184 ha
Input use			
Wheat	2800 Rs ha^{-1}	800 Rs ha^{-1}	5975 Rs ha^{-1}
Cotton	5050 Rs ha^{-1}	0 Rs ha^{-1}	13305 Rs ha^{-1}
Production			
Wheat	1.87 t ha^{-1}	0	5.93 t ha^{-1}
Cotton	1.21 t ha^{-1}	0	4.45 t ha^{-1}
Cropping intensity			
Rabi	70%	0	125%
Kharif	76%	6%	164%

The yields obtained in the area are generally below the average yields in Pakistan. For wheat, for instance, the national average is about 2.3 ton ha^{-1}. The cropping intensities have increased dramatically over the past 20 years. While the system was originally designed for 75-80% cropping intensity, it now shows annual cropping intensities in the range of 130-150%.

The farming systems are further characterized by a high use of machinery. Although only 25% of the farmers own a tractor, 90% of the farmers indicate that they use one at least once a season. Oxen are owned by 44% of the farmers.

More than 40% of the farmers have their own tube well, while 50-60% of the farmers purchase tube well water through water markets. Although there is some overlap between the tube well owners and tube well water purchasers, it appears that almost all farmers have gained access to groundwater as a complement to or a substitution for canal water.

Of the 278 farmers that were interviewed in 1994, 40% do not own the land they cultivate. They are either tenants, share croppers or lessees, reflecting a myriad of arrangements that are presently in place. However, a shift towards a more business or financial oriented relationship can be observed and tenancy arrangements are often replaced by contracts (Malik et al., 1996).

Two quite different societies can be distinguished in the study area. Farmers in the riparian tract, who have traditionally irrigated their lands with river water and through wells, are part of a feudal society that has been in place since centuries. This is reflected in a greater disparity in farm resources with a few big landlords and a lot of small farmers, tenants and servants. The farmers that arrived at the time of commissioning the Fordwah Canal or after Partition[2], were generally entitled to a piece of land that was equal in size. Differences in landholding are, therefore, much less pronounced.

2.2 Data collection and management

In the course of this study, or rather the project to which this study contributed, a large set of data has been collected in the study area. The types of data as well as the way they were collected will be detailed in Section 2.2.1. The data were generally stored, processed and analyzed using targeted computer software. This will be described in Section 2.2.2. An evaluation of the data collection and management will be undertaken in Section 2.2.3.

2.2.1 Data collection

Data were mainly collected for three purposes:
- to calibrate/validate the (bio-)physical models;
- to understand the decision-making processes; and
- to characterize the study area and develop a spatial database

(Bio-)physical models

The data requirements for bio-physical models are generally well defined, although the input requirements of these models can be minimized once sensitivity analyses have been carried out to determine the relative importance of various input parameters for the parameters that one is interested in. In this study, two (bio-)physical models were used, i.e. SIC - Simulation of Irrigation Canals, a hydraulic model, and SWAP93, a water flow - solute transport model.

SIC was used for the Fordwah Branch and for two secondary canals in the study area. Input data relate mainly to canal geometry, water levels and discharge ratings of structures, see Table 2.7. Data on canal structures were obtained from existing records of PID, while the actual state of channels and structures was determined in the field. Data were procured mostly in collaboration with PID, in some cases through training sessions organized by IIMI and PID (IIMI, 1995b).

2 During the transition period from British colonial rule to independence in 1947, an important migration occurred with Muslims from eastern Punjab settling in Pakistan and Sikhs and Hindus leaving Pakistan.

Table 2.7: Data collected for the calibration and validation of the hydraulic model SIC in the study area.

Data	Collection method	Sample size	Time step	Collecting institution
Canal geometry	Topographic survey	Fordwah Branch Masood distributary Fordwah distributary	Punctual	IIMI
Discharge rating structures	Current meter, cut-throat flume	All structures	Punctual	IIMI, PID
Water levels	Gauging	All structures	Hourly	IIMI
Gate operations	Field observations	All gated structures	Continuous	PID, IIMI

SWAP93 was used for four fields in the study area. Input data relate mainly to the water and salt balance and to a characterization of the soils. The data was collected by IIMI, while IWASRI provided advice on procedures. Soil and water samples were analyzed in the laboratories of DLR and SSP. The data collected for SWAP93 is listed in Table 2.8.

Table 2.8: Data collected for the calibration and validation of the water flow - solute transport model SWAP93 in the study area.

Data	Collection method	Sample size	Time step	Collecting institution
Soil characteristics	(Un-) disturbed samples	10 per field	Punctual	IIMI, IWASRI, DLR, SSP
Soil moisture	Disturbed samples	80 per field	Seasonal	IIMI
Soil salinity	Disturbed samples	80 per field	Seasonal	IIMI, DLR, SSP
Irrigation water quality	Samples	All irrigation sources	Seasonal	IIMI, DLR, SSP
Pressure heads	Tensiometers	8 per field	Bi-daily	IIMI
Crop development	Field observations	40 plants per field	Weekly	IIMI
Meteorological data	Weather stations	2	Continuous	Met. Dept., IIMI
Irrigation regime	Field observations	4 fields	Continuous	IIMI

Decision-making processes

Basically, two decision-making processes were studied, i.e. the operational management of irrigation managers and PID staff, and farmers' salinity management. The former was captured in a decisional model, Gateman, which is described in detail in Section 3.2. The latter is documented in Section 4.2.

The operational management of PID staff was studied through interviews and through field observations of discharges and gate operations, see Table 2.9. In addition, a field experiment was conducted with PID staff in which a steady state of the canal was ensured for 2 days, after which a wave was created by increasing the discharge at the head of the study area. The reactions of gate keepers to this positive discharge step were observed and compared with the results of a hydraulic model in order to understand the effects of the operations on discharges and water levels. A restitution exercise took place after completion of the experiment (Litrico et al., 1995). The collaboration with PID on the introduction of a management information system also provided insights into the daily management of the system.

Table 2.9: Data collected to study the operational rules of irrigation managers and staff of the irrigation agency.

Data	Collection method	Sample size	Time step	Collecting institution
Hydraulic targets	Interviews, field observations	All structures of Fordwah Branch	Punctual	IIMI, PID
Management targets	Interviews, field observations	All structures of Fordwah Branch	Continuous	IIMI

Farmers strategies and constraints were first studied by Rinaudo (1994) on the basis of interviews with 278 farmers in 8 tertiary units. A farmers' socio-economic typology was made on the basis of these interviews and 15 representative farms were selected. Pintus (1995) and Meerbach (1996) did detailed studies for these farms on farmers' practices related to wheat and cotton, respectively. Data on crop development, farmers' cultural and irrigation practices, and on yields were collected, see Table 2.10. Advice on recommended practices were obtained from the Punjab Agricultural Department (PAD), which served as a reference to detect atypical practices, which generally occur due to farmers' constraints, such as credit, water, salinity or inputs. Restitutions took place to discuss the results with the farmers and obtain a better understanding of their management. Farmers salinity management was studied in further detail by Kielen (1996a) through semi-structured interviews and mapping exercises with farmers. The results of soil and water samples that had been obtained in the area were combined with these observations and restituted to farmers (Kielen et al., 1996).

Table 2.10: Data collected to understand farmers' management related to irrigation, soil salinity and sodicity.

Data	Collection method	Sample size	Time step	Collecting institution
Farm characteristics	Interviews	278 farmers	Punctual	IIMI
Irrigation practices	Field observations, restitution	15 farmers	Continuous	IIMI, PAD
Cultural practices	Field observations, restitution	15 farmers	Continuous	IIMI, PAD
Crop development	Field observations	62 fields	Continuous	IIMI, PAD
Soil salinity	Disturbed samples	600 fields	Seasonal	IIMI, DLR, SSP
Salinity management	Interviews, mapping, restitution	6 tertiary units	Punctual	IIMI, farmers

Characterizing the study area

Most of the data collection to characterize the study area was undertaken in collaboration with government agencies. An overview is provided in Table 2.11.

Table 2.11: Data surveys undertaken to characterize the Chishtian Sub-division.

Data	Collection method	Sample size	Time step	Collecting institution
Soil type	Aerial photographs, field observations	All transitions	Punctual	SSP
Soil salinity	Disturbed samples, visual observations	120, all fields	Punctual	SSP, IIMI, DLR
Discharges	Gauging	All secondary canals	Daily	PID, IIMI
Tube well water quality	Samples	407 tube wells	Punctual	IIMI, SSP
Depth to groundwater table	Piezometers	50	Seasonal	SMO
Socio-economic characteristics	Interviews	600 farmers	Punctual	IIMI
System boundaries	Field observations	All tertiary units	Punctual	PID, IIMI
Cropping intensities	Remote sensing	Study area	Seasonal	Cemagref, IIMI

Large-scale surveys to determine soil types and soil salinity were undertaken with the Soil Survey of

Pakistan (SSP) and the Directorate for Land Reclamation (DLR). The daily discharges were observed by PID staff, as part of a collaboration on the introduction of a management information system at the main canal level. The tube well water samples were analyzed in the laboratory of SSP. Depth to groundwater table was obtained from secondary data of the SCARP Monitoring Organization (SMO), which is a research institute of WAPDA. A socio-economic characterization of the study area was done for 66 tertiary units in which about 600 farmers were interviewed. The boundaries of tertiary units, which are indicated on maps available with PID, were verified in the field by a retired irrigation manager, as boundaries had been altered substantially. Cropping intensities and genetic salinity were determined through the analysis of LANDSAT and SPOT satelite images (Vidal et al., 1996; Tabet et al., 1997).

2.2.2 Data management

Data were stored in computer databases, using specialized packages such as FOXPRO. In the case of canal water flows, the database was shared with PID. The data were as much as possible geo-referenced through the use of ARCINFO, once the system boundaries had been clearly defined through field observations and remote sensing. In a few cases, the data were made available to a wider audience through reports. This is the case for discharge ratings of the structures in the study area (IIMI, 1995b), tertiary outlet and characteristics and hydraulic details of secondary channels (Tareen et al., 1996), and soil types (Soil Survey of Pakistan, 1997). The satelite images along with a few examples of applications were made available through a CD-ROM, a product of Cemagref, IIMI and SPOT Image.

2.2.3 Evaluation of the data collection and management

There is no lack of data *per se* for the irrigation systems of the Indus Basin, but there are many complaints about the accuracy, the accessibility, the timeliness, and the inability to relate different data sets due to differences in sampling methods, a lack of geo-reference, and the fact that the primary data are often contained in bulky handwritten registers. This is perhaps a good synthesis of the many remarks made by authors who have attempted to interprete and analyze data collected by the various government organizations in Pakistan (Ahmed and Chaudry, 1988; Federal Cell, 1990; World Bank, 1994; IIMI, 1995a).

The following excerpts from two different sources give a flavour of some of the frustration felt by different authors:

"There are at present no means of knowing the discharges of outlets from day to day and month to month. Unless there is definite proof to the contrary it is assumed that the discharges of outlets are always equal to their permissible. But a glance at the annual efficienvy diagrams of any channel will show how erroneous this assumption is. What is wanted is a permanent and continuous record of the actual daily discharges of all outlets on a canal system. Then and only then, equitable distribution of water can be ensured" Erry (1936)

"... appropriate accounting of water is of fundamental importance to the process of investment planning. The discharge data of the rivers and tributaries are inconsistent and published with several years' delay. Records of water diversions to the distributaries/minors and outlets are either not kept or inaccessible. Similarly, the groundwater monitoring data and information collected under other monitoring programs is not cataloged systematically and is stored in paper registers, which makes the data inaccessible. The WSIPS [Water Sector Investment Planning Study, Federal Planning Cell, 1990] *found that investment planning is constrained severely by unavailability of the information about resource base, its use, and other technical parameters necessary for planning"* World Bank (1994)

The publication of Erry (1936) was intended to advocate the volumetric assessment of actual delivered irrigation water to farmers. Implementation of this would have imposed tremendous requirements on the existing data collection system of the PIDs. The quote from the World Bank publication (1994) provides evidence of the fact that information in the irrigation system is still an important problem. A number of points can be made to address this issue.

Firstly, great strides have been made around the world, particularly in industry, in the development of *information systems,* made possible through the rapid advances in computer technology. In addition, the development of Geographical Information Systems (GIS) has provided better opportunities for geo-referencing of data and of combining incongruent data sets. These information techniques have so far hardly been made use of in the Indus Basin irrigation system, but can offer great opportunities in the future in the management of the system (Rey, 1996; Federal Planning Cell, 1990). In the context of this study, the introduction of a management information system was undertaken on a small scale in collaboration with PID (Rivière, 1993; Rey et al., 1993). This experience emphasized the difficulty in daily collecting and communicating information on water levels and discharges for a 75,000 ha irrigation system.

Secondly, the size of the system and the number of parameters that are relevant for the performance of irrigated agriculture necessitate or even dictate that *information requirements are kept to a minimum.* Only those data that can be processed and analyzed should be collected. A visit to any of the government departments in Pakistan will convince anybody that collecting information does not imply that it will or can be used. The use of computer models can be useful to determine and minimize these requirements. By carrying out sensitivity analyses, those parameters likely to influence the performance of the irrigation system can be identified. This will be demonstrated in Chapters 3 and 4 of this study.

Thirdly, *better use can be made of existing data bases or routine data collection.* This has been done in Pakistan by processing and analyzing these data and making them available to a wider audience through publications. The best examples of this are perhaps the book on irrigated agriculture by Ahmed and Choudry (1988) and the book on hydraulics by Ali (1993). Another way of doing this is by processing these databases with modern techniques, such as computerized databases and geographical information systems (Asif et al., 1996). In this study, use has been made of data collected by government agencies. This was generally done in collaboration with IIMI, which provided opportunities to mix field expertise and manpower with modern information techniques (e.g. Soil Survey of Pakistan, 1996).

Fourthly, data collection can be better targeted by obtaining *expert advice*, thus obtaining an optimal mix of quantitative and qualitative data. In the course of this study, expert advice was often obtained through dialogue with scientists, managers, and farmers. In some cases this was done before initiating an activity (e.g. Soil Survey of Pakistan, 1997), but in many cases this was done *ex posteriori* through, for example, restitution exercises (Pintus, 1995; Kielen et al., 1996). In retrospect, these exercises could have been done much earlier, which would have saved a lot of effort in collecting quantitative data. In Chapter 5, the data requirements will be determined for the application of the integrated approach in the study area.

CHAPTER 3

IRRIGATION SYSTEM MANAGEMENT: FROM THE MAIN CANAL TO THE TERTIARY UNIT

The lower management boundary for the irrigation agency, the Punjab Irrigation & Power Department (PID), has traditionally been the tertiary outlet or *mogha*. Beyond this, farmers share the water through a roster of turns, *warabandi*, and PID intervenes only on the request of the cultivators in case of a dispute. The principal hypothesis underlying this study, i.e. an improved canal irrigation management will lead to better opportunities for farmers in dealing with salinity, implies interventions in the process of delivering water to the tertiary outlets. At a lower level intervening is much more difficult due to the *de jure* water entitlement of farmers (Strosser, 1997). This study will, therefore, focus on the main and secondary canal level.

In Section 3.1, the decision-making process that governs water deliveries is analyzed to determine the windows of opportunity for management interventions intended to improve the overall distribution. A methodology is then proposed in Section 3.2 to analyze the scope for management interventions and evaluate their likely impact on the water distribution. The methodology is applied to a case study in Sections 3.3 and 3.4 in order to test its suitability for analyzing the existing water distribution and for identifying an intervention strategy in the management of an irrigation system. In Section 3.3 the operations at the main canal level are analyzed for the Fordwah Branch. After a preliminary analysis of the actual situation, management interventions in the existing operational rules are proposed and evaluated for their impact on water deliveries to secondary canals. A similar analysis is carried out at the secondary level in Section 3.4, where the water deliveries to tertiary outlets, as a result of management interventions in the existing infrastructure, are evaluated. The implications of joint and individual interventions at the main and secondary canal level on the overall water distribution are evaluated in Section 3.5. The conclusions of Chapter 3 are presented in Section 3.6.

3.1 The irrigation agency: objectives and decision-making processes

3.1.1 General principles of canal irrigation management

The concept of large scale irrigation in the sub-continent fitted well with the policies of the British colonial administration. Confronted with a large rural population living in poverty and facing a great deal of incertitude with respect to their food supplies (as evidenced by the famines in the 19th century), the British were quick to realize the potential of the flat Indo-Gangetic plains to host what was to become some of the largest irrigation schemes in the world in order to address the food security of the sub-continent (Williams, 1937; Framji et al., 1984). Other less altruistic reasons for launching large-scale irrigation development were the containment of a large indigenous population prone to agitation by creating a relatively well-off "stable" agricultural class, the economic gains that were to be had by selling *crown waste land* to potential farmers, by the revenue generated through water taxes, and by the supply of low-cost unprocessed agricultural products to the industries in Great Britain (Mitchell, 1967; Gilmartin, 1994).

Irrigation development in the Indus Basin was associated with four main principles, viz. *equitability*, *water use efficiency*, *sediment management* and *minimum human interference* (Varma, 1917; Waterhouse, 1918; Malhotra, 1982; Kuper and Kijne, 1992; Gilmartin, 1994; Bandaragoda and Rehman, 1995). These principles will be further defined, as it is argued here that these principles are still governing water management in the Indus Basin, and because they have been interpreted differently in the literature.

Perhaps the most often cited principle yet interpreted differently is the notion of equity or *equitability* (e.g. Malhotra, 1982; Makin, 1987; Bhutta and Vander Velde, 1992; Vander Velde and Svendsen, 1994; Waterhouse, 1918; Varma, 1917). Design engineers such as Varma (1917) and Waterhouse (1918) viewed equitability in terms of sharing a water shortfall with reference to authorized discharges. However, when authorized discharges are achieved (supply is equal to the water allowance) users do not have equal access to irrigation water in terms of a volume or irrigation depth. This was shown in a study by Kuper and Kijne (1992) in the Fordwah Canal system, where the official water allowance ranges from 0.8 to 1.4 $l\ s^{-1}\ ha^{-1}$. Also, some canals are entitled to year round supplies (perennial), while others receive water only during the summer season (non-perennial).

The magnitude of issues such as food security, stability and economic gains, led the colonial government to a maximization of the area that was brought under irrigation, thereby imposing a relative water scarcity on the users and supplying them with just enough water for crop protection. This, in turn, would lead to a greater *water use efficiency* (Bandaragoda and Rehman, 1995; Malhotra, 1982; Jurriens, 1993). This is reflected in the way water charges (*abiana*) are levied. Even if the farmer receives only one irrigation turn during a season, he is bound to pay abiana, provided his crop reaches maturity. Another indication is the fact that non-perennial canals can be supplied with three waterings in winter *in order to save the wheat crop* (Siddiqi, 1991).

The present irrigation system in the Indus Basin was conceived in the second half of the 19th century by the British colonial administration, inspired by the presence of inundation canals, which diverted water from the rivers in times of flood. These canals often used old river beds to convey the water, supplemented by man-made stretches of canal. Problems that confronted these canals were the havoc inflicted by the uncontrolled rivers on the canal inlets and the sediment deposits that occurred because of the high sediment charge of the rivers, entailing high maintenance requirements. One of the finest achievements of the British engineers, addressing the problem of sediment management, has been the concept of non-scouring, non-silting[1] canals by achieving an optimal velocity throughout the channel. The construction of so-called "regime channels" effectively abolished the existing practice of *cheer* labour, where small farmers and servants of big landlords had to work many months in the winter far away from home to prepare the irrigation system for the summer irrigation season, kharif (Gilmartin, 1994). An *equitable distribution of sediment* to the different tertiary units serves then to keep the cultivators at home and to ensure that there is a fair distribution of work, while minimizing the maintenance requirements at the main and secondary canal levels.

Minimum human interference was a principle that was targeted both towards the end-users and the gate operators at lower levels of the irrigation system. A society that was feudal in nature was not considered to be likely to take to an irrigation system that was based on a far more equal distribution of land and water than customary. In order to avoid interference with water distribution by influentials, the canal system was designed with an intended disregard of the social situation, whereby the territories of the tertiary unit and the village did not coincide (Gilmartin, 1994). In addition to that, the design engineers arranged the irrigation system around proportional dividers, whenever possible, to obtain an "automatic" water distribution, thereby minimizing the number of gate operators and intervention occasions. This is illustrated, perhaps, by the fact that gate operators are locally referred to as gauge readers, expected to observe rather than to act.

Environmental concerns were not a premier concern at the design stage. Larger areas affected by salinity were as much as possible excluded from the command areas of irrigation systems, and farmers were expected, when these areas were included, to be able to handle this soil salinity (Williams, 1937). Only at a later stage, when groundwater tables were found to rise dramatically causing problems of waterlogging, and when it became apparent that salinity was not always easy to deal with, irrigation engineers took account of these issues in the design of the irrigation systems. Some of the measures that irrigation engineers have taken are listed in Chapter 1.

3.1.2 Irrigation management activities

The general principles defined in the previous section have determined to a large extent the design of the present irrigation system, as well as the rules governing operation and maintenance of the system. These rules are documented in the Manual of Irrigation Practice (Public Works Department, 1961), which is largely based on the Irrigation & Drainage Act of 1873. Officially, these rules have not been modified, despite the immense changes that have taken place in the way water is used in irrigated

[1] The term silt has been commonly used in the Indian Sub-continent to denote sediment.

agriculture. In practice, these rules are much less rigid and have been adapted to the present situation. Therefore, the official as well as the actual rules need to be understood, if interventions in water deliveries to tertiary outlets are to be proposed.

The official rules are perhaps best understood by using the management activities of the irrigation agency in the Indus Basin as an entry point. The *operations* in an irrigation scheme comprise the target setting and the process of matching deliveries with the targets. It is quite a complex process, involving activities such as *water allocation, water scheduling, and water distribution.* By *maintaining* the infrastructure of an irrigation system, the irrigation agency attempts to remove hindrances for the operations, and to extend the life time of the different components of the system.

During the design phase, the process of *water allocation* consisted of determining the extent of an irrigation system as well as the water entitlement per unit of land. For each tertiary unit, an authorized discharge was then determined based on the culturable command area (CCA) of that unit and the water allocation. The irrigation intensity, i.e. the yearly cropped area, was generally fixed at 70-80%. Also, a decision was taken whether a system was to be perennial or non-perennial. Non-perennial canals were given a higher water allocation, but were only supplied during kharif. On the basis of the authorized discharges of tertiary units, to which conveyance losses were added, the dimensions of canals and structures were determined. Kharif was taken to be the critical factor in determining the water allocation, because of the high crop water requirements (Public Works Department, 1961). Climate, soil and crop type, groundwater table, historical water rights (if any), and a negotiation process between the different riparian provinces and independent states to demarcate the share of water of a proposed irrigation scheme were important factors in this process.

The water allocation is revised regularly through the inclusion of hithertofore unirrigated land into the *CCA* of tertiary units. These local decisions, however, are generally not taken into account at the system level. Even when the authorized discharges for a number of tertiary outlets have been revised, for instance, the authorized discharge for a distributary remains unchanged. The actual water allocation of tertiary units is quite different from what it is officially. When secondary canals are supplied with their authorized discharge, there are substantial differences in water deliveries to large numbers of outlets.

Water delivery scheduling is undertaken at the beginning of each crop season. Based on the anticipated availability of flow, i.e. reservoir levels plus uncontrolled flow, a 10-day delivery schedule to the 21 canal commands of the Punjab is prepared by the central Regulation Office. If the forecasted availability is less than the combined canal capacities, the sanctioned discharges are adjusted downwards in order to remain within the specified shares for the provinces, as documented in the Indus Water Apportionment Accord of 1991. The length of this period takes the *warabandi* cycle of 7 days into account plus 3 days lag time for the water to reach the specified irrigation divisions.

During the season, the irrigation managers (usually the Sub-Divisional Officers) along a canal system formulate their demands from the tail sub-division upwards and place their combined demand, termed *indent*, with the Sub-Divisional Officer (SDO) incharge of the headworks, who releases the requested discharge, or the sanctioned discharge, for that particular 10-day period, whichever quantity is less (Siddiqi, 1994). The time lag for conveying the water to the required location is accounted for by the indenting officers (Shafi, 1994). Presently, the water demand almost invariably exceeds the water deliveries except in times of rain and during the harvest of wheat. This means that the indents formulated by the SDOs are generally equal to the authorized discharge of a sub-division. Over the past 20 years, rotational programmes within irrigation canal commands have been introduced, which specify an order of preference for all sub-divisions for 8-day periods. These sub-divisions are allowed to take an amount equal to their indent from the total indent in the order fixed in the schedule. Generally, there is not sufficient water for the sub-division that has the lowest preference, which then has to resort to an intra sub-divisional water rotation (Kuper and Kijne, 1992). This rotation is often specified by defining an order of priority for different secondary canals. This is done on the basis of a set of *operational rules*, which are derived from the water allocation, the rotational plan that was defined at the beginning of the irrigation season, and the available inflow during the season. The responsibility for the operational strategy lies with the irrigation managers, i.e. SDO and the Executive Engineer (XEN), while the implementation is done by the gate operators. An example of an operational rule for the irrigation manager is that he cannot plan a supply period for a given distributary of less than 8 days, since an uninterrupted supply has to be ensured for an entire *warabandi* period (7 days) with one day to stabilize supplies. The complexity of the water delivery scheduling at the different hydraulic levels creates uncertainty. It is not clear how much water can be expected at what time. In addition, the rotational plans are often ambiguous since they enter into use only on the occasion of a lower inflow than expected at each particular level. In daily reality these schedules have very limited practical value as shown by Kuper and Kijne (1992).

Water distribution is the set of activities to deliver water to secondary and tertiary offtakes in order to satisfy the schedule with a certain degree of precision, usually by regulating the gated structures. Water distribution is thus the implementation of the operational strategy, and is sometimes referred to as the tactical level in canal operations (Malaterre, 1994). Gate operators are guided by a set of tactical operational rules. An example of such a rule is the fact that a gate operator will initiate action as soon as the water level upstream of a cross-regulator deviates 2 cm from the target. At the *distributary* level, canal operations are much less important, as the water distribution is implemented largely automatically through fixed structures. Operational interventions are only possible by operating the gated structures at the intake of distributaries.

Monitoring of the performance of the actual water distribution is done mainly at the main canal level, where water levels and corresponding discharges at regulating structures are entered in registers. These data are then conveyed by various means to the SDO and XEN, who can decide to intervene in the water distribution. At the distributary level, no control structures exist and no information is collected routinely. However, periodically the working head of outlets is monitored and entered in the so-called H-register. This register can be consulted also for sediment clearance, because an increase in the water levels upstream of outlets can be an indication of sediment deposits (Shafi, 1994).

Rectifying the water distribution inside a distributary is traditionally done through the annual *Maintenance and Repair* (M&R) programme of the irrigation agency. In a cycle of 4 years, the different parts of a distributary should be targeted in order to maintain the channel and its structures (Firdousi, 1989). When it is observed that the functioning of a distributary can no longer be rectified by the routine M&R activities, a more extensive programme is defined to redesign the channel and its structures. This programme is usually referred to as the *remodelling* of a distributary and is often related to modification and upgrading of drops and outlets, redesign of sections or even lining of a channel.

Management interventions in the water deliveries to tertiary units can be undertaken both at the level of the main as well as the secondary canal. However, the nature of these interventions is not the same. At the main canal level, these interventions are possible through canal operations, while at the secondary canal level, interventions will have to focus on the infrastructure in the absence of regulating structures.

3.1.3 Scope for interventions

The present management activities of the irrigation agency, as defined in the previous section, provide ample opportunity for management interventions, i.e. operations at the main canal level and maintenance at the distributary level. The provision that is made for these interventions in the context of this study, is that they fall within the regular activities of the irrigation agency within the Chishtian Sub-division. Existing constraints, such as the inflow of the system, will be accepted as a given. In the present section, the management interventions at the main and secondary canal level will be further detailed.

Improving operations at the main canal level

In order to define a set of management interventions that are likely to improve the water distribution, the process of canal operations is further analyzed. Canal operations consist of an implementation part, the gate operations, as well as a more strategic part, which includes the target setting by the irrigation manager. The operational logic is represented in Figures 3.1 and 3.2.

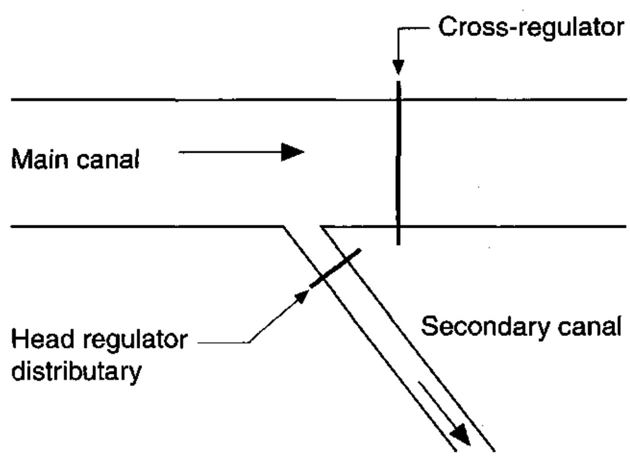

Figure 3.1: Typical lay-out of a cross-regulator and an offtaking secondary canal.

In Figure 3.1, a typical field situation is presented. A gate operator is responsible for the operation of a gated cross-regulator in the main canal and for one or more off-taking distributaries. For regulation the following situations can be identified:
- If a distributary is in priority, the gate keeper will try to keep the upstream water level constant, by operating the cross-regulator. The distributary regulator will generally not be moved.
- If a distributary is not in priority, the gate keeper will operate the distributary gate in order to keep the upstream water level constant for the other distributaries, which are located at this control point, and for the on-going discharge in the parent channel. The downstream water level will be monitored in order to maintain a constant discharge in the parent channel.
- If a distributary is not in priority and neither are the other distributaries at this location, the gate keeper does not maintain the upstream FSL and allows the water level to drop. In the study area, this happens usually only in rabi.

The irrigation manager formulates the target, which is either a discharge or a water level, and communicates this to the gate operator through an open loop taking the time lags into account, see Figure 3.2 (Malaterre, 1995). The gate operator can implement the instructions by changing the gate setting if the actual situation does not correspond with the target. A certain time after the gate has been manipulated, the gate operator will verify whether the manipulation has been successful in attaining the target. Generally the upstream water level will be verified (feed-back loop 1), but when the off-taking distributaries are not in priority the downstream water level will be checked (feed-back loop 2), as explained earlier.

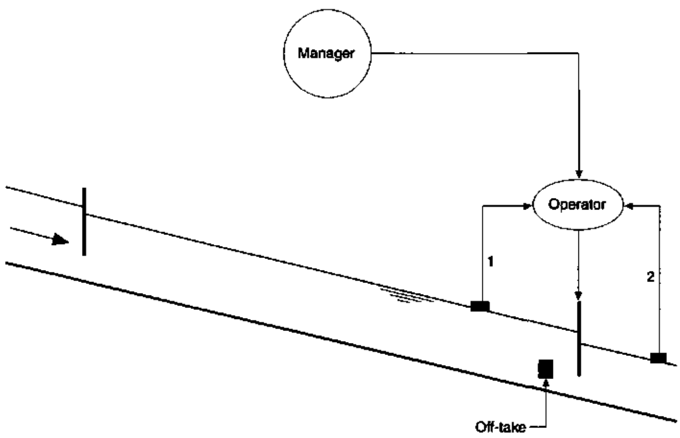

Figure 3.2: Representation of the operational control at the main canal level, showing a canal reach with two cross-regulators.

The question is now, whether interventions in order to redirect water supplies to different secondary canals, should take place in defining the operational targets, i.e. at the strategic level, or in the field implementation of the gate operators, i.e. at the tactical level. A study of the manual control of the gate operators in the study area, showed that they are generally capable of attaining operational targets (Kuper et al., 1994; Litrico, 1995). This was field tested in collaboration with PID, where the reaction of gate operators to operational problems such as discharge variations was observed (Litrico et al., 1995). Gate operators are, however, considerably constrained in their work due to a lack of information. They are not informed in case of abnormal events, such as a sudden increase in water supply, and have to react to whatever occurs at their control post. Since they are held responsible in case of breaches, gate operators keep a small safety margin and tend to react immediately to changes in water levels in the main canal by diverting extra water to the secondary canals. In many cases this is not necessary, and not reacting to these changes would stabilize the state of the canal and reduce discharge variability (Litrico, 1995). Improving the field implementation of gate operators by smoothing this variability, however, does not have much impact on the volumes of water that are delivered to secondary units. A much bigger volummetric impact can be obtained by focusing on the operational rules, which govern the decisions on gate operations. Officially, these rules are defined by the irrigation manager, but in the present situation, there are hardly any explicit operational targets, and the gate operators have obtained a large degree of independence. They tend to favour the distributaries under their control, with adverse effects on the water deliveries to distributaries that are located downstream. This infringes on the system objective of an equitable water distribution, and it seems, therefore, appropriate to focus the analysis at the main canal level on the operational strategy. The analysis is summarized in Table 3.1.

Table 3.1: Management decisions related to operations at the main canal level.

Issue	Water management activity	Level	Actor
Volummetric water deliveries	Allocation	Strategic	Irrigation manager
	Delivery scheduling	Strategic	Irrigation manager
Discharge variability	Distribution	Tactical	Gate operator

In case a redistribution of volumes of canal irrigation water is desired, e.g. to restore equitability or for salinity control, an intervention at the strategic level is required. This can be done through the existing management activities, i.e. water allocation and delivery scheduling. The responsibility for these activities lies with the irrigation manager. In case of discharge variability, an intervention at the tactical level suffices.

Another field in which interventions could take place, is the information flow and processing in the irrigation system. This is an intervention that would help the irrigation managers in assessing the degree of achievement of their targets. This intervention was attempted in the study area, following a similar study in Sri Lanka (Rey et al., 1993). Rey (1996) analyzed the potential contribution of information techniques to irrigation system management. This subject will not be treated in this study.

The analysis shows that improving the field implementation of gate operators contributes to reducing discharge variability. However, it does not substantially improve the water distribution in terms of volumes in the absence of clear operational rules. The aim of this study is to redistribute volumes of water, which can be used by farmers for salinity control. The management interventions at the main canal level should, therefore, focus on interventions in the operational rules at the strategic level.

Alternative operational rules at the main canal level

Irrigation management interventions in the strategic operational rules, can be focused on water allocation or on water delivery scheduling. *Water allocation*, as was shown earlier in this chapter, pertains mainly to defining the authorized discharge and the area entitled to water. A modification of authorized discharges seems to be the most effective way of intervening, as the CCA or irrigation intensity are no longer controlled by PID, as evidenced, for instance, by the tremendous increase in the actual irrigation intensities. An intervention in the authorized discharge can be done, for instance, by recognizing the actual water allocation or by redefining the authorized discharges at different levels of the canal irrigation system, including the inflow.

The rotational system is a myriad of global and local arrangements, and is not transparent (Kuper and Kijne, 1992). At each hierarchical level in the irrigation system a rotational plan exists. One way of improving the *water delivery scheduling*, would be to simplify these arrangements by abolishing the rotations at higher levels of the irrigation system as the basic unit of rotation is the distributary, which is under the administrative control of a sub-division. However, this would require a greater control over the water flows at different levels of the canal irrigation system of the Punjab. At the sub-divisional level, the rotational plan is possibly the most effective way of changing water deliveries. The official rule for supplying a distributary for 8 days, for instance, which is based on the water sharing system of farmers *warabandi*, makes sense. Violating this rule will likely have a negative impact on water deliveries to farmers.

Finally, water deliveries to tertiary units cannot be addressed only at the main canal level, because even at authorized discharge the water does not reach the tail in a number of distributaries (Tareen et al., 1996; Habib and Kuper, 1996). Interventions at the secondary level will need to complement interventions in operational rules at the main canal level.

Maintenance at the secondary canal level

The Maintenance & Repair (M&R) activities that relate to channel and structures are laid down in the Manual of Irrigation Practice (PWD, 1961). They are summarized in Table 3.2. The importance of routine M&R activities for the water distribution in secondary canals is emphasized for three reasons:
- Safety: "a failure of the bank of a channel, in addition to causing considerable damage to the country side and private property, may ruin the crops grown on that canal system by reason of interruption to supply."
- Maintenance of hydraulic characteristics with special reference to the carrying capacity of channels
- Equitable water distribution

Table 3.2: Routine M&R activities related to channels and structures carried out by the irrigation agency in the Indus Basin (adapted from Firdousi, 1989).

Main/Branch canal	Distributary/Minor canal	Objective
Maintenance of banks	Maintenance of banks	Safety
Rain cuts		Safety
Berm cutting and cleaning of bed	Berm cutting	Hydraulic characteristics
Jungle clearance	Jungle clearance	Hydraulic characteristics
Weed clearance		Hydraulic characteristics
Kila bushing[1]	Kila bushing	Hydraulic characteristics
Repair to masonry work	Repair to masonry work	Hydraulic characteristics
	Redimensioning outlets	Hydraulic characteristics, Equitable distribution
	Sediment clearance	Hydraulic characteristics, Equitable distribution

[1] Relates to the restriction of the width of the cross-section by inserting bamboo sticks and bushes

The annual closure, which occurs traditionally for a period of three weeks in January, permits the irrigation agency to carry out maintenance works. Sediment clearance and redimensioning of outlets are done exclusively at the distributary level. These measures are intended to serve as instruments for the irrigation manager to ensure the desired water distribution, as there are no control structures at the secondary level. These measures offer, therefore, good opportunities for management interventions.

In summary, the study of irrigation management interventions will be focused on analyzing existing and alternative operational rules at the main canal level, and on identifying appropriate modifications in the infrastructure at the secondary canal level.

3.1.4 Physical system constraints

In this section, the physical system constraints are described in order to characterize the context in which the proposed interventions take place, and to understand the limitations of the improvements.

The secondary intake structures are a mixture of gated orifices, and ungated weirs. These weirs can be controlled by placing horizontal or vertical wooden planks, in order to reduce the opening or the width of the structure. It is mostly the small distributaries with a discharge of less than 1 $m^3 s^{-1}$ that have such a weir. Obviously, the regulation of discharge into distributaries with such a weir is more cumbersome. Usually, these distributaries are, therefore, only regulated in case of either an emergency or a specific request from the farmers. The discharge of these distributaries is more a function of the water level in the main canal than of the regulation of the irrigation agency.

The escape at the tail of the Fordwah Branch (Ford-Bahawal Feeder), which was functional before 1976, has been abandoned, thereby reducing the flexibility of operations. As a result of fluctuations received from upstream, the operator at this location is forced to pass on any excess in discharge to any one of the large distributaries located at the tail, sometimes resulting in breaches. In fact, the Azim Distributary is now *de facto* used as an escape. In order to prevent mishaps, the operating staff tend to reduce the discharge supplied to the tail so that any surplus can be easily absorbed. In practice, this means that only one of the major distributaries at the tail (Fordwah, Azim) is fully open at a time, since the alternative of keeping the Fordwah and Azim distributaries open, would require much effort and vigilance from the manager and operating staff. As a result the capacity of the canal at the tail portion has decreased since a reduced discharge entails sediment deposition and a new "regime".

A number of weak points in the banks of the Fordwah Branch were identified during a modelling study (Litrico, 1995). Some of these points are located near cross regulators (RD 245, RD 353), but others are situated far away from the regulating points (RD 267, RD 298, RD 363), which prompts gate operators to maintain a safety margin by lowering the maximum permissible water level. This limits the operational range.

3.2 Methodology

3.2.1 General framework

The aim of this section is to develop a methodology that enables to assess the effect of irrigation management interventions, at the main and secondary canal level, on water deliveries to tertiary units. This methodology will be applied to the main and secondary canals of the study area in Sections 3.3 and 3.4, respectively. The main features of the approach are that it links human decisions with hydraulics, and that it includes the development of a tool, which can be used for a comparative analysis of the effects of different proposed management interventions. To enable this comparison, a modelling approach was adopted. Another advantage of such an approach is the fact that different variables can be modified separately or combined, and that projections into the future can be made. Finally, this approach was selected in order to integrate human decisions and physical processes by creating a common, quantitative platform.

The development of the approach follows the diagnosis that was carried out in Section 3.1, focusing on canal operations at the main canal level and the infrastructure at the secondary canal level. Because of the difference in nature of the management interventions, the study is carried out separately for the main and secondary canal level, see Figure 3.3. The combined impact of main canal and distributary interventions will be analyzed thereafter.

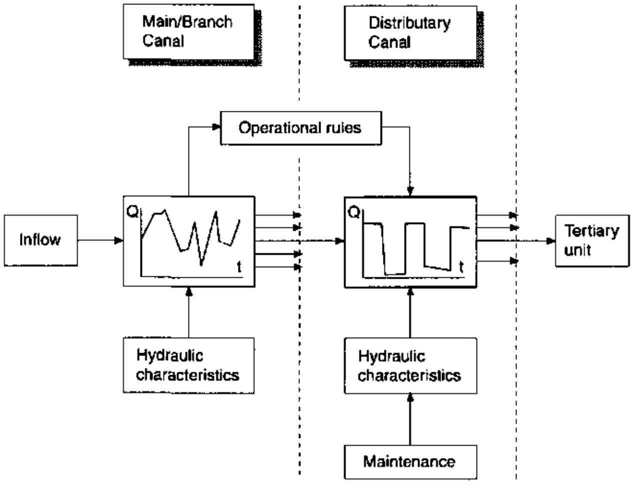

Figure 3.3: Representation of the water distribution for a canal distribution network in the Indus Basin

The different steps of the methodology are listed in Table 3.3. It should be emphasized that these steps were preceded by a thorough diagnosis, as presented in Section 3.1.

Table 3.3: Different steps of the developed methodology to analyze the effect of irrigation interventions at the main and secondary canal on water deliveries to secondary and tertiary offtakes.

Steps	Main canal	Steps	Secondary canal
1	Development of hydraulic model	1	Development of hydraulic model
2	Development of regulation module	2	
3	Analyzing official and existing operational rules	3	Analyzing official and existing water distribution
4	Developing an intervention strategy	4	Developing an intervention strategy
		a	Local analysis
		b	Global analysis
5	Simulating existing operational rules	5	Simulating the existing water distribution
6	Formulation of scenarios	6	Formulation of scenarios
7	Simulations	7	Simulations
8	Evaluation of results	8	Evaluation of results
9	Simulating the effect of main and secondary canal level interventions		

At the main canal level, the tool that is developed in this approach consists of two principal parts, a model that simulates canal hydraulics, and a regulation module, which describes the operational decision-making processes. The hydraulic model is described and set up for the main canal in the study area in Section 3.2.2 (*Step 1*). Since the physical characteristics of the canals and structures are represented in the model, the consequences of interventions in the physical infrastructure can be assessed by using this model. Interventions in operations are more complicated: the decision of a gate operation is a function of several inter-related variables, i.e. the target discharges, upstream and downstream water levels, the gate opening and the resulting discharges to off-takes and the parent channel. The operational logic of the irrigation agency was, therefore, captured in a regulation module, which translates operational rules into gate operations (*Step 2*). The module, which is presented in Section 3.2.3, is linked with the simulation model. Thus, the effect of the existing operational rules on the water distribution, can be quantified by the hydraulic model[2].

Before using the composite model, an analysis of the existing water distribution patterns is carried out in Section 3.3.1 to understand the differences in official and existing operational rules (*Step 3*). In doing so, proposed interventions in the operational rules can take the existing rules as a starting point. Then, in the same section, an intervention strategy is formulated, based on this analysis (*Step 4*). In *Step 5*, the model is used to analyze the existing situation. The impact of existing operational rules on the water distribution is assessed in Section 3.3.2. This serves two main purposes. Firstly, a verification of the

[2] This approach has been used to simulate automated regulation of irrigation canals (e.g. Malaterre, 1994; Kosuth, 1994), but is much more difficult in the case of manual operation due to the complexity of the operational logic (Lamacq, 1997).

validity of the model by comparing the predicted and observed water distribution. Secondly, a comparative analysis of the effect of operational rules on the water distribution, which permits the identification of alternative operational rules.

The experiences gained in earlier stages are applied in *Steps 6 to 8*. In *Step 6*, alternative scenarios are formulated. These scenarios relate to re-establishing the official rules, to restoring equitability in water distribution and to making water available for salinity and sodicity control. Simulations are then carried out in *Step 7*, the results of which are evaluated in *Step 8*. Steps 6 to 8 are presented in Sections 3.3.3, 3.3.4 and 3.3.5. Indicators to evaluate the results of the simulations are defined in Section 3.2.4.

At the secondary canal level, the hydraulic model is set up for two canals in the study area in Section 3.2.2 (*Step 1*). Then, the differences in intended and existing water deliveries to tertiary units are assessed in Section 3.4.1 to determine the scope for intervention (*Step 3*). Subsequently, the marginal impact of changes in physical parameters on the water deliveries to tertiary units is assessed in Section 3.4.2 and 3.4.3, for local and global interventions, respectively in order to formulate an intervention strategy (*Steps 4a and 4b*). Before applying this strategy to the two secondary canals, the existing water distribution is simulated in Section 3.4.4 (*Step 5*). This is necessary in order to specify a reference scenario for comparison.

In *Step 6*, alternative scenarios are formulated on the basis of the results of Steps 3 and 4. These scenarios relate to restoring equitability in water distribution and to making water available for salinity and sodicity control. Simulations are then carried out in *Step 7*, the results of which are evaluated in *Step 8*. Steps 6 to 8 are presented in Section 3.4.4. Finally, the impact of interventions at the main and secondary canal level are compared and combined in Section 3.5 (*Step 9*).

3.2.2 Developing a hydro-dynamic model (Step 1)

In order to simulate water flows in the system and water deliveries to secondary and tertiary off-takes, based on the existing hydraulic characteristics and a given inflow pattern, a model was developed for the main canal as well as for the secondary canals. This was done using a hydraulic unsteady state simulation model called SIC - Simulation of Irrigation Canals - developed by the french engineering research institute Cemagref in Montpellier[3]. SIC has been tested for computational accuracy using the benchmarks developed by the American Society of Civil Engineers, and is presently applied in various countries around the world (Malaterre and Baume, 1997).

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[3] SIC can be downloaded through internet at the following site: http://www.montpellier.cemagref.fr/~pom/canari.htm

SIC consists of three main units (Baume et al., 1993; Cemagref, 1992), as shown in Figure 3.4. Unit I is centered around the computer programme TALWEG that reads the canal geometry from a set of cross sections, acquired through a topographic survey, and from the location of canal structures, i.e. cross regulators and offtakes. The topographic file created by this unit (.TAL) includes the canal network as defined by the user (reaches, branches, location of nodes and structures), the bed/bank levels, bed slope (calculated through the cross-sections) and cross sectional areas at computational points. An example of a .TAL file can be found on the internet site, indicated above.

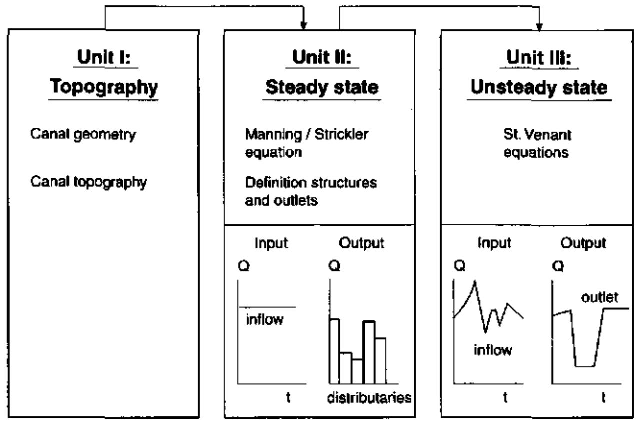

Figure 3.4: Schematic structure of the hydraulic model Simulation of Irrigation Canals (SIC).

Unit II, developed around FLUVIA reads hydraulic data and computes water surface profiles under steady state conditions, generating a .FLU file, using the Manning-Strickler equation expressed as a differential equation of the water surface profile solved by Newton's method:

$$dH = -S_f + (k-1)\frac{qQ}{gA^2} \tag{3.1}$$

where:

$$S_f = \frac{n^2Q^2}{A^2R^{4/3}} \tag{3.2}$$

and:

H	= energy head	[m]
x	= abscissa	[m]
S_f	= energy slope	[-]
k	= constant	[-]
q	= lateral inflow (k=0) or outflow (k=1)	[$m^2 s^{-1}$]
Q	= canal discharge	[$m^3 s^{-1}$]
A	= wetted area	[m^2]
n	= Manning's coefficient	[$m^{-1/3} s^{-1}$]
R	= hydraulic radius (A/P)	[m]
P	= wetted perimeter	[m]
g	= gravitational acceleration	[$m\ s^{-2}$]

To solve Equation 3.1, an upstream (discharge) and a downstream (water surface elevation) boundary condition needs to be defined after which the computations will commence from the tail of the modelled channel. Two sub-modules can compute the gate openings for offtakes and cross-regulators in case of target discharges and target water levels, respectively. The formulas that are used in SIC to calculate the discharges of structures as a function of the water levels, gate openings, structure dimensions and the flow conditions are summarized in Appendix 1. The formulas used in SIC deviate slightly from the classical formulas, as they take the transition in flow conditions, from free flow to submerged and vice-versa, into account.

Unit III computes unsteady flow conditions by solving the Barre de Saint Venant equations:

Continuity equation (conservation of mass):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{3.3}$$

Dynamic (momentum) equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial h}{\partial x} = -gAS_f + kqv \tag{3.4}$$

where:

h	= vertical depth of flow	[m]
v	= mean fluid velocity	[m s^{-1}]
k	= lateral in- (k=0) or outflow (k=1)	[-]

The initial water surface profile (steady state) is provided by Unit II. It then computes offtake discharge openings under varying flow profiles or discharges for fixed openings (.SIR file). The Saint Venant equations are solved numerically by discretizing the equations through a four-point semi-implicit Preissmann scheme. Upper (discharge) and lower (rating curve at downstream node) boundary conditions need to be defined in order to generate the water surface profile under unsteady state conditions. More details regarding input requirements and outputs provided by SIC are given in Cemagref (1992).

The selection of the time step used in SIC depends on the numerical solution of the (varying) water surface profiles. This is dictated by the numerical scheme (Preissmann) that is used in SIC to discretize the St. Venant equations. Malaterre (1994) tested this discretization scheme on its ability to reproduce the celerity, i.e. the velocity with which a wave is propagated, for a given wave length. That is to say, no numerical amplification or damping of the waves should occur. The indicator used by Malaterre (1994) is the *Courant number*, C_r:

$$C_r = \frac{\Delta t}{\Delta x}(v + c) \tag{3.5}$$

where:

Δt, Δx	= time and space steps in s and m, respectively	
v	= mean velocity	[m s^{-1}]
c	= celerity coefficient	[-]

and:

$$c = \sqrt{g \frac{A}{w}} \tag{3.6}$$

where:

g	= gravitational acceleration	[m^2 s^{-1}]
A	= wetted area	[m^2]
w	= top width of the wetted area	[m]

If any reach of the Fordwah Branch is selected, for example the reach just downstream of the Jagir Distributary from km 90.678 to km 92.354, with the hydraulic characteristics obtained from an earlier simulation of SIC, the celerity coefficient can be calculated as shown in Table 3.4.

Table 3.4: Inputs and outputs of calculations to determine the velocity v and the celerity coefficient c.

Input		Output	
Length of reach	1676 m	v	0.71 m s^{-1}
Volume	47658.4 m^3	c	3.84
Discharge	20.1 m^3 s^{-1}		
Width of top section	18.9 m		
Wetted area	28.4 m^2		
Δx	400 m		

When using the values of Table 3.4 in Equation 3.5, a Courant number of 0.011 per unit time (s) is obtained. This means:

if Δt is 5 minutes, C_r = 3.4
if Δt is 10 minutes, C_r = 6.8
if Δt is 30 minutes, C_r = 20.5

While the interest is in maximizing the time step for operational reasons, this is limited by the value of the Courant number, which should be as close to 1 as possible and should not exceed 10 (Malaterre, 1994), which is why 10 minutes has been taken as the time step for the calculation of the water surface profiles.

Calibration and validation

The calibration and validation is an important basis for the use of a physical model like SIC. The SIC model for the Fordwah Branch was calibrated during a three-day period in 1995, when in collaboration with the irrigation agency a steady state was created by securing a constant inflow and by instructing the gate keepers not to operate their gates. This served to demonstrate the advantages of having a steady state in the canal, i.e. no fear of breaches, little necessity to operate gates and a reduced discharge variability, but it also enabled an accurate calibration of SIC (Litrico et al., 1995; Litrico, 1995; IIMI, 1995b). SIC was also validated for the Fordwah Branch Canal for a different inflow. An error of less than 5% was obtained between predicted and measured discharges, while the difference in predicted and observed water levels was always smaller than 6 cm. In addition, the C_d coefficients for all distributaries were checked again and found in general to be satisfactory (Tareen et al., 1996; IIMI, 1995b; Litrico, 1995). A slight upward modification was undertaken for the Phogan Distributary (from 0.4 to 0.45) and Soda Distributary (from 0.32 to 0.4). This does not affect the global water levels and discharges much. The limitations of the model need to be defined:
- The lower limit of the model inflow has been fixed at 15 $m^3 s^{-1}$. Below that, there are risks that parts of the canal become dry because of time lags, an event that can be observed in the field at these discharges. However, the computation in SIC stops in this case due to numerical problems of steep water profiles and negative discharges due to back flow. On top of that, the model has been calibrated and validated for a discharge range above 15 $m^3 s^{-1}$, which would make the validity of the outcomes questionable.
- The present model cannot be used for branched canals (e.g. a main canal with the off-taking distributaries). A new version of SIC, which has been recently developed, will be able to do this.
- The formulas used in SIC to calculate discharges deviate from the classical hydraulic formulas to take into account the transition of flow conditions at structures, as stated before. Presently, an effort is underway to better integrate these classical formulas into SIC in such a way that the transition of flow conditions is well taken care of.

At the secondary level, SIC was calibrated and validated for the Fordwah and Masood Distributaries (Hart, 1996; Visser, 1996). The calibration/validation procedures were different in both cases. In the case of the Masood Distributary, a classical calibration/validation procedure was adopted with the following steps (Visser, 1996; Tareen et al., 1996):
- Calibration of head regulator, drops and offtakes
- Topographic survey of the distributary
- Determination of representative canal cross-sections
- Measurement campaign, whereby with a constant discharge at the head of the distributary, the outflow to offtakes and tail was measured; determination of seepage losses
- Model calibration in steady state with water levels and discharges by adjusting the Manning/Strickler coefficient
- Model validation with water levels and discharges of a second measurement campaign

The accuracy of discharge prediction of the model for offtaking outlets was within 5% for the calibration and the validation. The maximum deviation in water level was 4 cm.

For the Fordwah distributary an alternative approach was adopted (Hart, 1996). Only those offtakes with particular characteristics, e.g. those that were broken or had submerged flow conditions, were calibrated. Also, for each outlet type (fixed orifice, open flume, pipe) a number of representative offtakes were calibrated, in order to avoid the calibration of all 87 offtakes. During the measurement campaign discharges were not measured for the offtakes, but instead at regular intervals in the distributary. Finally, the model calibration was done in unsteady state because the inflow at the head of the distributary was not constant during the exercise. Measurements that have been done since this calibration exercise have confirmed that for outlets that are in good working condition and are of the type fixed orifice and open flume, the coefficient of discharge C_d is quite uniform (Tareen et al., 1996). This substantiates the calibration/validation procedure adopted by Hart (1996). At present, data are available to undertake a more classical calibration/validation procedure for Fordwah distributary, which would allow a comparison of the two procedures. The calibration resulted in an accuracy of discharge prediction of the model within 5%, while the predicted water levels were generally within 5 cm of the observed values. No validation was done for this distributary model.

At the distributary level, the limitations of the model are similar to what was observed at the main canal level. The limitation of tail dry, however, is more serious at this level, because the range of discharge fluctuations is greater.

Setting up a model like SIC is quite time-consuming. Based on the experiences in the study area, it can be estimated that the collection of field data takes about 15 man days per 10 km of length of canal. This includes the topographic survey, verification of structure dimensions, calibration of structures and outlets, and performing an inflow-outflow test for the calibration and for the validation of the model. In addition, a few days are required to set up the model on the computer.

3.2.3 Developing a regulation module for operations at the main canal level (Step 2)

Structure

The regulation module, Gateman, was developed to simulate decisions of irrigation managers on the irrigation targets, as well as the manual operations of gate keepers at the main system level. The regulation module is written in FORTRAN and is integrated in the unsteady state module of SIC, see Figure 3.5. A listing of the regulation module Gateman will be available shortly on internet, and can meanwhile be obtained from the author.

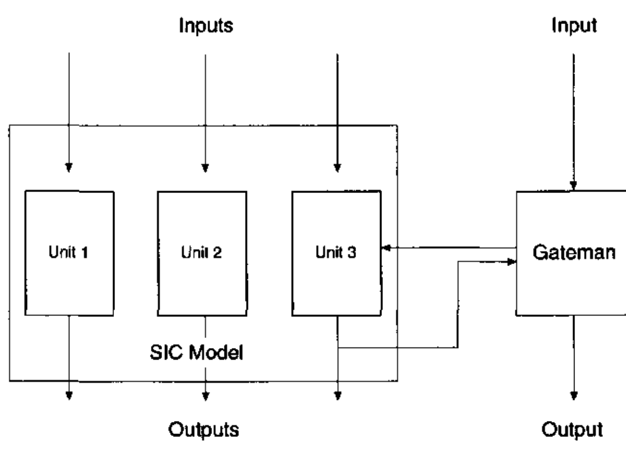

Figure 3.5: Integration of SIC and the regulation module Gateman (after Litrico, 1995).

The regulation module requires an input file (.REG), where the time parameters as well as the structures, cross-structures and offtakes, can be defined. Also, the rotational order can be specified in the strategic part of the input file. Finally, the inflow pattern can be defined if required. This is also possible through unit 3 of SIC. The output file of the regulation module specifies the delivered discharges with a time step, which can be changed according to the requirements of the user. In this study a 12 hour time step was selected. This output file summarizes the results of unit 3 of SIC.

Operational logic

The regulation of irrigation canals is based on instructions from the irrigation manager and the hydraulic logic of manipulating gates to achieve a certain target discharge or water level, while keeping certain safety margins in order to prevent breaches. This operational logic, which was discussed in Section 3.1, was formalized in the regulation module as shown in Figure 3.6.

Gateman has a strategic as well as a tactical component. In the *strategic* component, the regulation module generates an order of priority for the distributaries based on a set of rules, either the official ones or a set of alternative operational rules. This order is valid for a fixed number of days, which can be selected in the module. Then, the module decides based on this order and based on the inflow on a given day which distributaries should be open, which closed and determines the balance distributary, i.e. the channel that will absorb the fluctuations. This is done twice a day, as indeed is the official practice of the Irrigation Department. In a third step, in the *tactical* component, the module will generate the gate settings that are necessary to achieve the targets that have been defined (H_u, Q of distributaries), following the present practice of operating cross-regulators or distributary head regulators. This is done in conjunction with SIC, every 10 minutes.

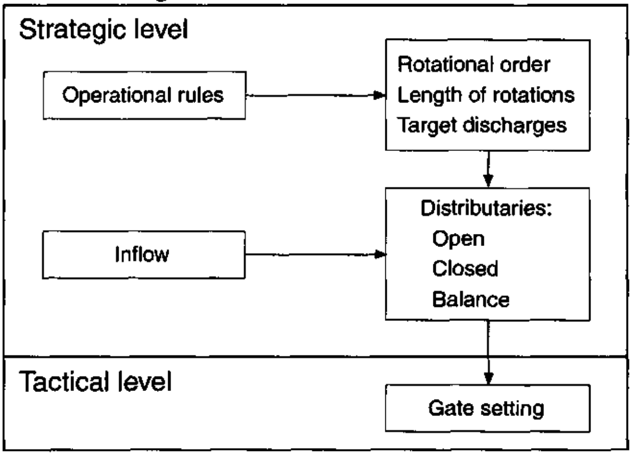

Figure 3.6: Decision steps in the operation of gated structures.

Strategic component

The priority order generated by the strategic component can be pre-defined in the input file of Gateman. In this file, it can be indicated which distributaries participate in the rotation. The duration of the rotation can also be varied. A verification of the logic and the robustness of the strategic component of Gateman, is undertaken in Section 3.3, by comparing the water deliveries predicted by the combined Gateman-SIC model with observed deliveries.

Tactical component

The *tactical* component is based on the approach developed by Malaterre (1989) to capture the logic of manual gate operations in an irrigation scheme in Sri Lanka. In continuation of this, a regulation module was developed by Litrico (1995) for the operation of cross-regulators in the study area. Basically, the module generates an action (open or close a gate) whenever the upstream water level H_u of a cross-regulator deviates more than 2 cm from a pre-defined Full Supply Level (FSL), as shown in Figure 3.7.

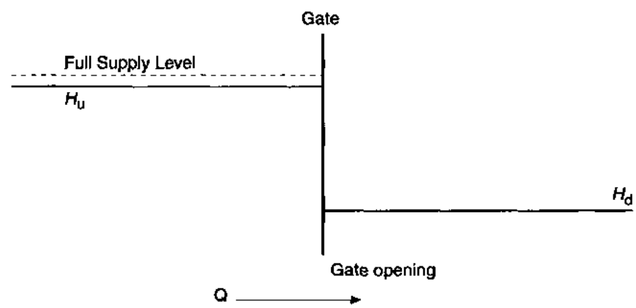

Figure 3.7: When the upstream water level, H_u, deviates from the full supply level (FSL), the gates of a structure will be manipulated in such a way that FSL is achieved.

This represents the decision-making process of a gate keeper whose responsibility it is to maintain a constant water level (generally FSL) upstream of a cross-regulator. The module also calculates the discharge using the SIC standard equations for the old, as well as the new, gate setting. Gateman uses SIC equations, which calculate the discharges through a gated structure as a function of the opening, the upstream water level and the downstream water level. If a gate keeper attempts to achieve FSL by operating a gate, the required gate opening can be determined as follows:

before operation:

$$Q = C_d \sqrt{2g}\, G_o\, w \sqrt{H_u - H_d} \tag{3.7}$$

after operation:

$$Q = C_d \sqrt{2g}\, G_o'\, w \sqrt{FSL - H_d} \tag{3.8}$$

with:	Q	= discharge through the gate	$[m^3\ s^{-1}]$
	G_o	= opening before operation	[m]
	G_o'	= opening after operation	[m]
	C_d	= discharge coefficient of the gate	[-]
	g	= gravitational acceleration	$[m^2\ s^{-1}]$
	w	= width of the gate	[m]

As Q and C_d are assumed constant, G_o' can be computed:

$$G_o' = G_o \sqrt{\frac{H_u - H_d}{FSL - H_d}} \tag{3.9}$$

Gateman was further developed for this study in order to include operations of distributary head regulators at the same location using identical parameters, i.e. H_u, H_d, Q, G_0, FSL, as for the cross-regulators. The operational preference for the cross-regulator or off-taking distributaries determines whether the gates of the former or of the latter structure are operated and also what the target water level will be. There are two pre-defined target water levels for each cross-regulator-cum-distributary head regulators, as explained in Section 3.1.

The required gate opening, G_0', that is calculated by the model in order to achieve the target discharge or water level, was compared with field observations of gate operators. Thus, the amplitude of gate operations predicted by Gateman was calibrated and validated by Litrico (1995). This was further checked during a field test conducted jointly with the irrigation manager, where a discharge fluctuation was generated at the head of the system. Observed gate operations matched very well those predicted by Gateman (Litrico et al., 1995), as shown in Figure 3.8.

In Figure 3.8, the gate opening ratios are presented, i.e. the predicted gate openings divided by the observed gate openings, for one of the cross-regulators of the Fordwah Branch. If the predictions are correct, the ratio should be equal to 1. The results show a very close match between predicted and observed values. The closing operations are performed with an average ratio of 0.99 and the opening operations with an average ratio of 1.08. During the monitoring period, an average of 4 operations a day were done, mostly to respond to fluctuations coming from upstream. The number of operations were also found to closely match those observed in the field.

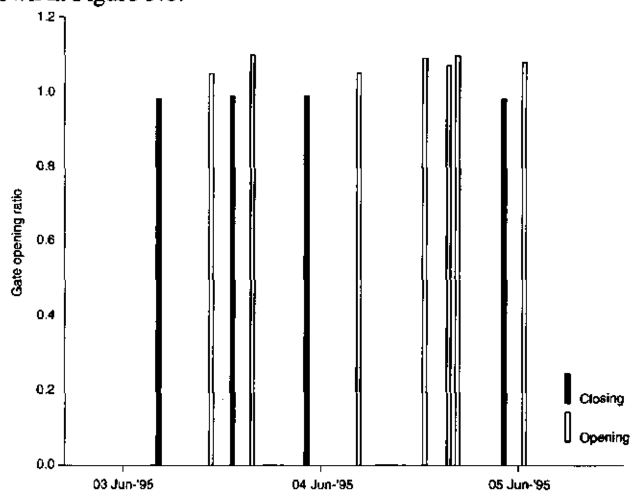

Figure 3.8: Gate opening ratios, predicted over observed, for the cross-regulator located at km 75 of the Fordwah Branch Canal.

One of the most important aspects of combining the regulation module and the hydraulic model is the selection of the time step for the operations (Gateman) as well as the numerical solution of the (varying) water surface profiles (SIC). The latter was defined above as 10 minutes. The time parameters for the gate operations, i.e. the time of an operation (T_{op}) and the time between operations (DT_{op}) have to be equal to, or larger than, the time step of SIC. Following a field calibration (Litrico, 1995), T_{op}, was determined at 10 minutes, while DT_{op} is 20 minutes for the cross-regulators at km 75 and 86, 30 minutes for those at km 96 and 108, and 1 hour for the tail regulator, i.e. Azim Distributary. The augmentation of DT_{op} follows the increased amplitude of the waves towards the tail. In order to stabilize the water levels, the gate keeper has to wait longer before implementing a second gate operation.

3.2.4 Water distribution indicators

In order to evaluate the simulations carried out with SIC, or with the combined SIC-Gateman model, certain criteria need to be defined with which the outcome of the simulations can be rated. These criteria will have to be related to the objectives of the irrigation system. IIMI's work on irrigation performance assessment has yielded a valuable list of indicators that are used to assess whether targets have been met. These indicators relate both to output indicators of the water delivery system and to indicators that assess the impact of water deliveries (Rao, 1993).

In Chapter 3, the interest is mainly in issues of operational performance, equity of water distribution and variability. Only in Chapter 5, a link will be made with the consequences of the canal water deliveries. The operational performance reflects how well the targets have been achieved, while the equity of water distribution relates to the system principles, as defined in Section 3.1.1. Variability relates to the quality of delivered discharges. At this stage, there is less interest in other performance themes mentioned in the literature, such as efficiency. Since the system is water short, all of the water that is delivered is assumed to be used by farmers.

An indicator that has been used by many authors to capture the operational performance is the *delivery performance ratio* (*DPR*), which is the ratio of delivered discharge over the target or intended discharge (Bos et al., 1991; Molden and Gates, 1992). This discharge generally does not represent the instantaneous discharge, but an average discharge for a given period of time, which is equal to a delivered or intended volume:

$$DPR = \frac{V_{act}}{V_i} \tag{3.10}$$

where:

V_{act}, V_i = actual delivered and intended volume, respectively [m^3]

Another indicator that has been defined for the Indus Basin context, in order to appreciate the operational performance, is a frequency distribution of the *DPR* (Habib and Kuper, 1996). The *DPR* is grouped into three classes, from 0 to 0.7, from 0.7 to 1.1 and greater than 1.1. This reflects the operational rule of the irrigation agency to supply a distributary always between 70 and 110% of the target discharge.

In the literature, several indicators have been proposed to express the equity in water distribution. Habib and Kuper (1996) found the *Modified Inter Quartile Ratio* (*MIQR*), which was proposed by Abernathy (1986), a suitable indicator. This presents the ratio between the average *DPR* for 25% of area with the highest water deliveries in a system and the average *DPR* for the area with the lowest 25%:

$$MIQR = \frac{\frac{1}{n}\sum DPR\ (Area_{highest25\%})}{\frac{1}{n}\sum DPR\ (Area_{lowest25\%})} \tag{3.11}$$

Another indicator that is often used to capture the equity in water distribution is the *spatial coefficient of variation*, cv_R, of the *DPR* represented by P'_E (Molden and Gates, 1992). For a given time T, the actual discharges of all offtakes *i, j* in a region R are evaluated with reference to the intended discharges:

$$P_E' = \frac{1}{T}\sum_{T}^{i,j} cv_R\ (DPR_{i,j}) \qquad (3.12)$$

where:

cv_R = the ratio of the standard deviation and the mean of a population [-]

An important difference in the application of these two equity indicators in this study is that the *MIQR* relates to the area that is supplied, whereas P_E' concerns irrigation canals, irrespective of their size.

The variability of supplies is probably best defined by Molden and Gates (1992), who define their dependability indicator P'_D for a region *R* as the *temporal coefficient of variation* (cv_T) of the *DPR*:

$$P_D' = \frac{1}{R}\sum_{R}^{i,j} cv_T\ (DPR_{i,j}) \qquad (3.13)$$

where:

cv_T = the ratio of the standard deviation and the mean of a population [-]

A summary of the proposed indicators, along with the performance standards, is presented in Table 3.5.

Table 3.5: Inventory of the performance indicators used in the study, and the performance standards of these indicators.

Indicators	Target	Performance standards		
		Good	Fair	Poor
DPR	1	0.90-1.10	0.70-0.89 1.11-1.30	<0.70 >1.30
MIQR	1	1.0-1.50	1.51-1.75	>1.75
P_E'	0	0-0.10	0.11-0.25	>0.25
P_D'	0	0-0.10	0.11-0.20	>0.20

The performance standards for these indicators are arbitrary, and depend on the nature of the irrigation system and the objectives of the study. In the literature, different authors do not agree on the exact limits of these indicators (Bos et al., 1991; Molden and Gates, 1992; Rao, 1993). The values of Table 3.5 are based on the values in the literature, but have been adapted by Kuper and Kijne (1992), and Habib and Kuper (1996) in the context of the Indus Basin irrigation system. These standards should be used only as indicative.

3.3 Improving operations at the main canal level

The aim of this section is to apply the methodology of Section 3.2 to the main canal in the study area, the Fordwah Branch, in order to verify its effectiveness in identifying irrigation management interventions to improve the canal water deliveries to secondary canals. The interventions focus on defining alternative operational rules, i.e. the implementation of a given set of rules for a given time period, governing the canal water distribution. The different steps of the methodology, defined in Table 3.3, will be followed. In Section 3.3.1, the existing operational rules are formalized in an operational scenario and simulated using the composite tool developed in Section 3.2. Simulated discharges can be thus compared with the observed values, thus allowing a verification of the existing operational rules. The study will use the data that have been collected from 16 October 1993 to 15 October 1994, i.e. during Rabi 1993/1994 and Kharif 1994. The actual simulated results will further serve as a reference for simulations of alternative operational scenarios. These scenarios will be investigated for kharif only, since in this season all distributaries receive water. In rabi, much less water is available and the effect of a redistribution of water is less interesting. In Section 3.3.2, the impact of the official operational rules on the water distribution will be analyzed. Then, in Section 3.3.3, the effect of operational scenarios that are undertaken in order to bring about an equitable water distribution, are evaluated. In Section 3.3.4, finally, the concept of redirecting water supplies to those areas that are confronted with salinity and sodicity is tested by changing the operational rules.

3.3.1 Analyzing the official and existing operational rules at the main canal level (Steps 3 and 4)

In order to identify the scope for changing the strategic operational rules, the existing rules are defined first, so that they can serve as a basis for management interventions. These rules relate mainly to the formulation of the rotation between secondary canals and the target discharges. Determining the existing rules is not easy, because the irrigation agency has adopted a set of rules that are not written down and deviate from the official rules. This deviation is caused by the fact that the official rules have been formulated in 1961 (PWD, 1961) and are mostly based on the Irrigation & Drainage Act of 1894. Since 1961, the cropping intensities have more than doubled, and the available supplies have also increased due to the construction of the Tarbela and Mangla reservoirs, and the link canals. The determination of the existing strategic operational rules will start with an inventory of the official rules, after which the existing rules will be obtained by comparing the actual water deliveries in the study area to secondary canals with what should have been delivered according to the official rules.

Official operational rules

The official operational rules of the irrigation agency can be obtained from the Manual of Irrigation Practice (PWD, 1961). Shafi (1994) and Siddiqi (1994) are also good references for understanding these rules. An inventory of the most important operational rules is presented in Table 3.6, along with the irrigation principles on which these rules are based.

Table 3.6: Inventory of strategic operational rules of the irrigation agency to ensure that target discharges are coherent with the system's objectives

Management activities	Official operational rules	Irrigation principle
Water allocation	Authorized discharges are based on *CCA* and irrigation duty	Equitability
Water scheduling	All distributaries involved in rotation in times of water shortage	Equitability
	Water supply to distributary secured for at least 8 days	Equitability
	Supply non-perennial canals occasionally in rabi	Water use efficiency
	Additional reclamation supplies are supplied to salt-affected areas in kharif	Environment
Water distribution	Discharge to a distributary varies between 70-110% of the authorized discharge	Sediment management Equitability (Safety)
	Tail of a distributary should be in running condition	Equitability

The information contained in Table 3.6 links the irrigation principles and water management activities of the irrigation agency, as defined in Section 3.1, with the official operational rules. These rules are a key to understanding the existing operational rules.

Existing water delivery performance

The performance of the existing water distribution in the study area was analyzed for Rabi 1993/1994 and Kharif 1994. A number of observations can be made. Firstly, the actual water distribution is not coherent with the system objective of equitably sharing the shortfall in irrigation supplies. This is shown in Table 3.7 for the secondary canals of the study area, using the indicators defined in Section 3.2: the delivery performance ratio (*DPR*), V_{act}/V_{auth}, and the spatial coefficient of variation (cv_R), the standard deviation divided by the average *DPR* for the canals considered.

Table 3.7: Water deliveries to distributaries in the Chishtian sub-division for Rabi 1993/1994 and Kharif 1994, expressed as a *delivery performance ratio* (*DPR*). The equity in water distribution is evaluated with the spatial *coefficient of variation*, cv_R; for rabi, only the perennial distributaries have been used to calculate this value (P stands for perennial).

Distributaries	*DPR* Rabi	*DPR* Kharif
Inflow study area	0.61	0.65
Major distributaries		
Daulat	0.03	0.72
Shahar Farid	0.04	0.71
Fordwah (P)	0.63	0.71
Azim	0.02	0.43
Other distributaries		
3-L	0.02	0.45
Mohar	0.01	0.53
Phogan	0.20	1.32
4-L	0.05	0.67
Khemgarh	0.02	0.67
Jagir (P)	0.38	0.61
Masood (P)	0.83	0.88
Soda	0.05	0.62
5-L (P)	0.78	1.58
Mehmud (P)	0.91	1.44
cv_R	0.26	0.44

The inflow is substantially below the target both in kharif as well as rabi with a *DPR* of less than 0.7. The shortage at the head of the system has an immediate effect on the supply to the 14 distributaries of the Chishtian sub-division, with 10 out of 14 distributaries registering a poor performance according to the standards defined in Section 3.2. However, this effect is not the same for all, as is shown in Table 3.7. Azim, for example, receives only 43% of its authorized supplies. This is also reflected by the relatively high values of the cv_R, which indicates a "poor" equitability both for kharif as well as rabi. In rabi, only the perennial distributaries (P) are entitled to water supply, which explains the low values of *DPR* for the non-perennial distributaries for this season.

The operational performance can be further analyzed by looking in more detail at the inflow and the water deliveries to the secondary canals.

The inflow is highly variable and generally lower than the combined indent of the distributaries, as shown in Figure 3.9. The authorized discharge is 36.3 $m^3 s^{-1}$ for kharif and only 12.8 $m^3 s^{-1}$ in rabi with an annual closure of 3 weeks for maintenance. Figure 3.9 depicts the actual and authorized discharge pattern based on daily stage measurements for Rabi 1993/1994 and Kharif 1994. On average, the discharge supplied in kharif is about 10 $m^3 s^{-1}$ less than the authorized discharge, while it is about 2-3 $m^3 s^{-1}$ less in rabi. *This implies that the SDO Chishtian has to implement a rotation within his sub-division during the entire irrigation year.* The low inflow is explained by a relatively high water intake of the upper sub-divisions, by a discharge at the head of the Fordwah Canal that is often lower than authorized to the benefit of Eastern Sadiqia Canal, and by an outdated PID rating table at the inflow point of the study area that overestimates the discharge (IIMI, 1995b; Habib and Kuper, 1996). In Figure 3.9, the updated rating curve was used to calculate the discharge. Figure 3.9 also highlights the variability of discharge, where the discharge can change several $m^3 s^1$ during a day. This is also evidenced when calculating the temporal *coefficient of variation*, cv_T, of the daily discharges. A cv_T of 0.4 was found for Kharif 1994 and 0.6 for Rabi 1993/1994 (Habib and Kuper, 1996).

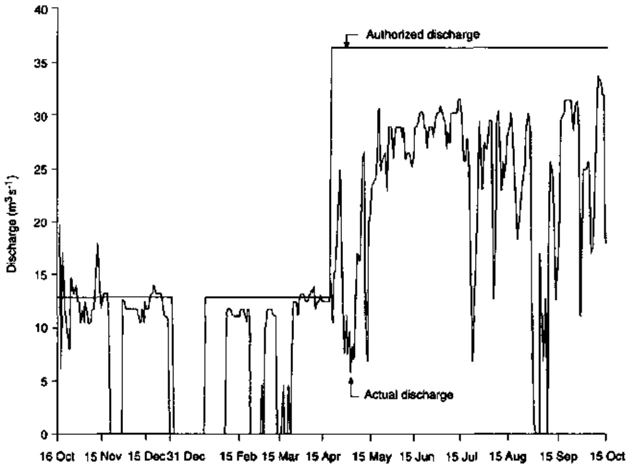

Figure 3.9: Authorized and actual discharges delivered to the Chishtian Sub-division in Rabi 1993/1994 and Kharif 1994.

The existing water deliveries to the secondary canals in the study area are characterized by an irregular delivery pattern. The difference between the authorized and the actual target discharges is illustrated in Figure 3.10 for the Fordwah Distributary during Kharif 1994.

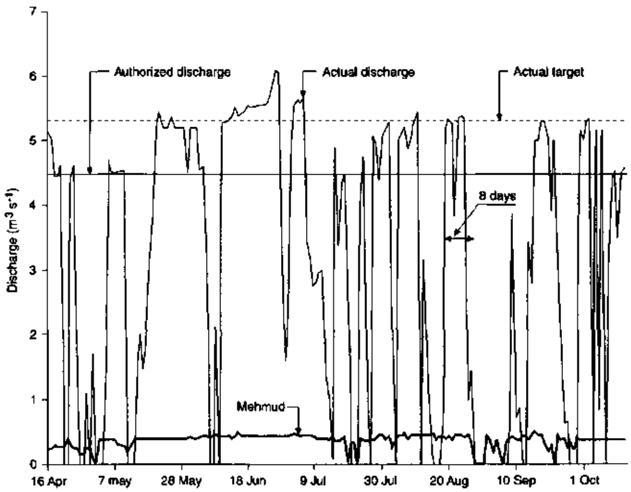

Figure 3.10: Comparison of actual discharge of the Fordwah Distributary of Kharif 1994 with the authorized discharge and the actual target discharge. The length of an 8-day supply period is indicated.

An actual target discharge can be determined, which is substantially higher than the authorized discharge.

Another observation that can be made from this figure concerns the rotations. Often the minimum duration of a supply period (8 days) to the Fordwah Distributary is not attained. At the same time, the rotations appear to follow one another too quickly. There is hardly ever a period where the distributary is closed for more than 2-3 days.

This contrasts with the observed supplies for some of the smaller distributaries, like Mehmud, which are hardly ever turned off, as shown in Figure 3.10. An almost constant supply can be observed for the entire season.

The actual target discharges of secondary canals in the study area are compared with the authorized values in Table 3.8.

Table 3.8: Comparison of actual and authorized target discharges of distributaries in the Chishtian sub-division for Kharif 1994.

Distributaries	Actual target ($m^3 s^{-1}$)	Authorized target ($m^3 s^{-1}$)	Difference (%)
Major distributaries			
Daulat	6.00	5.92	1.4
Shahar Farid	4.20	4.33	-3.0
Fordwah	5.30	4.47	18.6
Azim	5.00	6.91	-27.6
Other distributaries			
3-L	0.50	0.65	-23.1
Mohar	0.80	1.08	-25.9
Phogan	0.80	0.51	56.9
4-L	0.50	0.45	11.1
Khemgarh	0.64	0.85	-24.7
Jagir	0.85	0.79	7.6
Masood	1.12	0.99	13.1
Soda	2.20	2.18	0.9
5-L	0.25	0.11	127.3
Mehmud	0.42	0.25	68.0
Total	28.58	29.49	-3.1

Most distributaries have an increased target discharge, because of increased demand of tertiary units.

Shahar Farid and Azim Distributaries have 19 and 26 outlets, respectively, at the tail that never receive any water, which explains their decreased target discharge. Mohar and Khemgarh have been curtailed with their tail outlets drawing water directly from Fordwah Branch. Finally, 3-L is a high level channel and it is difficult to supply enough water to this distributary. The tail outlet now receives water directly from Fordwah Branch.

Existing operational rules: developing an intervention strategy

Discussions with and interviews of the operating staff of the irrigation agency confirmed a number of adaptations of the official rules. The *existing strategic operational rules* can thus be summarized as follows:

Water allocation:
- Change in target discharges of distributaries, as shown in Table 3.8;

Water delivery scheduling:
- Reduction in the closure time from 8 days to 4 days, as shown in Figure 3.10;
- Continued implementation of a rotation between the four major distributaries; the other distributaries are not involved in this rotation;
- A rotation between the Azim and Fordwah Distributaries;
- Non-perennial canals do not receive any supplies in rabi, as shown in Table 3.7; and
- Reclamation supplies have not been allotted since 3 years.

The main reason behind these changes in operational rules is the increased demand for water by farmers. Target discharges of distributaries have changed to cater for the changed targets of tertiary outlets. Closing a distributary for 8 days is difficult in the present context of unreliable water deliveries. As farmers are not sure about the implementation of the rotational plan, they put pressure on the irrigation agency as soon as their distributary is closed for more than 2-3 days. In the absence of a good communication network and the present uncertainties in inflow, the irrigation agency has resorted to a rotation between only the larger distributaries, thus simplifying the operations and minimizing the communication needs. Operation of the smaller distributaries is left *de facto* to the gate keepers, who operate these distributaries responding to farmers' needs. The rotation between the Azim and Fordwah Distributaries, located at the tail of the main canal, is related to the fact that there is no escape, as mentioned in Section 3.1.4. The irrigation agency minimizes the risk of breaches in the absence of a good communication system by supplying less water to the tail of the main canal.

The main differences between the official and existing operational rules pertain, therefore, mainly to the *target discharges of distributaries, the preference order for the different distributaries, and the delivery period.* In a sense, this represents the management interventions that have been adopted *de facto* by the irrigation agency. In this study, the same set of interventions will be considered for the definition of alternative operational rules in order to achieve the desired water distribution.

Representativeness

Finally, the representativeness of the studied seasons should be evaluated. The studies of Kuper and Kijne (1992) and Rivière (1993) in the same area for Kharif 1992 and Kharif 1993, show that the inflow pattern of Kharif 1994 is very similar. The actual rules that were identified, like the rotation between the four main distributaries, seem also valid. Occasional differences occur. In Kharif 1994, the operational preference for Shahar Farid had increased as compared to the previous years for socio-political reasons. Also, the non-perennial distributaries were given a little more water during rabi in previous years. In fact, an order was issued in 1993 by the super-intending engineer in the area that no water must be allowed for the non-perennial distributaries in rabi.

The existing strategic operational rules were identified for the study area through a comparison of the actual canal water deliveries, with what should have been supplied, based on the official operational rules.

3.3.2 Simulating the existing operational rules (Step 5)

The existing operational rules that were identified in Section 3.3.1 were formalized in an operational scenario, *M*0, for Kharif 1994 and programmed in Gateman. By running the module and SIC simultaneously, the seasonal deliveries to the different distributaries could be compared with the actual measured data of Kharif 1994. This was an iterative process. The initial results of the simulations showed a predicted water distribution that on average resembled reality in terms of volume. However, the average absolute error was more than 20%, and there appeared to be a need for further refinement of the operational rules. The final input data of scenario *M*0 are summarized in Box 1.

Box 1: Definition of Scenario *M*0

- There is a rotation cycle of 16 days in which the four major distributaries participate, as shown in Table 3.9. The length of an individual turn is 4 days. A preference order is adopted, whereby a distributary in fourth preference will be closed first in case of a water shortage, and so forth. A rotation was adopted that on average gives preference to the Daulat and Shahar Farid Distributaries as compared to the Fordwah and Azim Distributaries, following the analysis of the existing water delivery patterns, see Table 3.7.

Table 3.9: Inputs Scenario *M*0: rotations and target discharges for Daulat, Shahar Farid, Fordwah and Azim Distributaries for Kharif 1994

Distributaries	Day 1-4	Day 5-8	Day 9-12	Day 13-16	Target discharge ($m^3 s^{-1}$)
Daulat	4	2	1	1	6.0
Shahar Farid	1	1	4	2	4.2
Fordwah	2	3	3	4	5.3
Azim	3	4	2	3	5.0

- The Azim Distributary is assumed to be the tail of the system, which is coherent with the field observations showing that Azim often receives water, but usually far below the official target (Tareen et al., 1996; Hafiz Ullah, 1994).
- The ten smaller distributaries do not take part in the rotation.
- The target discharges for all distributaries were obtained from Table 3.8. However, the target discharge of some of the smaller distributaries was adjusted downwards for April to June. The water requirement of these distributaries is lower in these months because of the prominence of rice, which is generally transplanted only in July. This pertains especially to the Mohar, Jagir and Masood Distributaries. Adjusting the target discharge is relatively straightforward, both in the field as well as in the model, since these distributaries are gated. For other (ungated) distributaries, such as 3-L, 4-L and 5-L, this is more complicated since their discharge depends solely on the upstream water level. In the field, gate keepers sometimes put planks in the intake of these distributaries to reduce the discharge. Nothing was changed, however, in the model.
- From a hydraulic point of view the inflow pattern, based on a daily adjustment, was unsatisfactory. Abrupt changes of discharges (up to 11 $m^3 s^{-1}$) resulted in brusque interventions of the regulation module in the gate operations. The daily measured discharges were interpolated on an hourly basis and an extra sub-routine was added in the regulation module in order to read this hourly inflow pattern. This served an additional purpose, as the input restrictions of SIC were circumvented. Changes in inflow is normally restricted to 20, while with this new method up to 1700 changes were possible.

Results of the simulations: comparison of simulated and observed water deliveries to secondary canals

The simulation results of Scenario *M*0 are compared with the measured seasonal deliveries in Figure 3.11, which shows that the predicted deliveries of the composite SIC-Gateman model match quite well the field observations.

The absolute average error for the seasonal deliveries is just 5%. Perhaps more importantly, the average error for the major distributaries, accounting for more than two thirds of the supplies, is less than 4%. Only in the case of the Phogan Distributary, a small ungated channel that is not attended by a gate operator, the difference exceeds 15%. An error in the crest level cannot be excluded in this case, as farmers have tampered with this intake at various occasions. The main reason for the relative good match between predicted and observed water deliveries is the fact that the priority order as well as the target discharges are fairly close to reality.

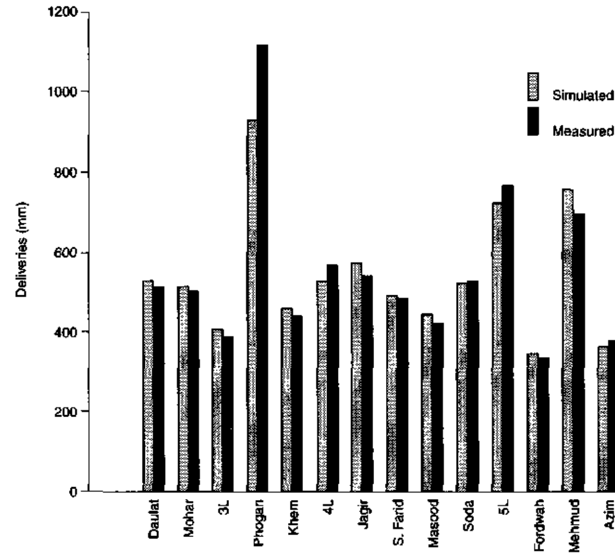

Figure 3.11: A comparison of the seasonal deliveries predicted by the model (*Scenario M*0) with the actually observed deliveries, expressed in terms of a depth (mm) for the command areas for all distributaries in the Chishtian sub-division.

The reasons for a difference between measured and simulated values are manifold:

- the punctual measurement (once a day) versus a simulation with a time step of 10 minutes;
- the inflow was measured once a day and interpolated for the hourly values, which may deviate from field patterns;
- errors in levels and dimensions of structures; and
- errors in discharge estimation; the equation used in SIC to convert water levels into discharges differ from the classical formulas (Cemagref, 1992); also, the estimation of the *coefficient of discharge*, C_d, is generally assumed to be in the range of 5-10%, depending on the accuracy of discharge observations (Corbett, 1962);

A comparison in volume does not say much about the quality of delivered discharge, such as the discharge level, the temporal variation in delivered discharge, and timing of deliveries. For this analysis the following four indicators will be used:

- a frequency distribution of the delivered discharge, with the limits of the desired discharge between 70 and 110% of the target discharge;

- the temporal coefficient of variation (cv_T) of the delivered discharge to represent the discharge variability;
- a correlation of the simulated and measured values through a linear regression; and
- a qualitative, visual comparison of the hydrographs.

The frequency distribution is based on three classes, daily discharges lower than 70%, 70-110% and higher than 110%. As discussed in Section 3.1, there is no possibility to control the water distribution beyond the distributary head regulator, and an equitable water distribution is only possible when the discharge is higher than 70% of the authorized discharge. The limit of 110% represents a safety criterion. The results are presented in Figure 3.12.

Particularly for Fordwah and Azim the simulated values match very well the measured values. In the case of Daulat and Shahar Farid, the distribution is somewhat more skewed (more days of supply between 70 and 110%), because of the logic of the model which attempts either to deliver the targeted discharge to a distributary or is closed. In reality, gate keepers sometimes increase the discharge in case of great demand, while they release less in periods of slack demand. This could be addressed by including an additional rule in the regulation module taking the demand of farmers into account.

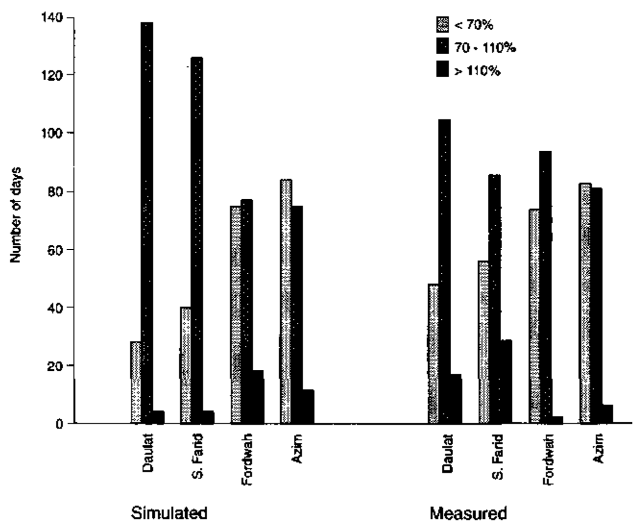

Figure 3.12: Frequency distribution of daily simulated and actually measured discharges to Daulat, Shahar Farid, Fordwah and Azim Distributaries. The classes are < 70%, 70-110% and > 110%.

The values of cv_T as a ratio of the standard deviation σ^2 and the mean μ, documented in Table 3.10, also demonstrate the extent to which the actual hydrographs have been reproduced.

Table 3.10: Comparison of the simulated and measured daily delivered discharges at the head of the Daulat, Shahar Farid, Fordwah and Azim Distributaries for Kharif 1994 through the temporal coefficient of variation (cv_T), standard deviation (σ^2) and mean (μ).

Distributaries	Simulated			Measured		
	σ^2	μ	cv_T	σ^2	μ	cv_T
Daulat	2.16	4.44	0.49	2.30	4.29	0.54
Shahar Farid	1.74	3.14	0.55	1.82	3.11	0.59
Fordwah	2.41	3.21	0.75	2.20	3.17	0.69
Azim	1.73	2.90	0.60	2.15	2.96	0.73

The temporal variability in discharges is fairly accurately predicted as shown by the values of σ^2 and cv_T. The fact that μ is well predicted was shown already in Figure 3.11.

A linear regression was carried out on the simulated and measured values. This was done after ranking these values in two columns. Thus, the exact day on which these discharges occurred is not accounted for in the analysis. A good correlation was found for all four major distributaries with R^2 values ranging from 0.86 to 0.97. For Daulat and Shahar Farid, the curves are quite similar. The lower values measured in the field are not reproduced by the model, which tends to deliver either the target discharge or close the distributary. In reality, the gate operators occasionally deliver smaller discharges in times of a slack water demand. An example of the correlation is presented for the Fordwah Distributary in Figure 3.13.

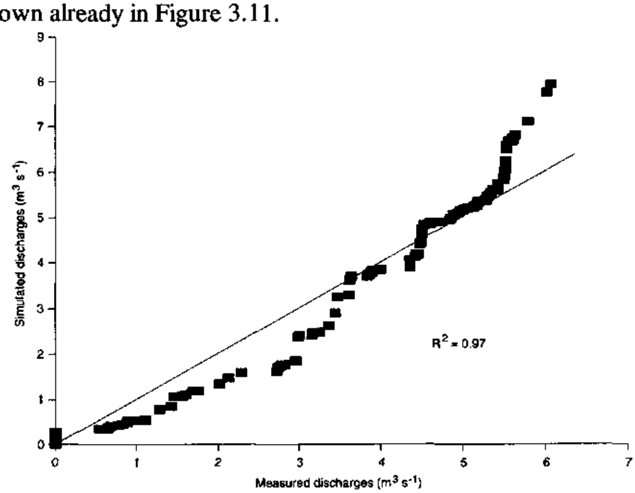

Figure 3.13: Linear regression of the simulated daily discharges of *Scenario M0* and measured daily discharges of the Fordwah Distributary for Kharif 1994.

Finally, the shape of the simulated hydrographs is compared with the measured values. A more quantitative approach is generally used in the field of electronics and digital signal processing, which gives information about the frequency and amplitude of the sum of sinusoids that make up a signal (see for instance Strum and Kirk, 1989). An example is given in Figure 3.14 for Shahar Farid Distributary. The figure shows that the measured and simulated target discharges correspond reasonably well and that the shape of the simulated curves is quite representative of what has been measured in the field. It should be noted that these results have been achieved with *average operational rules* without taking the punctual interventions that occur into account. A limitation of the results produced by the model is the fact that in case of a sudden excessive discharge at the tail when either Azim or Fordwah is closed, the excess discharge is absorbed by the distributary that is open and not passed on to the neighbouring distributary, which would happen in the field. This situation occurred very rarely during the simulations. An additional sub-routine in the regulation module would be necessary to address this situation.

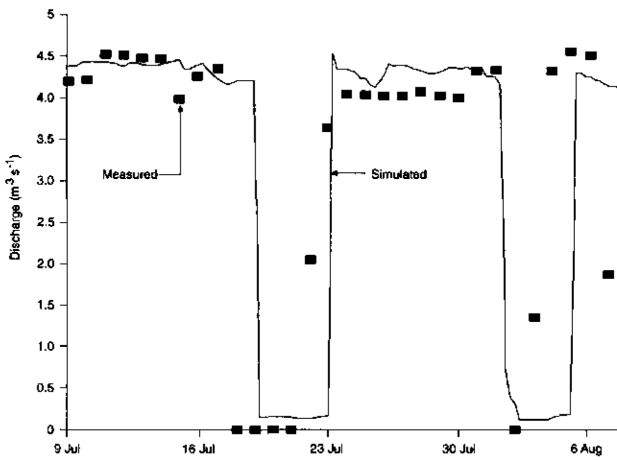

Figure 3.14: Hydrograph of the simulated discharges of *Scenario M0* and actually measured daily discharges delivered to the Shahar Farid Distributary during Kharif 1994.

The existing strategic operational rules at the main canal level have been formalized for the study area and their effect on the water distribution quantified by applying the combined Gateman-SIC model. The application of the model helped to further specify the operational rules by comparing predicted and measured water deliveries. The predicted and measured discharges match well, both in terms of total deliveries as well as the temporal pattern of the deliveries. This means that the existing operational rules have been successfully determined and their impact on the water distribution correctly quantified by combining the physical model SIC and the decision-making model Gateman. The results can be used as a reference for the different operational scenarios that will be tested in Sections 3.3.3, 3.3.4 and 3.3.5.

3.3.3 Simulating the impact of the official operational rules on the water distribution (Steps 6, 7, 8)

Based on the official operational rules, a rotational plan has been defined by the irrigation agency for the Chishtian sub-division:

Box 2: Official rotational plan for the study area

- An 8-day rotation exists between the Chishtian Sub-division and the more upstream located Bahawalnagar Sub-division; when Chishtian is in first preference, all its distributaries should run at their target discharge; and when it is in second preference, an internal rotation is implemented;
- Distributaries in the Chishtian Sub-division are divided into 3 groups, all of which get an order of preference during the period that Chishtian is in second preference (see Table 3.11);
- When there is not enough water to satisfy the target discharges of all distributaries, those distributaries in third preference will be closed in a pre-fixed order, i.e. from right to left in the order they are listed in the caption of Table 3.11; and
- The target discharges are equal to the official discharges unless an indent discharge different from those discharges is formulated.

Table 3.11: Example of the internal *official* rotation for the Chishtian Sub-division:
Group A: Daulat, Mohar, 3-L, Phogan, Khemgarh, 4-L
Group B: Jagir, Masood, Shahar Farid, Soda
Group C: Fordwah, Azim, Mehmud, 5-L

Preference order Chishtian	Preference order Group A	Preference order Group B	Preference order Group C
1	-	-	-
2	1	2	3
1	-	-	-
2	3	1	2
1	-	-	-
2	2	3	1

A close look at those rules reveals that it is impossible to implement them. Firstly, even during times of first preference, the inflow of Chishtian Sub-division is highly variable and is generally much below 33.1 $m^3 s^{-1}$, a limit below which a rotation is necessary. This amount comprises the sum of the actual target discharges of distributaries equal to 28.6 $m^3 s^{-1}$, a seepage of 3.2 $m^3 s^{-1}$ and a delivery of 1.35 $m^3 s^{-1}$ to the direct outlets of Fordwah Branch.

Secondly, a rotation involving all distributaries is impractical given the large fluctuations of discharge at the inflow point. A discharge variation of 3 m^3/s during a day, which is not uncommon, that needs to be absorbed by distributaries with discharges lower than 1 m^3/s would lead to a great number of operations and further discharge fluctuations. This is illustrated in Figure 3.15, where the results of a simulation with a rotation involving all distributaries for a typical small distributary is shown. In times of second preference, the distributary is opened and closed several times during a day. Also, this would increase the stress on the communication network between operators and the irrigation manager if the instructions for several distributaries change during the day.

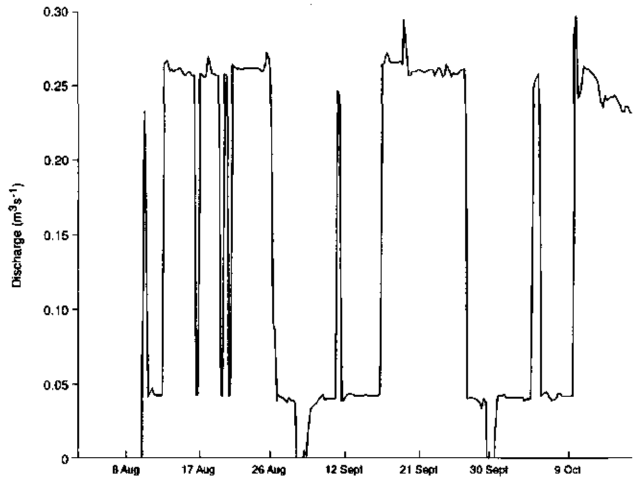

Figure 3.15: Simulated discharges for the Mehmud Distributary if the *official* rotation would be implemented.

Thirdly, it is physically very difficult to involve the ungated distributaries (3-L, Phogan, 4-L, Soda, 5-L) with a total off-taking discharge of 4.3 $m^3\ s^{-1}$ in a rotation, even though some regulation is possible through wooden stop logs and bushes. Removal and insertion of these accessories is, however, time consuming and cumbersome.

The official operational rules can only be implemented after modification. In their present form, they do not acknowledge the system reality of fluctuating inflows, while the implementation of a rotation with all distributaries is impractical in the absence of a good communication system.

3.3.4 Identifying the scope for an equitable water distribution by changing the operational rules (Steps 6, 7, 8)

Definition of scenarios

In this section, three alternative operational scenarios will be tested for their effectiveness in restoring an equitable water distribution in the Chishtian Sub-division. Since one of the irrigation principles is an equitable distribution, the official operational rules will be taken as a starting point for these scenarios. However, a number of modifications in these rules are necessary, as was shown above. In the formulation of alternative scenarios, an 8-day internal rotation is continued even when Chishtian is in first preference. The inputs for Scenario *M*1, *M*2 and *M*3 are summarized in Table 3.12. The input data of the reference scenario *M*0, which represents the actual situation, is also recapitulated.

Table 3.12: Input data for Scenarios *M*1, *M*2 and *M*3, with an aim to restore an equitable water distribution. The actual and official target discharges of the different distributaries are listed in Table 3.8.

Scenarios	Rotation period (days)	Participation in rotation	Target discharge
*M*0 (reference)	4	4 major distributaries	Actual target
*M*1	8	4 major distributaries	Actual target
*M*2	8	4 major distributaries and 5 small gated distributaries	Actual target
*M*3	8	4 major distributaries and 5 small gated distributaries	Official target

Scenario *M*1 is the closest to the actual situation (reference scenario). The rotation period is changed from four to eight days, in order to guarantee the supply to all farmers of a warabandi cycle. Also, the rotational plan is made more fair, as shown in Table 3.13. In case of Scenarios *M*2 and *M*3, the four major distributaries are involved in the rotation, while the small gated distributaries are open or closed following the major distributary close to which they are located, see Table 3.13. In fact, these smaller distributaries are within the same canal section, defined by the irrigation agency, and are sometimes operated by the same gate keepers of the large distributary nearby. In case of Scenario *M*3, the target discharges are reverted back to the official values, see Table 3.8. The deliveries to other distributaries, which are ungated, cannot be controlled and are depending on the water levels in Fordwah Branch.

The rotational plans for Scenarios *M*1, *M*2 and *M*3 are further specified in Table 3.13.

Table 3.13: Proposed rotation of the four major and other gated distributaries for Scenarios *M*1, *M*2 and *M*3. In Scenario *M*1, only the four major distributaries are involved, while in Scenarios *M*2 and *M*3 the other five smaller distributaries also participate.

	Day 1-8	Day 9-16	Day 17-24	Day 25-32
Daulat	1	4	3	2
Mohar	Open	Closed	Open	Open
Khemgarh	Open	Closed	Open	Open
Shahar Farid	2	1	4	3
Jagir	Open	Open	Closed	Open
Masood	Open	Open	Closed	Open
Fordwah	4	3	2	1
Mehmud	Closed	Open	Open	Open
Azim	3	2	1	4

Simulation results

The delivered quantities are summarized in Table 3.14 by calculating the delivery performance ratio, V_{act}/V_{auth}. The DPR_i (for all distributaries) has been calculated with reference to the official targets, thus allowing a comparison of the effectiveness of Scenarios *M*1, *M*2 and *M*3 to bring about equitability by changing the actual operational rules. The DPR_i was then divided by the *DPR* of the inflow, 0.65, since the objective is to share the shortfall in inflow equitably between the different distributaries.

Table 3.14: Simulated water deliveries to distributaries of the Chishtian Sub-division. A comparison of the application of actual operational rules (*Scenario M*0) and alternative operational rules (*Scenarios M*1, *M*2 *and M*3) for Kharif 1994 by means of the delivery performance ratio (*DPR*).

Distributaries	Scenario *M*0 *DPR*	Scenario *M*1 *DPR*	Scenario *M*2 *DPR*	Scenario *M*3 *DPR*
Inflow	0.65	0.65	0.65	0.65
Major distributaries				
Daulat	1.15	0.88	1.13	0.85
Shahar Farid	1.12	0.96	1.05	0.92
Fordwah	1.11	1.14	1.12	1.11
Azim	0.63	0.85	0.82	1.03
Other distributaries				
3-L	0.73	0.84	0.78	0.83
Mohar	0.84	0.83	0.63	1.09
Phogan	1.59	1.77	1.62	1.80
4-L	0.95	1.07	0.99	1.08
Khemgarh	1.08	1.07	0.82	1.09
Jagir	1.35	1.38	1.01	1.02
Masood	1.42	1.48	1.08	1.02
Soda	0.96	1.11	1.07	1.19
5-L	2.30	2.79	2.68	3.03
Mehmud	2.40	2.39	1.78	1.06

If the *DPR* is 1, a distributary has received 65% of the authorized allowance. Regarding the impact of the alternative rules on the water deliveries, a number of observations can be made:

- The inclusion of the small gated distributaries in the rotation, and the implementation of a fair rotational plan, leads to an augmentation in the *DPR* of the Azim Distributary from 0.63 to 0.85, which is an increase of almost 30%. A restoration of the official target discharges further improves the situation leading to a combined improvement of 63% and a *DPR* of 1.03;

- The excessive quantities delivered to small gated distributaries can easily be curtailed, by including, for instance, Mehmud in the rotation; in this case, the delivered volume is reduced by 25%, which is reduced by another 30% if the target discharge is reverted back to the official value;
- The excessive quantities delivered to ungated distributaries (5-L, Phogan) cannot be regulated by changing the operational rules, since water deliveries to these distributaries are directly dependent on the water levels in the main canal, see Figure 3.16; a physical intervention, such as a reduction in offtake dimensions or providing gates, would be required to change this; and
- Including the small gated distributaries in a rotation (Scenario *M*2) has a dramatic impact on the water delivery to these distributaries (e.g. Jagir, Masood, Mehmud).
- The operational performance improves drastically as a results of the interventions. While in Scenario *M*0 there are only three distributaries with a good and five distributaries with a fair performance, this has changed for Scenario *M*3 to eight distributaries with a good performance and four with a fair performance.

The equitability of distribution can be evaluated through two indicators that were defined earlier: the modified inter-quartile ratio (*MIQR*) and the coefficient of variation (cv_R) of delivered quantities. The difference between these indicators is that the *MIQR* is a weighted indicator, taking the command area of canals into account. In the case of cv_R, every canal is considered as an equal unit, whether 5-L Distributary with 360 ha is concerned or the Fordwah Distributary with 14,840 ha. The results are presented in Table 3.15.

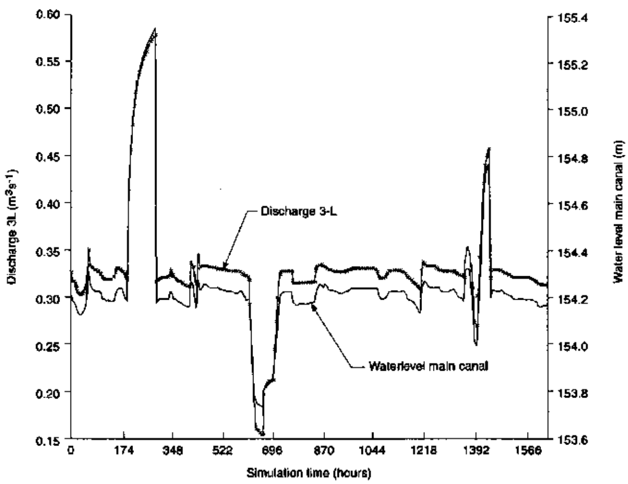

Figure 3.16: Simulated water deliveries to 3-L Distributary and simulated water levels at the main canal level for *Scenario M*0.

Table 3.15: Assessment of the equitability of the seasonal water deliveries for the simulated results of Scenarios *M*0, *M*1, *M*2 and *M*3. The assessment is done through two indicators, i.e. the spatial coefficient of variation (cv_R) and the modified inter quartile ratio (*MIQR*).

Indicator	Scenario *M*0	Scenario *M*1	Scenario *M*2	Scenario *M*3
cv_R	0.41	0.44	0.43	0.45
MIQR	1.93	1.60	1.53	1.41

The *MIQR* values clearly indicate that the equitability improves with the changes brought about by Scenarios *M*1, *M*2 and *M*3. In case of the reference scenario (*M*0), the fortunate quarter of the cultivated land receives almost double the amount of the opposite quarter, while this is less than one-and-a-half times the amount in Scenario *M*3. According to the criteria defined in Section 3.2, the equitability improves from poor for the reference scenario, to fair for Scenarios *M*1 and *M*2, and good for Scenario *M*3.

The cv_R values, on the other hand, remain at the same level and even show a slight increase for Scenarios *M*1, *M*2 and *M*3, which signifies an increased inequitability. This can be attributed to higher deliveries to the small, ungated distributaries, especially Phogan and 5-L, which command together only 1250 ha. This is also evidenced by the fact that the cv_R for the major distributaries, as well as for the small gated distributaries, show reductions in cv_R (from 0.21 to 0.10 and from 0.38 to 0.03, respectively).

Another observation that can be made from the results of Table 3.15, is that addressing the issue of inequitability cannot be achieved by either a change in the rotational plan or in target discharges alone. Both need to be changed in order to make a meaningful impact. The assessment of the trade-off of the efforts of necessary adjustments and the impact on the water deliveries, can be made by the user of the approach.

Reverting the length of the rotation time back to the official rules has a big impact on the average period of constant water delivery to distributaries, defined as the time period during which the discharge does not go below 70%. This has been detailed as an example for Scenarios *M*0 and *M*3 in Table 3.16. While the average constant delivery period for Daulat is markedly reduced and brought in line with the other major distributaries, these periods increase substantially in time for the Azim Distributary. The Shahar Farid and Fordwah Distributaries are much less affected by the length of the rotation time in this scenario.

Table 3.16: Simulated delivery pattern to four major distributaries in the Chishtian Sub-division, comparison between the effect of actual and alternative rules.

Distributaries	Scenario *M*0 Actual rules		Scenario *M*3 Alternative rules	
	Length delivery period	Number of periods	Length delivery period	Number of periods
Daulat	15.8	9	9.1	11
Shahar Farid	9.4	14	9.0	12
Fordwah	5.3	18	6.5	15
Azim	3.5	26	9.9	13

It was shown that the equitability of water distribution can be considerably improved by changing the operational rules, especially by modifying the target discharges and involving the small, gated distributaries in the rotation. In addition, the quality of deliveries is markedly improved by supplying distributaries for longer periods, of at least 8 days. However, there is a trade-off between the amount *of effort invested and the equitability that can be achieved. This is an issue the users of the approach have to consider.*

3.3.5 Identifying the scope for redirecting canal water supplies to areas with salinity or sodicity problems (Steps 6, 7, 8)

Definition of the scenario

Redirecting canal water supplies for salinity control has been a common practice in the past, through the installation of so-called reclamation shoots. These are pipes that function only for 3-4 months during kharif. In order not to disrupt the functioning of a distributary where these pipes are installed, the discharge should be increased to account for the extra water allocation. An increase in target discharge of say 10-15% can be relatively easily effected for the gated distributaries, as indicated by the discharge measurements. For ungated distributaries this is more complicated, as this would involve either structural adjustments or increases in the full supply level upstream of these distributaries.

A redistribution of water for the gated distributaries can be achieved by changing the length of the delivery period or by changing the target discharge. Since the latter is traditionally adopted by PID, a scenario was defined with interventions in the target discharges. The advantage of this scenario is that changes in delivered quantities can be more easily accomplished for individual distributaries. A global redefinition of operational rules would affect other distributaries, thus complicating the redistribution. However, one could define and simulate equally well a change in the operational rules, e.g. the length of rotation or the rotation order.

The model of the actual situation, i.e. Scenario *M*0, is taken as the basis of *Scenario M*4. The operational rules (rotation order, 4 days rotation cycle) remain unchanged. Extra water is directed to the Fordwah Distributary for salinity control. This is done by increasing the target discharge by 0.3 to 5.6 $m^3 s^{-1}$, which means an increase of a little over 5% of the actual target discharge. This is partly compensated for by decreasing the target discharge of Masood Distributary by 0.17 $m^3 s^{-1}$, which is a reduction of 15%.

Simulation results

The results of the simulations for Scenario *M*4 are presented in Table 3.17.

Table 3.17: Comparison of the effect of *actual* operational rules, *Scenario M0*, and *salinity targeted* operational rules, *Scenario M4*, on simulated water deliveries.

Distributaries	Scenario *M*0 Volume (10^6 m^3)	Scenario *M*4 Difference (%)
Major distributaries		
Daulat	70.1	+ 0.1
Shahar Farid	49.6	- 0.6
Fordwah	51.1	**+ 6.4**
Azim	45.0	- 2.5
Other distributaries		
3-L	4.8	- 0.3
Mohar	9.3	- 0.4
Phogan	8.3	- 0.1
4-L	4.4	- 0.1
Khemgarh	9.4	- 0.3
Jagir	11.0	- 0.3
Masood	14.5	**-12.6**
Soda	21.5	+ 1.4
5-L	2.6	+ 2.5
Mehmud	6.2	- 0.3

The interventions have had the desired effect on the water distribution in the sense that an increase of about 6% is achieved for Fordwah Distributary, while Masood gets 12.5% less. At the same time, the deliveries to other distributaries are only slightly affected, mainly around the targeted distributaries. Since the targeted reduction to Masood is smaller than the targeted increase to Fordwah, a certain quantity is taken from Azim Distributary. This reflects the locational disadvantage of Azim, which generally absorbs shortages as a result of overtapping of upstream distributaries. Since the quality of distribution in terms of duration or rate of delivery was not an objective of this scenario, no further indicators are calculated.

The methodology of Section 3.2 was successfully applied to the main canal operations in the study area. This methodology permitted to (1) identify the existing operational rules and carry out a more thorough diagnosis of existing water deliveries, and (2) to assess the impact of management interventions on the water distribution. It was shown that it is possible to restore an equitable water distribution between secondary canals without modifications in the infrastructure. An exception to this are the small ungated distributaries. It is also possible to redirect water to specific distributaries for salinity control without much disturbing the deliveries to other distributaries.

3.4 Improving the water distribution at the secondary canal level

The aim of this section is to apply the methodology of Section 3.2 to the secondary canal or distributary level to verify its effectiveness in identifying appropriate management interventions in the infrastructure to obtain a desired water distribution. This is done following the different steps defined in Table 3.4. The hydraulic model that is used for the analysis has been described already in Section 3.2.2 (Step 1). The functioning of the present and the desired water distribution at the distributary level is analyzed in Section 3.4.1, in order to understand the hydraulic behaviour of the channels and to identify possible interventions (Step 3). Then, a sensitivity analysis is carried out in Sections 3.4.2 and 3.4.3 to determine the marginal impact of interventions on the water distribution, in order to select those interventions with the best potential for achieving improvements (Step 4a and 4b). The existing water distribution is simulated in Section 3.4.4 in order to verify whether the simulated match the observed deliveries (Step 5). Finally, a number of operational scenarios are tested in Section 3.4.4, using the tool developed in Section 3.2, in order to assess the impact of management interventions on the seasonal water deliveries to tertiary units (Steps 6, 7 and 8). This is done on a seasonal basis, because this will provide insights into the total quantity of canal water that is delivered to the tertiary units, which is important for salinity control.

3.4.1 Analyzing the official and existing water delivery patterns: principles of water distribution (Step 3)

In this section, the two most important principles of water distribution at the distributary level, equitability and proportionality, are described.

Equitability

Distributary canals in the Indus Basin supply water to minor canals and to tertiary units through offtakes with fixed dimensions. No gates are present to control the off-taking discharge. A distributary should, therefore, be designed and maintained in such a way that "*at each point it will just carry as its full supply a discharge sufficient to supply all the outlets below that point, so that when the proper quantity enters the head* [of the distributary] *all the watercourses should just run their calculated allowances with no surplus at the tail*". This was stated by R.G. Kennedy, one of the most famous British design engineers, in the beginning of the century (Kennedy, 1906). This statement has a few very important implications:

- The inflow of a distributary should be kept constant at the authorized discharge;
- A distributary is functioning "properly" when all offtaking outlets take the authorized discharges, which refers to the earlier defined principle of *equitability*; and
- When the head discharge is equal to the authorized discharge, the tail outflow should also be equal to the authorized discharge; any deviation, whether positive or negative, means that there is an anomaly in the water distribution, which can be verified by measuring all offtaking discharges.

It was shown in Section 3.3.1, that the actual target discharges of distributaries are different from the authorized discharges. Also, the tail discharges of distributaries in the Chishtian Sub-division deviate substantially from the authorized outflows. Two distributaries in the Chishtian Sub-division, Shahar Farid and Azim, do not receive any water at all at their tails, while the tails of other distributaries receive water only part of the time (Tareen et al., 1996; Habib and Kuper, 1996). Both observations indicate that, contrary to the design concepts, there exists an inequitable water distribution at the distributary level.

This was further corroborated in a large measurement campaign that was undertaken in the Chishtian Sub-division (Tareen et al., 1996). Water deliveries to the tertiary units of all distributaries were measured, while a constant supply was ensured at the head of the distributary. On the basis of these measurements, the equity in water distribution was determined for all 14 distributaries, using the spatial coefficient of variation, cv_R, of the actual discharge of outlets divided by the authorized discharge, Q_{act}/Q_{auth}. When all outlets draw their authorized discharge, i.e. Q_{act}/Q_{auth} for all outlets is equal, the cv_R value for a distributary will be 0. Fairly high values of cv_R were found, which is mainly due to two reasons. Firstly, the actual dimensions of the outlets deviate from the official dimensions. Tareen et al. (1996) showed that 40% of the outlets in the Chishtian Sub-division were either oversized or broken. Secondly, the canal cross-sections of these distributaries are different from the design situation due to siltation/scouring, thereby inducing water levels different from the design water levels, resulting in outlets either overdrawing or not drawing enough discharge.

The cv_R values of the 14 distributaries are presented in Figure 3.17 as a function of the number of outlets in these distributaries. The figure shows that with an increase in the number of outlets the inequitability increases as well. A higher number of outlets means that there are more chances to find outlets with anomalies in offtaking discharge. The relatively low value of cv_R for the Fordwah Distributary is remarkable, as it concerns the longest distributary with the highest number of outlets of the Chishtian Sub-division. Irrigation engineers generally attribute this to a different, less feudal, society set-up in this area. This results in a canal and structures that are in a much better state than other distributaries in the area (Tareen et al., 1996).

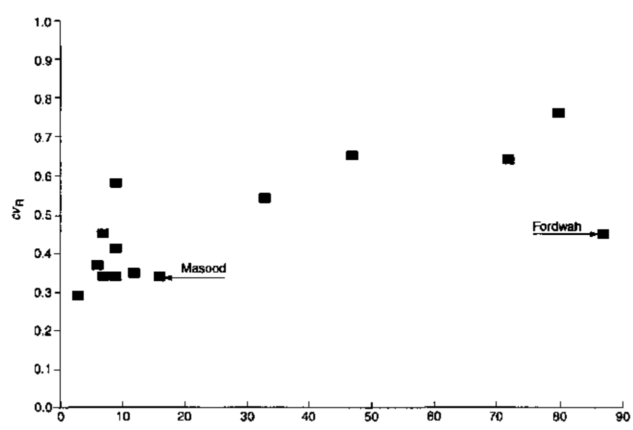

Figure 3.17: Equity in water distribution in distributary canals in the Chishtian Sub-division, expressed as a spatial coefficient of variation, cv_R, of Q_{act}/Q_{auth} of all tertiary outlets.

Proportionality

British design engineers endeavoured to conceive an irrigation system that would function with a minimum of human interference, as discussed in Section 3.1. This explains the preference for ungated proportional dividers at the main and distributary canal levels and the conception of the ungated tertiary offtakes. At the same time, the fact that the irrigation system was designed as a run-of-the-river gravity system inherently implied that the system would be subject to discharge variations. In order to avoid mishaps, minimize human interventions and achieve a satisfactory water distribution even during discharge fluctuations, irrigation engineers attempted to design the tertiary offtakes in such a way that a discharge increase/decrease at the head of a distributary would result in an equivalent change for the different outlets. This is referred to as the *proportionality principle*. For an individual outlet, this is generally expressed as the sensitivity ratio, S_i:

$$S_i = \frac{dQ_{off_i}/Q_{off_i}}{dQ_{con}/Q_{con}} \tag{3.14}$$

where:

Q_{con}	= ongoing discharge in the distributary channel	$[m^3\ s^{-1}]$
Q_{off}	= offtaking discharge	$[m^3\ s^{-1}]$

For an outlet to attain a perfect proportional behaviour S_i needs to be equal to 1. When using the Manning/Strickler equation for Q_{con} and the classical structure equations for Q_{off} , and inserting these formulas in equation 3.15, it can be proved mathematically (Appendix 2) that:

$$H_u = \frac{3\ u\ D}{5} \tag{3.15}$$

where:

H_u	= upstream water level above the crest of the offtake	[m]
u	= value of the exponent of H_u in the structure equations, (u=0.5 for orifices/pipes and u=1.5 for flumes)	[-]
D	= water depth in the distributary channel	[m]

Thus, in order to achieve proportionality, the crest of an offtaking flume should be placed at H=0.9D, which is 0.1D above the bed level of a distributary, and for an offtaking orifice or pipe at H=0.3D, which is 0.7D above the bed level. Setting the crest of an offtaking orifice at this level, caused sedimentation problems in the distributaries, as the silt draw of the offtakes reduce with increasing vertical distance from the bed level. Thus, the design setting of orifices, the predominant offtake type in the Punjab, was changed to 0.1-0.2D above the bed level of the distributary. *This means that individual outlets of the orifice type cannot achieve ideal proportionality and will generally be sub-proportional.* In practice, the proportionality of offtakes is further reduced when siltation occurs. This happens when the settings of offtakes remain unchanged with increasing bed levels of the distributaries. The situation for offtakes of the flume type is different. A flume is generally installed above the proportionality limit, as it will take too much discharge otherwise. *Often offtakes of the flume type behave super-proportionally.*

The principle of proportionality is further illustrated with a practical example of an orifice offtake behaviour as a function of the discharge at the head of a distributary in Figure 3.18. It is shown that the outlet is behaving sub-proportionally (S=0.84) in the design situation. The value for S is further reduced for the actual situation.

If all outlets in a distributary show a similar behaviour, which is generally the case in the Punjab where the majority of the offtakes are fixed orifices, this means that in times of reduced discharge at the head, the offtake discharges will reduce comparatively less. This means that there will be a great deficit in the water availability at the tail. This explains why the traditional tail gauge of the irrigation agency is such a sensitive and valuable indicator. Similarly, when there is an excess of water at the head, the offtakes in the head and middle reaches of the distributary will take less than their proportional share, which will cause an excess in discharge at the tail. Design engineers have addressed this last issue by putting flumes instead of orifices at the tail of distributaries. Thus, an excess at the tail is evacuated to the tertiary canals, avoiding breaches in the distributary.

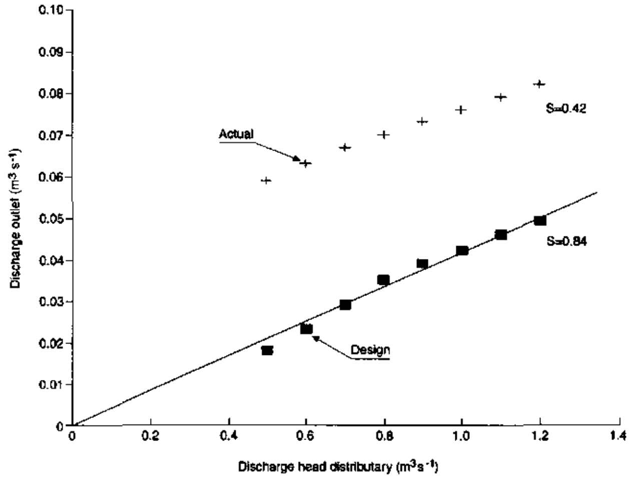

Figure 3.18: Sensitivity, S, of a tertiary offtake (fixed orifice) as a function of the discharge at the head of the distributary. The values for the design as well as the actual situation, for offtake 3700R of the Masood Distributary, have been calculated using the hydro-dynamic model SIC (after Visser, 1996).

The impact of a varying discharge at the head of a distributary on the water distribution is closely related to the principle of proportionality. This is shown in Figure 3.19, which is based on model data of Visser (1996) for the design situation of the Masood distributary. At the design discharge of 1 $m^3 s^{-1}$, the water is distributed equitably, with a cv_R close to 0. As soon as the discharge at the head of the distributary changes, the cv_R increases and the water distribution becomes more inequitable.

Management interventions at the distributary level

In order to identify the most appropriate management interventions, there is a need to know which parameters, if changed, have the greatest impact on the water distribution inside distributary canals. A *local analysis* will be carried out in Section 3.4.2 to assess which parameters of an outlet should be changed to influence the off-taking discharge. The impact of *global* interventions in the channel and its cross-structures will be analyzed using the steady state unit of the hydraulic model SIC. This is done in Section 3.4.3.

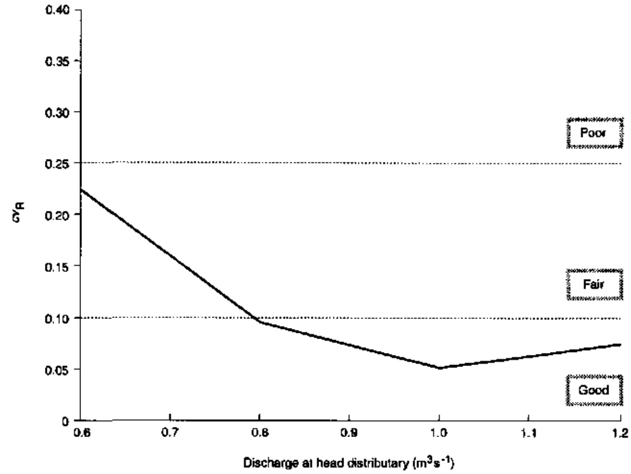

Figure 3.19: Evaluation of the simulated impact of the inflow at the head of a distributary in design conditions on the equitability of water distribution through the coefficient of variation, cv_R (after Visser, 1996). The performance criteria for cv_R are indicated.

3.4.2 Management interventions in the outlet characteristics: analyzing the local impact on the offtaking discharge (Step 4a)

A sensitivity analysis was carried out on the impact of changes in different outlet characteristics on the offtaking discharge by Visser (1996), by evaluating the classical offtake formulas for open flume, orifice and pipe outlet, as detailed in Equations 3.16-3.18:

Open flume:	$Q = C_d \, b \, H_u^{1.5}$	(3.16)
Fixed orifice:	$Q = C_d \, b \, y \, (2 \, g \, (H_u - y))^{0.5}$	(3.17)
Pipe outlet:	$Q = C_d \, \pi R^2 \, z^{0.5}$	(3.18)
	$z = H_u - H_d$	

where:

Q	= discharge	[$m^3 s^{-1}$]
b	= breadth	[m]
y	= height	[m]
C_d	= discharge coefficient	[-]
R	= hydraulic radius	[m]
H_u	= upstream water level above the crest	[m]
H_d	= downstream water level above the crest	[m]

Technical drawings of these outlets can be found in Ali (1993). The open flume and fixed orifice were evaluated for free flow conditions, while the pipe outlet was evaluated for submerged flow conditions. These are the predominant flow conditions for outlets (Tareen et al., 1996). In order to evaluate the impact of a change in an outlet parameter (width, height, crest level), Visser (1996) proposed to use the *responsiveness index, R*, which was defined by Loomis (Maheshwari et al. 1990) as:

$$R = \frac{100}{N} \sum_{i=1}^{N} \frac{(Q_{ni} - Q_{oi})}{Q_{oi}} \Delta^{-1} \tag{3.19}$$

where:

N	= number of offtakes analyzed, $N = 1$ in this study	[-]
Q_{ni}	= discharge for the i^{th} offtake with an adjusted parameter	[$m^3\ s^{-1}$]
Q_{oi}	= discharge for the i^{th} offtake with the reference value of the concerned parameter	[$m^3\ s^{-1}$]
Δ	= relative change of a parameter, expressed as a percentage of its reference value	[-]

In a sense, R represents a measure of the proportionality of change in the output value as a result of a change in an input parameter. When $R = 1$, for example, it indicates that a change of +1% in the input value results in a change of +1% of the output value. Also, $0 < R < 1$ indicates that the change in the output value is positive, but is less than the change in input value, while $-1 < R < 0$ indicates that an increase in input value results in a decrease in the output value. This decrease, expressed as a percentage, will be smaller than the increase in the input value. The R-index can be greater than 1 and smaller than -1, as was shown in the case of the proportionality of outlets. *For the analysis of outlet characteristics, the interest is in identifying those parameters with the largest R-index values, since those parameters will have the biggest impact on the offtaking discharge, if changed.* The results obtained by the analysis are presented in Table 3.18, expressed as R values.

Table 3.18: Sensitivity analysis of the impact of changes in hydraulic parameters on the offtaking discharge of tertiary outlet structures. The results are expressed in *responsiveness index* values, R (Equation 3.19).

Parameters	Open flume	Orifice	Pipe outlet
C_d	1	1	1
b	1	1	2
y	-	0.6-0.95	-
H_u	1.5	0.5	0.5
Crest level	< 0.5	< 0.25	< 0.25

For the coefficient of discharge C_d, and the width b, a value of 1 is obtained for all outlet types, which signifies that the offtaking discharge of an outlet reacts proportionally to a change in both parameters. For the open flume and the orifice, b was used, while in the case of the pipe outlet b was replaced by the diameter D. Since the diameter is taken to the exponent two in the discharge formula, the R-index also equals two. It is, of course, easier to modify b than C_d for an outlet.

The analysis for y was carried out for the orifice type only. Since y appears twice in Equation 3.17, and it is inter-related with H_u, the responsiveness of the outlet discharge to a change in y varies with H_u. It reaches a maximum value of about 0.95 for H_u higher than 1.5 m.

The value of R for a change of H_u is determined directly by the value of the exponent for the different outlet types in the Equation 3.16-3.18. While R is 0.5 for pipe outlets and orifices, it goes up to 1.5 for open flumes.

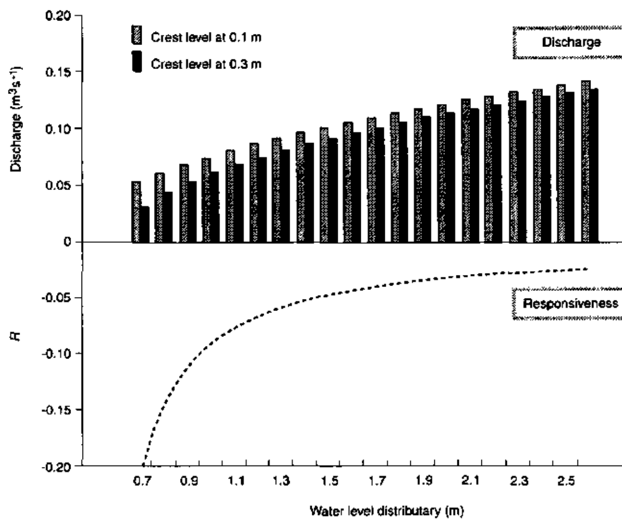

Figure 3.20: The impact of the crest setting on the off-taking discharge of an orifice outlet. With an increasing water level, the sensitivity of the outlet to changes in the crest level of the outlet decreases. The *responsiveness index R* represents the marginal impact of the change in crest setting.

The setting of the crest level has an impact on H_u, and thus directly on the offtaking discharge. This is depicted in Figure 3.20 for an outlet of the fixed orifice type. An increase in the crest level, from 0.1 to 0.3 m from the bed of the distributary will result in a lower discharge for a similar H_u. However, when H_u increases, the difference in the discharges for both crest settings decreases or, in other words, the sensitivity of the outlet to changes in the crest setting decreases at high water levels. An increase in the crest level of 20 cm, which in fact decreases H_u by the same amount, is considerable when H_u is only 60 cm, as it signifies an increase of one third. The same increase for a water level of 200 cm, on the other hand, is only 10%. This explains the decrease in R (less negative) with increasing water level. R is negative, because an increase in crest level will cause a decrease in discharge. Overall, R is relatively small (< 0.25), which means that a change in the crest level has a relatively small impact on the sensitivity of the outlet, particularly when H_u exceeds 0.5 m, which is generally the case for outlets in the Pakistani context.

The results of the sensitivity analysis indicate that the width of an outlet, b, is the most appropriate parameter to modify in order to change water deliveries to tertiary offtakes. It has a high R-index value and is relatively easy to modify. A change in b will have an impact on the water distribution in terms of equitability, but will not improve the water distribution in times of fluctuating discharge as the proportionality of the outlet is not touched.

3.4.3 Management interventions in channel and structures: analyzing the global impact on water distribution in secondary canals (Step 4b)

Definition of scenarios

The analysis was applied to the Masood Distributary, using the steady state unit of the hydraulic model SIC in conjunction with Gateman. The strategic and tactical components of Gateman were not used here, as there are no gated structures. However, this regulation module was used in order to facilitate the input of the inflow pattern as well as the analysis of delivered quantities.

The Masood Distributary is a relatively small secondary channel with an authorized discharge of 1.00 $m^3\ s^{-1}$, see Table 2.2. Despite the fact that 4 outlets on this channel now receive water directly from Fordwah Branch, the authorized discharge has not been reduced. In addition to that, the actual target discharge, around 1.12 $m^3\ s^{-1}$, exceeds the authorized discharge by more than 10%. Presently, 12 outlets are served by Masood Distributary. Generally, the command area of Masood does not face many salinity problems. Firstly, because there are no patches of primary salinity in the Masood command area and, secondly, because there is ample canal water supply.

The list of scenarios is presented in Table 3.19. The interventions are derived from the traditional Maintenance & Repair activities of the irrigation agency and the salinity targeted intervention of installing reclamation shoots.

Table 3.19: Definition of scenarios to assess the impact of potential management interventions on the water distribution at the distributary canal level, and the corresponding hydraulic parameters that are changed by the interventions.

Scenarios	Corresponding hydraulic parameters
Reference	
Lining	n, q
Redimensioning canal	$AR^{2/3}$
Desiltation	H, H_u, $AR^{2/3}$
Redimensioning drops	H
Crest levels drops	S_f, H
Reclamation shoots	Q_{off}, Q_{con}

The hydraulic parameters that are affected by the interventions, as presented in Table 3.19, are the key to quantifying the impact of these interventions. These parameters can be obtained from the classical Manning/Strickler equation (see Equations 3.1 and 3.2), which describes the discharge function in the distributary canal.

The reference scenario is the calibrated/validated model as developed by Visser (1996), which reflects the observed situation in the field. The inflow is kept at 1 $m^3 s^{-1}$. The first intervention, lining of the distributary, impacts on the Manning/Strickler coefficient, *n*, which is reduced from 0.025-0.057 in the actual situation to 0.019 after lining, as well as on the seepage *q*, which is considered zero after lining. The second set of interventions concerns the cross-structure at 5.5 km from the head. First the crest level is raised by 20 cm, an intervention that is sometimes undertaken to change the bed slope of a distributary, S_f, for reasons of sediment transport/deposition or to restore free flow conditions. The second change is a reduction in the width of the cross-structure. The third set of interventions concerns the maintenance of the channel. Firstly, the wetted cross-section, represented by $AR^{2/3}$, all along the distributary is reduced by 20%. A reduction in $AR^{2/3}$ can be obtained by reducing the bed width of the distributary (Visser, 1996). Secondly, the bed of the distributary is desilted by 15 cm over its entire length. The fourth intervention type is the installation of an extra outlet or reclamation shoot at 600 m from the head of the distributary.

Comparing the effectiveness of interventions through steady state simulations

The results are presented in Figure 3.21.

The results of the reference scenario, representing the actual water distribution, show that most outlets have a *DPR* higher than 1.4, taking over 40% more water than authorized. According to the earlier defined standards, this indicates a poor performance. This is water that is taken away from other outlets in the Chishtian Sub-division. Outlets 5 and 6 have submerged flow conditions, which explains their low *DPR*. It should be realized, when evaluating the results of Figure 3.21, that the tail discharge is relatively high as compared to the other off-taking discharges, which is camouflaged by the use of the *DPR*.

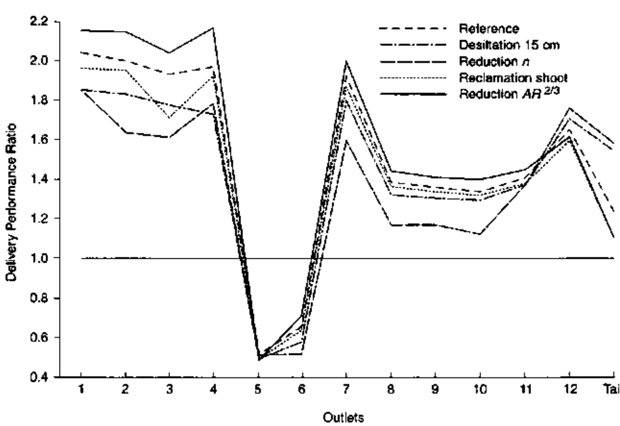

Figure 3.21: Impact of distributary level management interventions on water deliveries to tertiary outlets. The interventions are described in Table 3.20. The results have been generated by the steady state unit of the hydraulic model SIC for the Masood distributary.

The impact of lining on the water distribution is relayed by two hydraulic parameters, *n* and *q*. The reduction in *n*, causes the water levels in almost the entire distributary, except the last few hundred meters, to drop with a subsequent reduction in delivered discharges. The impact of a change in *q* both on delivered quantities and on the water distribution is negligible.

The impact of changes in the width, *b*, and the crest level of drops is very limited. Only locally can a small change in water levels be observed, which does not influence the water deliveries much. An intervention in a drop has a larger impact, if a minor with a substantial discharge offtakes at that point.

In this case, there is likely to be a redistribution of water between the off-taking minor and the on-going parent channel.

Maintenance measures, i.e. redimensioning of the channel and desiltation, have an effect on the water levels in the distributary, which can be quite substantial. A reduction of $AR^{2/3}$ results in an increase in water levels over most of the distributary, which increases the water deliveries to the tertiary units, see Figure 3.21. Subsequently, the water delivery to the tail will decrease. An increase in $AR^{2/3}$ would decrease the water levels. Desiltation lowers the water levels, thus reducing the offtaking discharges over almost the entire distributary, as was shown in Figure 3.21. The water distribution is slightly affected, as evidenced by the values of cv_R in Table 3.20. The simulated maintenance interventions were undertaken for the entire channel. Better results can be obtained if maintenance measures are targeted towards those parts of the distributary where problems exist, e.g. an excessive silt deposit (Bhutta et al., 1996). The effect of targeted maintenance measures was evaluated by Hart (1996) and van Waijjen et al. (1997), who showed that these measures respond better to the maintenance problems of a distributary. However, the anomalies for specific outlets were not solved, and the desired water distribution could not be attained by just global interventions.

The installation of a reclamation shoot at 600 m from the head results in an offtaking discharge of 0.055 $m^3 s^{-1}$, which is about 5% of the inflow. Interestingly, this is compensated mostly by the outlets located close to the reclamation shoot, i.e. outlets 1 to 4, see Figure 3.21. There is, therefore, a limited effect on the water distribution, see Table 3.20.

Table 3.20: Impact of various management interventions at the distributary level on the water distribution, captured in the spatial coefficient of variation (cv_R). The effect of the interventions has been calculated using the steady state unit of the hydraulic model SIC for the Masood Distributary.

Intervention	Corresponding hydraulic parameter	cv_R
Reference	-	0.32
Lining	$n = 0.019$	0.31
Lining	$q = 0$	0.33
Increase crest elevation cross-structure	Raise + 20 cm	0.32
Reduced width cross-structure	b: -25%	0.32
Redimensioning channel	$AR^{2/3}$: -20%	0.34
Desiltation	Bed level: -15 cm	0.30
Installation reclamation shoot	Extra outlet 600 m from head	0.32

The results indicate a poor performance of the various interventions in terms of equitability. This is not surprising when looking at Figure 3.21. The main water distribution problem is posed by two outlets in the middle reach, which are submerged. The global interventions do not tackle this problem, which is why the improvement in the water distribution brought about by global interventions is limited.

A more thorough sensitivity analysis for global parameters was carried out by Visser (1996) and Visser et al. (1997). By testing the responsiveness of water deliveries to changes in these parameters, so-called "sensitive" and "insensitive" parameters were identified. Sensitive parameters, with a corresponding high value for the R-index, turned out to be the dimensions of outlets and the C_d coefficient of outlets. The crest levels of drops were also assessed to be sensitive, but had only a local impact. Insensitive parameters were the crest levels of outlets, width of a cross-structure, the Manning/Strickler coefficient n, seepage losses q and the cross-sectional profile $AR^{2/3}$.

The results of the analyses above show that specific problems in water distribution because of anomalies in offtaking discharges can best be addressed through interventions in local parameters related to outlets. It was shown that the width b of an outlet is the most appropriate parameter to be changed. Only when water delivery problems are observed for a sufficiently long stretch of canal, a global intervention should be considered, e.g. by carrying out maintenance and desilting the channel.

3.4.4 Assessing the effect of management interventions on the water distribution at the secondary canal level

In the previous section, it was shown that modifying the water distribution at the distributary level, can be done most effectively by changing the dimensions of the tertiary outlets. In this section, the present *seasonal* water deliveries to tertiary units will be analyzed, using the combined Gateman-SIC model. Then, an intervention strategy is defined in order to restore an equitable water distribution and redistribute water for salinity control. The analyses are done on a seasonal basis for Kharif 1994. The methodology will be applied to two distributaries in the Chishtian Sub-division. In addition to the Masood Distributary, which was introduced in the previous section and which is a relatively small distributary, the Fordwah Distributary will also be used as a case study. The Fordwah Distributary is a large secondary canal with an authorized discharge of 4.47 $m^3 s^{-1}$ and an actual target discharge of 5.3 $m^3 s^{-1}$. It serves 87 outlets as well as Jiwan Minor with an additional 23 outlets. At the head as well as at the tail of the command area, farmers are faced with salinity problems, due to shortages in canal water supply at the tail and high groundwater tables at the head.

Simulating the existing water distribution (Step 5)

In order to enable a comparison of the existing situation for Kharif 1994, with improved water distribution patterns through interventions in the outlet characteristics, a reference scenario, *M0D0*, was defined. The inflow pattern that was used for this scenario, is the inflow pattern generated by the main canal model, *M0*, as detailed in Section 3.3. *D0* indicates that this scenario represents the actual situation at the distributary level. However, the difference between the inflow pattern generated by the model of Section 3.3, and the measured inflows of Masood and Fordwah Distributaries needs to be investigated first, in order to determine the impact on water deliveries to tertiary units. In order to do this another scenario, *M0D1*, was formulated, using the observed inflow pattern. Both scenarios are summarized in Table 3.21. The difference in simulated and observed seasonal inflows of the two distributaries, amounts to +5.6% in the case of the Masood and +2.0% in the case of the Fordwah Distributary. It is not a coincidence that the simulated inflow pattern of the Fordwah Distributary matches better the observed pattern than for the Masood Distributary, as the strategy defined in the module was specifically focused on the four main distributaries that together account for more than two thirds of the off-taking discharge. This reflects the interest of the irrigation manager. For the smaller distributaries, like Masood, the off-taking discharge is determined not only by the irrigation manager, but also by the gate keeper in consultation with the farmers. In times of rains, for instance, the water delivery to Masood is interrupted by the gate keeper, as farmers are closing their outlets.

Table 3.21: Definition of the reference scenarios *M0D0* and *M0D1* for simulations at the distributary level using SIC for Kharif 1994.

Scenarios	Canals studied	Inflow pattern
M0D0 (reference)	Masood, Fordwah	Generated by main canal model, Scenario *M0*
M0D1	Masood, Fordwah	Daily observations

The simulation results of Scenarios *M0D0* and *M0D1* were evaluated using the criterion of delivered quantities to the tertiary units. They are summarized in Table 3.22, using the performance indicators defined in Section 3.2. In these calculations the tail water deliveries are not included.

Table 3.22: Simulation results of Scenarios *M0D0* and *M0D1*, comparison of the effect of simulated and observed daily inflow pattern on the seasonal water deliveries to tertiary units, quantified through the delivery performance ratio (*DPR*) and the spatial coefficient of variation (cv_R).

Distributary	Scenario *M0D0*		Scenario *M0D1*		Average absolute error
	DPR	cv_R	*DPR*	cv_R	(%)
Masood	1.07	0.31	0.96	0.31	11
Fordwah	0.74	0.38	0.75	0.38	6

On average, delivered quantities to the tertiary units of the Masood Distributary for Scenario *M0D0* deviate about 11% from the quantities obtained through Scenario *M0D1*. For the Fordwah Distributary the average (absolute) difference amounts to 6 %. The fact that the average absolute errors increase from inflow to deliveries, 4.8 to 11% in the case of Masood and 2 to 6% in the case of Fordwah, is related to the sub-proportionality of outlets under existing conditions. The observed delivery pattern for the Masood Distributary, for instance, is much more irregular than the simulated pattern. The delivered discharge is further about 20% higher. Due to the sub-proportionality of the tertiary outlets, they only take about 10% extra discharge, which means that a super-proportional share of the extra discharge goes to the tail. Since in the observed situation, the distributary is closed for more days than in the simulations, there will be less water available for the tertiary outlets *per saldo*. This can, perhaps, be illustrated by analyzing the proportionality of the entire distributary by looking at the tail discharge as a function of the head discharge.

Simulations were carried out, using the model of the reference scenario, *M0D0*, to investigate the reaction of off-taking outlets on variations in discharge at the head of the distributary. The results are presented in Figure 3.22, showing that the distributary as a whole is super-proportional with the sensitivity ratio, *S*, at a value of 1.99. This means that an increase in discharge of 1% at the head will result in an increase of nearly 2% at the tail. This is a consequence of the sub-proportional behaviour of the fixed orifices that act as tertiary outlets. The theoretical value of *S* is 1, which is also depicted in the figure.

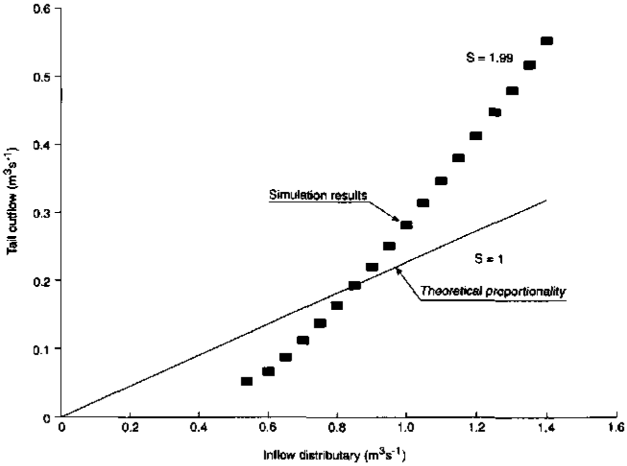

Figure 3.22: Simulated hydraulic behaviour of the Masood distributary in the actual conditions. The tail outflow is depicted as a function of the discharge at the head. The distributary as a whole is shown to be super-proportional.

The results that were obtained in this section, show that the water distribution with the simulated and the observed inflow pattern compare well, having a difference of about 10%. This corresponds with the measuring accuracy. Scenario *M0D0* will, therefore, be used as the reference scenario for alternative scenarios.

Defining alternative scenarios for improved water distribution at the distributary level (Step 6, 7, 8)

The interventions that are proposed for Masood and Fordwah Distributaries address the equitability of water distribution and salinity problems, respectively. They are defined in Table 3.23.

Table 3.23: Formulation of Scenarios *M0D2* and *M0D3*. Irrigation management interventions at the distributary level for the Masood and Fordwah Distributaries for Kharif 1994.

Scenarios	Distributary	Objective intervention	Intervention
M0D2	Masood	Equitability	1. Reduce size outlets that are overdrawing 2. Increase size outlets that are receiving too little
M0D3	Fordwah	Salinity control	Increase size outlets of saline areas

The selection of these scenarios corresponds with the diagnosis of earlier sections. In case of the Masood Distributary, the main issue related to irrigation management is an inequitable water distribution combined with a surplus in inflow. The Fordwah Distributary is faced with salinity and sodicity in part of the command area.

Restoring equitability in water distribution for the Masood Distributary (scenario M0D2)

A look at the present water distribution of the Masood Distributary by evaluating the results of Scenario *M0D0* reveals that there are 10 out of 12 outlets that receive 20% or more than the authorized quantity of water during Kharif 1994. Six outlets even get 40% or more than the authorized volume. This is caused by an excessive inflow, by the fact that seepage losses for Masood Distributary are lower than assumed (Tareen et al., 1996), by the fact that water levels in the Masood Distributary are higher than assumed in the design because of siltation, and because the actual dimensions of outlets are considerably different from the original ones. In Scenario *M0D2* the water distribution will be addressed only through a redimensioning of the outlets and not by resectioning the distributary.

In Scenario *M0D2* the size of the six outlets that are drawing 40% or more than the authorized discharge are reduced. In order to achieve this, the width, b, and height, y, of offtakes and the diameter, D, for pipes were changed. Preferably, b was altered, as this was shown to be the most effective intervention. However, for hydraulic reasons a minimum size of 6 cm is recommended for outlets such as the AOSM, which limits the possible changes (Ali, 1993). The reductions amounted to 25-30% and are detailed in Appendix 3. The flow conditions of the two submerged outlets that were not drawing enough water, i.e. Outlet 5 and 6, were made free flow on the assumption that field conditions permit this intervention. The intervention has big consequences for the off-taking discharge. The radius of the pipe of Outlet 5 had to be reduced by 10 cm, because the outlet would otherwise overdraw by more than 100%. For the AOSM structure of Outlet 6, the change was slightly less drastic.

The results of the simulations of Scenario *M0D2* are depicted in Figure 3.23. The seasonal deliveries are compared with the quantities that were generated by the reference Scenario *M0D0*.

The results confirm the effectiveness of interventions in outlet dimensions in improving the water distribution at the distributary level. Water deliveries of all outlets that were reduced in size by about 25-30% have decreased by an equal percentage. The improvements in the water deliveries to Outlets 5 and 6 are considerable. At the tail, extra water is available because of the reduced dimensions of outlets at the head of the distributary.

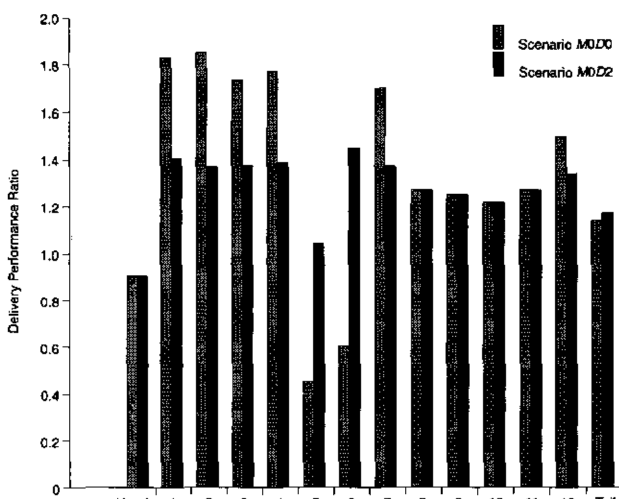

Figure 3.23: Comparison of simulated water deliveries for the actual situation (*M0D0*) and after intervention (*M0D2*) to outlets of the Masood distributary for Kharif 1994. The water deliveries are expressed as a delivery performance ratio (*DPR*).

The water distribution in the Masood Distributary has become more equitable due to the interventions in the outlets. This is evidenced when applying the equity performance indicators, such as the spatial coefficient of variation cv_R. This indicator decreases from 0.31 in the actual situation to 0.08 after intervention. This constitutes a tremendous improvement, and the equity performance rating improves from poor to good.

Improving salinity control in the Fordwah Distributary command (Scenario M0D3)

For the Fordwah Distributary, seven outlets were identified that have a limited access to canal water and whose command areas face high levels of salinity and sodicity. These levels were determined through a visual salinity survey in January-March 1996 by the Directorate for Land Reclamation, the authority that recommends the installation of reclamation shoots, i.e. pipe outlets with extra water for certain tertiary units during the flood season (Asif et al., 1996). These outlets were selected for an increase in water deliveries for Scenario *M0D3*. In order to have a real impact on the salinity, an increase in deliveries in the range of 75% was attempted for these tertiary outlets. A change in *b* of the concerned outlets was again preferred in order to obtain this increase. The extra water that is required for these outlets was taken away from a few other outlets and from Jiwan Minor, which are comparatively well off in the actual situation. Their deliveries were decreased about 20% by changing their outlet dimensions. The outlet dimensions were in a first step changed linearly with the intended change in water deliveries. This was tested in the steady state unit of SIC and where necessary (slightly) adjusted. The changed parameters for Scenarios *M0D0* and *M0D3* for the Fordwah Distributary are given in Appendix 3.

Then, the model with the redimensioned outlets was run with the inflow pattern that was used already for Scenario *M0D0*. The results of Scenario *M0D3*, are compared with those of Scenario *M0D0* in Figure 3.24.

The most important observation is that water in a distributary can be redirected by a simple intervention in the dimensions of tertiary outlets without disturbing the other outlets. However, a prerequisite is that the sum of the additional discharge matches approximately the sum of the decreases in discharge of the different outlets. If not, the tail outlets will suffer. This is also the case for Scenario *M0D3*. The decreases in discharge are smaller than the additional discharges, which results in a 25% decrease in the water deliveries to the last two outlets, despite the fact that they are unchanged.

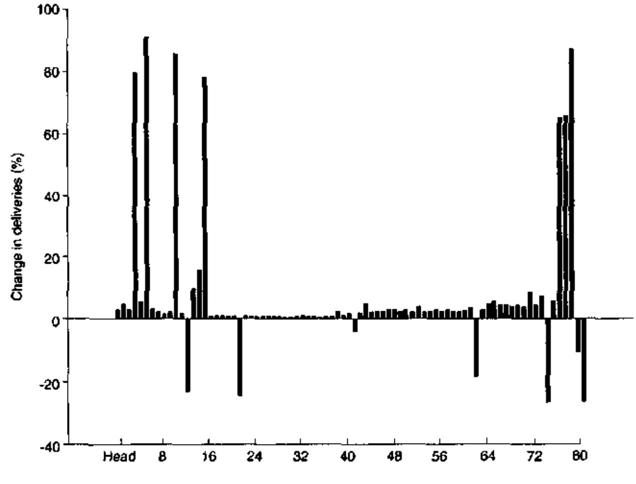

Figure 3.24: Comparison of simulated water deliveries of Scenarios *M0D0* and *M0D3* for the Fordwah Distributary for Kharif 1994, showing the effect of redimensioning selected outlets on the water distribution. The intervention serves to better target water supplies for salinity management.

The tool that was developed in Section 3.2, was successfully applied to a case study of two secondary canals in the context of Pakistan. The methodology served to (1) diagnose the existing water distribution of a secondary canal, (2) identify and categorize the different possible interventions to improve the water distribution, (3) elaborate a management intervention strategy, and (4) to quantify the impact of interventions on the water distribution. It is relatively straightforward to redistribute water in a distributary by changing the outlet dimensions, preferably the width, b. It was shown that it is possible to obtain an equitable distribution of water to tertiary units, while it is equally possible to direct extra water to those tertiary units that require it for salinity and sodicity management without disturbing the water distribution in the entire channel.

3.5 Analyzing the impact of management interventions at the main and secondary canal level on water deliveries to tertiary units

In Section 3.3, the composite Gateman-SIC model, capable of quantifying the effect of main canal interventions on water deliveries to distributaries, was applied to the Fordwah Branch Canal. In Section 3.4, the model was used to assess the effect of distributary interventions on the water supplies to tertiary units. In the present section, the impact of main canal interventions on the seasonal water deliveries to tertiary units, as well as the combined impact of main and distributary canal interventions on these deliveries, will be evaluated in Sections 3.5.1 and 3.5.2, respectively.

3.5.1 Water deliveries to tertiary units as a function of the inflow of secondary canals

Definition of scenarios

In order to quantify the impact of main canal interventions on water deliveries to tertiary units, two alternative scenarios were defined, taking Scenario *M0D0* once again as the reference scenario. Scenario *M3D0* quantifies the impact of a main canal intervention to bring about an equitable water distribution, and uses the inflow pattern generated by Scenario *M3* for Kharif 1994. This scenario attempted to bring about a more equitable water distribution between distributaries. Scenario *M4D0* uses the inflow pattern calculated by Scenario *M4*, which represented a salinity targeted intervention, whereby the water supply to the Masood Distributary was curtailed and the water supply to Fordwah increased in Kharif 1994. The scenarios are summarized in Table 3.24.

Table 3.24: Definition of Scenarios *M3D0* and *M4D0*, to quantify the impact of alternative inflow patterns, as a result of main canal interventions, on the seasonal water deliveries to tertiary units for the Masood and Fordwah Distributaries

Scenario	Distributaries studied	Inflow Masood (10^6 m^3)	Inflow Fordwah (10^6 m^3)	Objective main canal intervention
M0D0	Masood, Fordwah	14.2	53.3	Actual situation (reference)
M3D0	Masood	10.3	-	Equitable distribution
M4D0	Masood, Fordwah	12.6	57.4	Salinity control

Results of the simulations (Scenarios M3D0 and M4D0): Masood Distributary

The results of the simulations for Scenarios *M3D0* and *M4D0* for the Masood Distributary during Kharif 1994 are depicted in Figure 3.21 with reference to Scenario *M0D0*.

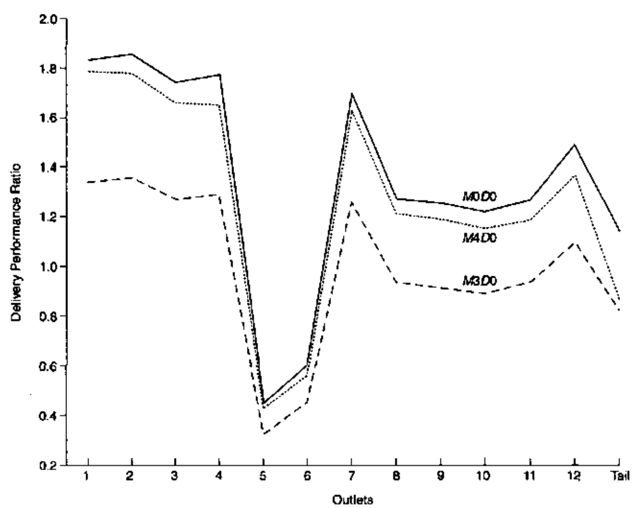

Figure 3.25: Simulated seasonal water deliveries to the tertiary units of the Masood Distributary as a result of management interventions at the main canal level. The results of Scenarios *M3D0* and *M4D0*, defined in Table 3.26, are compared with the reference scenario *M0D0*, by means of the delivery performance ratio (*DPR*).

The results indicate that the quantities delivered to the tertiary units are directly related to the total volume that is delivered to the distributary. In case of Scenario *M3D0*, the inflow is 27% less than in case of the reference scenario, *M0D0*. The discharge to all outlets is consequently reduced by 25-28%. The linearity in the response of the tertiary outlets is caused by the fact that the inflow of the distributary was reduced by curtailing the number of delivery days, while keeping the discharge at the head the same. All outlets get, therefore, about the same reduction in delivered quantities. In case of Scenario *M4D0*, the inflow is reduced by 11%. However, the reduction in off-taking discharges of the tertiary outlets is only in the range of 4-6%, while the volume delivered to the tail is much reduced. This is related to the discharge that is delivered at the head of the distributary. While the discharge for Scenario *M4D0* does not surpass 0.96 m^3 s^{-1}, which gives a discharge of about 0.25 m^3 s^{-1} at the tail, the discharge in the case of Scenarios *M0D0* and *M3D0* is often greater than 1.1 m^3 s^{-1}, which gives a much less beneficial ratio offtake discharges versus tail discharge. This is related to the super-proportional behaviour of a distributary, as explained in Section 3.4.4.

Results of the simulations (Scenario M4D0): Fordwah Distributary

The fact that the internal water distribution in a distributary is hardly affected by a main canal intervention, as shown for the Masood Distributary, is confirmed by the simulations for the Fordwah Distributary. Scenario *M4D0* for the Fordwah Distributary is not intended to do anything for the restoration of equitability, but an extra quantity of water is allocated to this distributary, i.e. about 6-7% (see Section 3.3.2), for salinity control. The results of the simulations show that an increase in the inflow of the distributary is translated in a global increase that is similar for most outlets. An average increase of 7% is attained for the tertiary outlets. The water distribution has, therefore, not changed much, as reflected in the values of the performance indicators of Table 3.25.

Table 3.25: Evaluation of the simulation seasonal water deliveries for Scenarios *M0D0*, *M3D0* and *M4D0*, to assess the effect of main canal interventions on the equity of the water distribution in the Masood and Fordwah Distributaries. The delivery performance ratio (*DPR*) and the spatial coefficient of variation (cv_R) are used for the evaluation.

Scenarios	Masood Distributary		Fordwah Distributary	
	DPR	cv_R	*DPR*	cv_R
M0D0 (reference)	1.35	0.32	0.73	0.38
M3D0	0.99	0.32	-	-
M4D0	1.26	0.33	0.78	0.38

The water distribution is "poor" for all scenarios, as reflected by the values of the cv_R. However, the inflow is partly rectified by the main canal interventions.

Main system interventions have been shown to have a similar impact on water deliveries to all tertiary units in a distributary, and the water cannot be directed towards particular outlets without interventions at the distributary level.

3.5.2 Combining and comparing the effect of main and secondary canal interventions on water deliveries to tertiary units

Defining scenarios

In previous sections, the impact of interventions at the main and distributary canal on seasonal water deliveries to the tertiary units was evaluated separately. The aim of these interventions were (1) restoring equitability, and (2) salinity control for the Masood and Fordwah Distributaries, respectively. In this section, the effect of these interventions is compared for Kharif 1994. Also, the combined impact of main and distributary canal interventions is quantified. This is done by simulating the earlier defined distributary scenarios (*M0D0*, *M0D2*, *M0D3*) for different inflow scenarios (*M0*, *M3*, *M4*). The *combined* scenarios are defined in Table 3.26.

Table 3.26: Formulation of Scenarios *M0D0*, *M3D0*, *M0D2*, *M3D2*, *M4D0*, *M0D3*, *M4D3*, quantifying the combined impact of main canal and distributary management interventions for the Masood and Fordwah Distributaries in Kharif 1994.

Scenarios	Distributary	Intervention	Inflow (10^6 m^3)
M0D0 (reference)	Masood	-	14.2
Equitability			
M3D0	Masood	Main canal	10.3
M0D2	Masood	Distributary	14.2
M3D2	Masood	Combined	10.3
M0D0 (reference)	Fordwah	-	53.3
Salinity control			
M4D0	Fordwah	Main canal	57.4
M0D3	Fordwah	Distributary	53.3
M4D3	Fordwah	Combined	57.4

Scenarios *M0D0*, *M0D2*, *M3D0*, *M4D0* and *M0D3* were presented earlier in Sections 3.4.4 and 3.5.1. Only the combined Scenarios *M3D2* and *M4D3* have not been presented in this study, yet.

Equitability (Scenarios M3D0, M0D2, M3D2)

The effect of the main and distributary canal interventions on the seasonal water deliveries to the tertiary units of the Masood Distributary are displayed in Figure 3.26. The deliveries are presented as a delivery performance ratio, *DPR*.

Figure 3.26 shows clearly the difference of intervening at the main canal (Scenario *M3D0*) or at the

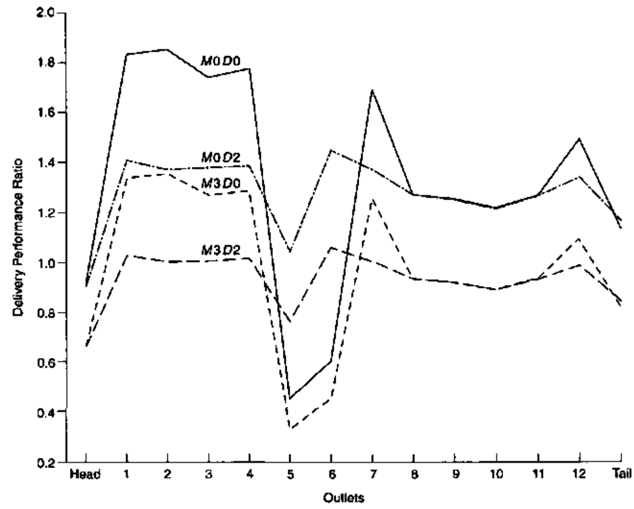

Figure 3.26: Comparison of the effect of main and distributary canal interventions on the simulated seasonal water deliveries to the tertiary units of the Masood Distributary. The scenarios, which are defined in Table 3.28, are evaluated through the delivery performance ratio, *DPR*.

distributary level (Scenario *M0D2*). While the intervention at the main canal level produces an analogous reduction in supplies to all outlets, an intervention at the distributary level causes a redistribution of water to tertiary outlets. In the case of *M0D2*, the water distribution becomes much more equitable. However, all outlets receive almost 40% more water than they are entitled to. This means in the water short environment of the Chishtian Sub-division that the tertiary units in other distributaries will suffer. A combination of both interventions (Scenario *M3D2*) is, therefore, the best solution. An equitable water distribution is achieved with all outlets having a *DPR* of around 1, which means that they receive an amount of water equal to their entitlement.

The results of all scenarios are summarized in Table 3.27, using the performance indicators that were defined in Section 3.2. The *DPR* and the cv_R were determined for all outlets of the Masood Distributary. To verify the implications of these interventions for other secondary canals in the study area, the *MIQR* for all secondary canals, including Masood, is also presented.

Table 3.27: Evaluation of the performance of simulated seasonal water deliveries to tertiary units of the Masood Distributary as a result of main and distributary canal interventions, using the delivery performance ratio, *DPR*, the spatial coefficient of variation, cv_R, and the modified inter quartile ratio (*MIQR*).

Scenario	Intervention	All secondary canals *MIQR*	Masood *DPR*	Masood cv_R
M0D0	Reference	1.93	1.37	0.32
M3D0	Main canal	1.41	1.00	0.32
M0D2	Distributary	1.93	1.31	0.08
M3D2	Combined	1.41	0.96	0.08

The values of cv_R indicate that the best results in terms of an equitable water distribution in a distributary, are obtained by intervening at the distributary level. By intervening at the main canal level, an equitable water distribution is achieved for all distributaries in the Chishtian Sub-division, as evidenced by the MIQR values for Scenarios M3D0 and M3D2. A restoration of equitability in the overall water distribution for tertiary units in the Chishtian Sub-division, requires, therefore, interventions both at the main canal as well as at the distributary level.

Salinity control (Scenarios M4D0, M0D3, M4D3)

The effect of a main canal intervention, which makes more water available to the Fordwah Distributary, on the seasonal water deliveries to the tertiary units is shown in Figure 3.27.

Figure 3.27 presents the changes in discharge to outlets as a result of a main canal intervention (Scenario *M4D0*), with reference to Scenario *M0D0*. The effect is shown to be fairly uniform for the different outlets of the Fordwah Distributary, except for two pipe outlet in the head end. The distributary acts super-proportionally, which explains the extra water that is available for the tail.

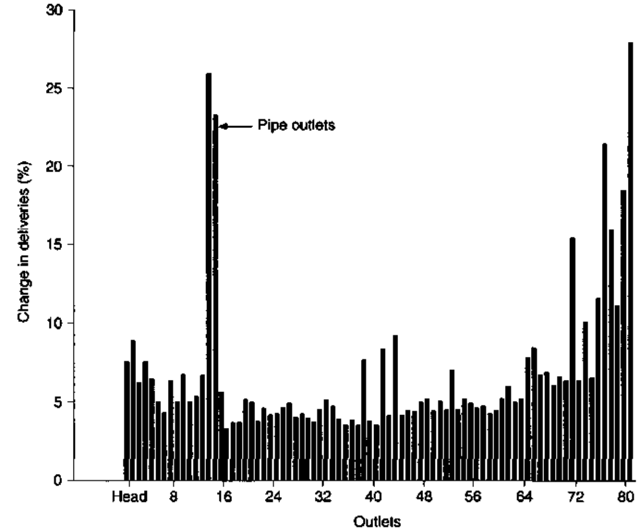

Figure 3.27: Assessment of the impact of making extra water available to the Fordwah Distributary on the simulated seasonal water deliveries to tertiary outlets. The results have been presented as a change in water deliveries for Scenario *M4D0* with reference to *M0D0*, see Table 3.28.

The combined effect of main and distributary canal interventions is presented in Figure 3.28. The difference in seasonal deliveries of Scenario *M4D3* with reference to those of Scenario *M0D0* are presented.

An extra quantity of water is available for the Fordwah Distributary, while the water inside the distributary is redistributed by remodelling a number of outlets. This remodelling has been described already for Scenario *M0D3*, see Table 3.23. The effect of the individual interventions in outlet dimensions are considerable. Seven outlets gain more than 80% in water deliveries, while four others have reductions to the tune of 20%. All other outlets gain about 5-10% water supplies, due to the fact that more water is available for the Fordwah Distributary.

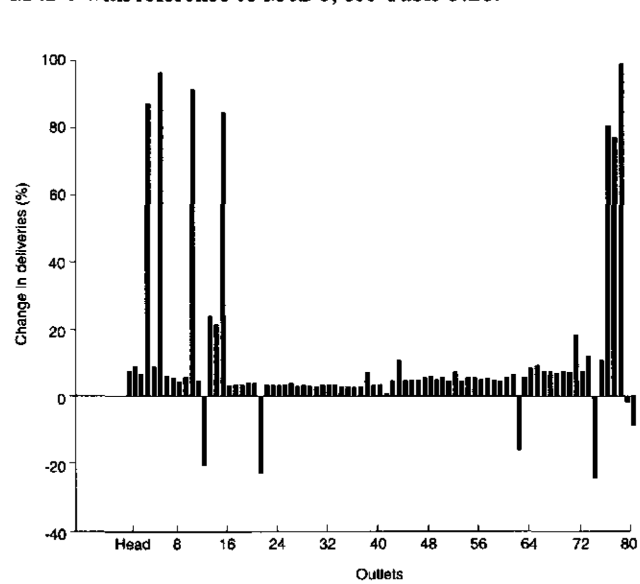

Figure 3.28: Change in simulated seasonal water deliveries to tertiary units of the Fordwah Distributary as a result of main canal and distributary level interventions (Scenario *M4D3*), with reference to Scenario *M0D0*, see Table 3.28.

Management interventions at the main and secondary canal level address anomalies in the water distribution at these respective levels. For the case study, interventions were necessary at both levels to obtain the desired water distribution. In other cases a single level intervention may suffice, which emphasizes the need for a thorough diagnosis of the existing situation. The tool that was developed in Section 3.2 was shown to be useful in elaborating such a diagnosis.

3.6 Conclusions

General

An approach was developed to assess *a priori* the impact of management interventions at the main and distributary canal on the water deliveries to tertiary units. The approach includes the development of a tool, which consists of a physical model to simulate the water flow in channels and off-taking structures, and a regulation module to capture the operational decision rules of the irrigation agency. The main advantages of the model are that it enables (1) to identify existing physical and managerial bottlenecks in water deliveries, and (2) an assessment of the comparative benefits of main and distributary canal management interventions, on the canal water distribution. However, during the analysis the model was also useful to gain a better understanding of the existing operational rules. The model can equally be used for other issues in irrigation management. Litrico (1995) showed that the tool is useful to diagnose the causes of the existing discharge variability and identify opportunities for improvement. The tool was applied to a case study, i.e. the main and secondary canals of the Chishtian Sub-division in Pakistan.

Case study

The main principles that have governed the design of the Indus Basin irrigation system, i.e. equitability, water use efficiency, minimum human interference and silt management, are still valid and guiding the official water distribution. However, increased demand for water and other changes in the irrigation environment have precipitated the introduction of an alternative set of operational rules, which deviate from the official rules. These existing operational rules are not transparent, and have induced an inequitable water distribution and an uncertainty among the water users as to when to expect water supplies. The necessity to update the official operational rules was echoed recently by representatives from the irrigation agency for reasons of transparency (Hafiz Ullah et al., 1996). When updating the official rules for practical implementation, it is time also to rethink the logic of water distribution. Is it possible to redefine the water allowances, directing water to where it is needed for salinity management, or to divide the water commensurate with the area commanded by irrigation channels? This question can be addressed in the present situation, because more irrigation water is available than at the time of conception of the system, particularly in rabi and the beginning of kharif. This is due to the construction of storage and conveyance facilities with respect to canal supplies, and due to the large scale exploitation of groundwater.

Before applying the approach to the Chishtian Sub-division, the hydraulic model and the regulation module, were calibrated and validated separately *at the main canal level*, i.e. the Fordwah Branch canal.

Then a calibration was done for the composite tool. It was shown that seasonal water deliveries were predicted within 5% accuracy for the Fordwah Branch canal, while the discharge pattern during the season matched well the actual delivery pattern. It would be interesting to undertake a validation exercise for a different irrigation season. The data necessary for this exercise are available. *At the secondary canal level*, where the water distribution depends solely on the infrastructure and on the inflow, the hydraulic model was calibrated and validated for two secondary canals. Seasonal water deliveries can be predicted within 10% accuracy.

The approach was then applied separately to the main and secondary canals, because the interventions at the main canal level focused on canal operations, while the infrastructure was targeted at the secondary canal level. *At the main canal level*, the impossibility to implement the official operational rules has been demonstrated. The inflow pattern is such that a rotation is necessary all of the time, although envisaged only for 2 weeks a month, while it was shown to be impractical to include all distributaries in a rotation. This explains the difference between official and actual operational rules. The actual operational rules are more practical, but have some serious repercussions on the water distribution, as well as the hydraulic state of the canal. The water distribution was shown to be very inequitable. Also, the fact that the operation of the small distributaries is outside the control of the irrigation manager means that shortages are created for the larger distributaries, as the combined discharge of the small distributaries is not negligible. In addition, emergencies are created at the tail of the main canal in times of an excess in water supply, e.g. during rains, when all small distributaries are closed all of a sudden.

The analyses have shown that it is possible to modify the water distribution through management interventions. The type and extent of management interventions that are required for improved water distribution, can be investigated using the composite Gateman-SIC model. *Interventions to address the water distribution in the main/branch canal can best be undertaken at the strategic level, i.e. the formulation and implementation of operational rules.* These rules pertain mainly to the rotational plan and target discharges of distributaries. *It was shown that by changing the operational rules, it is possible to restore equitability in water distribution at the main canal level as well as to improve the quality of water supplies to distributaries, so that they better match the water turns of farmers (warabandi). It is also possible to supply more water to specific distributaries without disturbing the water supplies to other distributaries.* Of course, the water mass balance needs to be in equilibrium. The extra quantity of water for a given distributary needs to be matched by a reduction in supply to another distributary. Interventions to attenuate the discharge variability and other operational problems need to be solved at a lower, tactical, level by improving the gate operations of gate keepers.

At the secondary canal level, a sensitivity analysis was undertaken to identify the most effective intervention strategy at this level. *Interventions to address the water distribution in a distributary canal can best be done by modifying the width of a specific mogha or group of moghas. Global interventions, such as desiltation or constriction of the channel width, have a limited effect on the water distribution when compared with the redimensioning of outlets.* These global interventions may be necessary, though, if a sufficiently long stretch of canal is affected. The composite tool can help to evaluate the effect of different management interventions on the water distribution. The principle of proportionality, a desire formulated by design engineers, could not be attained fully in the actual design of the system. Orifice outlets are generally sub-proportional, which means that any discharge fluctuation at the head of a distributary is propagated to the tail of the channel. Because of siltation in distributaries, the channels have become more prone to this phenomenon, which will require a more constant supply to distributaries at the level of the target discharge.

Finally, the main canal and secondary canal models were linked in order to compare and combine the impact of interventions at both levels on the water deliveries to tertiary units. For the case study, interventions were necessary at both levels to rectify existing anomalies in the water distribution. Substantial improvements in the water distribution could thus be obtained.

There are a number of physical constraints that limit the extent of the possible improvements in water distribution. At the main canal level, the water supply to ungated distributaries is difficult to manage, although in practice gate keepers have managed to do some sort of regulation by inserting bushed and wooden stoplogs in the distributary intake. The inflow to the irrigation system is an important constraint, which defines the limits of water deliveries further downstream. At the distributary level, it is not possible to change the water distribution without physical interventions.

Application elsewhere

Developing a hydraulic model like SIC is relatively time consuming and requires about 15 man days for 10 km of canal, mainly for a hydraulic survey, the calibration of structures and outlets, and the collection of water levels for the calibration and validation of the model. Additional time is required for setting up the model on the computer. For the regulation module, data over a longer period are required. For the calibration and validation of the gate operations, hourly observations were done at 6 locations along the main canal for more than a week. In addition, interviews were carried out. For the calibration of the operational rules, daily observations were used at all cross-structures and distributary intakes during a complete irrigation season of six months.

The hydraulic model has been used by researchers and engineers in different countries, and is fairly straightforward and user-friendly. A specific training and initial guidance is, however, essential, especially in the calibration phase. Transfer of the model to irrigation managers seems possible, although the use of the model in routine management of irrigation canals may not be necessary, given also the time requirements for setting up a model. Perhaps, the model is better suited for organizations like the Irrigation Research Institute, which are frequently called upon by irrigation managers to help solve management problems of problematic canals. The regulation module is still in a research phase, and is in its present form only accessible as an end product. Transfer of this tool seems only possible in a pilot project in which irrigation managers and researchers work together.

Another important issue relates to the transferability of the approach and the tools to other systems or issues. The hydraulic model can be considered generic, since it is based on physical laws. It has been shown to work in a wide variety of situations. The operational logic, however, varies from system to system, and a regulation module will, therefore, need to be adapted to a new situation. However, certain parts of the module can be transferred. This is evidenced by the fact that the algorithm (Equations 3.7 to 3.9), describing the gate operations, has been used both in Sri Lanka as well as in Pakistan.

CHAPTER 4

FARMERS' SALINITY AND SODICITY CONTROL: FROM THE FIELD TO THE TERTIARY UNIT

While interventions in irrigation management, as dealt with in Chapter 3, have focused on higher levels of the irrigation systems where most of the gains can be obtained, salinity management takes place in farmers' fields. The analysis of the series of events leading to soil salinity and sodicity will, therefore, start at this level. In Section 4.1, the physical and chemical processes that contribute to soil salinity and sodicity will be briefly discussed. In Section 4.2, the salinity management of farmers will be analyzed in order to find out which interventions would help farmers the most in coping with salinity and sodicity. A methodology will be developed in Section 4.3, to assess the impact of management interventions on soil salinity and sodicity. This methodology will be applied in Section 4.4 for salinity and in 4.5 for sodicity. In these sections, the most appropriate management interventions will be identified in the present physical conditions by assessing their comparative impact on soil salinity and sodicity, respectively. In Section 4.6 these analyses will be extrapolated to the level of the tertiary unit, in order to enable the integration of the results of Chapters 3 and 4, which will be done in Chapter 5. In Section 4.7, finally, the conclusions of Chapter 4 are presented.

There is a considerable difference in approach between Chapter 3 and 4. In Chapter 3, a common platform was developed linking the decisional rules of the irrigation agency with the physical process of water flow. This was possible, because the objectives and strategies of the irrigation staff are focused on the concerned physical process. In the case of soil salinity and sodicity, the situation is different. Although salinity and sodicity are important concerns for farmers, they need to be placed in a larger context of the farming systems. Decisions related to salinity and sodicity are often taken in order to achieve a larger farming objective, e.g. food security or maximization of the gross income. It was decided to limit the analysis of farmer's behaviour in the context of this study to salinity management, as treated in Section 4.2. A separate study of the farming systems was carried out parallel to this study, quantifying the impact of the irrigation environment on agricultural production based on the socio-economic background of farmers (Strosser, 1997). This study on the farming systems, will be integrated with the analysis of the physical processes of salinization and sodification in Chapter 5.

4.1 Salinity and sodicity processes: a brief description

Soil salinity and sodicity are very different phenomena as far as the processes leading to these conditions, the effects on soils and crops, and the management issues associated therewith are concerned. It is, therefore, important to distinguish between these phenomena and analyze briefly the pathways leading to soil salinity and sodicity. This is done in Section 4.1.1. A good understanding of these processes will be helpful in formulating management interventions for improving salinity and sodicity management. The indicators that capture the degree to which soils have been affected by these phenomena will be defined. Since the main interest in these phenomena pertains to their adverse effects on soils and crops, these effects will be treated in more detail in Section 4.1.2.

4.1.1 Pathways leading to soil salinity and sodicity

Salts in the soil solution are mainly introduced by irrigation, or through capillary rise, and removed through leaching, as depicted in Figure 4.1. However, solute transfer is also subject to the exchanges of salts between the soil solution and the exchange complex, and to the precipitation and dissolution of salts. Due to these processes, solute transfer in the soil profile is not entirely a function of the water transport.

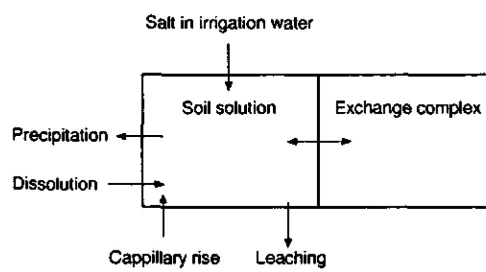

Figure 4.1: Schematic representation of exchanges of salts between the soil solution and the exchange complex. Salts are added to the soil solution through irrigation, capillary rise and dissolution, while they are removed through leaching or precipitation.

The solid and liquid phases of the soil frequently interchange different cations. Clay particles and organic matter have a negative surface charge, which is compensated for by the cations Na^+, K^+, H^+, Ca^{2+} and Mg^{2+}. In close proximity to the solid phase, there will be an excess of cations, while the negative charge of the solid phase will tend to drive away the anions. The sphere of influence of the solid phase is called the Gouy-Chapman Diffuse Double Layer (DDL). Beyond the DDL, the concentrations of cations and anions will be in equilibrium (van Hoorn and van Alphen, 1994). When the soil solution contains a lot of cations of a specific type, say Na^+, the cations in the DDL, e.g. Ca^{2+} or Mg^{2+}, will be exchanged with Na^+. The extent of the DDL is determined by the valency of the cations (the higher the valency the more the cations are attracted to the solid phase and the smaller the DDL), and by the concentration of the soil solution (the higher the smaller the DDL). This is an important phenomenon as the extent of the DDL determines the soils structure. When it is small the clay particles will form a loose "cardhouse" type arrangement, which guarantees a good soil structure. Increases in the size of the DDL, e.g. by replacing Ca^{2+} on the clay complex by Na^+, will tend to disperse the clays and reduce the permeability of the soil. The clay minerals in the Punjab, which are mainly illites, have a weak structure, and are quite susceptible to dispersion under the influence of sodium rich irrigation waters (Biggar, 1996; Rengasamy et al., 1984; Sumner, 1993).

Generally, the process by which the total salt concentration increases due to evaporation and transpiration or to introduction of salts through irrigation or capillary rise, is referred to as *salinization*. During this process, the divalent cations Ca^{2+} and Mg^{2+} remain dominant in the solution and there is no substitution of Ca^{2+} and Mg^{2+} on the exchange complex by Na^+. The total concentration of salts in the solution is generally approximated by the electrical conductivity of the saturated extract, EC_e in dS m^{-1}. An EC_e of 4 dS m^{-1} was proposed as a critical limit by the U.S. Salinity Laboratory (Richards, 1954) above which a soil is classified as saline.

Sodification is the process by which the divalent ions Ca^{2+} and Mg^{2+} on the complex are substituted for Na^+ ions, when the latter ions become dominant in the soil solution. This will affect the soil structure and stability. Generally, the ratio of sodium over the divalent cations, referred to as the *sodium adsorption ratio* (*SAR*) is used as an indicator:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \qquad (4.1)$$

with the concentrations in meq l^{-1}; the *SAR* is expressed in (mmol $l^{-1})^{0.5}$

Another important indicator is the percentage of sodium on the exchange complex, the *exchangeable sodium percentage* (*ESP*):

$$ESP = \frac{Exchangeable\ Na^+}{Cation\ exchange\ capacity} \times 100\% \qquad (4.2)$$

While the *SAR* is mainly used to evaluate the quality of waters, the *ESP* is only used for soils. Richards (1954) defined 15% as the critical limit for the *ESP*, which has subsequently been contested by scientists, who found evidence of soil degradation at much lower levels of *ESP*, i.e. in the range of 5-6 (Sumner, 1993). After inundations of parts of the Netherlands in 1945 and 1953, the critical limit of the *ESP* for clay soils was found to be in the range of 4-8% (van Hoorn and van Alphen, 1994). For the study area, Condom (1996) found evidence of soil degradation at also fairly low levels of sodium on the complex, i.e. with an *ESP* of 4. In fact, scientists have criticized the concept of the threshold level in view of the continuous effect of Na^+ (Sumner, 1993). Critical limits for *SAR* values of irrigation water follow generally the FAO classification (Ayers and Westcot, 1985), which depend on the concentration of the water to account for the fact that an irrigation water has a higher dispersion potential for water that is lower in concentration (Pratt and Suarez, 1990). The limits range from an *SAR* of 3 when the *EC* is equal to 0.7 dS m^{-1}, to an *SAR* of 40 for an *EC* of 5 dS m^{-1}. Rengasamy and Olsson (1993) define an *SAR* limit of 3, beyond which sodification is almost inevitable. The concept of the *SAR* has been criticized as Ca and Mg have been lumped together, although they have a different behaviour due to the difference in activity coefficient, the preference of many clays of Ca over Mg, and the fact that the Ca concentration is usually 2-5 times higher than that of Mg (Bresler et al., 1982). However, the *SAR* has been shown to be able to predict the sodium hazard of irrigation water in many areas around the world and is widely used.

Sodification of soils can occur either through a direct input of Na-rich irrigation water or through a more indirect process of precipitation/dissolution of minerals. This process can perhaps best be explained through the T-law (Vallès et al., 1989; Bertrand et al., 1994; Marlet, 1997). When two ions A^+ and B^- are present in the soil solution, all the minerals will remain in solution as long as the solution is under-saturated. When the soil solution is concentrated, for example because of evaporation, the concentrations of A^+ and B^- will increase equally until the saturation point is reached, see Figure 4.2. This saturation point is defined as the product of the ion activities, (A^+) and (B^-). At this point, the following reaction will take place:

$$A^+ + B^- \leftrightharpoons AB \tag{4.3}$$

When the equivalent concentrations of A^+ and B^- are not the same in a soil solution, the concentration of the ion that is present in greater quantities will continue to increase when concentrating the soil solution, while the other ion will diminish in the concentration.

Each mineral has a different saturation point, depending on the ion activities of the composing ions. Practically, in the soils being dealt with in this study, there is a need to consider calcite $CaCO_3$ and to a lesser extent sepiolite $MgSi_3O_6(OH)_2$ and gypsum $CaSO_4.2H_2O$.

The model of Hardie and Eugster (1970, quoted in Appelo and Postma, 1996) applies the T-law to the precipitation of calcite, sepiolite and gypsum for natural waters of different chemical composition, see Figure 4.3. The model has been applied to the soil solution as well (Appelo and Postma, 1996; Vallès et al., 1989; Tanji, 1990).

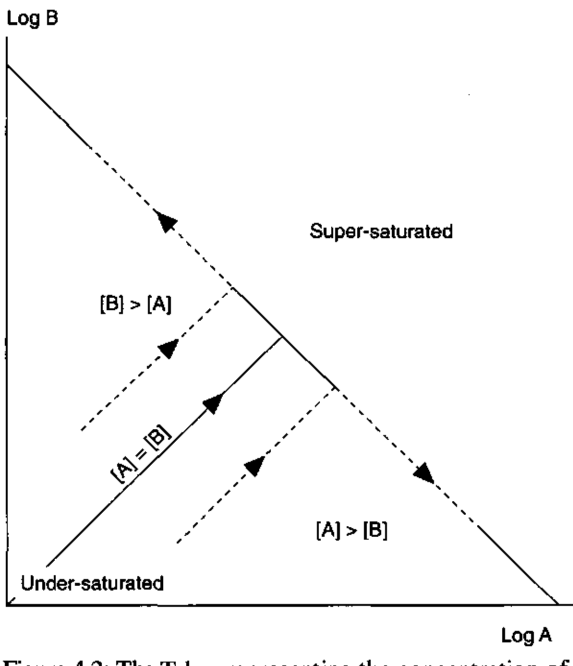

Figure 4.2: The T-law representing the concentration of a mineral AB in a solution (after Vallès, 1989).

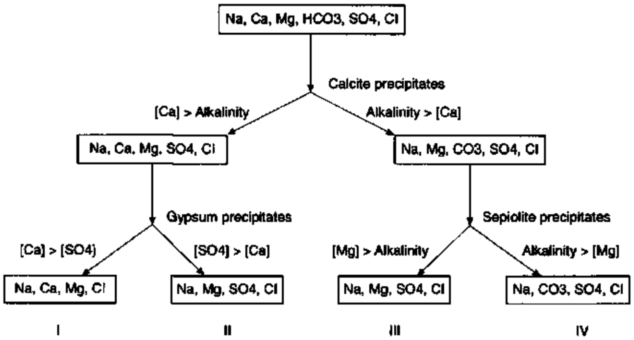

Figure 4.3: The Hardie-Eugster model of evaporative salinization of natural waters. [Concentrations] are in meq l^{-1}.

Upon precipitation of calcite, there will be an enrichment of Ca in the soil solution if the initial concentration of Ca in meq l^{-1} was higher than that of the alkalinity, which can be defined as the equivalent concentrations of HCO_3 and CO_3. In this definition, other anions, such as OH^- are neglected, because of the predominance of HCO_3^-. The concentration of Na, which does not precipitate, will also increase. However, the *SAR* values will remain nominal as long as sepiolite does not precipitate. If, however, the initial concentration of the alkalinity is higher than that of Ca, the *SAR* values will increase due to the decrease of the equivalent concentration of Ca, when concentrating the soil solution. A similar process occurs with respect to the precipitation of sepiolite. In case of gypsum precipitation, Ca and SO_4 concentrations determine whether there will be an enrichment or a decrease in the concentration of Ca.

Some evidence for the validity of this theory in the study area can be found when analyzing the composition of the groundwater pumped by tube wells. On the basis of more than 400 samples collected throughout the Chishtian Sub-division, Figure 4.4 could be constructed, which shows the *SAR* as a function of the *EC* for the tube well water.

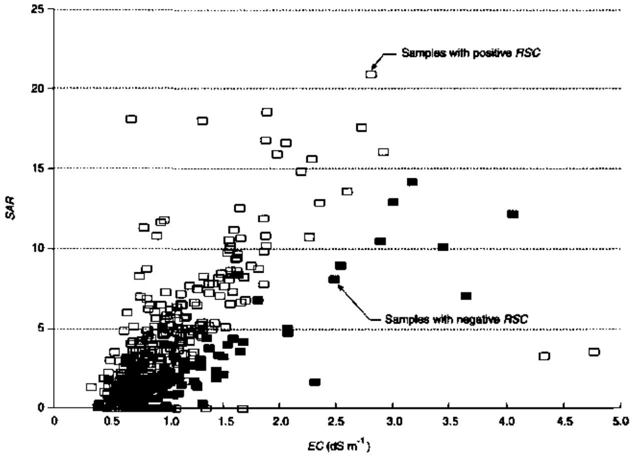

Figure 4.4: The sodium adsorption ratio (*SAR*) is given as a function of the electrical conductivity (*EC*) for 407 tube well water samples. A distinction is made between samples with a positive and a negative value of residual sodium carbonates (*RSC*).

Figure 4.4 shows that with an increasing concentration of the water, the *SAR* increases more rapidly for those waters that are dominant in (bi-) carbonates and have a positive *RSC*.

Through the analysis of soil samples, Condom (1996) demonstrated that the soils in the study area are generally over-saturated in calcite, which means that precipitation of calcite takes place at all soil moisture concentrations. However, precipitation of sepiolite and especially gypsum is likely only on non-cultivated fields, which are generally much drier than cultivated fields (Condom, 1996).

The process described above is

referred to as *alkalinization*, i.e. the process by which the Ca^{2+} and Mg^{2+} concentrations in the solution decrease and the CO_3^{2-} and HCO_3^- concentrations, which constitute jointly the alkalinity, increase while concentrating the soil solution. The importance of this process was emphasized by van Beek and van Breemen (1973), who introduced the concept of residual alkalinity, i.e. the equivalent concentrations of carbonates and bi-carbonates minus those of the divalent cations, to quantify the threat of alkalinization. This corresponds with the *residual sodium carbonates* (*RSC*) definition of Eaton (1950):

$$RSC = [HCO_3^-] + [CO_3^{2-}] - [Ca^{2+}] - [Mg^{2+}] \tag{4.4}$$

with all concentrations in meq l^{-1}.

If the *RSC* is positive, i.e. if the concentration of (bi-)carbonates exceeds those of the divalent cations, the precipitation of calcite will lead to a further increase in the alkalinity, because of the T-law. When the *RSC* is negative the alkalinity will decrease when concentrating the soil solution. An increase in the alkalinity will induce an increase also in the pH. The decrease in Ca^{2+} and Mg^{2+} ions can lead to a sodification of the soil in the long term if the sodium concentration becomes sufficiently elevated with reference to Ca^{2+} and Mg^{2+}.

Sodification occurs as a result of the application of Na-rich irrigation waters, but can also be caused by the presence of an excess of (bi-)carbonates with respect to the divalent cations. When concentrating the soil solution, the Ca concentration will decrease and the SAR will increase.

4.1.2 Effects on soils and crops

The adverse effects of soil salinity and sodicity have been described by various authors and are summarized in Table 4.1.

Table 4.1: Effects of soil salinity and sodicity on soils and plants (after Rhoades, 1982; Rhoades and Loveday, 1990; Shainberg and Singer, 1990; Läuchli and Epstein, 1990; So and Aylmore, 1993).

Causes	Effects
Salinity	Decrease osmotic potential
Salinity, sodicity	Toxicity
Salinity, sodicity	Disturbance of mineral nutrition
Sodicity	Clay swelling
Sodicity	Clay dispersion/flocculation
Sodicity	Slaking of aggregates

An important effect from an increase in the concentration of the soil solution is a decrease of the osmotic potential, which means that plants have to make more effort to extract water from the soil. Secondly, certain specific ions such as boron, chloride and sodium are toxic to crops. Besides a direct toxic effect, sodicity may also induce Ca and several micronutrient deficiencies as salt concentrations in sodic non-saline soils can be very low and the associated high levels of pH and alkalinity reduce their solubilities (Rhoades and Loveday, 1990).

Sodicity also affects plant establishment and growth through the process of soil degradation. Reduced intake rates causing aeration problems, development of surface crusts and hard or even impermeable layers, hamper water transfer in the rootzone, impede root development and may cause problems of fertility due to the dispersion of organic matter and peptization of clay particles.

The main causes of soil degradation are swelling and dispersion of clay particles, as well as slaking, i.e. dis-aggregation of soil particles into smaller units under the influence of mechanical forces, when the forces associated with osmotic swelling and air entrapment exceed the binding forces in the soil. Dispersion and slaking together lead to the formation of surface crusts and hard layers in the soil profile, which hamper infiltration and water movement through the soil profile. As soil clays are more readily dispersed under the influence of mechanical energy inputs (Sumner, 1993), the infiltration rate is much more sensitive to increasing levels of Na^+ than the hydraulic conductivity of the soil at greater depth. With mechanical disturbance, due to falling raindrops, clay movement is possible at lower *SAR* values than would be required within a saturated soil column. Consistent with what was reported above, large decreases in infiltration rates were observed by So and Aylmore (1993), even at *SAR* values of 3 when the *EC* was below 0.5 dS m^{-1}. This often leads to surface waterlogging, which affects the aeration of the soil, reduces germination, and delays cultural practices of farmers. In the study area, the existence of surface crusting and hardsetting of the soil, the occurrence of surface waterlogging, and the reduction in infiltration rates was observed by Kijne and Kuper (1995), Condom (1996) and Kielen (1996a).

4.2 Objectives and constraints of farmers dealing with salinity and sodicity

Farmers in the Indus Basin are habitually dealing with the problems generated by salinity and sodicity: "*Owners are reluctant to give up cultivation until the process of deterioration makes germination of seed impossible*" (Mehta, 1940).

There is a need to understand and analyze the salinity and sodicity management of farmers for a number of reasons. Firstly, the constraints farmers face need to be understood, since government irrigation and drainage interventions attempt to develop a physical environment that is more conducive for farmers to cultivate crops without adverse environmental effects. Only then, appropriate interventions can be formulated, which effectively help farmers to cope with the adverse effects of irrigation. Secondly, the experiences farmers have had in coping with salinity and sodicity can be beneficial for devising interventions. Finally, there is a large range in farmers' socio-economic background. This background will determine to a large degree whether farmers can or want to take advantage of the opportunities that are offered to them.

The way farmers cope with salinity and sodicity has not received much attention so far, despite the wealth of literature on salinity in the Indus Basin. In some cases, engineers have sought to understand why farmers did not adopt reclamation techniques, promoted by the agricultural services as part of the larger government programmes to deal with salinity (e.g. IWASRI, 1991). Although these reports contain useful information, they are often summaries of the responses of a large number of farmers spread over millions of ha to a questionnaire, which makes them difficult to analyze. Farmer observations are not geo-referenced, cannot be linked to the specific conditions they are faced with, and cannot be quantified. An analysis of farmer management is more interesting if it can be linked with a quantitative data set. In the study area a large data set had already been obtained regarding physical conditions, in terms of soils, salinity and sodicity, groundwater tables and on the farm characteristics. This provided a good foundation for a more qualitative survey on farmers' perceptions of salinity and sodicity (Kielen, 1996a and b, Kielen et al., 1996). In this section, some of the results from these studies are described and linked with other data available for the study area.

The following five questions will be addressed in this section:

- At which levels of salinity and sodicity do farmers experience adverse effects?
- How do farmers judge the quality of irrigation water?

In Section 4.2.1, the main effects of salinity and sodicity, according to the farmers, will first be described. The perceptions of farmers will then be cross-referenced with quantitative data that is available on the extent of salinity and sodicity of soils and waters. This will enable the determination at which levels of EC_e and SAR, farmers experience the adverse effects of salinity and sodicity. Apart from the identification of the causes of salinity and sodicity, the permeability hazard of irrigation water can be verified by once again linking quantitative data to farmers' assessments.

- What are the measures farmers take to cope with salinity and sodicity?
- How are these measures related to the farm characteristics?

In Section 4.2.2 an overview of these measures will be presented. A limitation of the study is that no observations have been made to quantify the effect of these measures on salinity and sodicity. These measures will then be analyzed in the light of the farm characteristics in order to understand under which conditions certain measures are taken.

- What are the present constraints that farmers face in their crop production related to salinity and sodicity?

This question will be addressed in Section 4.2.3 and will follow from the analyses in Sections 4.2.1 and 4.2.2.

4.2.1 Farmers' classification of salinity and sodicity

Farmers use a vernacular terminology to define and classify salinity and sodicity phenomena, see Table 4.2. The classification is based on visual characteristics, such as the white efflorescence on soil surfaces or the dark film caused by a dispersion of organic matter, the physical degradation (reduced intake rate, surface crust or hard layers), and the effects on crop growth, e.g. germination problems. The classification that was used by the Central Board of Irrigation (1941) resembles this classification. In this classification the Board of Irrigation tried to link the visual characteristics with the type of salts present in the soil solution. White salinity or *kallar* was associated with sodium and magnesium chlorides, while black kallar was mainly found in the presence of sodium carbonates. In this classification brown (KNO_3) and dark ($MgCl_2$ and $CaCl_2$) kallar were also defined. Farmers in the study area distinguish mainly between white or *chitta* kallar and black or *kala* kallar in terms of visual characteristics. A surface crust is mainly associated with white salinity, while black salinity is often accompanied by hard layers at the surface or in the profile, i.e. *zacht*. *Kallar shor*, mentioned in the 1941 classification as "impregnated with salts", is a soil that is difficult to cultivate due to its poor physical properties.

Table 4.2: Vernacular soil salinity and sodicity classification, based mainly on visual characteristics, (after the Central Board of Irrigation, 1941; Kielen, 1996b).

Classes	Characteristics
Chitta kallar	White (chitta) efflorescence, surface crust
Kala kallar	Black (kala) appearance with hard upper soil layer
Zacht	Hard layers in the profile
Kallar shor	White salts at the surface, extremely difficult to cultivate

When relating farmers' observations to the results of soil samples, it appeared that farmers observe *chitta kallar* to occur at EC_e levels of 2.4 dS m^{-1} and higher, while *zacht* happens at *SAR* levels as low as 6 (Kielen, 1996b), which corresponds to an *ESP* of only 7 when using the relationship developed by the USDA (Richards, 1954). The values that are thus obtained, are much lower than the criteria defined in the same publication (Richards, 1954), where an EC_e of 4 dS m^{-1} and an *ESP* of 15 are assumed to distinguish between non-saline and saline, and non-sodic and sodic soils. This is an important observation, as these criteria are often used in Pakistan as a reference. The distinction between salinity and sodicity is not as much appreciated by farmers as it is in the USDA classification while "sodic" and "saline" soils are sometimes grouped together by them. However, soils classified as kala kallar have higher levels of *SAR* than other soils, including those affected by chitta kallar. Soils classified as chitta kallar have higher EC_e levels than other soils (Kielen, 1996b).

Farmers recognize the different origins of salinity and/or sodicity status, relating them to *the presence of high groundwater tables, to genetic salinity and to the use of poor quality irrigation water.* Farmers appreciate the potential contribution of *high groundwater tables* to salinity and sodicity problems, even though these groundwater tables can provide considerable amounts of water to the crop. The extent of area affected by high groundwater tables in the study area is limited.

Genetic salinity and sodicity covered substantial parts of the Chishtian Sub-division, but farmers have reclaimed large tracts using canal water. Some of these soils, e.g. the dense sodic soils, have physical properties, which make them difficult to cultivate, and pose lasting limitations to farmers (Soil Survey of Pakistan, 1996).

The use of poor quality irrigation water, pumped by tube wells, is a relatively recent phenomenon, from

1985 onwards, but is well known by farmers. Farmers differentiate the impact of various tube well waters on soil and plants conditions. The importance of the quality of irrigation water can be appreciated from the farmers' classification of irrigation water. Generally, irrigation water is evaluated for its effect on soils and crops: the water of a certain tube well causes *zacht* or a hard layer in the profile. The classification is not entirely in line with the FAO classification of Ayers and Westcot (1985), who emphasize the risk of reduced infiltration rates with waters of low salt concentration and a relatively high amount of sodium (expressed as an *SAR*), see Figure 4.5. The greatest disagreement relates perhaps to canal water with an *EC* of 0.19 and an *SAR* of 0.2, which poses according to the FAO classification a moderate sodicity hazard but is judged to be of excellent quality by farmers. According to farmers, tube well water with an *SAR* greater than 5 and an *EC* greater than 1.0 dS m^{-1} causes hard layers in the soil, see Figure 4.5.

Farmers indicate that the adverse effects of poor quality irrigation water are felt quite rapidly. After 2-3 irrigations with such water, a surface crust develops, while hard layers in the soil can occur within an irrigation season. Their views were confirmed by Condom (1996), who used a geo-chemical model in conjunction with a solute transfer model and provided evidence for a rapid sodification of soils.

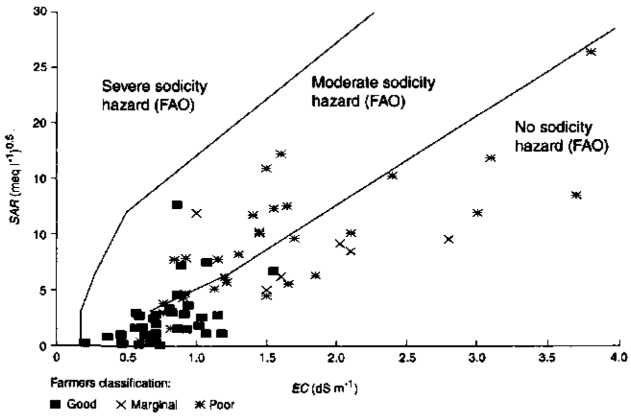

Figure 4.5: Farmers' perceptions of the irrigation water quality (good, marginal and poor) in comparison with the FAO classification (Ayers and Westcot, 1985). The figure depicts the measured salt concentration, expressed as an electrical conductivity (*EC*), versus the sodium adsorption ratio (*SAR*). The farmers' perceptions of the water quality are obtained from Kielen (1996b).

From Figure 4.5 it appears that the logic of the FAO classification does not correspond with farmers perceptions. The FAO emphasizes the physical logic. When a soil is irrigated with water having a low concentration in salts, the Diffuse Double Layer tends to increase in size, degrading the soil structure and reducing the hydraulic conductivity. This increase is favoured by the presence of the mono valent cation Na^+ as opposed to the divalent cations Ca^{2+} and Mg^{2+}, i.e. high values of *SAR*.

Farmers have a long term perspective. Irrigation waters with high salt concentrations are more likely to cause soil salinity and sodicity, especially when they are dominated by sodium bi-carbonates. The views of farmers were confirmed in a modelling exercise where the *ESP* of a soil was determined while concentrating the soil water (Condom, 1996). An *ESP* of 15 was attained with a 5-fold concentration of irrigation water with an *EC* of 1.4 dS m^{-1}, while a 10-fold concentration was required to obtain an *ESP* of 15 for an irrigation water with a lower *EC*, i.e. 0.8 dS m^{-1}, but with a similar chemical composition.

In Figure 4.6, the *RSC* is presented as a function of the *EC* of the tube well water. When the *EC* is lower than 1.5 dS m^{-1}, farmers appreciate the difference in positive and negative values of the *RSC*. However, the *EC* of the irrigation water is shown to be a more pertinent indicator for farmers. A comparison is made with the WAPDA classification (Qayyum and Sabir, 1975), which is more lenient than farmers' judgment. Where the WAPDA classification specifies 1000 ppm of total dissolved solids (equivalent to an *EC* of about 1.6 dS m^{-1}) as the limit between "safe" and "marginal" water quality, farmers tend to define the limit at 1 dS m^{-1}.

An explanation for the fact that farmers do not detect alkalinization may be the fact that the process is slow, which makes it difficult to detect for farmers as it is concealed by the more rapid processes of salinization and sodification. Some evidence for this explanation is provided by Condom (1996) in a modelling study with soils of the study area. It was found that an excess of bi-carbonates in the irrigation water, resulting in positive *RSC* values, did not lead to alkalinization. This was attributed to the stock of di-valent cations on the exchange complex which neutralize the alkalinity of the soil water. However, it must be kept in mind that the simulations were carried out only for a one year period and that alkalinization could not be verified for a longer time span.

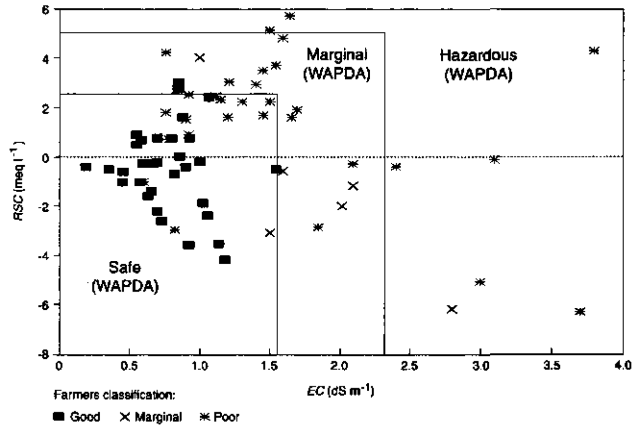

Figure 4.6: Farmers' perceptions of the irrigation water quality compared with laboratory measurements of the same tube well waters. The measured salt concentration is presented, expressed as an electrical conductivity (*EC*), versus the residual sodium carbonate (*RSC*). A comparison is made with the WAPDA classification, which is shown to be less strict than farmers are in evaluating the effects of irrigation water quality.

Farmers perceive the quality of the irrigation water pumped by tube wells as the main cause for salinization and sodification. The impact of sodicity on the physical properties of soils is rapid, i.e. within a growing season, and occurs according to farmers already at an EC_e *of 2.4 dS* m^{-1} *and an ESP of 7. Irrigation water with an EC higher than 1 dS* m^{-1} *can cause salinization and water with an SAR higher than 5 may cause soil degradation.*

4.2.2 Farmers' strategies and measures to cope with salinity and sodicity

Not all farmers think alike about salinity and sodicity. While some want to reduce levels of salinity and sodicity, others appear to do nothing. In order to understand how farmers will react to changes in their irrigation environment, it was necessary to analyze farmers' strategies and practices vis-à-vis salinity and sodicity. A complete analysis of farmers' salinity strategies was only possible once an understanding of the larger farming systems was gained through economic studies (Strosser and Rieu, 1993; Rinaudo, 1994). Rinaudo (1994) developed a farm typology for the study area, distinguishing between 11 farm types with an aim to differentiate between the reaction of farmers in terms of a crop choice and irrigation strategy to a change in access to irrigation supplies, see Table 4.3.

Table 4.3: Farm strategies for 11 farm types that were distinguished in the study area. After Rinaudo, 1994.

Farm strategy	Auto-consumption			Market orientation							
				Wheat-Cotton			Diversified cropping pattern				
	Intensive		Extensive	Tenants			Small landowners, limited credit		Large landowners, mechanized		
Group	1	7	8	4	5	6	2	3	9	10	11

The main distinguishing features are the intensity of agricultural production, i.e. subsistence versus market-oriented farmers, access to canal water, tube well ownership, land ownership and farm constraints, such as labour or credit. Groups 7 and 8 distinguish themselves by a smaller than average landholding size than other groups. Groups 4, 5 and 6 consist of tenants, who concentrate on wheat-cotton cultivation. The farmers of Group 6 have much less access to canal water than those of Groups 4 and 5. Farmers of Group 11 have very large landholdings, even compared with those of Group 9 and 10. Farmers of Group 9 have a better access to canal water than the farmers of Groups 10 and 11.

Based on interviews with farmers Kielen (1996b) identified a number of salinity and sodicity strategies in the study area. These have been adapted and are listed in Table 4.4. These strategies can be linked with the farm types identified by Rinaudo (1994).

Table 4.4: Farmers' salinity and sodicity strategies in relation to farm characteristics.

Salinity/sodicity strategy	Farm group
Mitigate the effects on crop yields	1, 2, 3, 4, 5, 6
Intensive salinity/sodicity control	7, 9, 10, 11
Extensive salinity/sodicity control	2, 3, 8, 4, 5, 6
No strategy	all

A large group of farmers is unable to reduce/prevent salinity and sodicity, because of financial constraints or because they do not feel concerned about the land when they are tenants. Even then farmers often try to *mitigate the adverse effects of salinity and sodicity on crops*, for instance, by increasing the frequency of irrigation to have a wetter soil profile. The measures that farmers take are generally low cost. In some cases, these farmers are faced with extreme physical limitations, such as shallow groundwater tables or no access to good quality water, which make it difficult to define a strategy.

Farmers with a better financial position, and involved in an intensive, high investment type of farming, are generally more inclined to go one step further and deal with salinity and sodicity more *intensively*.

They attempt to prevent or even reduce salinity and sodicity. Whether they prevent or reduce salinity largely depends on the physical conditions of their land. In addition to the measures of the previous group, these farmers also implement higher cost solutions, such as the application of gypsum.

A more *extensive* salinity and sodicity control is adopted by tenants, who have no security that they will remain on their lands for more than 1-2 years, and by a number of farmers that have no land constraint. They leave certain fields subject to increases in salinity and sodicity and concentrate on keeping the rest of their farm salt free. Cropping intensities are generally low for these farmers. The measures that farmers take in this category are generally low cost and require relatively little effort.

Farmers who do *not* appear to have a *clear salinity and sodicity strategy* do not belong to a single group. There are farmers who have only recently been confronted with salinity and sodicity, e.g., due to an increased cropping intensity and less access to canal water. They are hesitant to initiate measures and have limited experience in dealing with this problem (Kielen et al., 1996). Other farmers do not face problems with salinity and sodicity and thus have no need for a salinity strategy. Finally, there are also marginal farmers with low investments and low returns from agriculture, who often have serious financial problems, and do not have an explicit salinity strategy (Kielen, 1996b). Although no clear strategy was noted, some of these farmers occasionally implement measures that impact on salinity, but they do not amount to much.

Salinity and sodicity strategies are related to the overall farm strategies and characteristics. Four different salinity and sodicity strategies were identified. The choice of such a strategy is also influenced by the physical environment and by the experience of a farmer with issues of salinity and sodicity.

Farmers have adopted a large number of *measures* in their management of salinity and sodicity. Initial observations on farmers' practices showed that farmers were using tube wells to mitigate the effect of salinity on crop yields by irrigating more frequently (Kuper and van Waijjen, 1993). It was further shown that farmers mix poor quality groundwater with canal water to lessen the adverse effects on the soil. By mixing canal and tube well water, farmers often succeed in keeping the salinity of the irrigation water below an EC of 1.15 dS m^{-1}. An overview of these measures is presented in Table 4.5. The list of measures has been adapted from Kielen (1996a). The measures are grouped into four types of interventions, i.e. *water management, crop choice, cultural practices, and biotic and chemical amendments*. The salinity/sodicity strategies that are associated with these measures are also presented.

Table 4.5 Farmers' measures related to salinity and sodicity management. Measures are classified into four main categories. The measures are related to the salinity/sodicity strategy that farmers have adopted.

Category	Measures	Salinity/sodicity strategies
Water management	Maximize canal water quantity	All
	Minimize tube well water use	Extensive control
	Selection of tube well with the best quality water	All
	Mix tube well and canal water	All
	Intra-farm water allocation	Extensive control
	Frequency of irrigation	Mitigate effects
	Leaching prior to sowing	Mitigate effects
Crop choice	Plant priority crops in non-saline fields, others in saline fields	Extensive control
	Leave saline fields fallow	Extensive control
	Plant rice	All
	Plant salinity resistant crops	Intensive control
	Plant salinity tolerant crops	In- and extensive control
	Minimize fallow periods	Mitigate effects
Cultural practices	Land levelling	Intensive control
	Remove top layer	Extensive control
	Adding sand	Extensive control
	Hoeing to break the surface crust	Mitigate effects
Biotic and chemical amendments	Gypsum	Intensive control
	Sulphuric acid	Intensive control
	Farm yard manure	Intensive control
	Fertilizers	Intensive control
	Plant stems	Intensive control

Water management is widely used by farmers to manage salinity and sodicity and is thus associated with all salinity/sodicity strategies. The preference of farmers will generally be to maximize the amount of canal water they receive by increasing the flow to the tertiary unit. This was evidenced by the farmers of a tertiary unit near the study area, who managed to improve the quality of their irrigation water substantially, bringing down the average *EC* of their overall irrigation water from 1.46 to 0.73 dS m^{-1}. A subsequent increase of the cropped area was observed (Kuper and van Waijjen, 1993). Even farmers that have no clear salinity/sodicity strategy are unequivocal in their intention of obtaining the maximum amount of canal water. Farmers also try to minimize irrigating with tube well water as much as possible as they know the adverse effects on soils and crops, but are often not in a position to avoid it altogether. When they irrigate with tube well water, they try to obtain water from a tube well with a reputation for good water quality. Some farmers even eschew their own tube well water and purchase other water. Some farmers mix canal water and tube well water to increase the discharge, enabling a better irrigation application, and diluting the higher concentration tube well water. Other farmers use it alternately. Farmers plan the allocation of water to different fields carefully. Some farmers apply canal water to the non-saline/sodic fields in order not to contaminate them, others apply canal water to saline/sodic fields in order to prevent a further increase in salinity and sodicity. Thus, the intra-farm water allocation depends also on the salinity/sodicity strategy of the farmer. In all cases, farmers take the crop type into account when deciding on the water allocation. Priority crops will generally receive a larger share of canal water. The proliferation of tube wells has enabled farmers to irrigate more frequently, thus keeping the rootzone wetter and minimizing the osmotic effect of salts (Kuper and van Waijjen, 1993). Another measure farmers routinely take is the application of a large pre-sowing irrigation dose, preferably with canal water. This serves to flush some of the salts in order to prepare the seed beds (Smets, 1996; Meerbach, 1996). The effectiveness of the cyclic use of canal and tube well water in Pakistan and a large pre-sowing irrigation dose in particular was confirmed in a lysimeter experiment, where blending of canal and tube well water proved less effective in keeping EC_e and SAR levels low than alternate irrigations (Hussain et al., 1990).

The *crop choice* is an important intervention used by farmers in dealing with salinity and sodicity. This intervention is generally associated with farmers who mitigate the adverse effects of salinity and sodicity, or who adapt to the existing physical conditions and make the best of it. A first measure consists of planting the priority crops, either cash crops or those crops important to feed the family, in non-saline/sodic fields, while leaving those fields for non-priority crops such as oil seeds. Sometimes these fields are even left fallow. This measure is possible only if land is not a constraint to a farmer. Often rice is planted in saline or sodic fields, as rice is quite tolerant to salinity and sodicity, but more importantly because rice tolerates maintaining a layer of water on the fields thus enabling a leaching of the soil. Rice is often adopted also during a reclamation process. Other crops that are adopted to reduce the salinity and sodicity levels in fields are kallar grass (*Leptochloa fusca*) and janter (*Sesbania acculiata*). These crops are salinity resistant but do not generate much revenue. Farmers replace them usually as soon as possible with rice. When salinity/sodicity levels are not too high it is possible to cultivate a wider range of crops. Farmers take the tolerance of various crops to salinity and sodicity into account when deciding on the crop choice. Another development is the screening of salt-tolerant varieties of the major crops by researchers in Pakistan (Ahmed et al., 1990). In those areas where groundwater tables are sufficiently near the surface to cause capillary rise, farmers are keen to maintain a downward flux of water by minimizing the fallow periods.

The effects of sodicity on the soil structure are partially dealt with by farmers through their *cultural practices*. By levelling their lands they eliminate the high spots, which are more prone to salinity and sodicity, and ensure a better distribution of water. More crude measures include the removal of the top layer of soils, which is sold to brick kilns, thus removing a salinity and/or sodicity affected top soil and enabling a better water control by lowering their fields. Farmers generally consider the effect of removing the top layer short lived. Some farmers add sand to salinity and/or sodicity affected soils in order to cultivate better seed beds. The effect of this measure is also viewed to be short lived. Finally, the soil crust that formed after sowing and the first irrigation is often broken by farmers by hoeing. This is done especially in case of cotton, as the crop is planted in rows and is more accessible, and is viewed to be more susceptible to adverse effects on plant growth.

A number of *chemical and biotic amendments* are applied by farmers. This is generally practiced by those farmers with an intensive salinity control strategy. Gypsum is promoted by the provincial Agricultural Departments in Pakistan and has been widely investigated (e.g. Ahmad et al., 1990; Ghafoor et al., 1988). The positive effect of gypsum on the soil structure is recognized by farmers, but the difficulties in obtaining gypsum on the market prevent a more widespread use of this amendment. Only those farmers that have the resources to actively pursue the purchase of gypsum are using this amendment, despite its relatively low price. Sulphuric acid is even more difficult to obtain and is also difficult to handle. Its price is also prohibitive for large numbers of farmers. Traditionally, farmers use farm yard manure and plant stems of cotton or other plants to improve the structure of the soil. However, since both materials are also widely used in the family cooking stoves as fuel, not all farmers are in a position to apply these amendments. The effect of sodicity on plant nutrition is addressed by farmers through the application of fertilizers. They claim that fertilizers also have a positive effect on the soil by making the soil "soft".

Farmers apply a wide range of measures either to mitigate the effects of salinity and sodicity on crops or to control levels of salinity and sodicity. This salinity/sodicity control is in some cases rather extensive, especially by those farmers that have sufficient land so that they can leave aside their saline or sodic soils, but is in other cases intensive with large investments to reduce salinity and sodicity or prevent it from occurring. The measures are mostly related to water management, crop choice, cultural practices and the application of chemical and biotic amendments. The choice of the measure depends largely on the farm characteristics, the experience of the farmer or other farmers with certain measures, and on the strategy the farmer has adopted to deal with salinity and sodicity.

4.2.3 Scope for irrigation management interventions to help farmers in dealing with salinity and sodicity

The constraints farmers face in coping with salinity and sodicity are related both to the physical environment, and to farm characteristics. Physical constraints relate mainly to high groundwater tables, groundwater quality, saline/sodic soils, and access to canal water. High groundwater tables affect about 5-10% of the study area, to which farmers have adapted by planting rice and leaching practices. The soils in the study area are generally very suitable for crop cultivation. A limited area has natural sodic soils with poor physical properties (Soil Survey of Pakistan, 1997). Farmers have further demonstrated the ability to reclaim these lands provided they had access to sufficient fresh water resources. A little less than 50% of the tertiary units have groundwater resources that can be considered unsafe for irrigation, i.e. having an *EC* higher than 1 dS m^{-1}, an *SAR* higher than 5 and an *RSC* higher than 2.5. This figure is lower if the final irrigation water quality is calculated including canal water. Finally, an estimated 40% of the farmers, mainly those of Groups 6, 8, 10 and 11, have limited to no access to canal water. This is a problem in areas with a poor groundwater quality. In other areas, farmers can tap groundwater resources either through their own tube well or through water market (Strosser and Kuper, 1994).

The constraints associated with the socio-economic background of farmers, relate mainly to labour, credit, land ownership, education, etc. This makes it unlikely that all farmers will react to irrigation management interventions in the same way. An improved access to canal water, for example, will be used by a resourceful, market-oriented farmer of Group 11, to increase the production, while the auto-consumption oriented farmers of Group 8 have limited financial resources and not much land so that the impact is likely to be socially beneficial, but will probably not increase the production much. This qualitative statement can be quantified with the approach developed by Strosser (1997) and Rinaudo et al. (1997a), who propose the use of linear programming economic models to predict the impact of changes in water supplies on agricultural production.

The importance of good quality water confirms the results of an earlier survey carried out by IWASRI in the Punjab and Sindh, where more than 70% of the farmers attributed their reticence in reclaiming salt-affected areas to the lack of canal water (IWASRI, 1991). Of course, the attribute of canal water is not only its excellent quality, but also its low cost. How much farmers are prepared to pay for good quality water is probably not very difficult to answer given the importance of existing water markets, although the price will depend also on reliability of canal supplies (Meinzen-Dick, 1996). Strosser (1997) finds that farmers are on average ready to pay at least the price of tube well water, although this can be lower in case of a very unreliable supply.

The lack of financial resources constrains a number of farmers in their salinity and sodicity management. This is mainly associated with Groups 1, 2, 4, 5, 6 and 8, but affects almost all farmers except those of Group 11 (Rinaudo et al., 1997a). The main consequence of this constraint is that most farmers will try to avoid high cost measures, such as the application of chemical amendments. The labour constraint affects very few farmers, mainly of Group 11. In some cases they do not differentiate in the cultivation of their fields, whether saline or not, for lack of labour. Landownership and tenancy has been mentioned quite a few times in this section to explain the behaviour of farmers. About 30-40% of the farmers in the area are tenants or rent land, and are, therefore, less likely to adopt an active salinity/sodicity strategy. This is, therefore, an important issue. The status of these tenants makes a difference, though, because certain tenants are associated for longer periods with their lands and may resemble landowners in their decisions.

Although all these constraints seem overwhelming, they offer also opportunities for interventions arising from the heterogeneity of these constraints. If these interventions are designed to meet the site specific needs of farmers, a good balance can be found in meeting the economic and social objectives of an irrigation system. Although canal water in sufficient quantities is clearly seen by all farmers as the best solution to dealing with salinity and sodicity, there are farmers who can obtain good quality water from the aquifer, through their own tube wells or through water markets. A redistribution of canal water could meet the needs of farmers.

The availability of good quality irrigation water is seen as the most important condition for successful salinity and sodicity control by farmers. Changing the access to good quality water will not have the same effects on the decisions related to salinity, sodicity and agricultural production for all farmers, *due to the diversity in farm strategies and resources. This is investigated in the parallel study by Strosser (1997), the results of which will be used in an integrated approach in Chapter 5.*

4.3 Methodology

In this section, a methodology is presented to determine the effects of different irrigation regimes on soil salinity and sodicity. To quantify the impact of irrigation application on the soil salinity, a one-dimensional soil water flow - solute transport model, SWAP93 was used at the field level for the relevant soils of the study area. The model enables an assessment of the marginal impact of different irrigation regimes, and predictions for long-term salinity developments, but does not deal with the chemical processes that occur in the soil solution, i.e. precipitation/dissolution and exchanges between the soil solution and the exchange complex of clay particles. Prediction of long-term sodicity developments is more difficult than it is for salinity. Existing empirical relations were tested for the field observations in the study area. In addition, a regression analysis was carried out to establish an equation for the study area.

In Section 4.3.1, a description of the soil water flow and solute transport is given, which forms the basis of the model SWAP93. The model will be briefly described. In Section 4.3.2 the predictive sodium hazard functions will be further detailed.

4.3.1 Unsaturated flow of water and solutes: basic principles and description of SWAP93

SWAP93 has been developed to simulate water, solute and heat transport in the air-plant-soil environment (Feddes et al., 1988; van Dam et al., 1997). It considers one-dimensional vertical flow only. The basic principles underlying the model, i.e. soil water flow, solute transport and root water extraction, will be treated first. Then a short explanation of the use of the model as well as a description of the input and output files will be provided.

Soil water flow

Transfer of solutes in the unsaturated zone is linked closely with the soil-water flow, which is usually described by the Richards equation, which combines Darcy's law with the classical continuity equation (conservation of mass). The equation applies equally to saturated and unsaturated flow. If the flow is described only in the vertical direction, the equation reads:

$$C(h)\,\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[\,K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S(h) \qquad (4.5)$$

where:

$C(h)$	=	differential moisture capacity or $d\theta/dh$	[cm^{-1}]
θ	=	soil moisture content	[$cm^3\ cm^{-3}$]

$K(h)$	=	hydraulic conductivity	[cm d^{-1}]
h	=	pressure head	[cm]
t	=	time	[d]
z	=	height (positive upwards, origin at the soil surface)	[cm]
$S(h)$	=	root water uptake (sink term)	[d^{-1}]

The numerical solution of Equation 4.5 is not straightforward due to the non-linearity of the relationships between θ, h, and K.

The soil water retention function, $\theta(h)$, and the unsaturated hydraulic conductivity function, $K(h)$, need to be established in order to solve Equation 4.5. These functions have a determinant effect on the simulated soil water flux. For unsaturated flow, where part of the pores are filled with air, the higher the soil moisture content, θ, the higher K will be as the area that is available for flow (i.e. the pores) increases. The pressure head, h, on the other hand decreases when θ increases. It is 0 when the soil is saturated and 10^7 when it is oven dry. An example of these two important relationships is given in Figures 4.7 and 4.8 for a number of soil types in the study area.

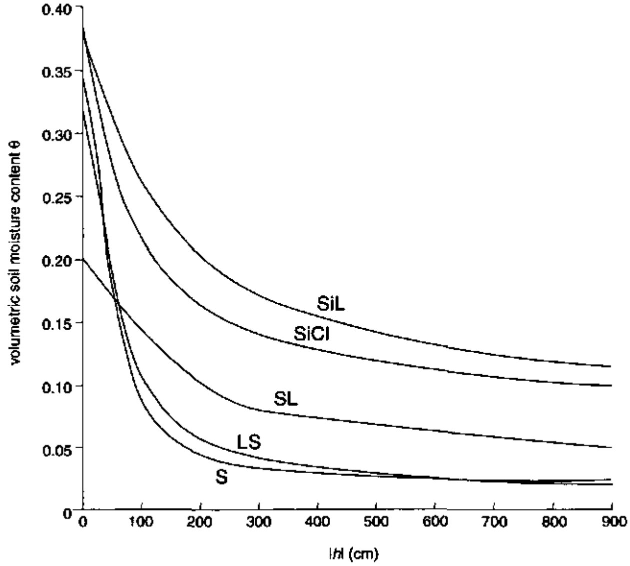

Figure 4.7: The volumetric soil moisture content as a function of the absolute value of the pressure head $|h|$ for a number of soils in the study area, i.e. a silty loam (SiL), a silty clay loam (SiCL), a sandy loam (SL), a loamy sand (LS) and a sand (S) (after Smets et al., 1997).

In SWAP93 the equation is discretized through a finite difference scheme, which applies both to the saturated and unsaturated zone and is mass conservative (Celia et al., 1990; van Dam and Feddes, 1996).

The h(θ) and K(θ) relations are determined here by the Van Genuchten-Mualem model. This analytical model describes the soil hydraulic functions with a limited number of parameters, the so-called Van Genuchten-Mualem parameters.

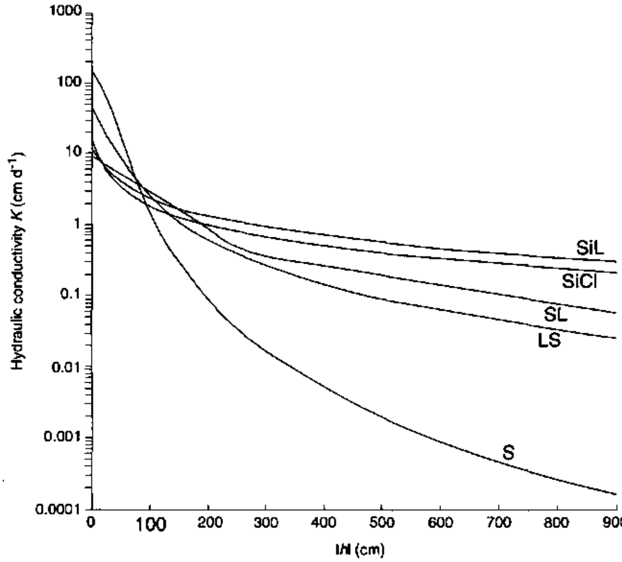

Figure 4.8: The hydraulic conductivity as a function of the absolute value of the pressure head $|h|$ for a number of soils of the study area, i.e. a silty loam (SiL), a silty clay loam (SiCL), a sandy loam (SL), a loamy sand (LS) and a sand (S) (after Smets et al., 1997).

The $\theta(h)$ relationship is expressed as:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \tag{4.6}$$

with:

$$m = 1 - \frac{1}{n} \tag{4.7}$$

where:

θ_s	=	saturated soil moisture content	[$cm^3\ cm^{-3}$]
θ_r	=	residual soil moisture content	[$cm^3\ cm^{-3}$]
α	=	empirical shape parameter	[cm^{-1}]
λ, n	=	empirical shape parameters	[-]

The $K(h)$ relationship is empirically expressed as:

$$K(h) = K_s \frac{[(1 + |\alpha h|^n)^m - |\alpha h|^{n-1}]^2}{(1 + |\alpha h|^n)^{m(\lambda+2)}} \tag{4.8}$$

where:

K_s	=	saturated hydraulic conductivity	[cm d^{-1}]

The parameter α roughly corresponds to the inverse of h at the inflection point of the retention curve ($\partial\theta/\partial h$ is maximal), n is the gradient $\partial\theta/\partial h$ and is a measure of the width of the pore size distribution. The parameter λ is a pore connectivity factor that expresses the correlation between pores and flow path tortuosity (Wösten and Van Genuchten, 1988). The values of the Van Genuchten-Mualem parameters for different soil types have been determined by several authors (Carsel and Parrish, 1988; Rawls et al., 1982; Wösten et al., 1987).

Solute transport

The most important transport mechanisms that govern solute transport in the unsaturated zone (if solutes are considered to be conservative and do not precipitate/dissolve) are convection, dispersion, diffusion and adsorption. Convection is the process by which solutes are transported in the liquid phase. Mechanical dispersion is caused by the differences in size and shape of the pores and results in an uneven distribution of the flow velocity. Molecular diffusion is prompted by the variation in solute concentration within the liquid phase. Adsorption is often considered in transport equations to account for observed retardation in solute transport (van Dam and Feddes, 1996).

To describe the unsteady state vertical solute transport the convection-dispersion equation is used in SWAP93:

$$\frac{\partial(\theta c)}{\partial t} = -\frac{\partial q_s}{\partial z} - S_r \tag{4.9}$$

with:

$$q_s = -\theta D(V,\theta)\frac{\partial c}{\partial z} + qc \tag{4.10}$$

and:

$$D(V,\theta) = D_h(V) + D_e(\theta) \tag{4.11}$$

and:

$$V = \frac{q}{\theta} \tag{4.12}$$

where:

q_s	= solute flux	[g cm^{-2} d^{-1}]
c	= solute concentration	[g cm^{-3}]
S_r	= sink term for solute loss due to plant salt uptake	[g $cm^{-3}d^{-1}$]
V	= average pore water flow velocity	[cm d^{-1}]
D_h	= mechanical dispersion coefficient	[cm^2 d^{-1}]
D_e	= molecular diffusion coefficient	[cm^2 d^{-1}]
D	= hydro-dynamic dispersion coefficient	[cm^2 d^{-1}]

This equation is solved numerically in SWAP93 using an explicit central difference scheme taken from Boesten and van der Linden (1991). The solute transport equation is valid for dynamic, one-dimensional, convective-dispersive, mass transport, including non-linear adsorption, linear decay and proportional root uptake in both the saturated and unsaturated conditions (van Dam et al., 1997).

Root water extraction

An important orientation of SWAP93 is the interaction between water and solute transfer and the extraction of water by plants, represented by the sink term in Equation 4.5 (Feddes et al., 1978; van Dam et al., 1997). The root water extraction rate under saline conditions can thus be analyzed by combining the direct water stress with salinity induced stress. In the model, this is done by adding the matric head, h, and the osmotic head, π, of a saline soil:

$$h_{total} = h + k_{osm}\,\pi \tag{4.13}$$

with

k_{osm} = crop specific coefficient [-]

k_{osm} can be adjusted in the input file. This is done only in dry conditions, i.e. at high values of h. In wet conditions, h_{total} is equal to h.

The root water extraction rate was described by Feddes et al. (1978) as a dimensionless, plant specific function, whereby the root water uptake is reduced when the pressure head h is either too low or too high, corresponding with a wet and a dry profile respectively. The sink term function α is presented in Figure 4.9.

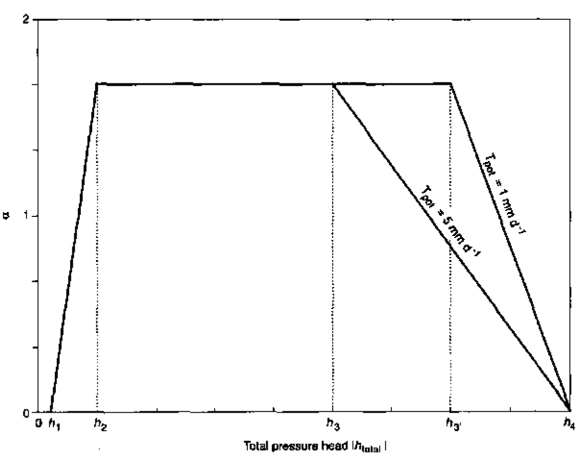

Figure 4.9: The dimensionless sink term α as a function of the absolute value of the total pressure head h_{total}. When h_{total} is below h_2 or above h_3, the root water uptake is reduced. Below h_1 no water uptake takes place due to oxygen deficiency, while above the wilting point, h_4, the plant is not able to extract water.

Model description

SWAP93 simulates water, heat and solute transport in the vertical direction. The inputs and outputs of the model are defined in Figure 4.8. The inputs include a definition of the top and bottom boundary conditions, a definition of the soil type through the Van Genuchten-Mualem parameters, which define the soil hydraulic functions, the crop schedule, and the time step.

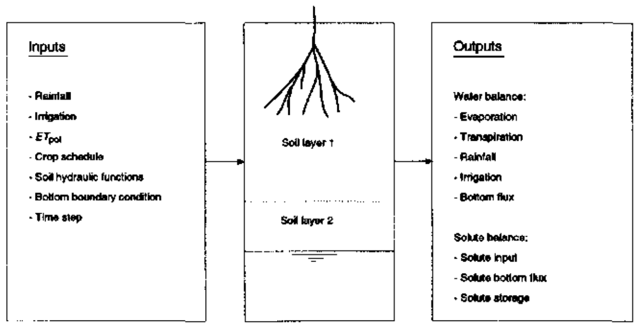

Figure 4.10: Representation of the soil water flow - solute transfer model SWAP93. Inputs and outputs of the model are defined.

The outputs, given also in Figure 4.10, are cumulative values of those parameters that constitute the water and salt balance. SWAP93 provides the moisture and salt content for each soil compartment at every time step in the output file. The cumulative daily potential as well as actual transpiration rate is also provided in the output file.

In SWAP93, a maximum of five different soil layers can be defined. In each of these layers, the Van Genuchten-Mualem parameters can be defined differently. The total soil profile can have a maximum of 40 compartments with a thickness generally in the range of 5 cm depending on the moisture gradient of the soil. Smaller thicknesses are applied near the soil surface in order to calculate more accurately the infiltration and evaporation.

Boundary conditions

The top boundary conditions are described by the daily potential evapotranspiration, ET_{pot}, by the precipitation and irrigation applications in quantity (cm) and in quality (usually in dS m^{-1}). ET_{pot} which is the sum of E_{pot} and T_{pot}, is usually obtained from the FAO package CROPWAT (Smith, 1992). The potential soil evaporation rate E_{pot} is first determined, if this has not been fixed in the input file, as a function of the leaf area index of plants, which depends on the soil cover. The actual soil evaporation rate E_{act} is then calculated taking the lesser value of the potential evaporation and the maximum soil water flux according to Darcy in the top soil. Since the calculated value of E_{act} is sometimes too high for the case of a dry upper layer, SWAP93 gives the user the option to calculate a third value using the empirical models of Black (Black et al., 1969) or Boesten (Boesten and Stroosnijder, 1986). The model then selects the lesser value of the three.

The cumulative daily potential rate, as well as actual evaporation rate is given in the output file of SWAP93. The actual transpiration rate, T_{act}, is as the integral of the sink term over the rooting depth, and depends also on T_{pot}. The lower boundary is more complex to define. In SWAP93 there are various options available to define the lower boundary as a groundwater level, as a flux or a flux as a function of the calculated groundwater level using steady state drainage equations, regional groundwater levels or fitted analytical relations (van Dam and Feddes, 1996). Both top and lower boundary conditions need to be defined in the input file.

Limitations of the model

The model was successfully calibrated and validated for a range of soils in the study area. The model can be used to analyze and quantify the marginal impact of irrigation practices on soil salinity and on T_{act}. The model can be used both in case of a well drained soil with a deep groundwater table, as well as for a poorly drained soil with a shallow groundwater table. Other irrigation practices, such as the frequency of irrigation or the application of a pre-sowing irrigation can also be evaluated with this tool. A slight retardation can be observed with respect to the solute leaching which can be attributed mainly to calcite precipitation and exchanges of ions with the exchange complex of the solid phase. These phenomena cannot be simulated with the present model, which should be kept in mind when evaluating the results of the analyses.

4.3.2 Predicting the sodium hazard

Several predictive empirical equations linking the quality of irrigation water and the sodium hazard of soils have been developed in the past. The most well known equations are those of the U.S. Salinity Laboratory (Richards, 1954), Bower (Bower et al., 1968), Rhoades (Rhoades and Merril, 1976; Oster and Rhoades, 1990; Rhoades et al., 1992), Suarez (1981), Ayers and Westcot (1985) and Jurinak and Suarez (1990). Generally, these equations relate the sodium content of the irrigation water with the *ESP* of the soil or assess the dispersive qualities of irrigation waters directly from their salt concentration and *SAR*. In some cases the salt concentration of the soil solution and the leaching fraction are taken into account. Some of these equations will be tested in the context of this study by comparing their predictions with the results of laboratory analyses of soil samples. In addition, a regression analysis will be carried out to develop an equation specifically for the study area.

Richards (1954) developed the following equation for a number of soils in the western U.S.A.:

$$ESP = \frac{100\ (-0.0126 + 0.01475SAR)}{1 + (-0.0126 + 0.01475SAR)} \tag{4.14}$$

This equation is also presented as:

$$\frac{ESP}{100 - ESP} = k_g\ SAR \tag{4.15}$$

The coefficient k_g is often assumed to be 0.015 $(\text{mmol l}^{-1})^{-0.5}$, but ranges from 0.008 to 0.016 and has to be adjusted for local conditions (Jurinak and Suarez, 1990).

Rhoades proposed a differentiation between the upper and lower layers of the rootzone to account for the effect of leaching in the lower layers (Rhoades and Merril (1976), quoted in Bingham et al., 1979; Rhoades et al., 1992). The equation for the upper layers is the same as the Bower equation (Bower et al., 1968):

$$ESP = SAR_{iw}\ [1 + (8.4 - pH_c)] \tag{4.16}$$

where pH_c, the Langelier index, is calculated from the concentrations of calcium, magnesium and (bi-) carbonates, and from the solubility constant of calcite and the dissociation constant of carbonic acid (Suarez, 1981). This index is often used to determine the probability of calcite precipitation/dissolution during irrigation and can provide insights regarding the sodium hazard of irrigation waters (Bower et al., 1968; Bresler et al., 1982).

For the lower layers, the *ESP* value of the Rhoades equation needs to be multiplied with a factor *k*, which depends upon the leaching fraction and the mineral precipitation-dissolution properties of the soil. A value of 1.62 is assumed for many soils that are subject to a leaching fraction of 0.15 (Bingham et al., 1979).

Suarez (1981) and Jurinak and Suarez (1990) suggested to calculate the adjusted *SAR* (SAR_{adj}) in order to account for the ionic strength and the ratio between concentrations of calcium and (bi-) carbonates. The SAR_{adj} is calculated with the following equation:

$$SAR_{adj} = \frac{Na_{iw}\ F_c}{(Mg_{iw}\ F_c + Ca_{eq})^{0.5}} \tag{4.17}$$

where F_c is the inverse leaching fraction and Ca_{eq} can be calculated from the molar ratio of (bi-)carbonates and calcium and the ionic strength of the irrigation water with the method proposed by Suarez (1981). The *ESP* can then be calculated with Equation 4.14.

These equations have been tested for various soils in different parts of the world (e.g. Bajwa et al, 1992; Manchanda, 1993; Yasin et al., 1986; Bingham et al., 1979; Oster and Schroer, 1979; Singh et al., 1992). Since they are empirical in nature, these equations cannot be applied without verification for local conditions.

Often the sodium hazard of an irrigation water is assessed from its salt concentration and *SAR* (Rhoades, 1982; Quirk and Schofield, 1955; Oster and Schroer, 1979; Rengasamy et al., 1984; Sumner, 1993; Ayers and Westcot, 1985; Ghafoor et al., 1985; Muhammed, 1987). Generally, the logic of the classification of Ayers and Westcot (1985) is followed, whereby a higher *SAR* of the irrigation water is tolerated with increasing salt or cation concentration, see Figure 4.5.

Recent strides in computer technology have enabled the development of computer models that predict the soil sodicity for a given irrigation water quality and quantity (e.g. Rhoades et al., 1992; Simunek and Suarez, 1994; Vallès and Bourgeat, 1988; Marlet, 1996). On some of the fields in the study area, the model GYPSOL was used (Condom, 1996), adapting the methodology developed by Marlet (1996) in Niger. The model was used to evaluate the impact of different water qualities on soil sodicity, after calibration. These type of tools are relatively difficult to calibrate/validate and require considerable input data. Although the model is not yet operational, and is not used directly for this study, the results of the modeling study can be used to understand differences between field observations and empirical equations.

4.4 Analyzing the effect of irrigation on soil salinity and crop transpiration

In earlier studies in the study area it was demonstrated that irrigation has an impact on soil salinity and transpiration (Kijne and Vander Velde, 1992; Kuper and van Waijjen, 1993; Pintus, 1995; Kuper and Anjum, 1995). An example of how existing irrigation practices of farmers influences the actual evapotranspiration, ET_{act}, is given in Figure 4.11.

The figure presents the results of field observations, analyzed with the help of the software package CROPWAT for wheat on a sandy loam (Smith, 1992). When taking an arbitrary critical limit of 0.8 for the ratio ET_{act} over ET_{pot}, a negative impact on the yield can be proved (Kuper and Anjum, 1995).

However, the results are at best indicative and there was no tool available to undertake a systematic evaluation of the comparative impact of these irrigation practices (*ceteris paribus*). This is possible by using a soil water - solute transfer model.

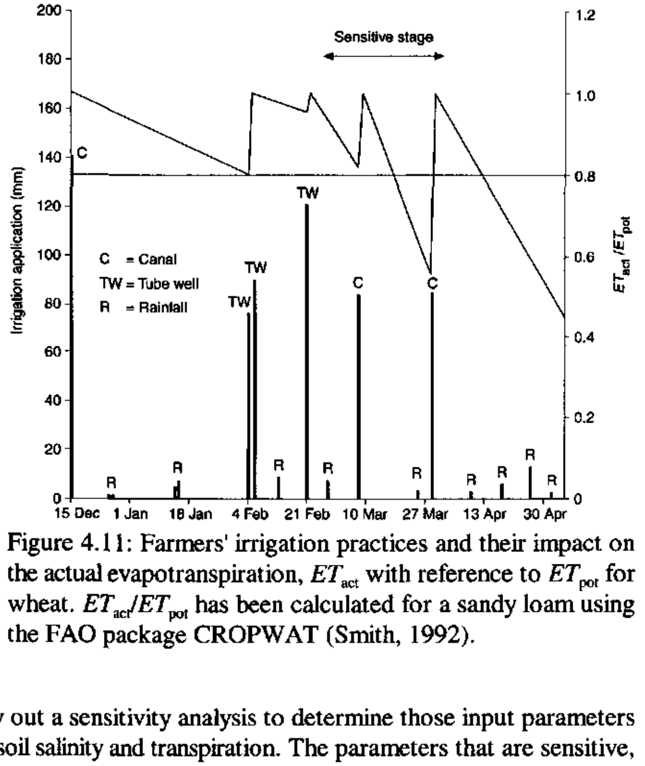

Figure 4.11: Farmers' irrigation practices and their impact on the actual evapotranspiration, ET_{act} with reference to ET_{pot} for wheat. ET_{act}/ET_{pot} has been calculated for a sandy loam using the FAO package CROPWAT (Smith, 1992).

In this section the effects of the quantity and quality of irrigation applications *at the field level* are evaluated with the help of such a model. In 4.4.1 the model is calibrated and validated. In 4.4.2 it is used to carry out a sensitivity analysis to determine those input parameters that have the biggest marginal impact on soil salinity and transpiration. The parameters that are sensitive, i.e. have a relatively big impact on both phenomena, need to be determined with much greater accuracy than insensitive parameters. In 4.4.3 the effects of irrigation quantity and quality are simulated and analyzed in the context of the existing physical conditions. Finally, in Section 4.4.4 the effect of farmers' irrigation practices at the field level on soil salinity is assessed.

4.4.1 Calibration and validation of the model

The soil water flow - solute transport model SWAP93 was calibrated and validated for four fields of 0.4 ha each in the study area, cultivated by farmers with a cotton-wheat rotation, and representing the dominant soil types in the area. These soil types represent almost 90% of the soils in the Chishtian sub-division, i.e. a loamy sand (LS), a sandy loam (SL), a loam (L) to silty clay loam (SiCL), and a loam to silt loam (SiL). The research was conducted on farmers' fields in order to capture the wide range in irrigation regimes adopted by farmers, who are dealing with a different access to canal water and are faced with different qualities of groundwater. A full description of the irrigation and cultural practices for these fields is given in Kuper and Anjum (1995). Carrying out modeling research on farmers' fields adds some difficulties to especially the calibration and validation process. Heterogeneity in soil characteristics and in irrigation application within a field are two of the most important reasons for the added complexity. For this reason, the results of a standard or reference calibration/validation procedure were compared with two other procedures that take the heterogeneity of both parameters into account. The first of the two alternative procedures relates to the non-uniform water distribution within a field, while the second relates to the concept of preferential flow.

Reference calibration/validation procedure

The calibration period covered two crop seasons, cotton and wheat, from May 1994 to April 1995, while the validation was done for cotton only, i.e. from May 1995 to December 1995.

Firstly, the soil layers for the respective fields were defined. In case of all fields, the top soil is underlain by a coarse textured soil, sandy material from alluvial origin. The modelled soil profile was greater in case of field 1 and 2, because of the presence of a groundwater table. For the other field the soil water and solute transfer was modelled down to 2.1 m, which should be sufficient as the main interest is in these processes in the rootzone, which does not extend beyond 1.4 m.

The main input parameters that are adjusted during the calibration/validation process are the Van Genuchten-Mualem parameters. The initial values were taken from the Staring series (Wösten et al., 1987) for soils that had similar texture, and thereafter adjusted in order to obtain a good fit between measured and simulated pressure heads, soil moisture profiles and EC_e profiles. The values of the Van Genuchten-Mualem parameters that have been adopted are presented in Table 4.6 for all soil layers.

Table 4.6: Input values of the Van Genuchten-Mualem parameters after calibration and validation for the four sample fields (after Smets et al., 1997).

Field	Soil layers	Depth (cm)	Soil texture	θ_r -	θ_s -	K_s (cm d^{-1})	α (cm^{-1})	n -	λ -	Water table (m)
1	1	0-140	LS	0.01	0.33	45	0.028	2.1	0.0	2.8
	2	140-315	S	0.02	0.35	150	0.026	2.6	1.0	
2	1	0-125	SL	0.045	0.33	40	0.050	1.8	-0.5	2.5
	2	125-290	LS	0.02	0.35	90	0.028	2.6	1.0	
3	1	0-105	SiCL	0.05	0.39	16	0.030	1.6	-1.0	Free
	2	105-210	LS	0.02	0.35	90	0.028	2.6	1.0	drainage
4	1	0-105	SiL	0.045	0.38	12	0.016	1.6	-1.0	Free
	2	105-210	LS	0.02	0.35	90	0.028	2.6	1.0	drainage

The transition in soil characteristics between the soil layers is quite marked for all fields with quite drastic changes in values for the input parameters. In case of field 1 and 2, a groundwater table is present at less than 3 m of the soil surface. This is accounted for in the model. In the other fields the groundwater table is deeper than 6 m. In addition to the Van Genuchten-Mualem parameters, some other input parameters need to be defined, related mainly to the crops. The simulations will focus on a cropping pattern of wheat-cotton, which are the pre-dominant crops of the area. The default values of the related input parameters were generally taken from the default values defined in the manual of SWAP93, unless data were available to justify the choice of a different value. The values that were finally decided on are presented in Table 4.7.

Table 4.7: General input parameters after calibration and validation for the four sample fields (after Smets et al., 1997).

Input parameters	Wheat	Cotton
Boesten parameter	$\beta = 0.90\ cm^{1/2}$	$\beta = 0.90\ cm^{1/2}$
Crop factors	0.4 - 0.8 -1.15 - 0.7 - 0.3	0.5 - 0.8 - 1.2 - 0.9 - 0.7
Maximum rooting depth	110 cm	140 cm
Limiting pressure heads	h_1= -0.1; h_2= -1.0; h_3= -500; h_3'= -900; h_4= -16000 (all in cm)	

The crop factors were obtained from Doorenbos and Pruitt (1977). They were used to calculate ET_{pot} with the help of CROPWAT (Smith, 1992). A comparison with measured moisture levels and pressure heads prompted a slight decrease of these crop factors. The different values presented in Table 4.7 represent the various crop stages. The rooting depth was checked in the field through excavation both for cotton and wheat. The limiting pressure heads were obtained for wheat from Taylor and Ashcroft (1972) and assumed to apply for cotton as well. The results of the calibration/validation are presented in Figures 4.12 to 4.15 for the soil moisture content and in Figures 4.16 to 4.19 for the salt storage for the four sample fields. In both sets of figures, field observations taken on the last day of the calibration period are used to make the comparison.

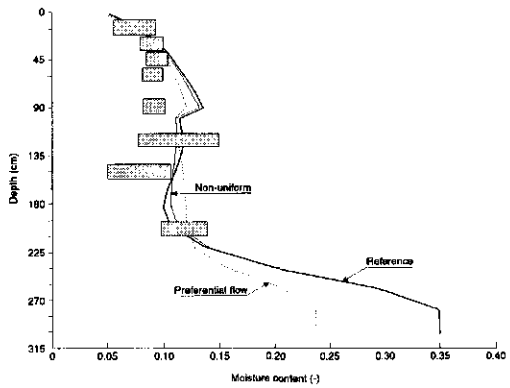

Figure 4.12: Soil moisture content distribution with depth for Field 1 (loamy sand). Comparison of measured and predicted results.

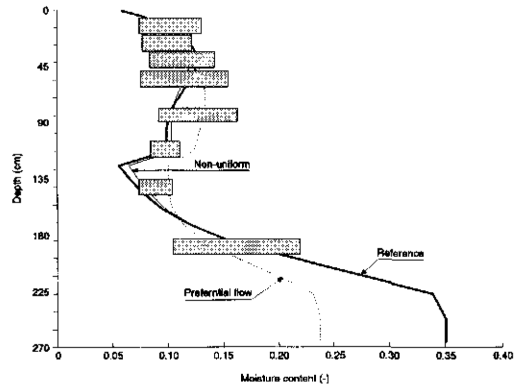

Figure 4.13: Soil moisture content distribution with depth for Field 2 (sandy loam). Comparison of measured and predicted results.

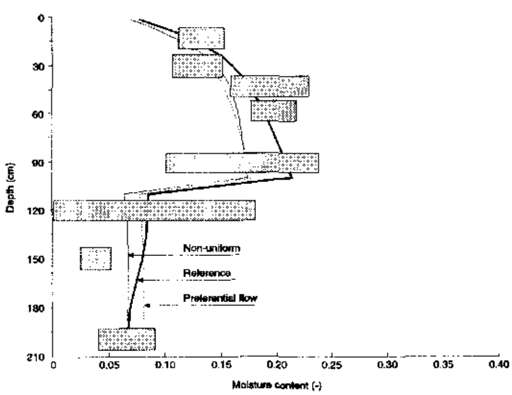

Figure 4.14: Soil moisture content in the profile for Field 3 (loam to silty clay loam). Comparison of measured and predicted results.

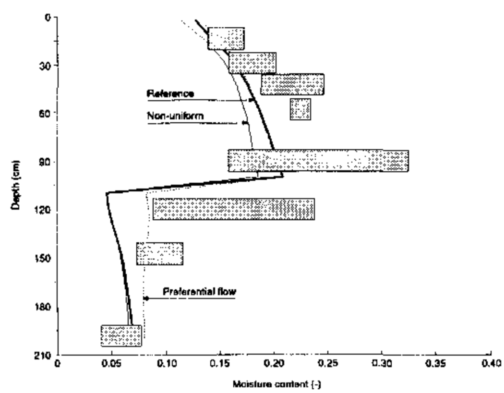

Figure 4.15: Soil moisture content in the profile for Field 4 (silty loam). Comparison of measured and predicted results.

There is a clear transition in soil moisture content from the first to the second soil layer due to the difference in physical characteristics. This applies both for predicted and for measured values and is valid for all fields. The influence of the groundwater table on the soil moisture content in the lower parts of the soil profile is evident from the figures. In general, the predicted values match the measured values well. The same applies to the bi-daily pressure heads (Smets et al., 1997). The resulting values of the soil water balance are presented in Table 4.8.

Table 4.8: Soil water balance for the calibration and validation period for the four sample fields. The calibration period covers a cotton and wheat crop, while the validation period consists of a cotton crop. The values presented in this table are cumulative for the modelling periods. The negative value for Q_{bottom} represents a capillary rise instead of a leaching.

		T_{act} (cm)	T_{pot} (cm)	E_{act} (cm)	E_{pot} (cm)	$P+I$ (cm)	Q_{bottom} (cm)	LF (-)
Field 1	Calibration	88.0	90.6	31.3	55.3	237.3	118.1	0.50
	Validation	45.3	45.5	21.3	29.4	205.8	133.5	0.65
Field 2	Calibration	98.6	109.6	21.8	43.8	136.9	16.5	0.12
	Validation	58.0	63.1	12.6	16.9	75.6	-7.8	-0.10
Field 3	Calibration	81.1	81.2	32.2	61.2	135.1	22.4	0.17
	Validation	46.9	52.5	16.7	26.8	63.9	4.3	0.07
Field 4	Calibration	83.7	89.5	29.5	55.8	118.9	5.8	0.05
	Validation	52.7	54.9	10.8	21.0	60.3	0.5	0.01

The farmer who cultivates field 1 applies much more water to his field than the others. This is partly due to the fact that the soil of this field is the coarsest of all with the lowest soil moisture retention capacity, and partly due to poor irrigation practices. The other extreme is represented by field 4. The farmer who owns field 4 has a farm with a high degree of mechanization. The fields of this farm are well levelled and the farmer succeeds in irrigating just those amounts that are required. This is reflected in the leaching fraction, i.e. the fraction of water that is leached beyond the modelled soil profile of the total irrigation application including rainfall. While the leaching fraction for field 1 exceeds 0.5, it remains less than 0.05 in the case of field 4. The leaching fractions for the other two fields seem to represent more average values in the area with a yearly fraction of around 0.15. The negative leaching fractions express the net capillary rise that occurs for the irrigation season.

All farmers succeed reasonably well in keeping the rootzone sufficiently moist for the plants. For all fields the cumulative values of T_{act} are within 90% of T_{pot}. E_{act} is in all cases substantially below E_{pot} due mainly to a reduced transmissivity in the upper layer of the soil in the hot season.

The results of the calibration for the salt balance are depicted in Figures 4.16 to 4.19.

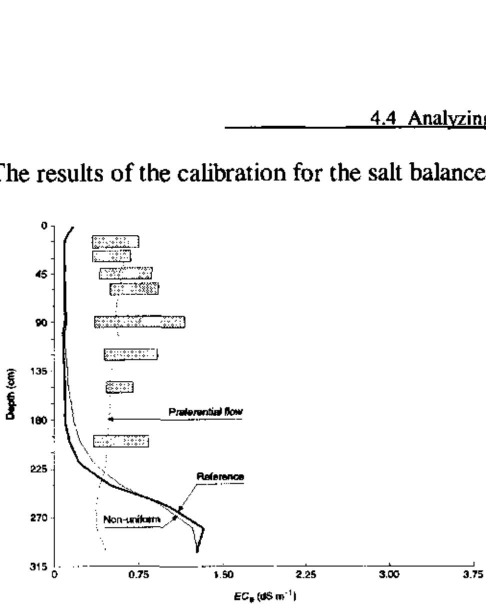

Figure 4.16: Simulated and measured salinity distribution with depth for Field 1 (loamy sand), expressed as an electrical conductivity.

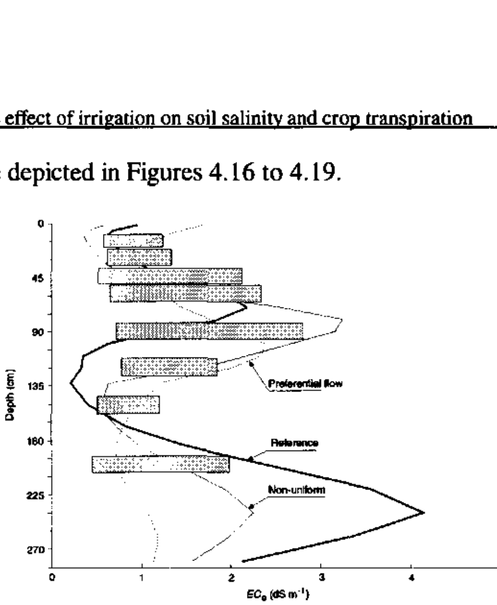

Figure 4.17: Simulated and measured salinity distribution with depth for Field 2 (sandy loam), expressed as an electrical conductivity.

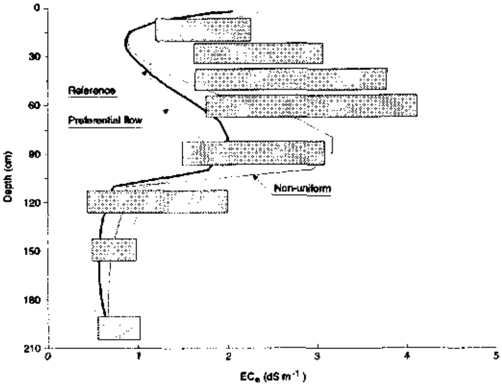

Figure 4.18: Simulated and measured salinity distribution with depth for Field 3 (loam to silty clay loam), expressed as an electrical conductivity.

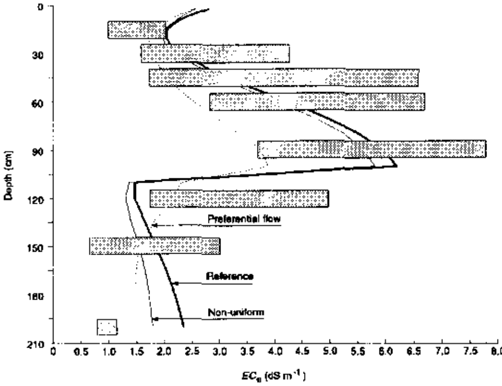

Figure 4.19: Simulated and measured salinity distribution with depth for Field 4 (silt loam), expressed as an electrical conductivity.

For all fields, the EC_e is lower in the coarser textured second layer of the soil. The results of the salt balance are reasonable although EC_e levels are slightly underestimated. Particularly for the coarse textured soil of field 1, the model overestimates the solute leaching, which leads to lower predicted EC_e values than measured, due to the large amounts of relatively good quality water that are applied to this soil. The retardation of solutes can probably be attributed to the precipitation of calcite and exchanges with ions on the soil complex. Condom (1996) provided evidence that samples of irrigated fields in the study area were super-saturated with respect to calcite. Secondly, there is a heterogeneity of water infiltration within the field. This can be partly attributed to the irrigation practices of farmers, who apply water in relatively large basins, and partly to the soil heterogeneity within a field. One of the fields studied, to give an example, was found to have a clay percentage ranging from 10 to 34% in the first 15 cm (n = 10, average is 16.5%, σ^2 = 6.4).

More details of the modelling results for the salt balance of the four fields are presented in Table 4.9. The solutes that were added to the soil through irrigation and precipitation (S_{I+P}), the solutes that were leached (S_{bottom}) and the difference in salt stored in the profile (ΔS) are presented in the table.

Table 4.9: Salt balance for the calibration and validation period for the four sample fields. The negative value for S_{bottom} represents the salts that have been brought into the soil profile through capillary rise.

Field		S_{I+P} (mg cm^{-2})	S_{bottom} (mg cm^{-2})	ΔS (mg cm^{-2})
1	Calibration	78.2	171.9	-93.7
	Validation	128.0	202.1	-74.4
2	Calibration	54.8	52.0	+2.8
	Validation	22.9	-9.6	+32.6
3	Calibration	104.9	106.0	-1.1
	Validation	56.7	21.7	+35.0
4	Calibration	106.0	67.5	+38.5
	Validation	56.1	3.4	+52.7

The negative value of ΔS for field 1 can be explained by the large amounts of water that are applied by this farmer. The amount of solutes leached is overestimated by the model, as explained earlier. The positive values of ΔS for the validation period of field 2 are explained by the contribution of the groundwater due to capillary rise. The validation period for field 3 and the calibration and validation period for field 4 show increases in salinity due to a low leaching fraction.

In summary, the calibration and validation of the model is satisfactory for the soil water balance for the four fields. The solute leaching is slightly over estimated especially for the coarse textured soils. This can be partly attributed to the precipitation of calcite, exchanges of ions with the exchange complex of the soil, and the heterogeneity of water infiltration due to differences in soil characteristics and irrigation practices of farmers.

Two alternative calibration/validation concepts: non-uniform distribution of irrigation application and preferential flow

The first of the alternative concepts consists of the assumption of a non-uniform distribution of irrigation application (see also Kuper and van Waijjen, 1993). The field was arbitrarily divided in three parts, i.e. 3/8 part receiving 67% of the average irrigation depth, 3/8 part receiving the average irrigation depth, and 1/4 part receiving 150% of the average irrigation depth. The model was run three times with different irrigation quantities, so that the water and salt balance could be calculated for all parts of a field. Research is underway in the study area to quantify the water distribution within fields, but results were not available in time to adapt the division of a field for the model.

The second concept was the incorporation of preferential flow in the simulations. This is an option available in SWAP93, generally used for water repellent sandy soils. The infiltration takes place in the so-called 'mobile' fraction, while the 'immobile' part participates only through diffusion with the water and solute transport. The use of this concept can be justified by the heterogeneity of soil characteristics, including the infiltration rate and hydraulic conductivity, although preferential flow has not been proven to exist in the considered fields.

The results of the calibration/validation of both concepts are presented in Figures 4.12 to 4.15 for the water balance and Figures 4.16 to 4.19 for the salt balance. While the results for the salt balance improve as compared to the reference procedure, the results of the water balance slightly worsen. This is inherent in both alternative concepts. Both in case of non-uniform distribution and in case of the mobile-immobile fraction, more water passes through a smaller part of the field, which means that the leaching fraction increases. The resulting average soil moisture content for the entire field is thus lower. Also, more salts are leached in those parts of the field where more water is applied, while in the other parts more salts are conserved. On average, this results in a higher salt storage. The results of the non-uniform water distribution seem to match measured results slightly better than those of the mobile-immobile fraction concept. The advantage of the non-uniform water distribution is that it is physically more straightforward and that unequal water distribution has been proven to exist. This in contrast with preferential flow, which has not been proven to exist and which was developed for sandy, water repellent soils.

It was decided to contend with the results of the calibration/validation of the reference procedure, thereby rejecting the added value of the two heterogeneity concepts. The main reason for doing this was the fact that no direct and quantified evidence exists about the heterogeneity of water infiltration. Finally, neither concept solves the problem of retardation through calcite precipitation. The values of the input parameters that are adopted for further use have been presented in Table 4.6 and 4.7.

4.4.2 Sensitivity analysis

A first use of the model consists of determining the comparative impact of the input parameters of the model on soil salinity and transpiration. The results of this sensitivity analysis will be evaluated with the use of the responsiveness index R, see Equation 3.19. The advantage of using such an indicator is the fact that the impact of various input parameters can be compared, to identify which parameters should be accurately determined. The parameters that have been evaluated are listed in Table 4.10. Also, their impact on soil salinity S (in mg cm^{-2}) and on T_{act} is presented. For most parameters a reduction of 25% in the input parameter was simulated, except for θ_s and for the crop factors since such a big reduction does not seem realistic. Instead, these parameters were reduced by 15%. The simulations were undertaken for a period of 3 years with the same initial salinity levels and soil moisture contents for all scenarios. This period is sufficient to reach an equilibrium situation, i.e. the salinity does not change anymore from year to year. The results of Table 4.10 represent the values that were found at the end of the cotton season, before the pre-sowing irrigation of wheat, at the end of the simulation period.

The irrigation regime was derived from the recommendations of the Agricultural Department in the study area and consist of 6 irrigations for wheat and 10 for cotton, including the pre-sowing irrigations. The total application is 132 cm. The initial soil moisture content is 15.7 cm for the profile, while the initial value of S is 153.2 mg cm^{-2}.

Table 4.10: Long term simulation results of SWAP93 to determine the impact of input parameters on soil salinity (total volume for the profile in mg cm^{-1}) and on the actual transpiration T_{act} for a silt loam. The annual irrigation application is 132 cm for all scenarios. T_{pot} is 102.9 cm for all scenarios except for the reduction in crop factors, where T_{pot} is 87.5 cm.

Parameters	Reduction (%)	Water leached (cm)	T_{act} (cm)	S (mg cm^{-2})
Reference	-	26.7	101.8	157.8
Boesten factor β	25	31.2	102.2	150.3
Rooting depth	25	27.1	101.2	164.0
Crop factors	15	43.9	87.4	143.6
θ_s	15	28.6	99.9	148.6
K_s	25	26.6	101.8	160.0

A reduction in crop factors reduces T_{act}, which is caused principally by a reduction in the T_{pot} . This increases drastically the amount of water that is leached, which reduces the amount of salts in the soil profile. The relative transpiration, i.e. T_{act}/T_{pot}, is not much affected by the reduction in crop factors. For all the other parameters, T_{act} is much less affected than the soil salinity. A decrease in the Boesten factor β increases soil salinity due to the fact that E_{pot} and E_{act} are decreasing and more water is available for leaching. However, T_{act} is hardly affected. A decrease in the rooting depth reduces the root water uptake slightly, while it causes an increase in soil salinity. Reduction of the saturated moisture content θ_s reduced the root water uptake and the salinity, because more leaching occurs due to the fact that the soil can contain less water. A reduced saturated hydraulic conductivity causes a very minor increase in soil salinity due to a slightly lower leaching fraction. This has no impact on T_{act}.

When applying the R-index to the results of the simulations, it appears that the crop factors and θ_s have the biggest impact both on soil salinity as well as on the transpiration, see Figure 4.20.

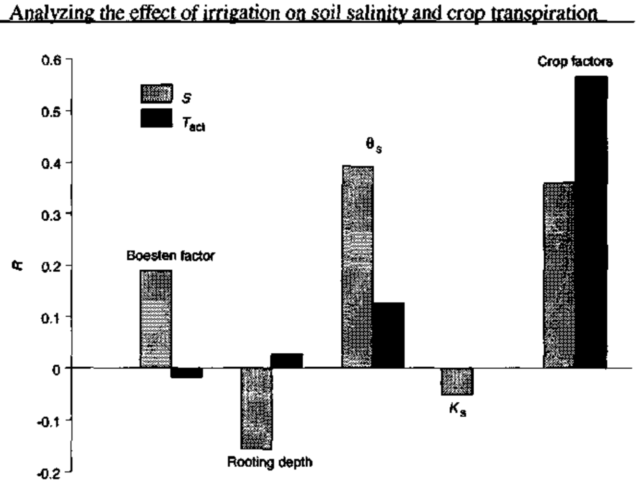

Figure 4.20: The simulated effect of a reduction of input parameters on salinity and crop transpiration for Field 4 (silt loam). The sensitivity is evaluated with the responsiveness index *R*.

Both for θ_s and for the crop factors the *R* values are positive, i.e. an increase in the input parameter yields an increase in the output parameter or as is the case here, a decrease in input leads to a decrease in output. The high *R* values underline the importance of establishing both θ_s and crop factors accurately. This is less important for the other input parameters.

The low *R*-index value for K_s is remarkable. A 25% decrease in hydraulic conductivity does not have a substantial impact, because the resulting value, i.e. 9 cm day^{-1}, is largely sufficient to deal with the irrigation quantities that are supplied. These quantities are usually around 5-10 cm. However, even when reducing K_s further, a phenomenon that can be observed in the field when the kinetic energy is transferred to the soil due to rainfall or the transfer of irrigation water, the effect on T_{act} and *S* remains limited. Simulations showed that only a drastic reduction of K_s from 12 to 0.5 cm day^{-1} in the upper 105 cm of the soil profile, has a considerable effect and results in a reduction of T_{act} from 101.8 to 90.2 cm. This is due to the fact that water is not made available to the plant in sufficient quantities at the required times. Thus, the leached amount will be higher, i.e. 37.7 cm. *S* is not much affected. While there is an increased amount of water leached, the efficiency of the leaching diminishes. This results in an equal amount of salts leached with a higher amount of water. This is probably due to the fact that the leaching occurs much more gradually, while in the reference scenario leaching occurs directly after an irrigation event.

The effect of the input parameters on soil salinity and on transpiration depends also on the irrigation quantities that are applied. This is due to differences in leaching of water and solutes, and to the fact that in drier conditions the root water uptake is stressed more by salts. For this reason, the effect of θ_s and K_s on *S* and T_{act} was simulated for different irrigation regimes, i.e. for 80, 93, 106, 119 and 132 cm. A comparison was made with simulations with the reference values of input parameters, as given in Table 4.7. The results were compared with the help of the *R*-index. The *R* values for T_{act} were fairly constant over the full range of irrigation regimes and were less than -0.01 for K_s and varied between 0.12 and 0.18 for θ_s. The *R* values vary more for the salts in the profile, especially for θ_s. They are given in Figure 4.21.

In the case of θ_s, R is much higher at lower irrigation quantities, which means that a change in θ_s will have a bigger impact on S than at higher irrigation quantities. This is related to the fact that the relative difference in leaching fraction is higher at lower irrigation quantities. While it increases from 0.02 to 0.05 for an application of 80 cm, it increases only from 0.17 to 0.18 for an application of 132 cm. The increased speed of the wetting front due to a decreased θ_s ensures a leaching even at relatively low irrigation levels.

In the case of K_s, the R values are much lower and remain so for the entire range of irrigation applications.

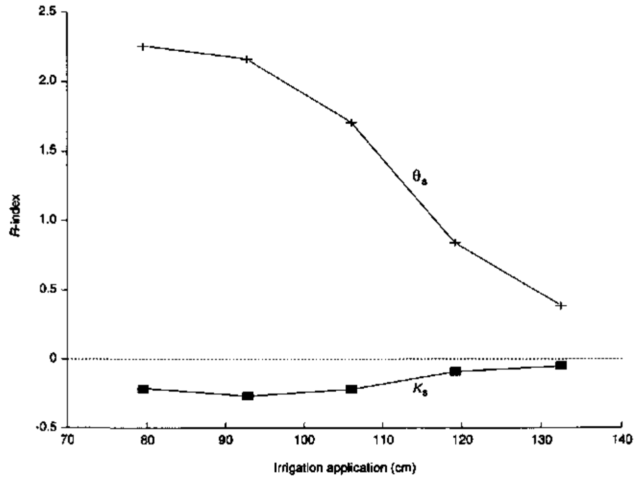

Figure 4.21: Effects of irrigation application on the amount of salts in the soil profile for a reduced saturated hydraulic conductivity K_s and saturated moisture content θ_s. The results were evaluated with the responsiveness index R.

The results of the sensitivity analysis indicate that crop factors and θ_s need to be established accurately in order to have accurate predictions of soil salinity and transpiration. Less sensitive input parameters are the rooting depth, the Boesten factor β, and particularly the saturated hydraulic conductivity K_s.

4.4.3 The effect of irrigation quantity and quality on soil salinity and transpiration for existing conditions

The model that has been calibrated and validated for four soil types in the study area, can now be used to evaluate the impact of different irrigation management interventions. Irrigation management interventions at the level of the irrigation system, are likely to influence the irrigation water quantity that farmers dispose of, but also the irrigation water quality, as farmers may decide to substitute canal water for tube well water or vice-versa. In this section, the effects of different irrigation quantities and qualities on the water and salt balance are simulated and compared. In a second step, the influence of the environment in which these interventions take place is assessed, by simulating the effects of the soil type and of the groundwater table on the water and salt balance.

Simulating the effect of the irrigation quantity and quality on the water and salt balance

The long term effect of different quantities and qualities of irrigation on salinity and T_{act} will be assessed using the model SWAP93. The scenarios are listed in Table 4.11.

Table 4.11: Definition of scenarios for an evaluation of the impact of the quantity and quality of irrigation on salinity and transpiration.

Management variables	Scenarios
Irrigation application (cm)	133, 120, 107, 93, 80
Irrigation water quality (dS m^{-1})	1, 2, 3, 4

The simulations for irrigation quantities and qualities were carried out for Field 2, a sandy loam. The same irrigation regime was adopted as for the sensitivity analysis with a total of 16 irrigations for a cotton and wheat crop. The groundwater table was assumed to be sufficiently deep in order to have free drainage. The water and solute transfer was simulated for a soil profile of 2 m. Since small quantities of water were applied in some of the scenarios, which influences the rapidity with which an equilibrium is reached, a total simulation period of 10 years was adopted. The results at the end of this period were compared. This is at the end of the cotton season, just before the pre-sowing irrigation for wheat. The simulation results are shown in Figures 4.22 and 4.23 for the relative transpiration and *S*, respectively.

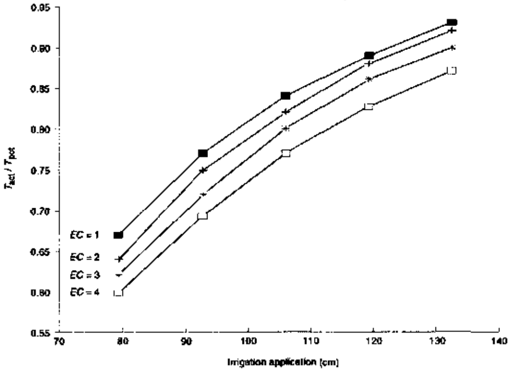

Figure 4.22: Simulation results of the effect of irrigation quantity and quality on the relative transpiration, T_{act} /T_{pot}, of cotton and wheat for a sandy loam. The water quality is expressed as an electrical conductivity (*EC*) in dS m^{-1}, (after Smets et al., 1997).

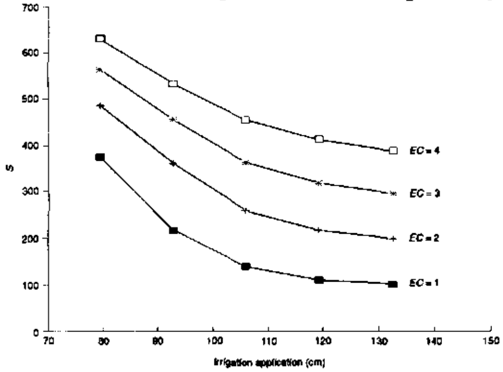

Figure 4.23: Simulation results of the effect of irrigation quantity and quality on the amount of salts in the profile *S* (in mg cm^{-2}) for a sandy loam. The water quality is evaluated by its electrical conductivity (*EC*) in dS m^{-1}, (after Smets et al., 1997).

Figure 4.22 shows the direct relationship between the irrigation quantity and the amount of water that can be extracted by plants. This relationship is curvi-linear with a tangent that decreases with the amount of water that is applied. A reduction in irrigation quantity leads also directly to a reduction in the leaching fraction. When irrigating with an *EC* of 4 dS m^{-1}, for example, the leaching fraction decreases from 0.22 to 0.09 when comparing the highest with the lowest irrigation quantity. This leads to increases in *S* with decreasing irrigation amounts, as shown in Figure 4.23.

Increases in the EC of the irrigation water lead to slightly higher leaching fractions. This is caused by the fact that in dry conditions the plants are more restricted in their water uptake when the soil water is saline. This positive effect attenuates to a certain extent the extra input of salts when irrigating with more saline water, although it cannot prevent the increase in S values for irrigation waters with higher concentrations. Also, the relative transpiration is clearly adversely affected by the increase of concentration of the irrigation water.

Simulating the effect of the soil type on the water and salt balance

The physical characteristics of soils, notably those related to the transport function for water, have a considerable effect on the water and salt balance. In Figures 4.24 and 4.25, the effect of the irrigation quantity on transpiration and soil salinity is depicted for the four soil types. The EC of the irrigation water is 3 dS m^{-1}. The same input parameters as for the evaluation of the irrigation regime are adopted. The simulation time is again 10 years.

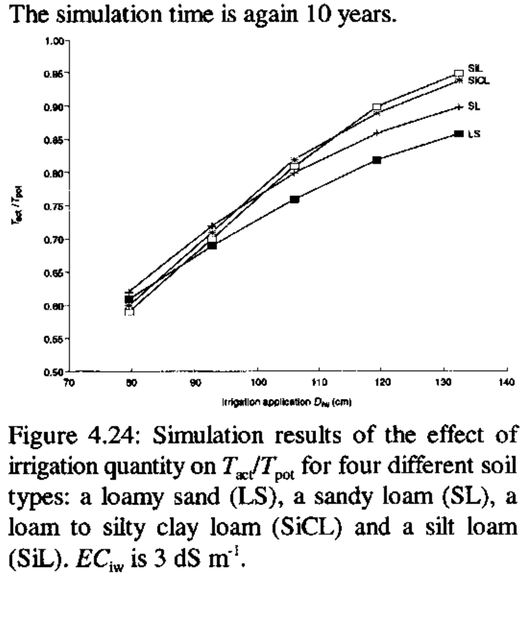

Figure 4.24: Simulation results of the effect of irrigation quantity on T_{act}/T_{pot} for four different soil types: a loamy sand (LS), a sandy loam (SL), a loam to silty clay loam (SiCL) and a silt loam (SiL). EC_{iw} is 3 dS m^{-1}.

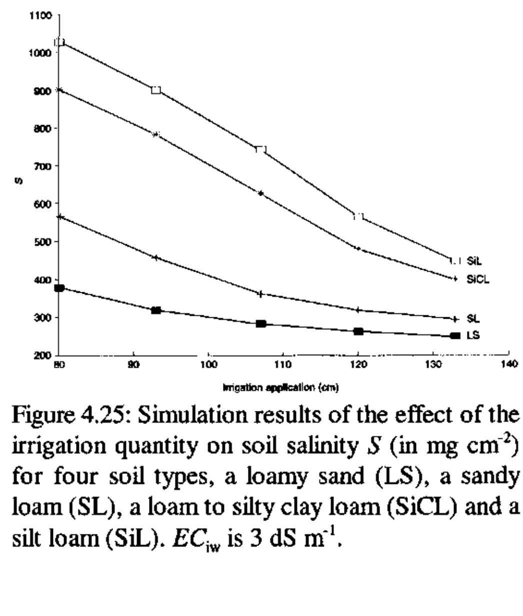

Figure 4.25: Simulation results of the effect of the irrigation quantity on soil salinity S (in mg cm^{-2}) for four soil types, a loamy sand (LS), a sandy loam (SL), a loam to silty clay loam (SiCL) and a silt loam (SiL). EC_{iw} is 3 dS m^{-1}.

Two phenomena can be discerned from the figures. On the one hand, the medium textured soils are shown to be less performing in terms of leaching, due to their higher moisture retention and lower hydraulic conductivity. Thus, the salinity levels become higher for those soils than for the coarser textured soils. On the other hand, the leaching fraction increases slightly for especially the medium textured soils due to higher salinity levels. Plants cannot extract as much water, which is then leached out of the soil profile. This effect is clearly shown in Figure 4.24, where the relative transpiration for medium textured soils is *lower* than for coarse textured soils at low irrigation applications. This is slightly unexpected as one would assume a higher relative transpiration for the medium textured soils due to a higher moisture retention capacity.

Simulating the effect of the groundwater table on the water and salt balance

In a limited part of the area groundwater tables are within 2-3 m of the soil surface. In the section on calibration/validation, it was already shown that this affects soil salinity. In this section, this phenomenon will be further analyzed. Long term simulations were carried out to assess the effect of a groundwater table at 2 m of the soil surface on the water and salt balance for four soil types, i.e. loamy sand, sandy loam, loam to silty clay loam and silt loam. The *EC* of the irrigation water is 3 dS m^{-1}. Apart from the presence of a groundwater table, the scenarios are identical to the earlier scenarios, assessing the effect of irrigation quantity and quality. The results of the simulations are presented in Figure 4.26 for the relative transpiration, T_{act}/T_{pot}, and in Figure 4.27 for the soil salinity.

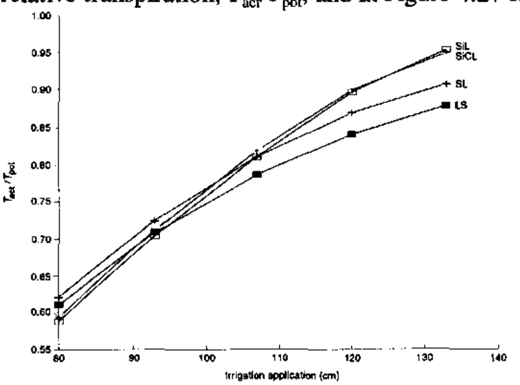

Figure 4.26: Simulation results of the effect of the irrigation quantity on T_{act}/T_{pot}, in the presence of a groundwater table at 2 m depth, for a loamy sand (LS), sandy loam (SL), loam to silty clay loam (SiCL), and a silt loam (SiL). The *EC* of the irrigation water is 3 dS m^{-1}.

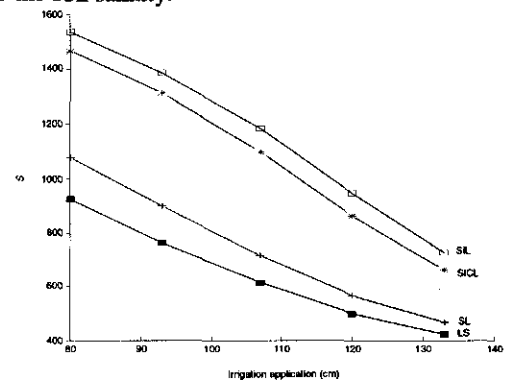

Figure 4.27: Simulation results of the effect of the irrigation quantity on the soil salinity *S*, in the presence of a groundwater table at 2 m depth for a loamy sand (LS), sandy loam (SL), loam to silty clay loam (SiCL), and a silt loam (SiL). The *EC* of the irrigation water is 3 dS m^{-1}.

The effect of the groundwater table is very pronounced. When comparing the figures with Figures 4.24 and 4.25, the salinity has in some cases more than doubled. This is related to the capillary rise that occurs, especially in the first 2-3 years of the simulations. The cumulative leaching fraction is very low in this period. At the same time, the soil profile is wetter due to the presence of the groundwater table, resulting in lower salt concentrations, and thus a smaller amount of salts that is leached. Soon, a relatively high salinity level is reached. Due to the fact that the plants are constrained in their root water uptake, the leaching fraction increases. At the end of the simulation period, the leaching fraction is only slightly smaller than in the case of free drainage. However, the salinity levels remain relatively high. In case of small irrigation quantities, the effect of the groundwater table is more important as is evidenced by the tangent of the curve in Figure 4.27, which is steeper than that in Figure 4.25. The presence of a groundwater table has also an impact on the transpiration. Two effects can be discerned. Firstly, the higher salinity levels reduce the transpiration. Secondly, the capillary rise contributes positively to the transpiration. For the medium textured soils, the two phenomena appear to have about the same importance with a relative transpiration that is the same with or without the presence of a groundwater table. However, for the coarse textured soils, which have a lower salinity level, the capillary rise is clearly more important and T_{act} increases by about 2 cm per year, as compared to a situation with a deep groundwater table.

The irrigation quantity and quality were shown to considerably influence soil salinity and crop transpiration. However, the existing physical conditions, mainly the soil type and the presence of a shallow groundwater table, play an important role in these processes. Both findings are important for the larger context of this study. While the former finding shows that there is ample scope for intervening in soil salinity, the latter indicates that irrigation quantities and qualities can be adapted to site specific physical conditions. This offers opportunities for a redistribution of canal water, with an accompanying positive impact on soil salinity, given the existing heterogeneity of physical parameters.

4.4.4 The effect of farmers' irrigation practices on soil salinity and transpiration

In Section 4.2, farmers were shown to dispose of a large array of measures to deal with salinity. In this section, the effect of some of these measures in the present physical environment will be evaluated. This will enable an assessment of how much of the salinity problem can be overcome by farmers themselves, and how the effectiveness of their measures compare with the proposed interventions. Two measures are investigated, i.e. the frequency of irrigation and the quality of the pre-sowing irrigation water, since farmers have expressed to use both techniques in order to mitigate the effect of irrigation water quality on crop production. The existing irrigation regime consists generally of a large pre-sowing application, in one or two applications, and a number of subsequent irrigations. In the study area, the number of irrigations for wheat is generally recommended to be 1 pre-sowing irrigation and 4-6 subsequent irrigations, while for cotton these are usually 2 and 6-8, respectively. Farmers generally prefer to apply good quality canal water (0.2 dS m^{-1}) for the pre-sowing irrigations. The reference scenario will follow the recommended practices. The first alternative scenario consists of applying the same amount of water in a higher number of applications, see Table 4.12. The second alternative scenario follows the frequency of the reference scenario, but the pre-sowing irrigations are done with poor quality water, i.e. an *EC* of 1.5 dS m^{-1}.

Both alternative scenarios will be compared with the irrigation management intervention, which was investigated in Section 4.4.3, i.e. a reduction of 40% in the quantity of water that is available. Also, a comparison will be made with a scenario showing a physical constraint in the form of the presence of a shallow groundwater table.

An analysis of the evolution of salinity and T_{act} will be carried out inside the crop seasons, because the interventions of farmers occur punctually during the season. The reference scenario is identical to the reference scenario of the sensitivity analysis of Section 4.4.2. The simulations are carried out for a three year period with cultivation of cotton and wheat under the same irrigation practices. The results of the third year are then analyzed.

Table 4.12: Definition of scenarios to evaluate the intra-seasonal effect of irrigation practices and a shallow groundwater table on soil salinity and transpiration.

Scenarios	Soil type	Irrigation application (cm)	Number of irrigations	Bottom boundary condition
Reference	SiL	132	16	Free drainage
High frequency	SiL	132	20	Free drainage
Pre-sowing irrigation with poor quality water	SiL	132	16	Free drainage
Under-irrigation	SiL	80	16	Free drainage
Groundwater table	SiL	132	16	Groundwater table at 2 m

The first results presented here pertain to the water balance. The leaching fractions for the high frequency irrigation and for the poor quality pre-sowing irrigation are very similar to that of the reference scenario. This is certainly not the case for the other two scenarios. Figure 4.28 shows the cumulative leaching fraction for different scenarios for a silt loam. The results for the high frequency and the pre-sowing scenarios have been omitted from the figure.

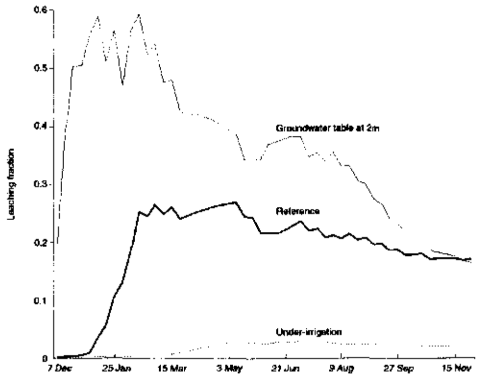

Figure 4.28: Cumulative leaching fraction under different irrigation practices for a silt loam. Model results.

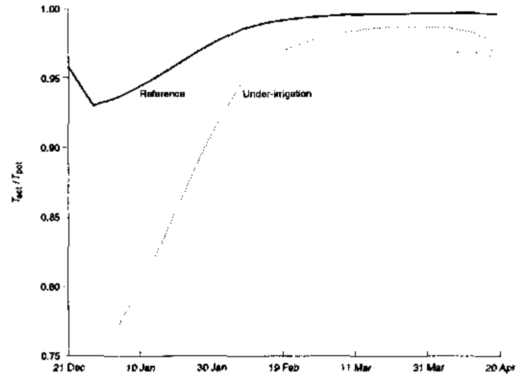

Figure 4.29: Simulation results of the impact of irrigation practices on the relative transpiration, T_{act}/T_{pot} for wheat on a silt loam.

In Figure 4.29 the resulting relative transpiration is depicted. There was almost no effect of the different practices on the transpiration as compared to the reference scenario and they have, therefore, not been presented. Only in case of under-irrigation there is a considerable effect.

The high leaching fraction in the period January-March is clear from the figure. Interesting is also the fact that the leaching fraction for the under-irrigation scenario is almost zero in that same period, resulting in a substantial salinization. Finally, the effect of a groundwater table at 2 m is shown to impact greatly on the leaching fraction. However, the concentration of the water that is leached is much lower than for other scenarios due to the wetter profile. Thus, only in case of under-irrigation there is a considerable impact on T_{act}. This applies both to cotton and wheat. In the case of wheat, the fact that the pre-sowing irrigation in December as well as the first subsequent irrigation are 40% lower than in the reference scenario is shown to especially affect adversely T_{act}.

The effect of the different irrigation practices on the salt accumulation for the same soil (silt loam) is presented in Figure 4.30.

Generally, the salinity tends to be lower in Kharif than in Rabi. This is due to the fact that in the period January to March before the beginning of Kharif over-irrigation takes place. The temperatures are not so high yet resulting in low values of ET_{pot}, which makes leaching possible. In Kharif farmers have difficulty to even keep the profile moist and leaching reduces to a minimum, see also Figure 4.28. Thus, salinity gradually increases and is at its peak at the onset of Rabi.

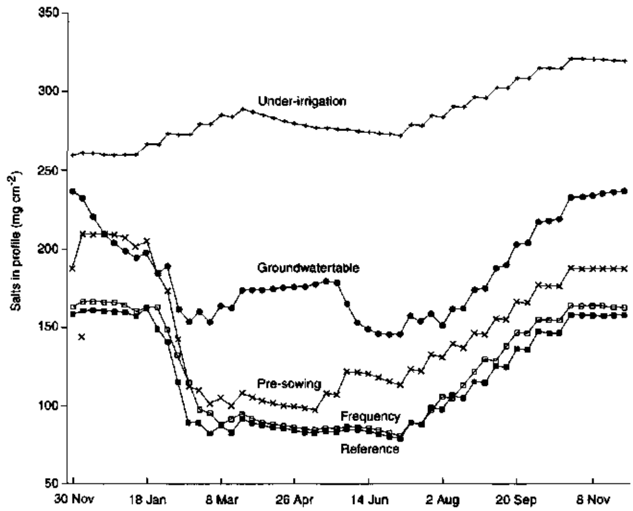

Figure 4.30: Weekly simulation results of the impact of irrigation practices on soil salinity S (mg cm^{-2}) for a silt loam. The scenarios are listed in Table 4.12.

Figure 4.30 shows that applying the same amount of irrigation water in a higher frequency does not affect much the salinity as compared to the reference scenario, a finding which was also established for irrigation with a lower frequency, i.e. 12 irrigations yearly, for the same soil (Smets et al., 1997). This may well be related to the soil type. Smets (1996) found for a loamy sand that the frequency of irrigation is very important due to its lower soil moisture retention. Moisture stress more easily occurs in this case when the irrigations are too far apart.

More impact has the decrease in water quality for the pre-sowing irrigations for wheat and cotton, resulting in a higher soil salinity. The impact of the pre-sowing irrigations, one in December and two in May/June can be detected in Figure 4.30.

A slightly different pattern is observed only in case of a groundwater table at 2m. In this case, capillary rise contributes to a salinization in April/May, when farmers are not irrigating and the temperatures are high. A shallow groundwater table contributes considerably to salinization. An interesting observation was made by Smets (1996), who showed that in case of over-irrigation soil salinity may actually *decrease* in the presence of a shallow groundwater table. This was attributed to a higher leaching fraction, induced by a higher soil moisture content. However, in case of under-irrigation, a shallow groundwater table clearly increases S in the soil profile as shown in Figure 4.30.

The under-irrigation scenario is shown to affect salinity very much. It is also the only scenario where after 3 years of irrigation, still no equilibrium is attained. The most important impact of a reduction of irrigation quantity is that farmers are no longer able to reduce salinity in the period January-March. The remainder of the year the salinity trend is very similar to the reference scenario.

There is considerable variation in soil salinity during the year with higher salinity levels in Rabi than in Kharif. The period January-March is shown to be of utmost importance for salinity management. In winter time farmers can leach salts due to low values of ET_{pot}. The effect on transpiration due to high salinity levels seems limited, but is highest towards the end of Kharif for cotton as well as the beginning of Rabi for wheat. Farmers' practices, within the existing limits of irrigation water availability and physical conditions, were shown to influence soil salinity. This enlarges the limits within which irrigation quantities and qualities can be delivered to groups of farmers. However, the effects of farmers' practices are certainly much smaller than a change in the irrigation quantity or quality.

4.5 Predicting the effect of irrigation on soil sodicity and soil degradation

In this section the sodification as a function of the irrigation practices will be treated at the farm and field levels. A large data set is available for eight sample tertiary units in the study area on irrigation quantities and qualities and on soil salinity and sodicity. This data set will be used to develop a regression equation that can be used to predict the development of soil sodicity as a function of the irrigation water quality for various soil types. In Section 4.5.1 the empirical equations that were presented in Section 4.3.2 will be applied to this data set. The results will be compared with the outcome of the regression equation. The impact of soil sodicity on the soil degradation will be studied in Section 4.5.3 in order to determine critical limits for the study area.

4.5.1 Predicting the soil sodicity risk

Empirical formulae

The equations that are found in the literature and were given in Section 4.3 use by and large the same parameters to predict the soil sodicity. In the equations of Bower, Rhoades and Jurinak & Suarez both the *SAR* of the irrigation water and the volume of irrigation is taken into account. The *SAR*, however, is in all cases adjusted for calcite precipitation. Since they developed their relationships mainly with lysimeter experiments, the leaching fraction is taken as the variable to represent the irrigation quantity. The equation of Jurinak & Suarez goes one step further and takes the Pco_2 pressure and the activity coefficients of mainly Ca and HCO_3 into account. However, in this study a default value of 13 kPa is assumed for the Pco_2 pressure, as this is difficult to measure in the field (Suarez, 1981). An increase in

Pco_2 pressure, which is induced by CO2 production of plants and microbial respiration and regulated by diffusion processes, causes a reduction in the pH, which influences the solubility of calcite.

The above mentioned equations were applied to 74 sample fields in a tertiary unit, Fordwah 130R. The results are depicted in Figure 4.31 for the Bower equation and in Figure 4.32 for the Rhoades and the Jurinak & Suarez equation.

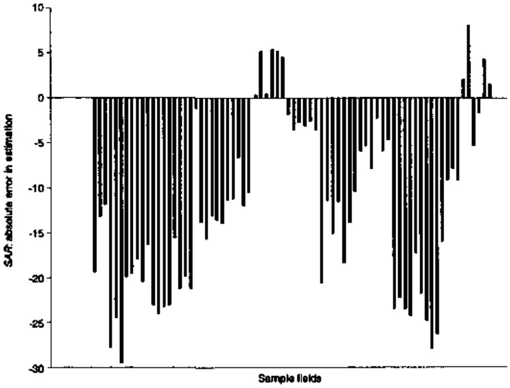

Figure 4.31: Application of the equation of Bower et al. (1968) to predict the soil sodicity as a function of the leaching fraction and the SAR_{iw} adjusted for calcite precipitation. It is applied to 74 fields, consisting of loamy sands, sandy loams and some loams. The difference between the measured and predicted *SAR* values is given.

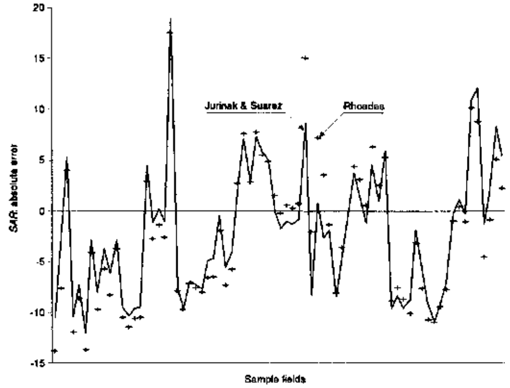

Figure 4.32: Application of the equations of Rhoades (Rhoades et al., 1992) and Jurinak & Suarez (1991) to predict the soil sodicity as a function of leaching fraction and SAR_{iw}, adjusted for calcite precipitation and Pco_2 pressure. The equations are applied to 74 sample fields, consisting of loamy sands, sandy loams and some loams. The difference between the measured and predicted *SAR* values is depicted.

The Bower equation is shown to over-predict the *SAR* values. The difference between measured and predicted values is negative in almost all cases. The over prediction of the Bower equation has been proved before in lysimeter experiments (Suarez, 1981). In fact, the Rhoades equation multiplies the outcome of the Bower equation with an empirical coefficient in order to reduce the predicted values. The outcome of the application of the Rhoades and the Jurinak-Suarez equations is considerably better than those obtained from the Bower equation, although the fit with the measured data is still not perfect. Both equations predict values that are quite close from one another.

Developing a linear regression equation

The relationship between irrigation practices, soil characteristics and soil sodicity can be investigated for the study area. A regression was performed using the field data for three out of eight tertiary units. In this way, the equation can be verified for the other tertiary units. In these three tertiary units, i.e. Azim 43L and Fordwah 46R and 130R, soil samples were taken on a total of 60 farms. On each farm 3-5 fields were sampled with a total number of 174 fields. These fields consist mainly of loamy sands and sandy loams and a few loams. For each farm, the irrigation quantities and qualities were available for a one year period. The water distribution to individual fields, however, was not available. A multiple linear regression was carried out between on the one hand the *SAR* of the irrigation water (SAR_{iw}), and the percentage of sand (%sand), and on the other hand the *SAR* of the saturation extract at 90 cm depth (SAR_e). The percentage sand is taken here as a proxy of the soil texture. The results of the regression are given below:

$$SAR = 16.86 + 1.22SAR_{iw} - 0.17\%sand \qquad (4.18)$$

with a standard error of estimate for both variables of 0.13 and 0.04, respectively. R^2 is 0.36.

The results of the regression seem coherent when looking at the signs of the x-coefficient. An increase in the *SAR* of the irrigation water will lead to sodification. A lower percentage of sand, or conversely a higher percentage of silt and clay, corresponds with higher levels of sodicity. The results show a reasonable correlation between SAR_{iw} and the percentage of sand on the one hand and soil sodicity on the other hand. About 36% of the soil sodicity can thus be explained by the irrigation water quality and soil texture. When including other parameters that are known for the study area, such as the irrigation quantity and EC_e (both at the farm level), the results of the regression do not improve. The R^2 value that is obtained for the regression equation is lower than the values that were found for the empirical formulae treated above. This is not surprising, as these formulae were obtained in lysimeters under controlled conditions. The regression analysis of Equation 4.18 is hampered by the fact that farmers' practices, e.g. their frequency of irrigation, influence the salinity and sodicity levels, as was shown in Section 4.4. However, this same phenomenon explains partly the incompatibility of the predictions of the empirical formulae with the measured soil sodicity. Another problem encountered in developing the regression equation is that the water distribution between the fields of a farm is not known, whereas it is known to be quite variable.

Comparing the predictions of the regression equation with those of the empirical formulae

In order to enable a comparison between the predictions of the different formulae and the regression analysis, an indicator is defined, which captures the difference between predicted and measured values. The standard error of estimate ($S_{x.y}$) was selected for this purpose. $S_{x.y}$ is defined as (Sanders et al., 1987):

$$S_{x.y} = \sqrt{\frac{\sum (Y-Y_c)^2}{n-2}} \qquad (4.19)$$

where:

- Y = the measured value
- Y_c = the predicted or calculated value
- n = the sample size

The empirical formulae were applied to 491 fields in the eight sample tertiary units. The results of these predictions, which were evaluated with Equation 4.19, are presented in Table 4.13. When genetic sodicity is present, the ultimate *SAR* levels will be higher than the predicted values as the equations do not take the existing levels into account. The fields with genetic sodicity were, therefore, excluded from the analysis.

Table 4.13: The standard error of estimate ($S_{x.y}$) for the prediction of soil sodicity for various equations for 491 fields in 8 tertiary units, i.e. Azim 20, 43, 63, 111 and Fordwah 14, 46, 62, 130. The reference values are the *SAR* values measured at 90 cm for the sample fields, while excluding 18 fields that are affected by genetic salinity as determined by the Soil Survey of Pakistan (1996).

Tertiary units	Indicators	Bower	Rhoades	Jurinak-Suarez	SAR_{iw}	Equation 4.18	Measured at 90 cm
Azim 20	$S_{x.y}$	3.2	3.6	3.7	4.0	1.9	
	SAR (μ)	1.2	0.7	0.8	0.4	6.2	4.4
Azim 43	$S_{x.y}$	4.9	5.6	5.7	6.4	1.7	
	SAR (μ)	2.1	1.2	1.3	0.6	8.6	6.9
Azim 63	$S_{x.y}$	5.9	8.3	8.4	9.5	3.1	
	SAR (μ)	4.6	2.6	2.1	1.1	7.4	10.4
Azim 111	$S_{x.y}$	4.1	5.6	5.3	9.4	1.2	
	SAR (μ)	17.8	10.2	8.5	4.5	12.5	13.7
Fordwah 14	$S_{x.y}$	4.6	1.3	1.7	5.5	1.7	
	SAR (μ)	13.9	7.9	7.6	3.9	7.6	9.3
Fordwah 46	$S_{x.y}$	3.0	3.7	3.8	4.4	1.3	
	SAR (μ)	2.1	1.2	1.3	0.7	3.8	5.1
Fordwah 62	$S_{x.y}$	2.6	4.4	4.5	5.7	1.4	
	SAR (μ)	4.3	2.4	2.4	1.3	5.5	6.9
Fordwah 130	$S_{x.y}$	9.3	0.4	0.1	5.6	1.2	
	SAR (μ)	19.8	11.3	10.7	5.2	9.5	10.7

The standard error of estimate is quite high for all equations, although Equation 4.18 appears clearly to work the best in the study area, even for those tertiary units for which the equation was not developed. The differences in predicted and measured values can be attributed to a host of reasons. Data were collected in uncontrolled conditions and are as far as the irrigation quantities are concerned based on farmers' interviews. There is further a large heterogeneity of *SAR* levels within fields due to the spatial heterogeneity of soil characteristics and due to farmers' irrigation practices. An additional problem for the empirical formulae is that the fields are generally irrigated by a sequence of different water qualities, whereas the equations have been developed for steady state conditions. The Jurinak-Suarez equation is difficult to apply to field conditions since the Pco_2 pressure is required. In this study a default value of 13 kPa is assumed as found by Suarez (1981). This will be a source of inaccuracy for the results of this equation. When applying the formula with a Pco_2 pressure of 3 kPa, a value more in line with suggestions of, for instance, Appelo and Postma (1996) or Jurinak and Suarez (1990), predicted *SAR* values will be slightly higher. Another reason explaining the differences in predicted and measured values is the contribution of the groundwater table. This is depicted for one of the tertiary units, i.e. Fordwah 46R, in Figure 4.33, using the equation of Jurinak-Suarez.

In the head of this unit, groundwater tables are fairly high, contributing to the sodification of the fields located there. In Figure 4.33, the fields on the x-axis are presented going from the head to the tail of the tertiary unit. The greater differences in predicted and measured values in the head of the tertiary unit is apparent in the figure. While the average irrigation water quality in this tertiary unit is of excellent quality due to a good canal water supply, the groundwater quality is much less good. If an *SAR* of 3.4 is assumed for the groundwater, the quality of a nearby tube well water, the predicted value of the soil sodicity with the formula of Jurinak-Suarez yields an *SAR* of 7.7, which is closer to the observed values.

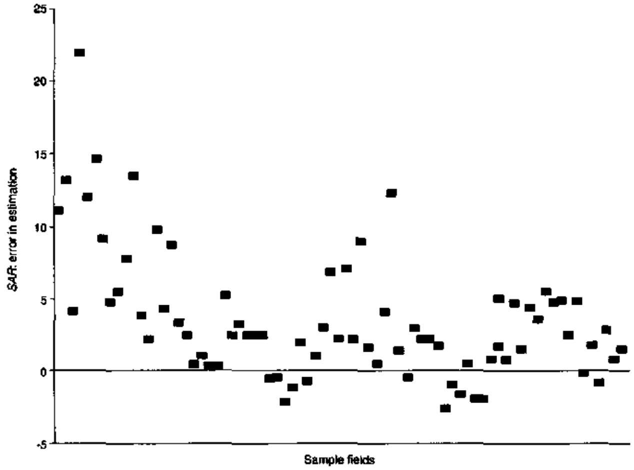

Figure 4.33: Application of the equation of Jurinak-Suarez to predict the soil sodicity as a function of the leaching fraction, the quality of irrigation water, calcite precipitation and Pco_2 pressure for 75 fields in *Fordwah 46R*, consisting of loamy sands, sandy loams and some loams. The difference of the measured and predicted values of *SAR* is depicted.

The equations taken from the literature predict the trend rather than the actual values. The predicted and measured values are very close for Fordwah 130, where the irrigation water quality is very poor, the soils are light and where sodification is a recent phenomenon. In a tertiary unit such as Azim 111, where sodicity is of old "genetic" origin and soils are heavier, the predictions underestimate the present sodicity status. However, the equations predict that sodicity will decrease. This observation is confirmed when we look at the sodicity levels over time. In Table 4.14 the average *SAR* values for a depth of 30 to 90 cm for 106 fields in the eight tertiary units are presented for December 1992 and December 1994.

Table 4.14: Evolution of soil sodicity from 30-90 cm (*SAR* with all concentrations in meq l^{-1}) for 106 fields in eight tertiary units from December 1992 to December 1994, compared with the SAR_{dw} value predicted using the equation of Jurinak & Suarez (1990).

	Azim 20	Azim 43	Azim 63	Azim 111	Fordwah 14	Fordwah 46	Fordwah 62	Fordwah 130
SAR '92	6.2	9.5	5.5	14.1	5.8	3.1	7.2	5.7
SAR '94	6.3	6.9	6.4	14.1	8.5	4.5	7.9	9.3
n	9	12	15	13	15	15	15	12
SAR_{dw}	0.8	1.3	2.1	8.9	6.2	1.6	5.0	13.0

A decrease in soil sodicity is correctly predicted for Azim 43, while the increase for Fordwah 14 and Fordwah 130 is also foreseen. However, the fact that sodicity has remained constant for Azim 20 and has even slightly increased for Azim 63 and Fordwah 46 cannot be explained by the quality of the irrigation water, on which the equation of Jurinak & Suarez is based, alone. High groundwater tables play a role in Fordwah 46, while in Azim 63 some fine textured soils have high levels of sodicity.

On the basis of the results of Table 4.13, it was decided to adopt Equation 4.18 for further use in this study. The first application of the equation is to plot the predicted sodicity levels, i.e. SAR_{dw}, as a function of the irrigation water quality, expressed by the SAR_{iw} for the different soil types in the area. This has been depicted in Figure 4.34.

The figure should be taken only as indicative, as it is an empirical formula. However, the figure shows some interesting issues, particularly when comparing this figure with Figure 4.25 in Section 4.4.4.

The figure emphasizes the importance of irrigation water quality, in addition to the irrigation quantity which was earlier shown to be important for the evolution of the EC_e. In Equation 4.18 the irrigation water quantity does not appear, as it could not be proven to significantly affect the soil sodicity. The effect of the irrigation quantity, usually expressed in terms of a leaching fraction, is generally accepted not to be trivial, as shows the lysimeter work of for instance Bower et al. (1968) and Suarez (1981).

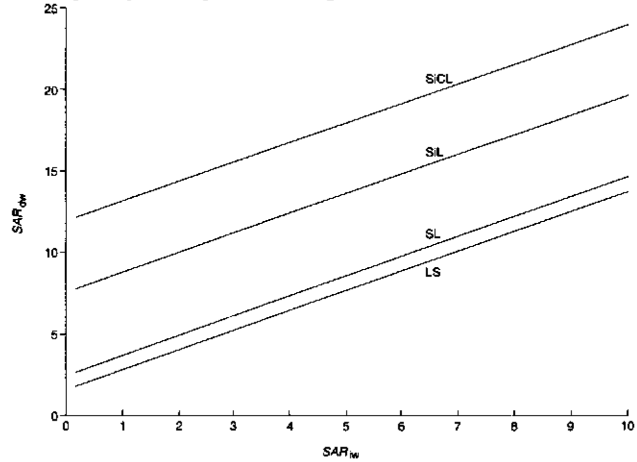

Figure 4.34: Prediction of the soil sodicity, expressed as the sodium adsorption ratio SAR_{dw} (mmol l^{-1})$^{1/2}$ as a function of the SAR of the irrigation water for different soil types, a loamy sand (LS), sandy loam (SL), silty clay loam (SiCL) and a silt loam (SiL). The figure is based on Equation 4.18.

The fact that the effect of the irrigation quantity is not significant in real life settings may, perhaps, be explained by findings of Rengasamy and Olsson (1993). They found that a reduction in the leaching fraction impacts on soil sodicity only when the leaching fraction is lower than 0.1. At higher levels, the SAR_{dw} remains more or less constant. The leaching fractions that were found in the study area were generally in the range 0.1 to 0.3.

A real comparison between the impact of irrigation quality and quantity, using for instance the approach that was developed and applied in Section 4.4.4, is not possible at this stage without a geo-chemical model in conjunction with a soil water - solute transfer model. In the study area, experiments were undertaken with such a tool (Condom, 1996). Although the tool is not yet operational, it is interesting to compare the results of the empirical formulae developed here with the more process oriented results obtained by Condom (1996) using the geo-chemical model GYPSOL. On a sandy loam three different irrigation waters were applied, after which the soil solution was gradually concentrated. The SAR_{dw} values that results from a five-fold concentration are compared with the predicted SAR_{dw} values of Equation 4.18 in Table 4.15.

Table 4.15: Comparison of the prediction of Equation 4.18 of the SAR_{dw} (mmol $l^{-1})^{0.5}$ and of the prediction of a geo-chemical model in the study area for a sandy loam (Condom, 1996).

Input	Model prediction 5-fold concentration	Equation 4.18
SAR_{iw}	SAR_{dw}	SAR_{dw}
0.2	3.8	3.5
6.1	9.0	10.9
8.2	13.0	13.3

The results of both methods compare well, as appears from the results of Table 4.18.

A regression equation was developed to predict the soil sodicity as a function of the SAR of the irrigation water and the soil texture. This relationship was compared with other formulae developed in the literature and with the results of a more process-oriented modelling study. It was shown that the empirical equation can be used for predictions of the soil sodicity risk in the study area. The proposed irrigation system management intervention, i.e. a redistribution of canal water, is relevant to address the issue of sodicity. The quality of irrigation water was shown to have considerable impact on soil sodicity.

4.5.2 The effect of sodicity on soil degradation

The combination of a low total electrolyte concentration of the soil water and high levels of exchangeable Na has long been associated with adverse effects on soil physical properties (e.g. Quirk and Schofield, 1955). Other parameters, such as the organic matter content, the clay mineralogy, oxide contents were also shown to impact on these properties. However, in the USSL classification of 1954, 15% was adopted as a critical limit of *ESP* to delineate sodic and non-sodic soils, thereby focusing only on the level of exchangeable Na. Lower values, in the order of 5-10%, were found by other researchers for a range of soils (e.g. Hodgkinson and Thorburn, 1995; Shainberg and Singer, 1990). The general threshold concept has been contested in recent work, as sodic properties have been demonstrated to occur even at fairly low levels of Na, for instance through the kinetic energy transferred to the soil surface by falling rain drops or by the velocity of water with a low electrolyte concentration passing through the soil (Sumner, 1993; So and Aylmore, 1993). Their conclusion is that soil degradation is a continuous function of the electrolyte concentration of the irrigation water and the Na saturation of the soil. Whether or not sodic properties will be exhibited by the soils is further influenced by soil characteristics, such as the organic matter content, the clay mineralogy, structure of the soil, texture etc.

The principal effect of sodium on the soil is the breakdown of aggregates and the accompanied reduction in water conducting properties. Although many soils slake upon wetting, it is only when this is followed by dispersion that adverse effects on the soil hydraulic properties can be observed (So and Aylmore, 1993). This is particularly true for the soils in Pakistan, which are dominantly illites. These clay minerals are nonswelling due to the K^+ fixation, but are more susceptible to dispersion than other clay minerals (Shainberg and Singer, 1990). Dispersion of clay particles may lead to surface crusting and/or hardsetting when the soil consolidates during drying. Two types of crust are distinguished, depositional crusts formed by the deposition of fine particles in solution and structural crusts due to the breakdown in aggregated, e.g. through the direct impact of rain drops. These phenomena affect adversely the infiltration rate and the hydraulic conductivity, leading to problems of aeration and drainage, which may ultimately impact on the crop production.

In the study area, much anecdotal evidence exists of reductions in infiltration rates and hydraulic conductivity due to the use of tube well water (Kielen, 1996b). Indications of a relatively low permeability of soils became also evident during a survey in 1991, when for about 200 fields the hydraulic conductivity was determined with the help of a Guelph permeameter (Reynolds and Elrick, 1987). Permeability ranged for a sandy loam, for instance, between 1.7 10^{-4} to 3.3 10^{-2} cm^2 s^{-1}, which gives a coefficient of variation of about 1.4. This corresponds with the observations of Jury (Jury, 1989 in Kutílek and Nielsen, 1994) who found *cv* values larger than 1 for saturated as well as unsaturated hydraulic conductivity. For some fields a zero reading was even obtained.

A more thorough study of the soil degradation was undertaken in the study area by the Soil Survey of Pakistan (SSP, 1996) and Condom (1996). The Soil Survey of Pakistan determined infiltration rates and hydraulic conductivity for all soil types in the study area. For cultivated fields, infiltration rates ranged from 0.9 to 3 mm/hr. These values appear low for the light textured soils found in the sample watercourses, where one would expect an infiltration rate of the order of 20 to 40 mm/hr. The sample is too small to carry out a statistical analysis.

Visual observations related to the colour of the surface of the soil, the hardness of the surface as measured with a penetrometer, the presence of vegetation and the uniformity of the stand, and the descriptions farmers use to describe the presence of crusts and hard layers, were recorded by Condom (1996). These were correlated with data of soil samples obtained from the same sites and analyzed by the Soil Survey of Pakistan. Although the *ESP* values of the crusted soils showed considerable variability, the data show clearly that crusting can occur in soils of the sample area at *ESP*'s below 4%. In fact, the hazard of soil degradation due to sodicity can be categorized on the basis of *ESP*, as follows:

- soil with a *ESP* below 4% (*SAR* of 4): no risk of degradation
- soil with *ESP* of about 4%: there is a risk of surface degradation and the appearance of a surface crust that would reduce the infiltration rate
- soil with *ESP* between 4 and 12%: the soil exhibits surface crusts and hard layers
- soil with *ESP* above 12% (*SAR* of 10): the soil shows serious signs of degradation.

The *SAR* values (between brackets) have been obtained using Equation 4.14. In Section 4.2, farmers' experiences in soil degradation showed adverse effects with an *SAR* of 6.

As discussed earlier, the limits depend also on the total electrolyte concentration. This was shown also in the same study for 17 sample fields, where with EC_e levels of less than 1 surface crusts were observed at *ESP* levels even lower than 4%. There is not sufficient data for the study area to establish clear-cut relationships between the *ESP* and EC_{iw} levels for various soils on the one hand and reductions in the hydraulic conductivity and infiltration rates on the other hand.

Although the process of soil degradation was not observed in time, there are several indications that it is a relatively rapid process in the study area. Formation of soil crusts occur after only a few irrigations with poor quality groundwater according to farmers. This was confirmed in simulations with a geochemical model linked with a soil water - solute transfer model, where it was shown that within a year's time, the *ESP* levels increase rapidly to values of above 20%.

Soil degradation was found to occur in the study area at fairly low levels of sodicity, i.e. an ESP of 4%, possibly due to the illitic nature of the clay minerals.

4.6 Predicting soil salinity and sodicity at the level of the tertiary unit

The aim of the present section is to verify whether the results that were obtained in Sections 4.4 and 4.5 on soil salinity and sodicity at the field level, can be used at the level of the tertiary unit. This is necessary in order to be able to integrate the analyses of salinity and sodicity processes with those of the irrigation system management in Chapter 3, which went down to the level of the tertiary unit.

The verification was done for the eight sample tertiary units for a one year period, i.e. Kharif 1994 and Rabi 1994/1995, for which sufficient data was available. Salinity as well as sodicity levels were predicted using the model SWAP93 and equation 4.18, respectively.

Input data

The input data for the models, related to irrigation, are summarized in Table 4.16. These data are average data for the tertiary unit, based on farm level data collected by field staff. Seepage losses have been deducted to arrive at field level data.

Table 4.16: Field level irrigation quantities and qualities for eight tertiary units in the study area for a one year period (Kharif 1994 and Rabi 1994/1995).

Tertiary units	V_{CW} (mm)	V_{TW} (mm)	$I + P$ (mm)	EC_{iw} (dS m^{-1})	SAR_{iw} (mmol l^{-1})$^{0.5}$	EC_e (dS m^{-1})	SAR_e (mmol l^{-1})$^{0.5}$
Azim 20	831	203	1223	0.28	4.02	1.24	4.60
Azim 43	590	368	1147	0.36	3.66	2.74	7.63
Azim 63	292	549	1030	0.49	4.18	2.31	7.73
Azim 111	9	1107	1305	0.96	9.52	2.56	11.13
Fordwah 14	508	273	969	0.87	9.19	2.76	7.04
Fordwah 46	784	130	1103	0.29	4.07	1.07	3.41
Fordwah 62	761	266	1216	0.35	6.64	1.56	5.88
Fordwah 130	400	655	1244	0.77	11.49	1.61	9.35

In addition to this, data on soil type and on groundwater tables are required. The soils data were derived from the survey data obtained by the Soil Survey of Pakistan (1996), while data on the groundwater tables were available for the tertiary units from piezometer readings. The data are summarized in Table 4.17.

Table 4.17: Soils and groundwater table data for eight tertiary units in the study area. The barren and inhabited areas have been omitted from the data.

Tertiary units	Soil type						Groundwater table depth
	LS (%)	SL (%)	L (%)	SiCL (%)	SiL (%)	Total (%)	(m)
Azim 20	9	16	14		26	65	3
Azim 43		8	44		36	88	4
Azim 63	1	51	26	14	3	95	4
Azim 111		78			3	81	6
Fordwah 14	15	79	4			98	2.5
Fordwah 46	40	39	16			95	3
Fordwah 62	23	30	42			95	2.5
Fordwah 130	43	44	8			95	3

There is a distinctive difference in the coarser textured soils of Fordwah and the medium textured soils of Azim. Another important difference is the higher fragmentation of soils in the Azim command area of coarse and medium textured soils. These tertiary units are on the transition of two different river terraces with a subsequent marked change in soil types. The low total percentage of cultivated land in Azim 20 is due to the presence of a lake in part of the command area.

Salinity

The EC_e levels of a soil profile were predicted at the field level using SWAP93, and the question is now, whether the model can be applied with a degree of accuracy for mean values at the level of the tertiary unit. The irrigation data of Table 4.16 were used as input values for SWAP93. Long term simulations of 6 years were done to calculate the water and salt balance. The choice of soil type follows the data of Table 4.17 with the exception of those soils that make up less than 5% of the area of this unit. Their percentages have been added to the next finer textured soil. The barren areas have been deducted from the tertiary units. The area consisting of loamy sand has been added to the sandy loam, since the absolute differences in predicted EC_e are negligible. An average EC_e value was then calculated for each tertiary unit, based on the areas for each soil.

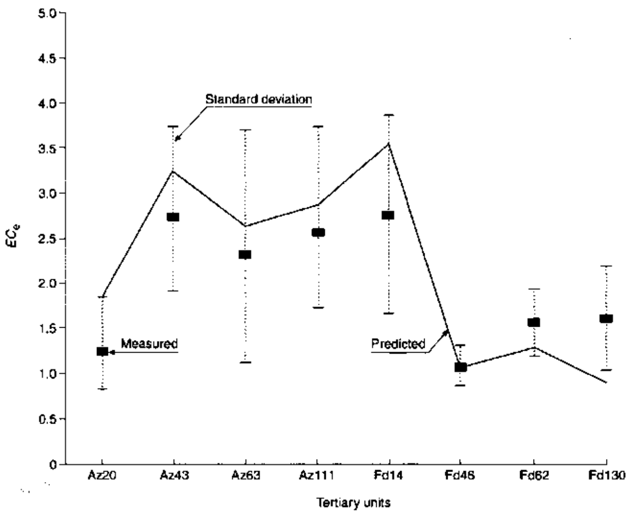

Figure 4.35: Comparison of predicted (SWAP93) and measured EC_e levels for eight tertiary units.

The predicted EC_e values were averaged for the upper 90 cm of the profile in order to enable a comparison with the measured values. The results, which are presented in Figure 5.4, are fairly good: predicted and measured values follow the same pattern for all tertiary units. The differences can probably attributed partly to the fact that mean values at the level of the tertiary units were used. Another reason may be that the predicted EC_e values result from long-term calculations with an identical irrigation regime, while the measured values are the result of an irrigation regime that can vary from year to year. The difference for Fordwah 14 may be due to the fact that the groundwater table is not at the same depth in this tertiary unit. While at places it is at 1.5 m below the soil surface, at other places it is found at more than 3 m. An average value is bound to introduce some error. Another explanation is that farmers have learned to deal with high groundwater tables by introducing a different irrigation frequency in order to keep a downward flux of water and keeping the land always cropped (Kielen, 1996a). In case of the medium textured soils, the predicted values appear to be slightly higher than the measured values. The fragmentation in soil types plays a role here and affects the measured salinity values. This is indicated by the standard deviation of these measured values, which is much bigger for the medium textured soils, as indicated in Figure 5.4.

The data that were used in the tertiary unit level calculations, are also available at the farm level for the eight tertiary units. For a few farms, calculations were done with farm level data in order to verify whether more accurate predictions could be obtained. This was not the case. In fact, the predictions even loose some accuracy. This can probably be attributed to the fact that the intra-farm water distribution of farmers is not uniform, causing a wide range of salinity levels within a farm. Also, variations in soils occur even within the farm. In some cases, the coefficient of variation in EC_e levels is even greater for an individual farm than for the tertiary unit. Since there was no information on the irrigation application to individual fields, for which the soil type is known, an analysis at the field level was not possible. By disaggregating tertiary unit irrigation data up to the farm level, no advantage was gained in the prediction of salinity levels. Therefore, mean values for tertiary units will be used during this study, as far as the irrigation quantities and qualities are concerned.

The mean values of irrigation quantities and qualities as well as soil types allow for a certain heterogeneity in soil salinity within a tertiary unit and even within a farm. The same applies to the groundwater table depth. Whether or not an average value for an entire tertiary unit will suffice depends on its marginal impact on EC_e. This can be quantified by using SWAP93.

To illustrate the importance of differentiating in soil types within a tertiary unit and the impact of the presence of a shallow groundwater table, the result of Figure 4.38 are specified for one of the tertiary units, Azim 20L. The results are presented in Table 4.18.

Table 4.18: Predicted mean EC_e levels for the soil profile (0-210 cm) for *Azim 20L* as a function of the soil type and the groundwater table.

D_{iw}	EC_{iw}	Groundwater table	Soil type			
(mm)	(dS m^{-1})		LS	SL	L to SiCL	SiL
1034	0.27	Free drainage	0.16	0.39	2.89	3.35
1034	0.27	At 2.5 m		1.13		5.10

The first observation that can be made is that a distinction should be made between the coarser textured soils on one hand, i.e. LS and SL, and the medium textured soils, SiCL and SiL, on the other. When a tertiary unit contains soils of very different textures, this will have a relatively big impact on salinity. In the case of Azim 20, for instance, 40% of the cultivated area is medium textured, while 25% is coarse textured. The average EC_e taking into account the different soil types is about 2 dS m^{-1}, while it is only 0.5 dS m^{-1} for the coarse textured soils and around 3 dS m^{-1} for the medium textured soils in this tertiary unit. Another important observation concerns the groundwater table depth. When it is at 2.5 m depth or shallower, it affects considerably the soil salinity for the current irrigation practices.

The analysis shows that predictions of the average soil salinity and sodicity for tertiary units are fairly good when using average irrigation water quantities and qualities for each unit. The soil types should be distinguished even within the tertiary units. Depth to groundwater table needs to be known for all tertiary units.

Soil sodicity

The *SAR* was predicted using Equation 4.18 for the actual situation. The input data were obtained from Tables 4.16 and 4.17. The results are depicted in Figure 5.5.

In order to predict *SAR*, the soils data had to be converted into textural values. Based on soil samples that had been taken and analyzed, the following percentage sand was assumed for the five textural classes of Table 4.17: 85%, 70%, 55%, 30% and 30%.

The predictions of the average *SAR* levels based on the actual irrigation quantities and qualities seem very reasonable: the predicted and measured values match quite well.

The analysis shows that the soil sodicity risk is fairly well predicted by Equation 4.18 for the tertiary units using average irrigation quantities and qualities for each unit. The soil types will be distinguished even within the tertiary unit.

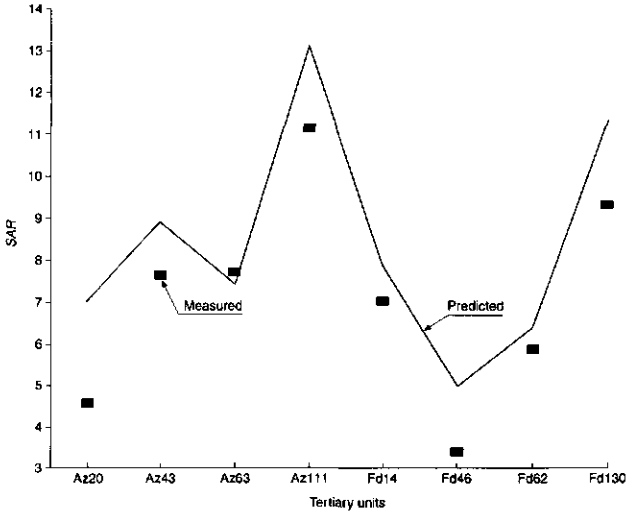

Figure 4.36: Comparison of predicted (Equation 4.24) and measured *SAR* levels for eight tertiary units.

4.7 Conclusions

An approach was developed to assess the effect of interventions in the irrigation water quantity and quality on soil salinity and sodicity at the level of the tertiary unit. This was done by first developing and applying predictive tools at the field level. This level was selected as it forms the interface between on the one hand the physical processes of salinization and sodification, and on the other farmers' irrigation practices, which govern to a large extent these processes. Then, the tools were applied to the level of the tertiary unit, in order to enable the integration between the analyses of soil salinity and sodicity with those of irrigation system management described in Chapter 3. A verification of the results with field data for eight sample tertiary units showed that the tools can be used at this level.

Farmers' decisions on the irrigation water quantity and quality were shown to determine to a large extent the soil salinity and sodicity. Other practices, such as changing the frequency of applications, were also shown to have an impact, but to a much smaller extent. At the same time, the importance of the physical conditions to which the farmers are confronted, i.e. soil type and the presence of a shallow groundwater table should be emphasized. Both findings confirm the relevance of the proposed irrigation management interventions, i.e. a redistribution of canal water, for addressing soil salinity and sodicity. These interventions will change the irrigation water quantity and quality that is available to farmers. Since canal water is not available in sufficient quantities to serve all farmers, choices have to be made as to where the water should be delivered. Irrigation management interventions to redistribute canal water are possible due to the heterogeneity in physical constraints, such as the groundwater quality and the soils. Since especially soil sodicity was observed to be associated with soil degradation at fairly low levels of *ESP*, a process which is difficult to reverse, irrigation management interventions are not only important for reclaiming sodic soils, but also for the prevention of sodification.

Changing the access to good quality water will not have the same effects for all farmers, due to the diversity in their socio-economic background and farming objectives. This is investigated in the parallel study by Strosser (1997), the results of which will be used in the integrated approach in Chapter 5.

CHAPTER 5

IRRIGATION MANAGEMENT FOR IMPROVED SALINITY CONTROL: TOWARDS AN INTEGRATED APPROACH

In Chapter 3, an intervention oriented analysis of the canal irrigation system was carried out. A tool was developed to quantify the impact of changes in present operational rules and modifications in the existing infrastructure on the water deliveries to tertiary units. In Chapter 4, a process oriented analysis of salinization and sodification was carried out at the field level. A tool was developed to quantify the effect of irrigation quantity and quality on soil salinity and sodicity for different soil types. In the present chapter, both approaches are combined in order to assess the risk for salinity and sodicity for tertiary units, as a function of the canal water supply and interventions therein. Research results from the socio-economic study that was carried out parallel to this study are used to ensure the rigour and continuity of this link (Strosser, 1997)[1]. In Section 5.1 the parallel socio-economic study focusing on farming systems is first introduced, after which a general framework is presented to deal with the integration. In Section 5.2 a research methodology is proposed to integrate the analyses of irrigation system management, salinity and sodicity processes, and the farming systems. The methodology is subsequently applied to a case study in Section 5.3. Finally, in Section 5.4, the integrated approach is evaluated.

5.1 Developing a framework for the integrated approach

5.1.1 Introducing the economic component of the integrated approach

The economic component is briefly introduced here. For more detail, reference is made to Strosser (1997). This economic component focuses on the analysis of the impact of changes in water supply on farmers' decisions and on agricultural production (Strosser and Riaz, 1996; Strosser, 1997). As is shown

1 Parallel to this study, Strosser (1997) conducted an economic study of the farming systems in relation to water markets in the study area. The development of an integrated approach on the basis of the study of Strosser and this study, was a joint effort. This development is documented in this chapter. The concept for the integrated approach was earlier documented in IIMI (1996).

in Figure 5.1, these authors analyzed the impact of the quantity and variability of the canal water supply on cropping pattern and gross income at the *farm level* based on data for almost 300 farms in the study area.

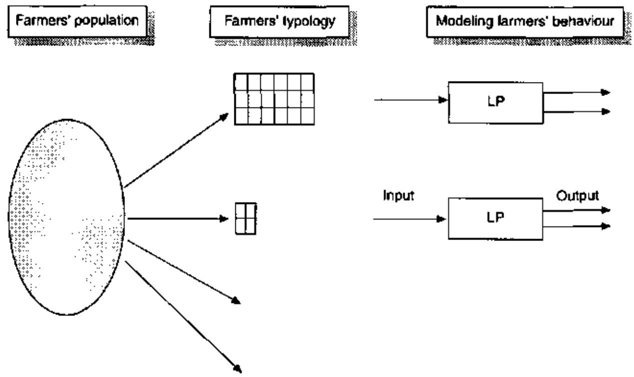

Figure 5.1: Representation of the economic analysis carried out at the farm level.

A farm typology was made using the statistical package SOLO, using more than 20 parameters, ranging from landholding, resources, market orientation to cropping pattern/intensity (Chohin, 1992; Rinaudo, 1994). Linear Programming (LP) models were developed for nine representative farm types in order to represent farmers' decisions under a given set of constraints, in which the attitude of farmers towards risk was taken into account. When constructing the models, the decision rules of farmers were formalized and captured in mathematical equations, based on field observations for the representative farms. The farmers anticipate in their decisions on the coming growing seasons on the availability of water resources, and on the prices of inputs and products. When using the LP models the objective function of the model is to maximize the gross income of crop production. Other objectives include the auto-consumption of wheat and minimizing the risk. The main decisions, inputs and outputs and constraints under which the LP models function, are presented in Table 5.1.

Table 5.1: Details of the linear programming (LP) economic models used by Strosser (1997) in a study on the functioning and development of water markets in Pakistan.

Decisions	Inputs	Outputs	Constraints
Cropped area	Canal water	Gross income	Landholding size
Cropping pattern	Tube well water prices	Marginal value product of water	Availability irrigation water
Tube well water use			Availability labour
Tube well water sales and purchase			Credit

The main decisions that are considered relate to the crop portfolio and to the tube well water use. A number of input variables can be adjusted in the LP models, of which the most important one for this study is the canal water supply. The canal water supply is defined as a monthly average and standard deviation in daily discharges. Output of the models are the marginal value product of water and the gross income, defined here as the total production multiplied by the output price minus the variable costs, such as fertilizer, pesticides and temporary labour.

Water markets are accounted for in two ways. For tube well water, purchasing and selling activities of farmers are first counted and then matched. Although farmers are restricted in the number of hours they operate their tube well daily, in practice this poses hardly any constraint on farmers due to the over-capacity of tube wells. For canal water, each farmer starts with a given water allocation. Water markets will lead to a reallocation of this water, whereby farmers with a higher gross margin per unit of water obtain water from other farmers with a lower gross margin. This in turn influences the tube well water pumpage and sales/purchases. The tube well water use is further influenced by tube well pumpage costs and the price when purchasing it from another farmer. The tube well water prices are not included in the variable costs in the model, but are specified separately in order to be able to change them for a given scenario. The constraints relate mainly to the farm characteristics, as shown in Table 5.1, i.e. landholding, labour and credit. The availability of irrigation water is partly an economic constraint, e.g. the ability to purchase tube well water, but is also related to the availability of canal water. The LP models were calibrated for the individual farms (Rinaudo, 1994). Strosser (1997) has subsequently calibrated/validated these models at the level of the tertiary unit.

For the present study, the LP models at the level of the tertiary unit were made available, but they had not been validated yet. For the prediction of the cropping intensities and pattern, this makes almost no difference. The consequence for the predicted tube well pumpage, however, is that it is slightly overestimated. This overestimation is due to the fact that there are a number of restrictions governing the tube well pumpage, social as well as economic, which have been taken into account in the validated models (Strosser, 1997). Another source of error is the implementation of the economic models. For the present study, all tertiary units were surveyed on the basis of which they were classified into a limited number of different tertiary unit level socio-economic profiles with related LP models. This means that for a given tertiary unit, a socio-economic profile is selected that resembles this unit. These profiles are based on a specific collection of farmers, which may be slightly different from the actual situation. In future, the LP models at the level of the tertiary unit could be constituted of individual farm models, which match the collection of farmers in a unit better.

5.1.2 General framework to analyze the effect of canal irrigation management on salinity and sodicity

In developing the framework to analyze the effect of canal irrigation management, and interventions therein, on soil salinity and sodicity, two main issues were kept in mind. *Primo*, a common platform was developed, relating bio-physical and human decision-making processes. This was done because physical processes that lead to the existing and future levels of salinity and sodicity are governed by human decisions. These decisions need to be compared and quantified for their physical impact. *Secundo*, intervening in the functioning of an irrigation system in order to improve its performance, requires an understanding of the present cause-effect relationships of the system, and an ability to compare a range of interventions, which can take place at different levels of the system and at different time intervals, in order to *predict* their impact.

In the context of this framework, a tool was developed integrating a set of models that were developed in the three main components of this study and the parallel study of Strosser (1997), i.e. the irrigation system management, the salinity, and the economic component.

The inflow of the irrigation system is distributed with the help of SIC and Gateman, respectively a physical and a management model, to the different tertiary units as a function of operational rules and the infrastructure. These deliveries serve as an input for the economic LP models, which give the tube well pumpage on a monthly basis, the seasonal cropping pattern/intensity and the yearly gross income of different farm types as a function of their socio-economic characteristics. These outputs will be available as total values for tertiary units. This information is provided to the salinity (SWAP93) and sodicity (Equation 4.18) models, which also obtain information on the canal water quantities from Gateman-SIC. The salinity model will be run for a 10 year period. Thus, the resulting or dynamic salinity and sodicity levels can be predicted. After evaluation of the results, a new intervention at the main or distributary canal level can be considered. This is represented by the dashed line in Figure 5.2. Other feed-back loops can be considered, but are not automated in the tool. A farmer could be confronted, for instance, with an increase in salinity and sodicity, and decide to decrease his cropping intensity in order to be able to give better quality water to the remaining fields. Presently, the only way to take these feed-back loops into account is by iteratively developing and simulating specific scenarios.

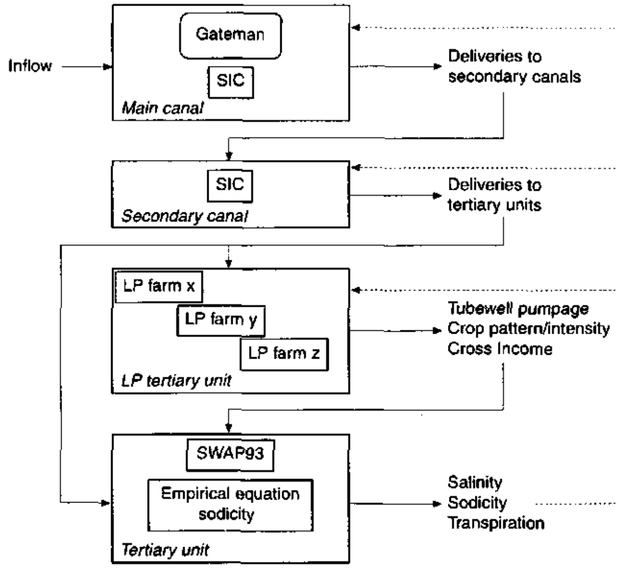

Figure 5.2: Linking physical and decision-making models to assess the impact of irrigation management interventions on agricultural production and salinity and sodicity.

A framework was proposed for an integrated analysis of the effect of canal irrigation management interventions on soil salinity and sodicity, by linking bio-physical models and management models that define human decision-making processes.

5.2 Methodology

Based on the general framework that was presented in Figure 5.2, a methodology is developed and made operational. In Section 5.2.1, an inventory is made of the parameters that are considered in this study, and it is shown how they are generated. The methodology is subsequently made operational in Section 5.2.2. Finally, in Section 5.2.3, the indicators are identified that will be used to evaluate the outputs of the analyses.

5.2.1 Identification of relevant parameters/variables

Earlier analyses in this study have enabled the identification of physical parameters that influence the evolution of salinity and sodicity. These are related to the irrigation water quantity and quality, as well as the soil type and the cropping pattern and intensity. This is presented in Figure 5.3.

This inventory helps to identify the parameters and variables that are necessary to make the framework of Figure 5.2 operational. An inventory is given in Table 5.2. The links between the different models are also indicated.

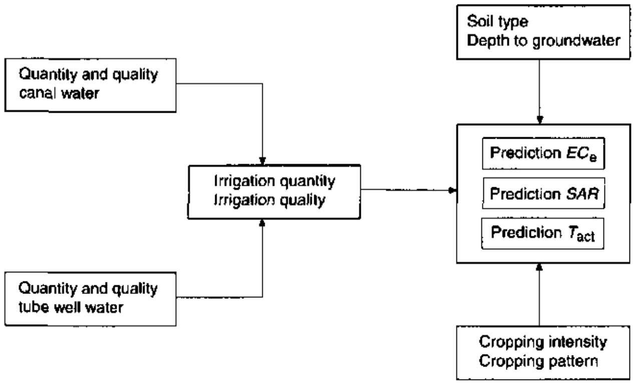

Figure 5.3: Representation of the physical parameters required for the prediction of irrigation induced salinity and sodicity.

Table 5.2: Inventory of relevant parameters and variables linking the models for operationalizing the integrated framework of Figure 5.2.

Variables/Parameters	Model output	Model input	How determined
Variables			
V_{cw}	SIC-Gateman	LP, SWAP93	Model
V_{tw}	LP	SWAP93	Model
Cropping intensity	LP	SWAP93	Model
Cropping pattern	LP	SWAP93	Model
EC_e	SWAP93		Model
SAR	Eq. 4.18		Model
T_{act}	SWAP93		Model
Parameters			
EC_{cw}, SAR_{cw}	Considered fixed	SWAP93, Eq. 4.18	Sampling
EC_{tw}, SAR_{tw}	Considered fixed	SWAP93	Sampling
Soil type	Considered fixed	SWAP93, Eq. 4.18	Survey
Depth to groundwater	Considered fixed	SWAP93	Survey

The SIC-Gateman composite tool enables an assessment of the quantity of canal water, V_{cw}, that is delivered to a tertiary unit. This is then used as an input for the salinity models. The tube well water use, V_{tw}, is calculated by the LP models and depends on the socio-economic profile of farmers, captured in these models, and on the canal water supply, generated by SIC. This means that redistributing canal water supplies will have a direct, i.e. access to good quality water, as well as an indirect impact, i.e. adjusted tube well water use, on soil salinity and sodicity.

Cropping intensities/patterns are required in order to know over what area the water is spread and to calculate the crop water requirements. This is an output of the LP models, based on the socio-economic profile of farmers and partly in reaction to an expected canal water supply. This information is used in SWAP93 to determine the total depth of irrigation for a given tertiary unit.

The outputs of the salinity models, i.e. EC_e, SAR and T_{act} / T_{pot}, are the result of long-term simulations and represent equilibrium values. For this reason, the present salinity and sodicity levels are less important, as the ultimate values will depend solely on the irrigation regime and the soil characteristics.

The quality of canal water, given by EC_{cw} and SAR_{cw}, is excellent and the salt content is generally in the range of 150 to 250 mg l^{-1} (Ghassemi et al., 1995). It is considered to be uniform for the entire study area. The quality of the groundwater, expressed by EC_{tw} and SAR_{tw}, pumped by tube wells varies considerably in the study area. Although some patterns can be detected, e.g. a decrease in quality going away from the river, the causes for this variation cannot be determined as no groundwater study was conducted. A survey was, therefore, the best alternative in the present circumstances. More than 10% of the tube wells in the area were sampled through a stratified random survey. All tertiary units were included in the survey. An average tube well water quality was determined for each tertiary unit.

The soil physical characteristics were shown to be important for the assessment of salinity and sodicity. The information on soil types is available for almost the entire country on 1:200,000 scale maps made by the Soil Survey of Pakistan. These maps provide data on the boundaries between soil associations, which may need to be complemented by a more detailed survey, if one is interested in smaller areas, e.g. a set of tertiary units. Such a survey was done for the study area, determining the physical characteristics of soils and mapping their spatial extent (Soil Survey of Pakistan, 1997). For all tertiary units, the percentage of soil types, corresponding with the calibrated/validated soil hydraulic functions that are input for SWAP93, is known.

5.2.2 Operationalizing the integrated approach

Spatial aspects

When developing an integrated framework, links have to be quantified between different processes occurring at different spatial scales. A common spatial unit of analysis has to be selected and different parameters will need to be aggregated or disaggregated to this level. The main physical scale concern in the context of this study is probably related to the question whether the microscale equations that are used in the model SWAP93 can be used at a larger scale, due to the non-linearity of some of the physical processes governing the water and salt balance (Blöschl and Sivapalan, 1995). This was investigated for the case study in Section 4.6.

In this study, the tertiary unit was selected as the spatial unit of analysis. This choice was made because canal water supplies are known accurately down to this level, it is a transfer point of responsibility from the government to groups of farmers, and there are a reasonable number of tertiary units, which is easier for computational reasons. The *spatial heterogeneity* of those parameters relevant to the analysis of the issues of soil salinity and sodicity, is taken into account when determining the average values of parameters at the level of the tertiary unit. Average values are determined for physical parameters at this level by aggregating point values. This was generally done by collecting field data, detecting patterns in those data, and then determining an average value per spatial unit (Blöschl and Sivapalan, 1995), see Table 5.3.

Table 5.3: Spatial aggregation of parameters relevant for the analysis of the impact of irrigation management on soil salinity and sodicity.

Parameter	Criteria	Initial information	Transformation method
Soils	Texture	Soil map	Expert knowledge SSP
Groundwater table	Depth	Piezometer readings	Interpolation, expert knowledge WAPDA
Groundwater quality	*EC*, *SAR*, *RSC*	Water samples	Arithmetic mean per tertiary unit
Tube wells	Number, type	Count	-
Cropping intensities	Cropped area	Pixel information	Aggregated through GIS
Climatic data	-	Two nearby weather stations	Arithmetic mean, valid for all units

As shown in Table 5.3, there is quite a difference in the processes of aggregating relevant parameters. The pattern of soils was analyzed and mapped by the Soil Survey of Pakistan (SSP), which was subsequently digitized and used in a GIS. Texture was used to classify the soils into five soil types. This information is available even within each tertiary unit. In the case of depth to groundwater table depth the interpolation carried out by WAPDA was adopted. For the groundwater quality the arithmetic mean was calculated for each tertiary unit. A value was attributed to all tertiary units through the GIS. Particularly for the groundwater quality, which was shown to be an important parameter in Chapter 4, there is certainly scope for improvement in the aggregation process. The number and type of tube wells, as well as the cropping intensities were determined for the entire study area. The climatic data, such as rainfall and potential evaporation, were arithmetically averaged for two nearby weather stations, and are considered to apply for all tertiary units.

Farmers' diversity

A socio-economic profile was developed at the level of the tertiary unit, based on socio-economic variables and spatially related parameters such as proximity and distance to specific points, to account for socio-economic relationships between tertiary units and the influence of specific markets. On the basis of the socio-economic profiles of farmers, eight distinct classes of tertiary units were distinguished. Each of these classes, has a matrix containing information on the type and number of farmers, which is the basis for the calculations of the LP models. A given tertiary unit in the study area is allocated to any of these eight classes on the basis of information on the following variables, which were collected during a survey: tractor ownership, tube well ownership, landholding, area leased, the yearly cropping intensity, proximity to markets.

Temporal aspects

The main time steps, concerning the calculations of the models and the output that is provided, are summarized in Table 5.4.

Table 5.4: Time steps that are used in the models of the framework of Figure 5.2.

Parameter	Model	Calculation step	Output
V_{cw}	SIC, Gateman	> 10 min	Daily average, monthly mean/standard deviation
V_{tw}	LP	1 month	Seasonal sum
CI/CP	LP	Punctual	Seasonal value
EC_e	SWAP93	< 0.2 day	Punctual or seasonal value
T_{act}	SWAP93	< 0.2 day	Punctual or seasonal sum
SAR	Eq. 4.24	Punctual	Seasonal value

The month was selected as the common temporal unit of analysis for the integrated tool. Within a month, 1-2 irrigations take place and it is, therefore, an appropriate planning period for farmers. A longer time unit, e.g. a season, would be too long, as irrigation impacts differently at the various crop stages. A shorter period can be considered, but will require a lot more data manipulations. From the irrigation agency point of view, the month represents a period that may require specific operational rules, e.g. rains in July and August. The time step of the individual models does not change, the consequence of which is that there are differences between the bio-physical models with relatively small time steps and the decisional models with larger steps, as is shown in Table 5.4.

The selection of the month as a unit is particularly important for the *transfer of data* from one model to another. The water deliveries, calculated by the joint SIC-Gateman model for 10 minutes intervals, will be summarized through a monthly average and standard deviation to serve as an input for the economic models. The calculation steps of the (bio-) physical models will be kept as they are.

The *temporal variability* is taken into account only as far as the water and salt balance is concerned. This is the case for the combined SIC-Gateman tool, which calculates canal water deliveries on the basis of the inflow and operational rules, which vary both during the season. This is also the case for the soil water flow - solute transfer model SWAP93, which calculates the water and salt balance in the unsaturated zone on the basis of irrigation events, climatic data and crop development, which all vary during the season. The monthly tube well pumpage is a model output and varies with time, depending on crop water requirements and canal supplies. All other parameters are considered fixed. This does not pose a problem for certain parameters, such as the texture of soils, but can be an important issue for other parameters, such as the quality of tube well water. In addition, there may be an evolution over time, which is the case, for instance, for the depth to groundwater table. In the present framework of this study, the effect of these events can be simulated by formulating specific scenarios.

Information

One of the main problems confronting the coupling of different processes is the *information flow and storage.* A common database has been created for the study area comprising different physical and socio-economic characteristics, mainly properties that are considered permanent like soils, groundwater quality, etc. The data were stored as much as possible in their original spatial coverage, and the units were geo-referenced through the use of a GIS. The advantage of storing the original data sets is that they can be used for different purposes. From this larger database, smaller data sets can be prepared, e.g. to obtain averages for the different tertiary units. In addition to the common database, independent databases continue to exist. There is, for instance, no need in the study to integrate the canal topology data in the common database. Sensitivity analyses carried out through the thematic studies enabled the simplification of the database by reducing the number of parameters that need to be stored.

5.2.3 Performance indicators

To take into account the large range of objectives considered by different actors, different performance indicators will be computed. Those indicators represent:

- Water supply performance: adequacy, relative water supply (supply/demand), tube well water use, equity in water deliveries;
- Agricultural production: cropping intensity; and
- Environmental issues: area affected by salinity, sodicity, irrigation water quality.

The indicators related to these issues are presented in Table 5.5. Most of them have been defined earlier in this study.

Table 5.5: List of performance indicators that will be used to evaluate the impact of irrigation management interventions on water deliveries, agricultural production and the environment.

Issues	Indicators	Remarks
Water supply performance	DPR	Equation 3.10
	$cv_R\ (DPR)$	Equation 3.13, equity in water distribution
	V_{tw}/V_{iw}	Dependency on tube well water
	D_{iw}/ET_{pot}	Relative water supply
Agricultural production	CI	Cropping intensity
	$cv_R\ (CI)$	Equity in cropping intensity
Environment	A_{sal}	Fraction of the CCA with $EC_e > 4$ dS m^{-1}
	A_{sod}	Fraction of the CCA with $SAR > 13$
	EC_{iw}	
	SAR_{iw}	
	$cv_R\ (SAR_{iw})$	Equity in irrigation water quality

The relative water supply, RWS, is adapted from Levine (1982) and Bird and Gillot (1992), representing the ratio between the available water supply and the water demand. It is defined by:

$$RWS = \frac{D_{iw}}{ET_{pot}} \tag{5.1}$$

where:

D_{iw}	= depth of irrigation water delivered at the farm level	[mm]
ET_{pot}	= potential evapotranspiration	[mm]

The fraction of tube well water of the total irrigation supplies at different levels of the irrigation systems can be calculated by dividing the volume of tube well water V_{tw} by the total volume of irrigation water, excluding rainfall, V_{iw}.

The cropping intensity, CI, is calculated as a percentage of the Culturable Command Area, CCA:

$$CI = 100 \times \frac{Annual\ area\ cropped}{CCA} \tag{5.2}$$

This implies that when a piece of land is cultivated more than once, CI will exceed 100%.
The area affected by soil salinity, A_{sal} is defined as:

$$A_{sal} = \frac{Area\ having\ an\ EC_e{>}4\ dSm^{-1}}{CCA} \tag{5.3}$$

The area affected by sodicity, A_{sod}, is defined as:

$$A_{sod} = \frac{Area\ having\ an\ SAR>13}{CCA} \tag{5.4}$$

The limits for EC_e and SAR are values that were obtained from the Agricultural Department.

A methodology is proposed to assess a priori the impact of irrigation system management interventions on soil salinity, sodicity and crop transpiration. An integrated tool, linking the models developed in the different components of this and the parallel study (Strosser, 1997), is proposed to execute the necessary calculations. In order to make this tool operational, a common spatial and time step was selected. The results of the computations will be evaluated with a number of indicators that are proposed.

5.3 Irrigation management interventions and their effect on soil salinity and sodicity: application to the Fordwah Branch and Distributary

The developed methodology was tested on the Fordwah Branch canal, a 36 $m^3 s^{-1}$ main canal in the study area, and on the Fordwah Distributary, a large 5 $m^3 s^{-1}$ secondary canal, serving an area of about 14,000 ha. Three scenarios were formulated, a reference scenario to analyze the actual situation, and two alternative scenarios to study the effects of salinity targeted interventions at the main and secondary canal level. The scenarios are listed in Table 5.6.

Table 5.6: Definition of scenarios for the Fordwah Branch and Distributary to assess the impact of management interventions at the main and secondary canal level on agricultural production and salinity and sodicity

Scenarios	Level of intervention	Basis for intervention	Described in
Reference (*M0D0*)	-		Table 3.21
M0D3	Secondary canal	Existing salinity	Table 3.23
M4D4	Main, secondary canal	Prediction of salinity and sodicity for the existing irrigation management	New

For the definition of the scenarios, the results of Chapter 3 are used. The reference scenario is identical to Scenario *M0D0* of Section 3.4.4. The inflow of the Fordwah Distributary has been generated by the

SIC model of the main Fordwah Branch (Scenario *M0*), simulating the actual water distribution pattern.

In case of Scenario *M0D3*, the interventions at the distributary level for improved salinity control, which were proposed in Section 3.4.4, are assessed for their effect on salinity and sodicity. This scenario was described already in Section 3.4.4. The inflow pattern is generated by Scenario *M0*, and seven outlets have been increased in size to allow for more water for salinity control.

Scenario *M4D4* is new. The inflow pattern is generated by SIC (Scenario *M4*), giving about 6.4% more water to the Fordwah Distributary in order to deal with salinity problems in its command area. The tertiary outlets of those command areas confronted with salinity have been increased in size, while the outlets of areas without salinity, which are too big in the present situation as compared to the water entitlement or which are blessed with good quality groundwater, have been decreased in size.

Scenarios *M0D3* and *M4D4* were both formulated to address salinity and sodicity problems in the Fordwah Distributary command area. The main difference between both scenarios is that *M0D3* was formulated *before* analyzing the actual situation (reference scenario) with the integrated model, while *M4D4* was defined *after* running the reference scenario. In the case of the latter scenario, the effects of a continuation of existing irrigation management practices on the salinity and sodicity of different tertiary units was taken into account.

The results of the simulations will be presented in three steps. In Section 5.3.1, the results of the reference scenario, which represents the actual situation, will be analyzed. In Section 5.3.2, the results of Scenarios *M0D3* and *M4D4* will be compared with the reference situation in order to assess the possibility to improve the salinity control of farmers in the Fordwah Distributary through interventions in the canal irrigation system management. Finally, in Section 5.3.3 an overall evaluation of these interventions is carried out.

5.3.1 Irrigation management and salinity control in the Fordwah Distributary: actual situation

In the present section, the actual situation is represented in a reference scenario (Table 5.6), and analyzed using the integrated framework of Figure 5.2. The simulations are done for a period of one year, Rabi 1993/1994 and Kharif 1994.

Irrigation supplies

In reaction to the expected canal water distribution of the reference scenario, i.e. Scenario *M0D0*, farmers in the Fordwah Distributary decide on a cropping pattern and intensity, for which they need to obtain a certain amount of tube well water. Both canal deliveries and tube well water use for the different tertiary units are presented in Figure 5.4. The tertiary units are presented from head to tail of the Fordwah Distributary. The canal water supplies were simulated using the SIC-Gateman model, while the tube well pumpage was predicted using the LP models.

The predicted tube well pumpage constitutes on average almost 65% of the irrigation supplies. As indicated in Section 5.1.1, these predictions seem to slightly overestimate the amounts of water pumped by farmers.

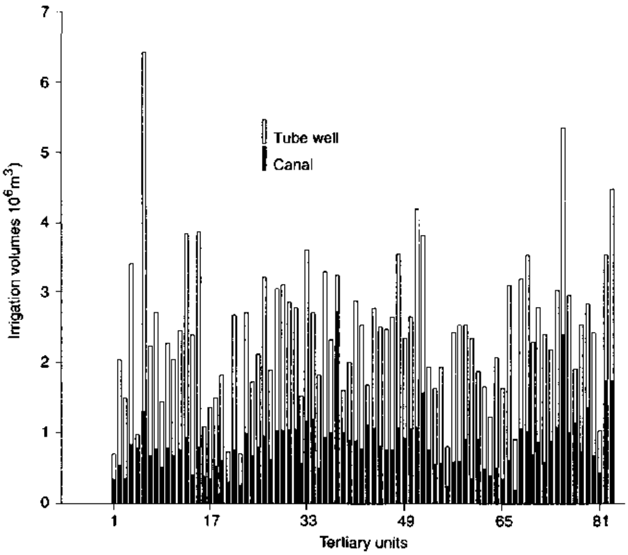

Figure 5.4: Simulated canal water supplies and predicted tube well water use during one year in the tertiary units of the Fordwah Distributary for the reference scenario.

Cropping intensities

The cropping intensities that are predicted appear more reasonable. They are depicted in Figure 5.5 for all the tertiary units of the Fordwah Distributary.

Only for two tertiary units, the results seem aberrant (high). For the other units the results are coherent with field observations.

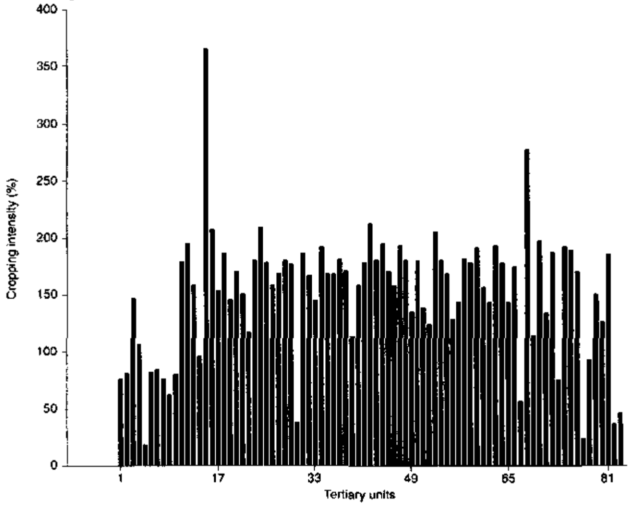

Figure 5.5: Predicted cropping intensities for the tertiary units of the Fordwah Distributary for the reference scenario.

Model verification using cropping intensities

The model predictions were verified with data that were obtained through remote sensing for the study area (Vidal et al., 1996). In this way, it can be investigated whether the coupling of individual models has amplified the errors or not.

The results of this verification are

presented in Figure 5.6.

The results for the Fordwah Distributary seem quite coherent with the measured values. The pattern of predicted and measured cropping intensities match quite well, and only for a few tertiary units larger differences can be observed.

The accuracy of the prediction can be verified with the standard error of estimate S_{xy}, see Equation 4.19. In the case of the Fordwah Distributary, S_{xy} is 28.4 ha, while the mean command area and the mean cropped area are 167.5 and 111.7 ha, respectively. The error is, therefore, in the range of 17-25%.

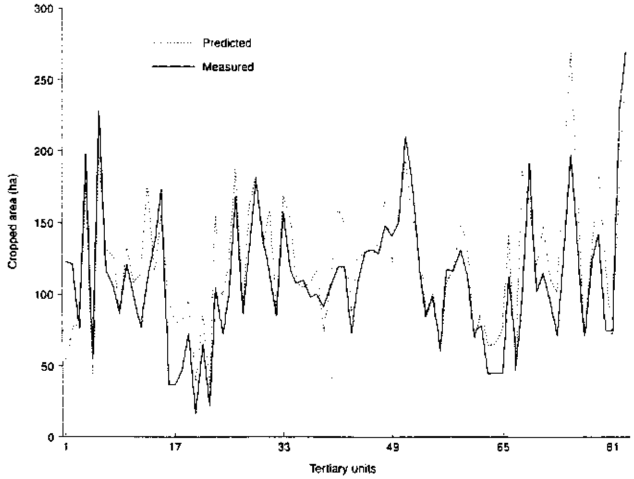

Figure 5.6: Comparison of measured and predicted cropped area for Rabi 1994/1995 for the tertiary units of the Fordwah Distributary for the reference scenario.

This shows that the errors in prediction of cropping intensities are not amplified. A more complete verification of the model output, looking at tube well pumpage and cropping pattern can now be undertaken, since the LP models have been validated.

A regression analysis was also carried out to check the match between measured and predicted results. This is depicted in Figure 5.8. The correlation seems good and the linear regression between both data sets gives an R^2 of 0.73 with 81 degrees of freedom.

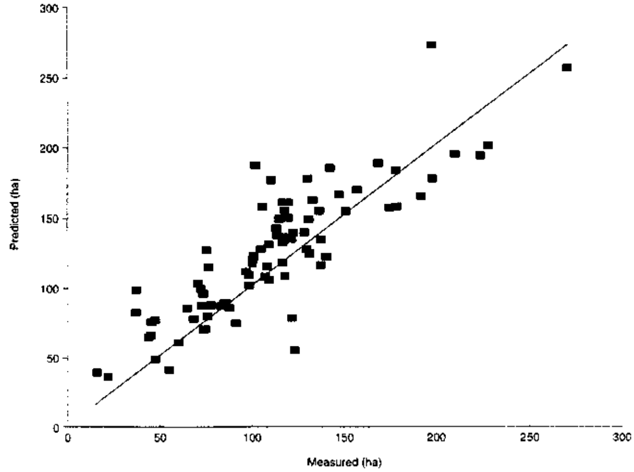

Figure 5.7: Regression analysis of predicted and measured cropped areas of the tertiary units of the Fordwah Distributary for the reference scenario.

Transpiration, soil salinity and sodicity

The effect of irrigation water quantity and quality on crop transpiration, salinity and sodicity can be determined with the tools developed in Chapter 4. The relative transpiration T_{act}/T_{pot}, and the amount of salts stored in the upper 2 m of the soil profile, S, can be calculated using SWAP93. However, it is easier to use directly the information that is contained in the Figures 4.22 to 4.27. These data represent the results of long-term simulations. To obtain the resulting T_{act}/T_{pot} and S values, the irrigation quantities and qualities need to be known. The former are an output of the SIC and LP models for canal water and tube well water, respectively. The canal water quantity at the field level is obtained by assuming 25% seepage losses from the mogha up to the field, based on estimates of Barral (1994). No seepage losses are taken into account for tube well water. In case of tube well water, the average groundwater quality values for each tertiary unit are used.

In Figure 5.8, the average relative transpiration for all tertiary units of the Fordwah Distributary is presented. The different soil types within each tertiary unit were taken into account when determining T_{act}/T_{pot}. The average T_{act}/T_{pot} for all units is 0.94, and there is only a slight variation. The reduction in T_{act}/T_{pot} that is observed for a few tertiary units is due to an accumulation of salts that takes place in the soil profile. Although S is on average only 131 mg cm^{-2}, there are five units with relatively high amounts of salts, due both to a low leaching fraction, and a high concentration of irrigation water. The values of S go up to 443 mg cm^{-2}.

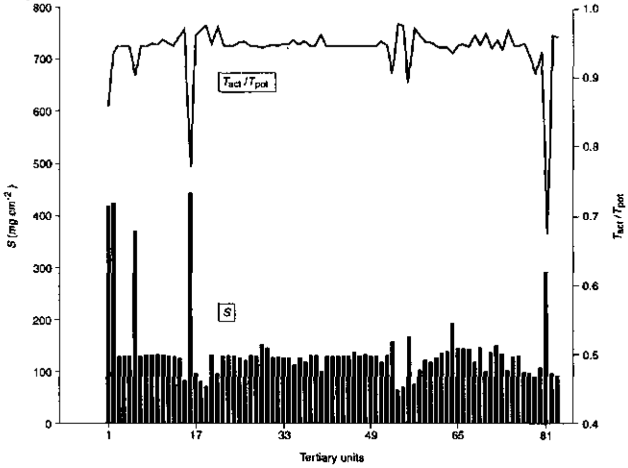

Figure 5.8: Average relative transpiration, T_{act}/T_{pot}, and soil salinity storage, S for the tertiary units of the Fordwah Distributary for the reference scenario.

The sodicity risk is represented by the *SAR* levels, depicted in Figure 5.9.

Figure 5.9 shows quite a variety in sodicity risk. A number of tertiary units face a risk of high levels of *SAR*. An area of about 3300 ha, which is about 25% of the *CCA* of the Fordwah Distributary, is confronted with an *SAR* higher than 13. The variety in sodicity risk can be explained by the spatial heterogeneity of the groundwater quality and the soils, by the different access to canal water, and by the volume of tube well water used.

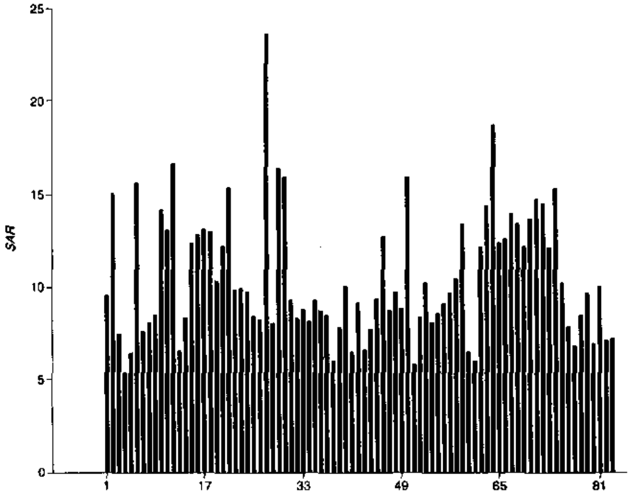

Figure 5.9: Sodicity risk for the tertiary units of the Fordwah Distributary for the reference scenario.

It is interesting to compare the results of Figure 5.9 with the analysis of Section 3.4.4, which led to the formulation of Scenario *M0D3*. On the basis of a visual salinity survey, seven tertiary units were selected for extra canal water supplies. The predictions of the integrated tool, however, show that in the long term these units are not the ones with the highest sodicity risk. This is related to the fact that the sodicity threat is much more related to the irrigation water quality than to the existing soil sodicity.

5.3.2 Improving the salinity control for the Fordwah Distributary

In this section Scenarios *M4D4* and *M0D3* will be compared with the reference scenario. These scenarios are defined in Table 5.6.

Irrigation supplies

In case of Scenario *M0D3*, which was taken from Section 3.4.4, seven outlets were increased in size, and four decreased. The seven outlets received about 80% more water, while four outlets received 25% less. The difference is that for the remaining outlets, unlike in Scenario *M4D4*, no extra water was available due to the fact that the inflow was identical to that of the reference scenario. The change in canal water deliveries as compared to the reference situation was depicted in Section 3.4.4 (Figure 3.24).

The simulation results obtained for the actual situation give an indication of which tertiary units are threatened by salinity and sodicity. This information was used for defining Scenario *M4D4*. Twelve outlets were selected with the highest SAR level for increased canal irrigation supplies. The width *b* of these outlets was increased by 100%. To compensate for this, twenty outlets with the lowest SAR values were decreased in size by about 25%.
In addition, extra supplies were scheduled for the Fordwah distributary, corresponding with the inflow generated by Scenario *M4* in Section 3.3. The details of Scenario *M4D4* are presented in Appendix 3. The resulting deliveries to tertiary units were calculated using the combined Gateman-SIC model. The changes in water deliveries are depicted in Figure 5.10.

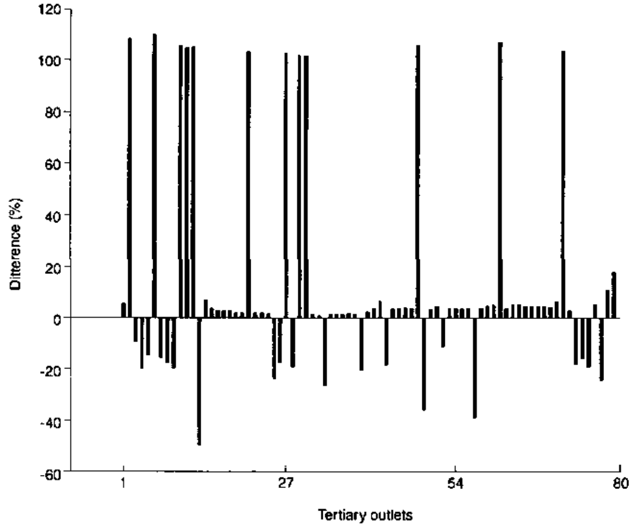

Figure 5.10: Comparison of canal water deliveries to the tertiary outlets of the Fordwah Distributary of Scenario *M4D4* with the reference scenario, expressed as a percentage change in deliveries for Scenario *M4D4*.

The figure shows that the intended increase in deliveries by 100% is attained for the twelve outlets. On average, the intended 25% decrease in deliveries to the twenty outlets is also attained, although the percentage decrease is slightly irregular. This is due to the fact that the most straightforward way to increase or decrease deliveries to outlets is by changing *b*. However, the minimum value of *b* is, for hydraulic reasons 6 cm, and a number of outlets are 6 to 7 cm wide. This necessitates changing the height *y*.

Cropping intensities

Two effects of an increase in the canal water supplies can be discerned. Firstly, farmers reduce the tube well water use and substitute this with canal water. Secondly, farmers may increase their cropping intensities. These effects are not instantaneous, but take place gradually after the interventions have taken place. The results in this study represent the equilibrium values and integrate this adaptation process.

In case of Scenario *M0D3*, the seven outlets with increased canal water supply show only a slight increase in cropping intensities. The extra canal water leads, in most cases, directly to a reduction in tube well supplies. However, overall a modest increase in the cropped area can be observed of 132 ha. This is about the same as in the case of Scenario *M4D4*, but is achieved without an increase in inflow. This means that slightly less water is available for crop transpiration. However, the differences are very small.

In case of Scenario *M4D4*, an overall decrease of 3% in the tube well pumpage can be observed for the Fordwah Distributary. There is also a modest effect on the cropping intensities with 135 ha of land that are cultivated additionally. This is less than one percent increase. The effects for the individual tertiary units are depicted in Figure 5.11.

The farmers in tertiary units, where the canal water supply is reduced by about 25%, tend to compensate by pumping more groundwater. In those tertiary units where supplies are increased by 100%, farmers will substitute tube well water up to a certain extent, but take advantage of the extra supplies to increase their cropping intensities.

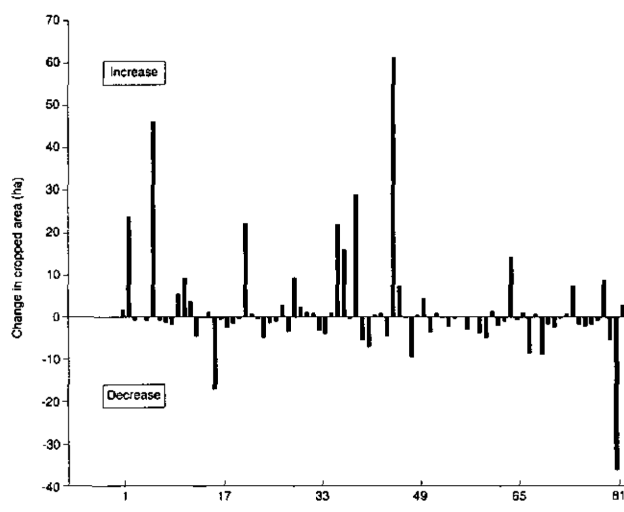

Figure 5.11: Comparison of the cropped areas of the tertiary units of the Fordwah distributary for the reference scenario with Scenario *M4D4*. The results represent the cropping areas of Scenario *M4D4* minus those for the reference scenario.

The average T_{act}/T_{pot} for the tertiary units of the Fordwah Distributary hardly changes as a result of the irrigation management interventions in case of Scenario *M4D4*, see Figure 5.12. The average *S* decreases slightly from 139 to 128 mg cm^{-2}. Out of the 12 tertiary units, where canal water deliveries were increased, a decrease in soil salinity can be observed for 10 units. In the other two units, the irrigation water had a low concentration in the reference scenario, so that no further decrease was possible.

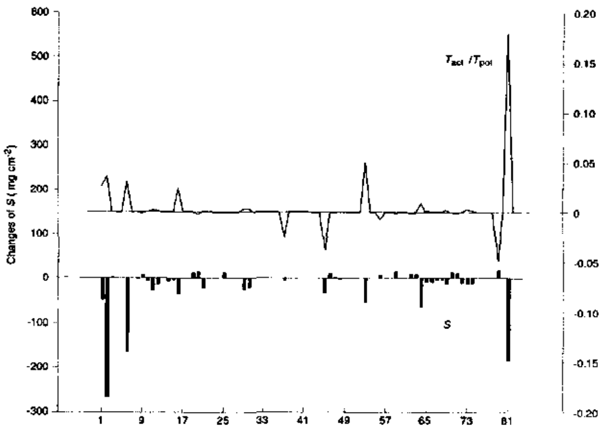

Figure 5.12: Change of the average relative transpiration T_{act}/T_{pot} and the salt stored in the upper 2 m of the profile, *S*, for the tertiary units of the Fordwah Distributary, as calculated for Scenario *M4D4* with respect to the reference scenario.

Surprisingly, in case of Scenario *M0D3* an *increase* of the average salinity was observed from 139 to 178 mg cm^{-2}. This means that this scenario does not accomplish its aim of reducing soil salinity.

It is difficult to give an indication about the time that it will take for the new salinity levels to develop. The values that are given here, represent values obtained after 10 years of simulations. However, the analyses of Chapter 4 indicate that these levels are generally obtained after 2-6 years, depending on the soil type, initial salinity levels, irrigation depths and tube well water quality.

The effect of the irrigation management interventions on the profile salinity is further illustrated in Figure 5.13, where an example of an output of SWAP93 is presented.

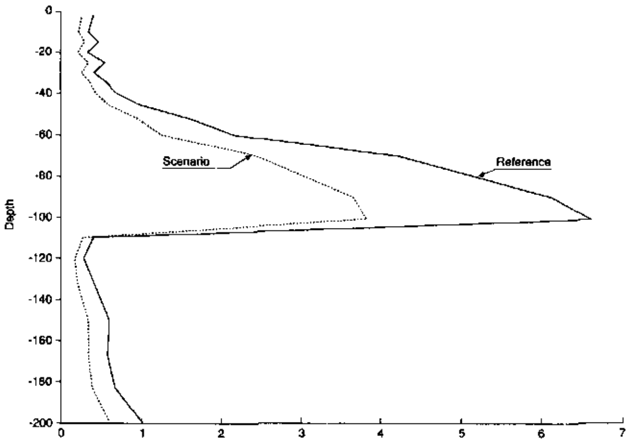

Figure 5.13: Comparison of soil salinity profiles, expressed as the EC_e, for a loam to silty clay loam for the reference scenario and for Scenario *M4D4*.

Figure 5.13 presents the outputs of SWAP93 for a loam to silty clay loam in tertiary unit 29. For Scenario *M4D4*, this unit has been given almost double the canal water supply as compared with the reference scenario. However, the overall increase in irrigation quantity is only 13%, because almost two thirds of the extra amount of canal water substitutes tube well water. On top of that, the farmers have cultivated an additional 5% of the area, so that the available water has to be spread over a larger area. Nevertheless, the extra irrigation water quantity and the fact that the *EC* of the irrigation water decreases from 1.31 for the reference scenario to 0.87 for Scenario *M*4*D*4, causes a considerable reduction in the EC_e of the soil profile.

Soil sodicity

The impact of the canal irrigation management interventions on the soil sodicity is presented in Table 5.7 for all scenarios. The area confronted with a sodicity risk in the Fordwah Distributary is classified in different classes, showing an increasing *SAR* level. These classes have been obtained from the Punjab Agricultural Department.

Table 5.7: Area (*CCA*) confronted with sodicity

Sodicity risk	*SAR*	Reference (ha)	Scenario *M*4*D*4 (ha)	Scenario *M*0*D*3 (ha)
None	0 - 7	1940	1350	2445
Low	7 - 13	8650	10640	8600
Considerable	13 - 20	3230	1920	2755
Severe	> 20	75	-	105

In the actual situation (reference scenario) about 3300 ha have an *SAR* higher than 13. After intervention, this area is reduced by almost 1400 ha in case of Scenario *M*4*D*4, which is more than 40%. At the same time, about 600 ha face an increase in the *SAR* level and move from an *SAR* smaller than 7, to one between 7 and 13. This is the price that is paid for reducing the areas with a considerable risk of sodicity. The end result is a more equitable sodicity status for the Fordwah Distributary. This is also evidenced by calculating the spatial coefficient of variation, cv_R for the *SAR* levels in the different tertiary units. It is 0.32 in the actual situation and improves to 0.25 for Scenario *M*4*D*4. In case of Scenario *M*0*D*3, the impact of the canal irrigation management interventions is much less. The total area with an *SAR* higher than 13 reduces by 445 ha, which is a little over 10%. The advantage of this scenario is that the area not affected by sodicity (*SAR* < 7) increases by 500 ha, despite the redistribution of canal water.

The impact of the canal irrigation management interventions of Scenario *M*4*D*4 on soil sodicity is presented in Figure 5.14, where the change of the average *SAR* levels of tertiary units as a result of these interventions are depicted.

The tertiary units that have a high risk of soil sodicity in the actual situation, show a considerable decrease in *SAR* level for Scenario *M4D4*. Since the reductions in canal water supplies were done for tertiary units where the groundwater quality is relatively good, they are able to pump more tube well water without doing much harm in terms of soil sodicity. The overall *SAR* level for the Fordwah Distributary decreases slightly from 10.6 to 10.0, which can be attributed mainly to the extra inflow of canal water. Perhaps a more important result is the decrease in the cultivated area threatened by sodicity.

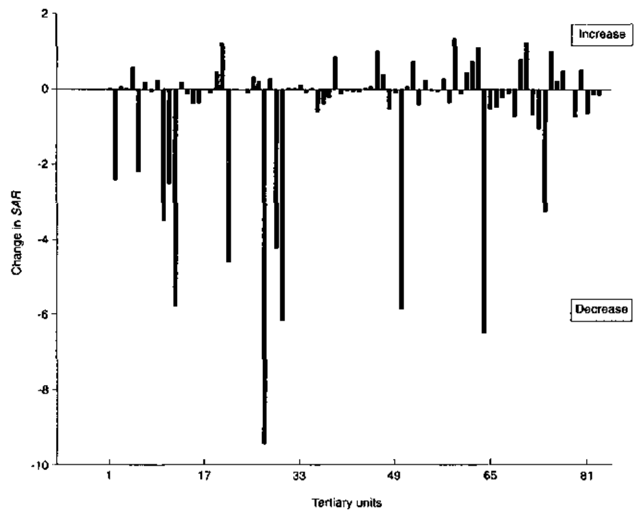

Figure 5.14: Comparison of the *SAR* levels of the tertiary units of the Fordwah Distributary for Scenario *M4D4* with the reference scenario. The results represent the *SAR* levels of Scenario *M4D4* minus the reference scenario.

The time period that is required for these new sodicity levels to develop can only be given as indicative values. Condom (1996) and van Dam and Aslam (1997) show that within a year's time the upper 30 cm of the soil profile is impregnated with sodium when irrigating with poor quality irrigation water. However, it takes a few years for the deeper layers to be affected. The reclamation of sodic soils is also a lengthy process. Farmers say they are able to reclaim most of these soils within 3-5 years time, provided canal water is available.

5.3.3 Evaluation of the impact of canal irrigation management on cropping intensities and salinity and sodicity for the Fordwah Distributary

The impact of the present canal irrigation management and interventions therein, on the irrigation supplies, the agricultural production, and salinity and sodicity are summarized in Table 5.8 using the performance indicators that were defined in Section 5.2.

Table 5.8: Performance indicators showing the impact of canal irrigation management interventions on canal water supply, agricultural production and salinity and sodicity.

Issues	Performance indicators	Actual situation	Scenario *M4D4*	Scenario *M0D3*
Water supply	DPR	0.72	0.81	0.77
	cv_R (DPR)	0.40	0.53	0.38
	V_{tw}/V_{iw}	0.65	0.61	0.62
	RWS	1.75	1.76	1.63
Agricultural production	CI	152	153	152
	cv_R (CI)	0.36	0.36	0.34
Salinity, sodicity	A_{sal}	0.03	0.01	0.14
	A_{sod}	0.24	0.14	0.21
	EC_{iw}	0.94	0.87	0.91
	SAR_{iw}	4.14	3.73	3.99
	cv_R (SAR_{iw})	0.55	0.44	0.56

There is more canal water supply available for the tertiary units of the Fordwah Distributary after intervention in case of Scenario *M4D4*, as evidenced by a higher *DPR*. The distribution of canal water, however, is (purposely) less equitable, as shown by a higher coefficient of variation, because extra supplies are routed to a number of units that require the water for salinity control. Farmers react to this, partly by substituting the tube well water for canal water, explaining the lower value of V_{tw}/V_{iw} after intervention, and partly by increasing slightly the cropping intensity. However, the impact on the cropping intensity is quite small, which shows the importance of tube well water as a source for irrigation. The impact of the intervention on salinity and especially sodicity, is substantial. The area with an *SAR* superior to 13, for example, decreases from 24% to 14% of the *CCA*. This is caused by a decrease in the average SAR_{iw}, but the coefficient of variation shows that, perhaps more importantly, the distribution of irrigation water quality is more equitable after intervention with less extreme values for individual tertiary units. The results of this scenario show that by taking advantage of the existing heterogeneity in groundwater quality and soil types, a decrease in salinity and sodicity can be achieved by reallocating water in the Chishtian Sub-division.

In the case of Scenario *M0D3*, no extra water is made available to the Fordwah Distributary, and only a redistribution of water between tertiary units occurs on the basis of a visual salinity survey. However, by decreasing the supply to those units that were taking more than their fair share, the average *DPR* for all tertiary units is more favourable. The water distribution is slightly more equitable than in case of the reference scenario. The impact on the cropping intensities is rather small, although it is remarkable that by merely redistributing the available water, a few hundred ha of land are added to the cultivated area. The effect on salinity and sodicity is not as expected. The area affected by salinity increases considerably, while a small decrease in the area affected by sodicity can be observed. This shows that suitable interventions can only be developed *after* a thorough analysis of the existing situation.

Preliminary results were obtained from the application of a model that integrates a canal irrigation management, an economic, and a salinity component, to a case study, the Fordwah Branch and Distributary. The first application related to the analysis of the actual situation, which showed that the cropping intensities were predicted with an error in the range of 17-25%. Tube well pumpages were less well predicted and are overestimated. In the actual situation, 3300 ha or 24% of the CCA of the Fordwah Distributary, is confronted with a considerable risk of sodification with an SAR > 13. It was shown that through targeted canal management interventions at the main and secondary canal level, the salinity control of farmers can be improved. The area with a considerable risk of sodification is reduced by almost 1400 ha. It was further shown that conceiving canal irrigation management interventions, should only be done after a thorough analysis of the existing situation. Otherwise, these interventions will have a limited or even adverse impact on salinity and sodicity.

5.4 Evaluation of the integrated approach

The application of the integrated model to a case study in Section 5.3, provides opportunities for an evaluation of the added value of such a tool as part of a larger integrated approach. In this section, the evaluation of the integrated approach that was developed and tested in this study will be carried out in three steps. In Section 5.4.1, the results of the integrated approach will be evaluated. In Section 5.4.2, the process of integrating the different thematic studies will be analyzed. Finally, in Section 5.4.3 some perspectives for further work on integration in irrigation management are formulated.

5.4.1 Product evaluation

The integrated approach: more than an integrated model

Before evaluating the integrated approach, it is perhaps good to recapitulate the main points of the approach that was developed in this study:
- The approach combines the analyses of bio-physical and decision-making processes;
- The approach incorporates a set of models that can be linked to assess the impact of interventions in canal irrigation management on soil salinity and sodicity;
- The approach uses a geo-referenced database; and
- The approach addresses intervention strategies on the basis of a thorough analysis of the effect of existing irrigation management on soil salinity, sodicity and agricultural production.

A logical assertion that follows this synthesis, is that an integrated approach is more than an integrated model. The individual models of the bio-physical processes and the individual studies of decision-making processes also form an important part of the approach. In addition, the process of developing an integrated approach, including the diagnosis of the existing situation, provides insights in the functioning of a complex system, even though the predictive capability of the integrated model itself can be questioned. These issues can be further elaborated.

Firstly, the approach is aimed at the actors, helping them to selecting appropriate management interventions to address existing (or future) problems. The needs of these actors relate only part of the time to a complete integrated model. More often, they need intermediary outputs, perhaps with a different degree of precision than delivered by the integrated model. By providing these intermediary outputs, the tool becomes more transparent, so that actors learn to trust and understand the tool. This was done by making the approach as modular as possible, where every single model of the approach can be taken out at any time for a specific study.

Secondly, the constitution of an integrated model is only one step in a larger framework, which comprises also a diagnosis, a representation of the system, identification of relevant processes and parameters, analyses of these processes, and the modelling of the individual processes. After the constitution of the integrated model, the required management interventions need to be identified, and a database needs to be established to apply the model to an irrigation system. Different pieces of the integrated approach may be required to propose the right management interventions, the effect of which can be calculated with the help of the integrated model. The interpretation of the results, will need to be done on the basis of the understanding obtained from each of the thematic studies. Since the integration covers several disciplines, this is likely to involve a number of people.

Thirdly, the complexity of an irrigation system makes it difficult to develop an integrated model that has accurate predictive capability. This is due to the interaction of human and physical processes and the large variability over time and space of the different characteristics of an irrigation system. It is, therefore, better to focus the overall approach more towards creating an understanding of the impact of management interventions on salinity and agricultural production than on an accurate prediction. The approach should also provide insights in the cause-effect relationships in an irrigation system. These things can not be achieved by only an integrated model, and the underlying diagnosis, analyses and experiences gained during the research should be shared with the actors of the irrigation system in order to improve the management of the system.

Validation or evaluation?

The classic approach to verifying a model is to validate model output for a different situation, a different time period or for a different location, thus authenticating the truth and accuracy of the model (Konikow and Bredehoeft, 1992). This is extremely difficult for an integrated approach in a complex system, because of the inter-dependency of relationships and the mixture of bio-physical and human processes. Results that seem numerical in the outcome of the models become fuzzy in reality as people have a tendency to adapt/react to changes in the bio-physical environment, thereby changing the nature and format of relationships that were assumed in the approach. Konikow and Bredehoeft (1992) further argue that understanding and prediction of a process in physical sciences need not be symmetrical, i.e. being able to understand and model a process does not mean one is capable of prediction, due perhaps to factors beyond the scope of the scientist such as farmers' behaviour.

A sensitivity analysis can help in determining which factors/variables are important for the outcome of the approach, thereby contributing to an evaluation of the validity of the outcomes. In the case of this study, the importance of the groundwater quality was thus demonstrated. This can be further strengthened through an analysis of the possible range of use of the integrated approach, which is a function of the ranges identified during the calibration/validation procedures of the different models.

Researchers suggest a number of alternatives for validating an integrated approach, focused on testing the scientific rigor and the usefulness of the approach. Firstly, the approach can be verified by explaining the present situation of the study area in terms of heterogeneity and distribution of water supplies, salinity and agricultural production. This will provide valuable insights into existing relationships and their interactions. The coherence of the results as compared to the existing situation is an important way of evaluating this. In Section 5.3 a comparison between predicted and actual cropping intensities for the Fordwah distributary was presented. This showed that in addition to the accuracies of the individual models and analyses, the outputs of the integrated model were coherent with the actual situation in the field. The overestimation in predicted tube well use showed that there is still room for improvement. Secondly, the integrated approach can be validated by restituting the approach to the irrigation managers as well as the policy makers, or farmers. If the outcomes of the approach seem plausible to them and help them to take better decisions on irrigation management, this confirms the validity of the approach. A similar restitution can be done to researchers and obtain their views on the validity of the approach.

Accuracy

Accuracy of the predicted results is an important criterion for complex models. This accuracy is firstly related to the accuracy of individual models. The bio-physical models that have been used in this study, i.e. SIC and SWAP93, have shown relatively small errors, generally in the range of 5-10%, during their calibration and validation for a wide range of physical conditions. If the conditions change, e.g. a sediment deposition in a canal that was studied, the models generally remain valid or need to be updated, which is fairly straightforward. For the models that formalize decision rules, i.e. Gateman and the economic LP models, the issue of accuracy is more complicated. Farmers have certain strategies and constraints, which can help to understand their behaviour and predict likely reactions, but individual events and preferences are not taken into account. However, these individual reactions are partly compensated by the large number of people in the study area. In addition, asymmetry between understanding and predicting human behaviour is likely to be even more pronounced than what was observed for bio-physical models by Konikow and Bredehoeft (1992). This is related to the fact that conditions can change from those which existed when the model was developed and human behaviour is influenced by a wide range of external events (Parker et al., 1995). This means that not only are model outputs concerning human behaviour likely to be less accurate than those concerning bio-physical processes, but the accuracy can decline rapidly when predictions are done for the future.

The accuracy of a complex model is also related to the information that is available. Usually, this information is aggregated or interpolated from a number of point values. The quality of the transformation of information will play a role in the overall accuracy of the predictions of the model.

In the context of this study, there have been two instances of verification of the accuracy of model output of an integrated model. In Section 3.3, the combined Gateman-SIC model was verified using historical data. An average error of less than 10% was obtained. In addition, the accuracy of predictions in gate operations in the case of an intervention was tested in the field in collaboration with the irrigation agency. Inaccuracies in the range of 10% were obtained (Litrico et al., 1995). In Section 5.3, a combination of Gateman-SIC and the economic LP models was used to calculate cropping intensities and cropping pattern, and to provide input data for the calculation of the sodicity risk. The inaccuracy of the predictions was verified for cropping intensities, for which a range of 17-25% was found. In both cases, predictions have not been verified for future developments.

Potential management interventions

An inventory of possible policy and management interventions for improving irrigation system performance and minimizing the risk for salinity and sodicity is presented in Table 5.9. The interventions have been shown already in Figure 5.2.

Table 5.9: Inventory of possible irrigation policy and management interventions.

Intervention categories	Main canal	Secondary canal	Tertiary unit/farm
Construction	Lining Infrastructure	Lining Infrastructure	Lining
Management	Change inflow Change in operational rules	Maintenance Farmers' federation	Improved irrigation practices
Enabling environment			Constraints on cropping pattern Water pricing (canal, tube wells) Water markets Quota Change in output prices

Most of the interventions at the main and secondary canal level were tested in this study, while the policy level intervention, which change mainly the enabling environment, are tested in the parallel study (Strosser, 1997). Interventions at the field level, e.g. through improved irrigation methods such as furrow irrigation, and in the institutional arena, e.g. the establishment of a farmers' federation, have not been analyzed, but could be integrated in the present study, by modifying for example certain parameters in the LP models to account for losses. This will be relatively straightforward for the interventions at the field level, but much more difficult for institutional interventions, because the impact of institutional change is not easy to assess.

Depending on the level at which the intervention takes place and the type of intervention, a choice can be made as to the analysis that will be carried out. Testing various types of maintenance for a given secondary canal, for instance, does not require the main canal model. Also, the user may decide to first assess the impact of a range of maintenance measures on the water distribution before assessing the effect of the most successful interventions on agricultural production and soil salinity and sodicity.

Users of the integrated approach

Potential users of the *information* generated by the application of the integrated approach are mainly policy makers, planning sections in the irrigation and agricultural departments and donors in the present situation in Pakistan. The analysis of Section 5.3 shows that intervention strategies benefit from an analysis through the integrated approach. The role of farmers in decision-making on the formulation and implementation of projects is very limited. The information provided through the application of the integrated approach could play a role in involving farmers in discussions about future interventions. Potential users of the *tools* that have been developed as part of the integrated approach will presumably be limited to researchers, although certain models could also be used by the line agencies. SIC is used, for instance, by engineers of WAPDA and PID.

Application of the integrated approach in other cases

An important question that should be responded to is whether the integrated approach that has been developed can be successfully applied elsewhere. Part of this question is answered because of the fact that the framework was used by Strosser (1997) to answer a different research question in the same area. This discussion can, perhaps, be continued by looking at the individual parts of the approach, i.e. the framework, the diagnosis, the analyses of decision-making processes, the simulation of bio-physical processes, and the results.

The *integrated framework* was developed specifically for the case study and is, therefore, not generic. Certain elements are, therefore, transferable to studies in other irrigation systems. An example is the concept of combining the operational logic of the irrigation agency with canal hydraulics through a composite model. A specific integrated framework, however, will need to be conceived for any given situation, and will depend on the objectives of the study and the situation in the field.

The *diagnosis* of the actual situation was a recurrent phenomenon in the present study. This took place for the thematic studies, but equally for the last part of the study, when the actual situation was analyzed using the integrated framework. New situations probably require an equally thorough diagnosis, given the importance of understanding the cause-effect relationships in the actual situation in order to formulate management interventions. However, the diagnosis can be accelerated. In the present study, it was shown how the combination of using bio-physical simulation models and understanding decision-making processes have led to the diagnosis of the present situation. A composite model like SIC-Gateman is quite efficient in helping to understand what decisions lead to the present canal deliveries. Understanding why this happens is then easier and better discussions can take place with the actors. Perhaps, the overall system diagnosis can be accelerated by constructing in an earlier stage a simplified version of an integrated framework, and carrying out an analysis of the present situation.

In the present study, the *decision-making processes* of the irrigation agency both at the strategic as well as at the tactical level were captured in operational rules in a regulation module, and linked with a physical model to assess its impact. Since the tactical operation of an irrigation system is mainly dealing with water levels and discharges, irrespective of the irrigation system, the tactical operational rules are likely to be quite comparable for any given situation. This is demonstrated by the use of these regulation modules in other systems in the world (e.g. Malaterre, 1989). In the new version of SIC, this is further accommodated, because the user can programme alternative operational rules in the software Matlab, which issues instructions to SIC for opening and closing gates. However, before using the regulation module, a study is required to calibrate/validate the module. At the *strategic* level, an application elsewhere is slightly more complicated. As shown in this study, the strategic operational rules can be obtained by monitoring actual water deliveries for a sufficiently long time period, at least 1 year, and by interviews. The way these strategic rules have been formalized in the regulation module is probably generic, although a given situation is likely to require additional or alternative sub-routines in the regulation module. The second example of *decision-making processes* that were analyzed, is the farmer irrigation management. The tools that were used to make a typology of farmers and to formalize their decision rules, i.e. SOLO and Linear Programming, respectively, have been used elsewhere. However, the basic data to do this, will have to be collected again for any new situation. In the case of an application in Pakistan, the data requirements will be much less, as insights have been obtained regarding the relevant parameters.

The *models* that were used to simulate *bio-physical* processes are generic tools that are currently used in a lot of different countries around the world. Provided a good data set is available to calibrate/validate these models, there is no doubt that these tools can be applied successfully elsewhere. The use of the models in carrying out sensitivity analyses to reduce the input requirements for application at a larger spatial scale and to identify those parameters that are most likely to have the largest effect, if changed, on the desired properties (e.g. salinity), is universal. However, the analyses will likely have to be carried out for the new system, as the range of values for different parameters change. The choice of the models depends, of course, on the research objectives and the decision on which process needs to be selected for further study.

The *results* of the case study, obtained through the integrated approach, are not generic, of course, although they contribute to the overall understanding of the functioning of an irrigation system. Obtaining these results for a new study, however, should take less time than was the case for this study by adopting the integrated framework and carrying out targeted sensitivity analyses. The recommendations for future implementation of an integrated approach are presented in Section 5.4.3.

The conclusions regarding the application of the integrated approach elsewhere are, therefore, that much time can be saved by applying the lessons that were learnt in the present study. The general concept of the approach as well as certain specific elements appear to be generic and could be applied elsewhere. However, this should be done with care. A blanket prescription is not possible and the importance of a thorough diagnosis should be emphasized. The closer an application is to the context for which the present study was conducted, i.e. within the context of agriculture or irrigation, the easier it will be to transfer large parts of the approach. This is also evidenced by the application of the integrated approach by Strosser (1997) to the impact of the development of water markets on agricultural production.

The strengths and weaknesses of the integrated model were defined as part of a larger integrated approach. The approach is focused on providing insights into the functioning of an irrigation system and assessing the long term impact of irrigation management interventions on soil salinity. The accuracy of the predictions can be ascertained for the present situation through a process of calibration and verification. However, predictions for the future should not be evaluated for their absolute values, because there are likely to be unforeseen events like the prices of the agricultural products. Instead, these predictions should be evaluated for the understanding and information they provide to actors such as irrigation managers on the impact of alternative management interventions (what-if scenarios), so that these actors are better prepared for events in the future.

5.4.2 Process evaluation

Integrating bio-physical and decision-making processes

In this study two bio-physical processes were modelled and linked with two decision-making processes. Canal water flow was modelled using a generic hydraulic model. The human control over this flow, canal regulation, was analyzed in order to identify the intervention instruments and timing, and to understand the logic of control. Subsequently, a combined model was developed integrating the hydraulics of canal flow and the human control in order to quantify the impact of human decisions on physical processes. In the second case, the vertical transfer of water and salts in the unsaturated zone was modelled using a generic soil water flow - solute transfer model. The human control over salt and water balance, exercised by farmers, was analyzed to identify the tools available with farmers to influence this process, and to understand their motivation and constraints in dealing with soil salinity. From this analysis, it appeared that salinity control was not the only concern of farmers, and issues like crop production, revenues and self-sufficiency are also important. This signifies a vital difference with the canal irrigation processes, and makes it difficult to predict the soil and water balance as a function of farmers' salinity control. Instead, a separate study was necessary to understand farmers' irrigation practices on the basis of socio-economic characteristics. Then, this behaviour was modelled with the help of Linear Programming models (Strosser, 1997). Subsequently, these models were linked with not only the bio-physical salinity model, but also with the combined canal irrigation models.

What was learnt from these integrations? Firstly, the integration of studies of bio-physical and decision-making processes was easier when the latter were found to be focused for an important part on one bio-physical process, as was the case for canal irrigation. The degree of difficulty of integration was, therefore, determined by the nature of each of the component parts. Secondly, integration was a process of going back and forth between the two studies. Relevant parameters causing soil salinity or governing canal water distribution were identified by modelling the bio-physical processes. Thus, the study of human behaviour could be better focused by taking the actions related to specific parameters as a starting point. For example, a sensitivity analysis with the bio-physical soil water flow - solute transport model, exposed the importance of irrigation water quantity and quality, which enabled the integration with a socio-economic study of irrigation management of farmers. On the other hand, discussions with the actors involved helped to focus the bio-physical studies. Thirdly, the present study is intervention-oriented, which necessitated the quantification and integration of studies of bio-physical and decision-making processes. In this way, the marginal impact of both types of processes became evident, which allows a better judgment of the comparative advantage of intervening in either process. The impact of human decisions became measurable. It should be emphasized that the integration does not mean that the thematic studies are only focused on those elements that are relevant for the links between these studies. The physical model SIC was used to study the causes of discharge variability, which falls outside of the scope of the integrated study. However, the study was useful to clarify the distinction between a strategic and a tactical level of canal irrigation management and their relative impact on canal deliveries. The farm level studies exposed the itinerary of farmers' practices and their motivations for this itinerary (Pintus, 1995; Rinaudo et al., 1997b). Only part of this analysis was used for the calculation of scenarios, but without this analysis farmers' irrigation practices cannot be understood.

Simplification

Both for the hydraulic model as well as for the soil water flow - solute transfer model, a *simplification* of the models was considered when using them for the integrated tool. This is done to reduce input requirements and computational time. One can ask the question whether the required output of the deterministic models, which are, for instance, in the case of SIC monthly averages and standard deviations of discharge, justify the care that is taken in developing and using such a model. This is a pertinent question, and the model selection should be based on an analysis of input-output requirements in the framework of the integrated approach. However, this does not necessarily question the use of the deterministic models in the overall approach, as was argued in Section 5.4.1.

In the application of the approach at the main and secondary canal level, a number of simplifications can be adopted as regards the physical model depending on the objectives of the study. This was studied by Visser et al. (1997). The simplifications relate mainly to the canal topography and geometry:
- Reduction of the number of cross-sections
- Use of official crest levels
- Estimate seepage
- Estimate Manning coefficient n

The main draw-back of these simplifications is that the use of the model is restricted to discharges closer to the calibration values. Otherwise large errors will arise. Another approach, further simplifying the tool used was compared with the tools developed in this study and the one developed by Visser et al. (1997). It consists of a spreadsheet-based steady state model, which calculates the discharges to tertiary outlets in a secondary canal based on Manning's equation (Mobin-ud-Din et al., 1997). Thus, the lag times and fluctuations in water levels and discharges are not taken into account and the model is basically a simplification of the steady state unit of SIC. This model could replace SIC at the secondary canal level for specific studies, e.g. seasonal water distribution, when less accuracy of discharges is required.

The use of SWAP93 can also be compared with two alternative approaches. Firstly, it can be compared with the salt & water balance spreadsheet model developed by Kijne (1996) and Perry (1996) and modified by Van Waijjen (1996). The approach is based on the paper of Van Hoorn and Van Alphen (1995). Secondly, a comparison will be made with the outcome of an empirical equation, developed specifically for this study. This equation was developed in a similar way as Equation 4.18. Based on farm level irrigation and soils data, a regression analysis was done for 33 farms in Azim 43, Fordwah 46 and Fordwah 130. The resulting equation is given below.

$$EC_e = 4.23 + 2.08EC_{iw} - 0.046\%sand \tag{5.5}$$

The R^2 of the equation is 0.62, and the standard errors of the x coefficients are 0.5 and 0.007, respectively.

A comparison was made between all three methods by applying them to the eight tertiary units, for which the input parameters were used from Tables 4.19 and 4.20. The results are presented in Figure 5.15.

For the coarser textured soils, the salt & water balance seems to better predict the soil salinity, but a large overestimation occurs for Azim 63 and Fordwah 14. For the latter tertiary unit, this is probably related to the presence of a shallow groundwater table. In the salt & water balance approach, the capillary rise cannot be calculated and has to be estimated by the user. In case of Azim 63 , this is possibly related to the heterogeneity in soil types in this unit. A weak point of the salt & water balance approach is that no validation has taken place. The values of the input parameters have not been verified for other tertiary units. In the case of the empirical equation, the different soil types were taken into account. The results of equation 5.1 show that the equation slightly overestimates the soil salinity. A larger difference occurs for Azim 20, Azim 111 and Fordwah 130. This is probably related to the fact that the formula does not take the existing EC_e into account and bases its predictions on the likely EC_e under a given irrigation regime. In the other tertiary units, the results are better.

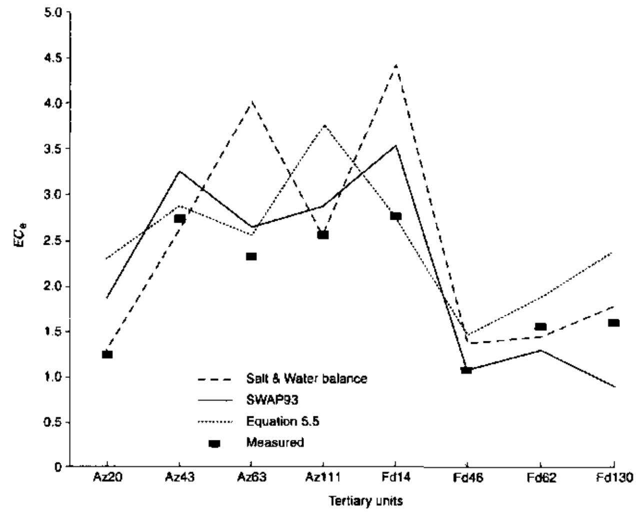

Figure 5.15: Comparison of SWAP93 with the salt and water balance approach (Van Waijjen, 1996) as well as with Equation 5.5.

The analysis shows that the EC_e predictions of SWAP93 compare favourably with the predictions of the two simplified approaches. This is mainly due to the soil fragmentation and the presence of a groundwater table in the case of the salt and water balance approach, and to the presence of salts in the soil for the empirical equation.

Finally, the use of the LP models can be simplified by substituting the main decisions that concern salinity and sodicity by empirical equations. The tube well water use, for instance, can be calculated by assuming that all farmers will apply 80% of the crop water requirements.

The models used in the present study are quite complex, which is related to the integration of thematic research components with specific objectives, as opposed to an approach that would have been integrated from its inception phase. As indicated above, two approaches were initiated in this study. Firstly, the input parameters of these models can be simplified by carrying out sensitivity analyses (Visser et al., 1997; Smets et al., 1997). Secondly, the deterministic models can be replaced by simpler models that require less input and computation time. However, it should be realized that in these simpler models certain relationships or parameters are considered fixed, which can generally also be made fixed in more complex models. In any case, in an integrated approach it is perhaps good to offer the user a choice between different models.

The integration of studies of bio-physical and human decision-making processes was analyzed on the *basis of two practical examples obtained from the case study. It was shown that from studying them together, both studies benefitted by (1) obtaining better insights in the motivation of the decisions governing physical processes and (2) quantifying the impact of decisions on physical properties. The integration is facilitated if the decision-making process is oriented largely towards the bio-physical process one is interested in.*

5.4.3 Perspectives

The perspectives for the application of an integrated approach in research on irrigation systems, will be analyzed in two steps. Firstly, the possible improvements of the methodology of the present study will be identified. Secondly, the potential contributions of an integrated approach will be summarized.

Possible improvements

The title of this chapter has been given on purpose a transitionary character. In the initial phases of the research, different thematic studies were formulated keeping in mind that the results of these studies would serve as components of an integrated approach. On the basis of the progress that was made with the thematic studies, an integrated tool has been proposed in this study as well as in the parallel study (Strosser, 1997). This is a first version, which has been tested for a case study, and many gaps exist. An inventory of the potential improvements of the present product shows a wide spectrum of issues.

The integrated model in its present configuration does not allow for an automated optimization of the management interventions in response to an identified demand. This could be done through an additional module with, for instance, a computerized multi-objective analysis. An example of this was presented by Quemer (1993). Another option would be to include an optimization loop in some of the individual components. At this stage of the integrated approach, there was a preference not to include an automated optimization in order to underline the principle of the management intervention strategy as an iterative approach. This also improved the understanding of the functioning of the system.

There is a scope for improvement for the individual models that were used in the integrated approach and for the integrated tool. Due to the modularity of the latter, improved versions of individual models can be quite easily integrated. This can apply to the simplifications that have been dealt with above already, or even by substituting the deterministic models SIC and SWAP93 by simpler tools. On the other hand, certain tools can be further improved. This applies, for instance, to the work on the geo-chemistry, where it was shown by Condom (1996) and van Dam and Aslam (1997) that it is possible to use state-of-the-art tools such as GYPSOL (Vallès and Bourgeat, 1988) or UNSATCHEM (Simunek and Suarez, 1994) for soils in Pakistan to predict salinity and sodicity levels. However, these models have not been calibrated/validated, yet. Another possible improvement is linking the hydraulic models of main and secondary canals. This is now possible with the latest version of SIC (Malaterre and Baume, 1997).

At present, the models function independently, and information exchanges take place manually. A start was made in improving the informatic environment by using the software MatLab to manage the information flow and provide a more user-friendly interface (Belouze, 1996). This is particularly important since the aim of the programme is to provide to users not only the outputs of the integrated tool, but also the ability to test their own scenarios. The development of an interactive interface is considered. In the foreseeable future, the direct users of the integrated tool are likely to be researchers because of the complexity of the tools and the interpretation of the results, which will remain necessary.

Is there still scope for improvement related to the calibration and verification of the integrated tool? The calibration and validation of the tool for the present conditions was carried out separately for the individual models and partially for the integrated tool, i.e. for the cropping intensities in Section 5.3 for 80 tertiary units and for salinity and sodicity in Section 4.6 for eight tertiary units. This showed that *errors in individual models were not amplified when integrating the models.* Strosser (1997) verified also the predicted tube well pumpages. The verification of predictions for the future has not been done, and the question is whether this is an important issue. As discussed in Section 5.4.1, the focus of the approach is more on creating an understanding of the present functioning of the system and of the impact of management interventions than on accurate predictions.

In the application of the approach to large areas, a number of simplifications were made in the aggregation and disaggregation of parameters to tackle spatial heterogeneity. Groundwater quality, for instance, was sampled for about 10% of the tube wells, and average values were determined per tertiary units. This procedure could definitely be improved by better determining the patterns in groundwater quality, and by using different interpolation techniques. Another problem related to scale was the fact that the canal irrigation quantities were known up to the level of the tertiary unit. The decision rules of water distribution between farmers within a tertiary unit, and between fields within a farm, could be further studied to identify these rules.

Feed-back loops have not been incorporated yet in the approach. It is possible to study some loops by rearranging the individual models. To give an example, if through external influences a considerable number of farmers switch from cotton to rice, this is likely to require a different canal water delivery pattern, i.e. more water in June, July and August and less water in September and October. By employing alternative operational rules some of these requirements can be met. The resulting canal water supplies can be calculated by the joint Gateman-SIC models, after which the cropping intensities and tube well pumpages can be determined through the LP models. These models will need to be slightly adjusted in order to account for the changed preferences of farmers for rice. This in turn makes it possible to estimate the effect on salinity and sodicity. However, most of the feed-back loops, e.g. the effect of increased salinity on the decisions of farmers of crop choice and tube well pumpage cannot be determined automatically with the present tools. An iterative procedure is required. When considering the introduction of feed-back loops, the problems of numerical stability of a complex model should be emphasized (Kosuth, 1994). Errors can increase during a looped computation.

Potential contributions of an integrated approach to irrigation systems research

The arguments for pursuing an integrated approach are found both in the nature of an irrigation system as well as in the assertion that linking bio-physical and human decision-making processes will lead to more cognizance on the comparative advantages of management and physical interventions to improve irrigation system performance. This was also illustrated for the case study in Section 5.3, where a diagnosis of the existing situation using the integrated tool was shown to drastically improve the effectiveness of the irrigation management interventions.

Issues related to irrigation system management, i.e. the acquisition, conveyance, distribution, use, and disposal of water, generally involve a combination of bio-physical and socio-economic factors. This implies that problems related to irrigation systems must be studied in the field. In doing so, one loses the traditional advantages of bio-physical research (Levine, 1993): "*replication, control of the research environment and the imposition of differential treatments*". This requires on the one hand research to enable the application of small scale bio-physical models at a larger scale, and on the other hand the development of approaches that enable to differentiate in the impact of management interventions on the physical environment. In the upscaling of bio-physical models, considerable progress has been made especially in the field of hydrology and groundwater management (Aragüés et al., 1985; Blöschl and Sivapalan, 1995; Shaw, 1996). On the development of approaches to quantify decision-making as well as bio-physical processes in irrigation systems, some work has been done in different projects around the world (e.g. Skogerboe et al., 1979; Shafique and Skogerboe, 1984; Agarwal and Roest, 1996), but much less work has been done on the conceptualization of an integrated approach and the quantification of human decision-making processes.

The complexity of an irrigation system is emphasized by the wide diversity in farmers, a great spatial heterogeneity in the physical environment, a temporal variability related to the nature of the irrigation infrastructure (e.g. siltation) and agricultural production (e.g. prices of products, diseases), a number of external influences on which the farmers have no control, and a dependency on water on which they have very limited control, and in this case study even very little information. In addition, there is a strong inter-dependency between users, who share the water as a common resource, which can lead to conflicting objectives or even competition for the same resources (Levine, 1993; Molle and Ruf, 1994; Millan and Berbel, 1992). In this context, developing a common platform, providing information to all actors involved, can help in managing a common resource (Röling, 1994; Shaw, 1996).

Recent concepts of managing common resources in river basins, catchment areas and irrigation systems, involving individuals, community groups and government agencies strengthen the argument of further stimulating the concept of an integrated approach (e.g. Shaw, 1996). Decision-making needs to be tailored towards proposing optimal solutions for the management of these resources. This requires information, accessible to all, in order to diagnose the effect of current practices on economic, social and environmental resources, and to assess the marginal impact of various policy or management interventions on these resources. When comparing the effectiveness of various options, which do not necessarily target the same space and time scale nor the same organization level, an integration of knowledge and experiences from different disciplines is required. When evaluating the results of a research study, they are matched with the wishes of all actors involved and are studied in relation to other parameters that were considered fixed in the analysis. Thus, an integration takes sooner or later place. The better solution is, perhaps, to consider this integration in the early stages of research.

Finally, the concept of an integrated approach becomes easier as the thematic, disciplinary fields become conceptually clearer and the tools more efficient. The scope for conceptualizing and implementing an integrated approach in irrigation management has, therefore, probably won much in applicability.

The desire to assess the comparative impact of management and physical interventions on agricultural production and salinity and sodicity, and the complex nature of an irrigation system, which implies that any intervention is likely to affect both social and physical factors, explain the need for an integrated approach of irrigation system management, linking bio-physical and decision-making processes. The possible improvements of the present version of the integrated model were listed, mainly related to feed-back loops, the computer software environment, the calibration and verification of the integrated tool, and scaling.

CHAPTER 6

SUMMARY AND CONCLUSIONS

An integrated approach was developed to assess *a priori* the impact of policy and management interventions in the context of irrigated agriculture. This approach was implemented in this study for an irrigation system in Pakistan, testing the effects of irrigation management interventions on soil salinity, sodicity and crop transpiration. In a parallel study, the approach was verified by analyzing the impact of policy interventions on the development of water markets and on agricultural production in the same study area (Strosser, 1997). In Section 6.1, the findings of the present study are summarized and concluded. The general lessons from the application of the integrated approach in both case studies are discussed in Section 6.2.

6.1 Irrigation system management interventions for improved salinity and sodicity control: lessons from the case study in Pakistan

Salinity and sodicity in Pakistan

Traditionally, salinity has been associated with irrigated agriculture in the Indus Basin. Three main causes can be identified: (1) weathering of parent material from marine origin, (2) waterlogging and the rise in groundwater tables due to the introduction of large-scale irrigation, which displaces salts and brings them into the root zone through capillary rise, and (3) use of poor quality groundwater through tube wells. The first two causes have been extensively studied and may, presently, not constitute the main problem. Farmers have managed to bring large areas affected by genetic salinity and/or sodicity under the plough. Also, groundwater tables decline in large parts of the Punjab, which makes the issue of waterlogging in relation to salinity control less urgent. Salinity due to the use of poor quality groundwater, which is used in addition to canal water, is a relatively recent phenomenon and has gained importance due to the massive deployment of tube wells. This threat has not received much attention, yet, and research is needed to assess the extent of the problem and the scope for improvement.

Canal water is of excellent quality, and has tremendous value for farmers who are dealing with salinity and/or sodicity. With canal water they reclaim areas affected by genetic salinity, while the effect of poor quality tube well water is mitigated by applying it in conjunction with canal water. The surface water resources are not unlimited, and farmers will have to complement canal water with tube well water to sustain present cropping intensities. However, since not all farmers face the same physical conditions, such as groundwater quality and soil types, a reallocation of canal water could reduce the pumpage in those areas with the worst quality groundwater or with soils susceptible to salinization. This leads to the assertion that *a reallocation of canal water, making it available to areas with the biggest environmental constraints, will contribute to minimizing salinity and sodicity, and to mitigating their effects on soils and crops.*

The objectives of the present study were thus formulated as follows:
- To define the scope for canal irrigation management interventions and assess their impact on canal water distribution;
- To assess the impact of canal irrigation supplies at the farm and field level on soil salinity and sodicity and the likely effect on crop production; and
- To develop and apply an integrated approach to assess the impact of canal irrigation system management interventions on salinity, sodicity and crop production.

Methodology

At present, no tools or methodologies are available to investigate the scope for changes in canal water deliveries, and to determine the impact of such changes on enhancing the farmers' capability to control salinity and sodicity. There is a need for the development of such tools to support policy makers and irrigation managers in assessing the impact of management interventions and to evaluate whether a better canal irrigation management could reduce the need for high cost works on infrastructure.

There are two principal research axes in this study, an intervention-oriented analysis of canal irrigation management, and a process-oriented study of salinity and sodicity at the farm and field levels. These studies were combined, by developing and operationalizing an integrated approach, which translates the effect of interventions in canal irrigation management on the development of salinity and sodicity, and on transpiration. The study was conducted in a 75,000 ha irrigation system, the Chishtian Sub-division, which forms part of Pakistan's Indus Basin. The study area is located in south-east Punjab, where cotton and wheat are the main crops in summer and winter, respectively. The climate is (semi-) arid with annual evaporation far exceeding the rainfall.

Results of the studies

A tool was developed to simulate the water flow in canals and quantify the impact of interventions at the main and distributary canal on the water deliveries to tertiary units. The tool consists of an unsteady state hydraulic model, SIC - Simulation of Irrigation Canals - based on the St. Venant equations, linked with a regulation module that captures the operational decisions of the irrigation agency both at the implementation or *tactical* level as well as at the target setting or *strategic* level. At the main canal level, the *existing* operational rules have induced an inequitable water distribution and an uncertainty for the water users as to when to expect water supplies. Restoration of the official rules is not a solution, because the simulations showed that it is impossible to implement these official rules. These rules envisage a full supply to all secondary canals during periods of operational priority of the irrigation system concerned, whereas when there is no priority, all secondary canals participate in an internal rotation. The implementation of the former rule is impossible due to a lower inflow even in times of operational priority, while the second rule is impractical as small secondary canals are not able to absorb the relatively large discharge fluctuations in the main canal. The existing operational rules are more practical, but have negative repercussions on the water distribution. It is possible to improve the water distribution at the main canal level, by adopting alternative operational rules. This can be done by implementing a rotation throughout the season, involving mainly the larger secondary canals, while maintaining fixed 8-day delivery periods. This is beneficial for the farmers who share the water through a 7-day roster of turns. Thus, an equitable water distribution, the official principle of irrigation in Pakistan, can be restored. For the main canal in the study area, the Fordwah Branch, the *modified inter-quartile ratio* could be reduced from 1.9 to 1.4, which means that the most favoured 25% of the area gets 1.4 times the water supply of the poorest quarter instead of almost twice the amount. This could be further improved if gates would be provided to small ungated secondary canals or when the smaller secondary canals would be included in the rotation. This would require some investments in the communication system or interventions upstream of the study area to stabilize the inflow. Another intervention could be the redistribution of water to secondary canals with a high salinity and sodicity risk. Simulations showed that when six percent more water was delivered to the Fordwah Distributary, which was recovered by reducing the supplies to the Masood Distributary by more than 12%, the other secondary canals in the study area were hardly affected.

The existing physical infrastructure at the secondary canal level, particularly related to tertiary outlets, induces an inequitable water distribution, with a *spatial coefficient of variation* in the actual water deliveries divided by the authorized deliveries, ranging from 0.3 to 0.8 for all secondary canals. It is possible to modify the present water distribution, by changing the dimensions of tertiary outlets. In case of the Masood Distributary the coefficient of variation was reduced to 0.1. Also, water can be reallocated to specific tertiary units, e.g. for salinity control, by changing the outlet dimensions. The side effects on other outlets are quite small due to the sub-proportional hydraulic behaviour of these outlets. A change of 10% in the discharge in a secondary canal, causes only a 5% change in offtaking discharge for the tertiary outlets. Global interventions, such as desiltation or constriction of the channel width, are generally necessary to maintain the safety and carrying capacity of the channel, but this is often quite a rough instrument for intervening in the water distribution, since the main problems relate to specific outlets.

Salinization was studied in farmers' fields to assess the effect of irrigation practices on salinity, sodicity and crop transpiration for a range of soil types. A combined soil water and solute transfer model, SWAP93, based on the Richards' equation and on the convection-dispersion equation, was calibrated/validated for representative soil types, i.e. a loamy sand, sandy loam, loam to silty clay loam, and a silt loam. A sensitivity analysis was carried out with the model. It was determined that the crop factors and the saturated soil moisture content θ_s were important parameters influencing the water and salt balance, which means that they need to be determined accurately for the calibration/validation of the model. The rooting depth, Boesten factor and the saturated hydraulic conductivity K_s are much less sensitive parameters for the existing conditions. The model was also used to assess the relative importance of irrigation quantity and quality for soil salinity and transpiration. A curvilinear relationship with a decreasing tangent was found between the irrigation quantity and soil salinity. Increases in the *EC* of the irrigation water result in a curve that is parallel to the original curve, but with higher salinity levels. The relative transpiration T_{act}/T_{pot} as a function of the irrigation quantity was also found to have a curvilinear relationship with a decreasing gradient. However, the relative impact of reductions in irrigation quantity or increases in the *EC* of irrigation water on transpiration is smaller than the effects on soil salinity. The relationships for salinity and relative transpiration as a function of irrigation quantity and quality were established for all representative soil types and for conditions of free drainage and in the presence of a groundwater table at 2 metres depth. The findings of these analyses are important for two reasons. Firstly, it shows that changing the irrigation quantity and quality considerably influence soil salinity and transpiration, which means that irrigation management interventions are important instruments for salinity control. Secondly, environmental parameters, like the soil type and depth to groundwater table, play an important role in processes related to the water and salt balance. With the existing heterogeneity in these parameters and in the groundwater quality, there is sufficient scope for a positive effect of the reallocation of canal water. The impact of farmers' irrigation practices within the present physical constraints, i.e. irrigation quantity/quality, groundwater table depth, groundwater quality and soil type, was investigated. Measures such as applying a large pre-sowing irrigation or changing the frequency of irrigation can influence soil salinity to a certain extent, but the effects are much smaller than changing the irrigation quantity and quality.

The sodification process was studied and a regression equation (Equation 4.18) was developed for the study area to quantify the risk of sodification as a function of the irrigation quality (SAR_w) and soil texture. The equation was verified for other field observations and was shown to better predict the sodicity risk than existing empirical formulae with a standard error of estimate of the *SAR* at 90 cm depth of around 1.5. The predictions were also verified with the outputs of a geo-chemical model, GYPSOL, which showed a good match in both sets of outputs. It was further shown that problems of sodicity and soil degradation are fairly rapid processes. Within the course of an irrigation season, the upper layers show clear signs of structural degradation like surface crusts and hardsetting in the profile. Sodicity leads to structural degradation of soils at *ESP* levels as low as 4%, due to the illitic nature of the clay minerals.

Farmers' irrigation strategies and practices related to salinity and sodicity were studied in the larger context of farm objectives and constraints. In a parallel study, Strosser (1997) studied the decision-making process of farmers with respect to the crop portfolio and water acquisition and distribution, as a function of the farm strategy, farmers' constraints, and the physical and irrigation environment. Farmers' decisions were captured in Linear Programming (LP) models.

An integrated approach was developed on the basis of the present study and the study of Strosser (1997). This was done by developing a common platform in which physical processes and the human decisions that are governing these processes are quantified. A common tool was developed and applied to two case studies. The first case study is described by Strosser (1997), who tests the feasibility of developing water markets and their impact on agricultural production. The second case study, described here, relates to the assessment of the effect of canal irrigation management interventions on salinity and sodicity for the command area of a 14,000 ha irrigation canal command, the Fordwah Distributary.

Application to the actual situation in the Fordwah Distributary showed that the cropping intensities were predicted with an accuracy in the range of 17-25%. The tube well pumpage was overestimated, due to the fact that the economic LP models had not been calibrated yet at the level of the tertiary unit. Strosser

(1997) shows that after calibration/validation, a more realistic tube well pumpage is predicted. In the actual situation, 3300 ha or 25% of the CCA of the Fordwah Distributary, is confronted with a considerable *risk* of sodification with an SAR higher than 13. Canal management interventions that provided extra water to areas that are presently affected by salinity were shown to be not very effective, as the risk for future sodification was not accounted for. After a diagnosis of the future trends with the existing irrigation regime, canal management interventions were defined to address this salinity and sodicity risk. It was shown that through targeted canal management interventions at the main and secondary canal level, the salinity control of farmers can be improved. The area with a considerable risk of sodification is reduced by almost 1400 ha.

The analysis has shown the strengths and weaknesses of the integrated model as part of a larger integrated approach. The approach provides insights into the functioning of an irrigation system and into the impact of irrigation management interventions on soil salinity and sodicity. The accuracy of the predictions can be ascertained for the present situation through a process of verification, but is not seen as a necessary step. Predictions for the future should not be evaluated for their absolute values, because there are likely to be unforeseen events. Instead, these predictions should be evaluated for the information they provide to actors such as irrigation managers on the relative effect of management interventions on salinity and sodicity (what-if scenarios), so that these actors are better prepared for events in the future.

6.2 General application of the developed integrated approach to irrigation management

Using the integrated approach: outlook

The integrated approach has been tested for two case studies, yielding valuable insights into the functioning of an irrigation system, the effects of interventions in the system, as well as into the issues related to operationalizing an integrated approach. The most important follow up of the present studies relates to the utilization of the developed approach. In collaboration with the actors in the irrigation system that was studied, different scenarios should be formulated and simulated using the combined tool. This could form the basis of continued discussions between actors to improve the performance of the system during a more action-oriented phase. A successful implementation of the approach would strengthen the arguments of this study on the pertinence of an integrated approach, and could lead to the identification of other necessary refinements in the approach. Based on the present experiences, some further improvements in analyses and tools can be identified. Firstly, feed-back loops between different processes, such as the impact of salinity on farmers' strategies, should be included in the approach. Secondly, the software environment could be improved to facilitate running multiple scenarios. In addition to this, improvements on the individual models or analyses should be considered. This pertains, for example, to the incorporation of a geo-chemical model or the inclusion of a larger range of household objectives and constraints in the modelling of farmers' decisions. The inclusion is relatively straightforward due to the modular set-up of the approach. The interface between different models and processes needs also attention. Finally, a more detailed analysis of the transfer of inaccuracies should be studied. In the present configuration, it was found that looped computations did not amplify errors in individual models. This phenomenon should be analyzed and tested for a larger range of scenarios. It should be emphasized, however, that all these improvements seem desirable, but that the first priority should be to use the combined tool in its present configuration, within the general context of the integrated approach.

The process

An integrated approach is a concept heralded by many researchers, but applied by few. This is probably related to difficulties in the implementation. Different disciplinary teams need to coordinate the research, and in doing so have to harmonize research objectives and methodologies. In addition, some of the choices that need to be made in the research will be constrained by other disciplines. This relates to very practical details like the choice of the study area, sampling frame, and the time frame. It may also be related to a choice between the relative certainty of a disciplinary outcome, as compared to the uncertainty in outcome of an integrated approach. However, the case studies discussed here have shown that disciplinary research and the development of an integrated approach can coexist.

Depth or breadth ? In order to achieve a successful integration, this process should start as far upstream as possible in the flow of research. Combining and linking research results and tools will yield valuable lessons and cannot be left to the last minute when it is discovered that important relationships have not been studied. It is recommended to develop a simplified integrated model in the early stages of the research, on the basis of an integrated framework. This can be subsequently adjusted or replaced in the process, but it gives clear signals about the relationships that need to be studied, helps to identify the weak points of the approach, and gives indications about the variability of key parameters that are studied. However, an integrated approach will need to leave sufficient room for disciplinary teams to carry out their studies, as sufficient depth needs to be attained in the research. The value of the integrated approach depends on the rigour of the individual parts. The balance between disciplinary research and integration is a difficult equilibrium to find.

In implementing an integrated approach, there are many difficulties related to information. The information requirements are high, although they can be reduced by carrying out sensitivity analyses, and the information needs to be shared between groups of people, studying different processes at different spatial and temporal scales. In order to do this, common spatial and time steps need to be defined and databases need to be standardized.

Heterogeneity and variability

The spatial heterogeneity of physical parameters and temporal variability of different processes, as well as the diversity of farms are inherent in the analysis of irrigation systems. This is a disadvantage, because it implies that the spatial and temporal structure of information needs to be analyzed, requiring a more substantial data set, and advanced geo-statistical techniques to classify and extrapolate. For policy makers and irrigation managers, this poses also a serious problem as the effectiveness of global interventions are reduced.

However, heterogeneity/variability can also be seen as an important strength and opportunity. Strength because the system is better adapted to external shocks, and opportunity because the heterogeneity and variability offer possibilities for redistribution of resources. This was shown in both case studies. Strosser (1997) showed that by making use of the seasonality of irrigation, a reallocation of water would lead to an increase in agricultural production. In the present study, it was shown that due to a heterogeneity in groundwater quality and soil types, a redistribution of water can lead to a considerable decrease in the area affected by salinity and sodicity.

The challenge is thus in understanding and quantifying the existing heterogeneity/variability in order to use it for defining policy and management interventions.

Interventions

The policy and management interventions that were proposed and analyzed in the present study and the parallel study of Strosser (1997) cover a wide range. While the former study focuses on irrigation system management interventions, i.e. changing the operational rules of the irrigation agency and modifying the characteristics of tertiary outlets, the latter analyzes policy level interventions, such as water pricing and the development of water markets. In practice, policy makers and irrigation managers have a choice in selecting a mix of different policy and/or management interventions. The complementarity of the interventions that were analyzed in both studies has not been investigated so far, and provides an interesting scope for further work. This is especially true, because a large number of variables, reflecting the complexity of an irrigation system, have been included in the tools that were developed in these studies. This means that a comparison is possible of the impact of different policy and management interventions on the agricultural production and on the sustainability of irrigated agriculture, i.e. salinity, sodicity and groundwater mining. Thus, a better combination of interventions can be proposed to the different actors.

Transferability

The application of the integrated approach to two different case studies showed that the developed approach allows an investigation of a wide range of policy and management interventions, and captures adequately the complexity of an irrigation system. This is due to the fact that a large number of physical and human decision-making processes were analyzed and modelled, allowing the modification of a wide range of variables. This makes the approach of interest also to policy makers and irrigation managers in other irrigation systems, dealing with similar or related issues. The transfer of the integrated approach should not be confined to the combined tool, but should be applied as part of an integrated concept, which includes phases of diagnosis, identification of relevant processes and parameters, and discussions with actors. These phases are important learning stages for understanding the physical and human relationships in a system. In doing so, the focus can remain on understanding the actual functioning of an irrigation system and preparing the future by assessing the effect of policy and management interventions, rather than attempting to make accurate predictions for the evolution of specific parameters.

Appendix 1

Structure equations used in the hydraulic model Simulation of Irrigation Canals (SIC), version 2.1 under DOS

The equations used in SIC are generally of the type (Kosuth, 1996):

$$Q = f(H_u, H_d, G_o) \qquad \text{(A1.0)}$$

where

H_u, H_d	= upstream and downstream water levels above the sill of a structure	[m]
G_o	= gate opening	[m]

If the flow conditions are free flow only H_u is taken into account, if the structure has submerged flow conditions, H_d is also taken into account. G_o is taken into account if the structure is gated.

In SIC both cross-regulators, perpendicular to the flow direction, and offtake structures can be defined. Different structure types can be defined, see Table A.1.1.

Table A1.1: Structures defined in the SIC software, version 2.1 under DOS

Structure type	Structure	Equations
Cross-regulators	Weir	A1.1a, 1b
	Undershot	A1.2a, 2b, 2c
	Overshot	A1.3a, 3b
Offtakes	(Un-)gated orifice	A1.2a, 2b
	Weir	A1.3a, 3b

Equations in SIC are specifically intended to account for the continuity between different flow conditions, i.e. from free flow to submerged flow conditions (and vice versa) and between open channel and orifice conditions (Cemagref, 1992).

A1.1 Regulators

Weir - free flow:

$$Q = \mu_F \; G_o \sqrt{2g} H_u^{1.5} \qquad \text{(A1.1a)}$$

Weir - submerged flow:

$$Q = k_F \; \mu_F \; G_o \sqrt{2g} H_u^{1.5} \qquad \text{(A1.1b)}$$

with:

k_F	= coefficient of reduction for submerged flow	[-]
g	= gravitational acceleration	[m^2 s^{-1}]

k_F is a function of the submergence ratio and of the ratio H_d / G_o, expressed by α, which is defined as (Cemagref, 1992):

$$\alpha = 1 - 0.14 \frac{H_d}{G_o} \qquad \text{(A1.1c)}$$

The function determining k_F has been determined experimentally (Cemagref, 1992):

let

$$x = \sqrt{1 - \frac{H_d}{H_u}} \qquad \text{(A1.1d)}$$

if $x > 0.2$:

$$k_F = 1 - \left(1 - \frac{x}{\sqrt{1-\alpha}}\right)^{\beta} \qquad \text{(A1.1e)}$$

if $x \leq 0.2$:

$$k_F = 5x\left(1 - \left(1 - \frac{0.2}{\sqrt{1-\alpha}}\right)^{\beta}\right) \qquad \text{(A1.1f)}$$

with:

$$\beta = -2\alpha + 2.6 \tag{A1.1g}$$

Submerged flow occurs when the submergence ratio (H_d/H_u) is greater than α.

Undershot gate - free flow:

$$Q = w\sqrt{2g}\,(\mu H_u^{1.5} - \mu_1(H_u - G_o)^{1.5}) \tag{A1.2a}$$

with:

w	=	width of the structure	[m]

Undershot gate - partially submerged:

$$Q = w\sqrt{2g}\,(k_F\,\mu H_u^{1.5} - \mu_1(H_u - G_o)^{1.5}) \tag{A1.2b}$$

Undershot gate - fully submerged:

$$Q = w\sqrt{2g}\,(k_F\,\mu H_u^{1.5} - k_{Fl}\,\mu_1(H_u - G_o)^{1.5}) \tag{A1.2c}$$

The transition between free flow and submerged flow conditions is determined by the value of α. The transition from free flow to partially submerged flow occurs at a value of α of 0.75. The transition from partially to fully submerged flow occurs for:

$$H_d > \alpha_1 H_u + (1 - \alpha_1)G_o \tag{A1.2d}$$

and

$$\alpha_1 = 1 - 0.14\frac{H_d - G_o}{G_o} \tag{A1.2e}$$

Overshot gate - free flow:

$$Q = 0.4w\sqrt{2g}\,(H_u - G_o - h_g)^{1.5} \tag{A1.3a}$$

where

h_g = gate height [m]

Overshot gate - submerged:

$$Q = \mu' w \sqrt{2g}\ (H_u - H_d - h)^{0.5} * (H_d - G_o - h) \qquad \text{(A1.3b)}$$

with

μ' = 1.04

The discharge calculated using the formulas 3a and 3b, is added to the discharges obtained from the equations of the undershot gate. The transition from free flow to submerged flow conditions follow the same logic as for the weir flow.

A1.2 Offtakes

Offtakes that are defined as a gated orifice or as a weir will use the same equations that have been defined for the regulators. Only in the case of ungated orifices and pipes, additional equations have been defined. Offtaking discharges are calculated starting from a downstream boundary condition, which is either fixed, varies with the upstream water level or varies following a pre-defined rating curve. H_u is generated by determining the water surface profile in the main canal and H_d is determined through the downstream boundary formulas. The discharge is then calculated, using the known values of upstream and downstream water levels, through a numerical method referred to as Newton's iterative method (Cemagref, 1992). The unknown variable is the gate opening.

Appendix 2

Mathematical derivation of equation 3.15[1]

The discharge of an off-taking outlet can be represented by the equation:

$$Q_{off} = aH_u^u \tag{A2.1}$$

where:

Q_{off}	= Off-taking discharge	[$m^3 s^{-1}$]
a	= Constant, usually breadth multiplied with height of an outlet	[m]
H_u	= Upstream water level above the crest	[m]
u	= Exponent	[-]

The discharge in the ongoing canal is generally represented by the Manning's equation. In the Punjab situation where the width of the canal B is much bigger than the depth H, the hydraulic radius R can be assumed equal to the depth H. Thus can the Manning's equation be simplified to:

$$Q_{con} = bH^{5/3} \tag{A2.2}$$

where:

Q_{con}	= Continuing discharge in the parent channel	[$m^3 s^{-1}$]
b	= Constant, representing the breadth of the channel multiplied with the energy slope and the Manning coefficient ($1/n$)	
H	= Water level in the parent channel	[m]

1 This derivation can be found in different variants following the discussions of Varma (1917) and Ali (1993).

In reaction to a change in the discharge in the parent channel dQ_{con}, the off-taking discharge will change by dQ_{off}. Differentiating formulae A7.1 and A7.2 and substituting them into the sensitivity equation:

$$S = \frac{\dfrac{dQ_{off}}{Q_{off}}}{\dfrac{dQ_{con}}{Q_{con}}} \qquad \text{(A2.3)}$$

where:

S = Sensitivity factor [-]

will give the following equation:

$$S = \frac{\dfrac{uaH_u^{u-1}}{aH_u^u}}{\dfrac{5/3bH^{2/3}}{bH^{5/3}}} \qquad \text{(A2.4)}$$

If one wants to achieve full proportionality, i.e. $S = 1$, it can then be easily calculated that:

$$H_u = \frac{3uH}{5} \qquad \text{(A2.5)}$$

Thus, the ideal crest settings in order to achieve full proportionality can be determined:

1. In case of a weir, i.e. $u = 1.5$, H_u should be 0.9 of H. This means that the crest should be placed at 9/10 of the water depth of the canal H at full supply depth starting from the water level, i.e. 1/10 above the bed of the canal.
2. In case of an orifice, i.e. $u = 0.5$, H_u should be 0.3 of H. This means that the crest should be placed at 3/10 of the water depth of the canal H at full supply depth starting from the water level, i.e. 7/10 above the bed of the canal.

In the present situation, many tertiary outlets, especially the orifices, have been placed at 1/10 to 2/10 above the bed of the canal in order to improve the sediment draw of these outlets. Using Equation A2.4, it can be shown that S < 1, which means that the outlets will have a sub-proportional behaviour. In response to a 10% increase of Q_{con}, for example, Q_{off} will increase by a percentage smaller than 10.

Appendix 3

Modifications in outlet dimensions for the Masood and Fordwah Distributaries for various simulation scenarios of Sections 3.4.4 and 5.3.

The scenarios that are described in this appendix are listed below:
- Masood Distributary, Scenario *M*0*D*2 (Section 3.4.4)
- Fordwah Distributary, Scenario *M*0*D*3 (Section 3.4.4)
- Fordwah Distributary, Scenario *M*4*D*4 (Section 5.3)

Masood Distributary, Scenario M0D2 (Section 3.4.4)

Six outlets were reduced in size to limit the offtaking discharge, while for two other (submerged) outlets free flow conditions were restored in order to increase their discharge. The modifications are listed in Table A3.1.

Table A3.1: Changes in outlet dimensions of Masood Distributary for Scenario *M*0*D*2. Changes relate to the width and height of offtakes and to the diameter for pipes.

Outlet	Changed parameter	Actual value (m)	Scenario *M*0*D*2 (m)
1	*y*	0.39	0.28
2	*b*	0.11	0.08
3	*y*	0.38	0.28
4	*R*	0.27	0.19
5	*R*	0.27	0.17
	Flow conditions	Submerged	Free flow
6	Flow conditions	Submerged	Free flow
7	*b*	0.10	0.08
12	*b*	0.18	0.16

Fordwah Distributary, Scenario M0D3 (Section 3.4.4)

Seven outlets with limited access to canal water were selected for increased canal water supply. In order to do this the sizes of these outlets were increased. Four other outlets as well as Jiwan minor were reduced in size in order to make extra water available for these seven outlets. The modifications are listed in Table A3.2.

Table A3.2: Input parameters for Scenarios *M0D0* and *M0D3* for the Fordwah Distributary.

Outlet	Changed parameter	Actual value (m) Scenario *M0D0*	Modified value (m) Scenario *M0D3*
3	*b*	0.07	0.14
5	*b*	0.06	0.12
10	*b*	0.06	0.12
12	*b*	0.08	0.06
15	*b*	0.08	0.14
21	*b*	0.08	0.06
Jiwan minor (41)	*b*	0.93	0.85
62	*b*	0.07	0.06
	y	0.13	0.12
74	*b*	0.10	0.07
76	*b*	0.16	0.25
77	*b*	0.16	0.25
78	*b*	0.10	0.20

Fordwah Distributary, Scenario M4D4 (Section 5.3)

The breadth *b* of outlets 2, 6, 10, 11, 12, 21, 27, 29, 30, 49, 62 and 72, of the Fordwah Distributary were all increased by 100% for Scenario I3. To compensate for this, a total number of 20 outlets were decreased in size. It was attempted to reduce *b* by 25% for all these outlets. However, this is constrained by the minimum size of *b*, which is 6 cm. In those cases, the outlet height *y* was decreased. The exceptions are outlets 3 and 53, which have fairly high levels of salinity and sodicity, and were thus decreased by 15% only. The modifications are presented in Table A3.3.

Table A3.3: Modifications in outlet dimensions for Scenario *M4D4* of the Fordwah Distributary

Outlet number	Parameter	Old value (m)	New value (m)
3	*b*	0.07	0.06
4	*b*	0.12	0.09
5	*y*	0.47	0.35
7, 8	*y*	0.42	0.32
9	*b*	0.09	0.07
13	*D*	0.27	0.20
25	*b*	0.08	0.06
26	*y*	0.55	0.41
28	*b*	0.07	0.06
	y	0.44	0.40
33	*b*	0.11	0.08
39	*b*	0.07	0.06
	y	0.38	0.34
44	*y*	0.30	0.23
50	*b*	0.07	0.06
	y	0.29	0.20
53	*b*	0.07	0.06
58	*b*	0.12	0.07
74, 75	*b*	0.10	0.08
76	*b*	0.16	0.12
78	*b*	0.10	0.07

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IRRIGATIEWATERBEHEER STRATEGIEËN VOOR EEN BETERE ZOUT- EN SODIUMHUISHOUDING: SAMENVATTING EN CONCLUSIES

Een geintegreerde aanpak is ontwikkeld om de consequenties van beleids- en beheersinterventies in een irrigatiesysteem *a priori* te beoordelen. Deze aanpak is in deze dissertatie toegepast in een irrigatiesysteem in Pakistan om de gevolgen van ingrepen in het irrigatiewaterbeheer op bodemverzouting, sodificatie en gewastranspiratie te kwantificeren. In een nevenstudie, is deze aanpak toegepast om de effecten van beleidsmaatregelen ter bevordering van watermarkten te analyseren en de consequenties voor de gewasopbrengsten te kwantificeren (Strosser, 1997). In het eerste deel van deze samenvatting worden de bevindingen van de casus, behandeld in de huidige dissertatie, samengevat en worden conclusies getrokken. De lessen uit beide toepassingen van de geintegreerde aanpak, zullen behandeld worden in het tweede deel.

Irrigatiewaterbeheer interventies voor een verbeterde zout- en sodiumhuishouding: lessen van de casus

Verzouting en sodificatie in Pakistan

Verzouting wordt van oudsher geassocieerd met geirrigeerde landbouw in het stroomgebied van de Indus. Drie hoofdoorzaken kunnen onderscheiden worden: (1) verwering van oude afzettingen van mariene origine, (2) waterstagnatie en de stijging van de grondwaterspiegel door de komst van grootschalige irrigatie, welke een migratie van zouten naar de wortelzone met zich mee brengt door capillaire opstijging, en (3) het oppompen en gebruik van brak of zout grondwater voor irrigatie. De eerste twee oorzaken zijn uitgebreid bestudeerd en vormen op dit moment niet meer de grootste bedreiging voor de geirrigeerde landbouw. Boeren zijn erin geslaagd om gebieden welke traditioneel verzout zijn in cultuur te brengen en de zouten te verwijderen. Tegelijkertijd dalen de grondwater spiegels in grote delen van met name de Punjab, hetgeen de problemen, gerelateerd aan de capillaire opstijging, minder groot maakt. Aan de andere kant, levert het gebruik van zout grondwater, naast het kanaalwater, pas sinds kort echt grote problemen op door de proliferatie van kleine, door de boeren geinstalleerde pompen. Deze bedreiging heeft tot dusver nog niet veel aandacht gekregen en onderzoek is nodig om de omvang van het probleem alsmede de mogelijkheid tot verbetering van deze situatie te bestuderen.

Kanaalwater heeft een uitstekende kwaliteit en is dus voor de boeren zeer waardevol in de beheersing van hun problemen met verzouting en sodificatie. Met kanaal- of oppervlaktewater worden zouten uitgespoeld, terwijl het zoute opgepompte water ermee wordt aangelengd teneinde bodemverzouting tegen te gaan. De hoeveelheden oppervlaktewater zijn echter niet toereikend voor het huidige areaal aan geirrigeerde landbouw, en er zal dus grondwater moeten worden opgepompt. Aangezien de kwaliteit van dat grondwater varieert en er ook verschillen bestaan in gevoeligheid van bodemtypes voor verzouting, zou een herverdeling van kanaalwater overwogen kunnen worden teneinde het gebruik van grondwater van slechte kwaliteit te beperken. De belangrijkste hypothese van deze studie luidt dan ook dat *een herverdeling van kanaalwater, waarbij dit wordt verstrekt aan die boeren die met de grootste omgevingsbelemmeringen te kampen hebben, zal bijdragen aan een verminderde verzouting en sodificatie, en een geringere belasting op de gewasopbrengsten.*

De doelstellingen van het onderzoek worden dus als volgt geformuleerd:
- het onderzoeken van mogelijke beheersinterventies in een irrigatiesysteem en het kwantificeren van het effect van die interventies op de kanaalwater verdeling
- het analyseren van het effect op veldniveau van de kwaliteit en kwantiteit van het irrigatiewater op de zouthuishouding, de sodificatie en gewasopbrengst
- het ontwikkelen en toepassen van een geintegreerde aanpak om de effecten van interventies in het irrigatiewaterbeheer op de zouthuishouding, de sodificatie en gewasopbrengst te beoordelen

Methodologie

Op dit moment zijn er geen instrumenten of methodologieën voorhanden om de potentiele veranderingen in de kanaalwater verdeling te onderzoeken en om de invloed te bepalen van die interventies op een verbetering van de mogelijkheden voor boeren om de verzouting en/of sodificatie tegen te gaan. Een ontwikkeling van dergelijke instrumenten is noodzakelijk teneinde de beslissingen van beleidsmakers en waterschappen ten aanzien van beheersinterventies te ondersteunen. Op die manier kunnen deze ingrepen beter worden toegespitst op de problemen en worden overbodige kosten van aanpassingen in de infrastructuur beperkt door een effectievere benutting van de bestaande infrastructuur.

Deze dissertatie bevat twee centrale onderzoeksassen, een interventiegerichte analyse van het kanaalwater distributiesysteem en een procesgerichte studie van verzouting en sodificatie op veld- en bedrijfsniveau. De resultaten van beide studies worden gecombineerd in een geintegreerde aanpak, welke de effecten van veranderde irrigatiewaterbeheer strategieën kwantificeert voor de verzouting, sodificatie en gewastranspiratie van verschillende velden en boerenbedrijven. De studie is uitgevoerd in een irrigatiesysteem ter grootte van 75.000 ha, de Chishtian sub-divisie, welke deel uitmaakt van het 16 miljoen ha grote Indus Basin systeem. Het gebied ligt in het zuid-oosten van de provincie Punjab, waar katoen en tarwe de belangrijkste gewassen vormen in respectievelijk de zomer en winter. Het klimaat is semi-aride, waarbij de jaarlijkse verdamping de regenval verre overtreft.

Onderzoeksresultaten

Een gecombineerd model is ontwikkeld om de waterlijn in kanalen te simuleren en het effect van ingrepen in het hoofd- en secundaire kanaal op de watertoelevering aan tertiaire vakken te kwantificeren. Het gecombineerde model bestaat uit een niet-stationair hydraulisch model, SIC - Simulation of Irrigation Canals, gebaseerd op de vergelijkingen van St. Venant, gekoppeld aan een besturingsmodel, waarin de operationele beslissingen van de irrigatiedienst zijn vastgelegd. Deze beslissingen bestaan uit een tactisch deel, i.e. de manipulatie van de schuiven van kunstwerken, en uit een strategisch deel, i.e.

het vaststellen van de streefdebieten en waterstanden. *In het hoofdkanaal* hebben de *huidige* verdeelregels geleid tot een ongelijke verdeling van water en een onzekerheid voor de boeren ten aanzien van het tijdstip van de aanlevering. Het in ere herstellen van de *officiele* regels is geen oplossing, omdat dit in de praktijk onmogelijk blijkt. Het bestudeerde irrigatiesysteem krijgt officieel 10 dagen een zodanige aanlevering van water dat alle secundaire kanalen het maximale debiet krijgen. In de daaropvolgende 10 dagen krijgt het systeem minder water en moeten alle secundaire kanalen participeren in een rotatie. De eerste regel is onmogelijk uit te voeren, aangezien de aanlevering ten allen tijde minder is dan het streefdebiet. De tweede regel is niet practisch. Er zijn grote fluctuaties in debieten en als kleine secundaire kanalen meedoen in de rotatie, dan moeten deze meerdere malen per dag open en dicht. De bestaande regels zijn practischer, maar leiden tot een ongelijke verdeling. De studie laat zien dat het mogelijk is alternatieve beheersregels op te stellen om de situatie te verbeteren met de bestaande aanlevering van water als uitgangspunt. Er moet dan het hele seizoen een rotatie met de grotere secundaire kanalen worden uitgevoerd, waarbij de hand wordt gehouden aan 8-daagse toeleveringen aan deze kanalen. In de casus wordt voor het hoofdkanaal, de Fordwah Branch, aangetoond dat in de huidige situatie het kwartiel areaal met de hoogste wateraanvoer bijna twee keer zoveel water krijgt als het kwartiel met de laagste aanvoer. Dit verschil kan door een verandering in de beheersregels tot 40% gereduceerd worden. Dit kan nog verder worden beperkt door de kleinere secundaire kanalen in de rotatie te betrekken of enkele secundaire kanalen zonder inlaatkunstwerk van schuiven te voorzien. Deze maatregelen zouden echter investeringen in de communicatie vereisen, alsmede een stabielere aanvoer voor het gebied. Een andere doelstelling welke kan worden bereikt met ingrepen in de beheersregels, is het verstrekken van extra water aan secundaire kanalen die met een zoutprobleem hebben te kampen. Simulaties laten bijvoorbeeld zien dat 6% meer water kan worden geleverd aan de Fordwah Distributary, welke wordt gecompenseerd door een reductie met meer dan 12% van de kleinere Masood Distributary, zonder de toevoer aan andere secundaire kanalen noemenswaardig te beinvloeden.

De bestaande fysieke infrastructuur *in de secundaire kanalen*, in het bijzonder de verdeelwerken naar de tertiaire vakken, induceert een ongelijke waterverdeling, i.e. van bestaande gedeeld door de streefdebieten, met een spatiale variantie, die varieert van 0.3 to 0.8. De studie laat zien dat het mogelijk is dit te veranderen door de dimensies van de tertiaire inlaten te veranderen. Voor de Masood Distributary is de variantie beperkt tot 0.1, hetgeen een zeer redelijke gelijkheid in de waterverdeling oplevert. Ook kan er een herverdeling van water plaatsvinden, bijvoorbeeld door extra water te leveren aan die tertiaire vakken, die het nodig hebben voor de bestrijding van verzouting en sodificatie. Doordat de tertiaire onderspuiers een sub-proportioneel gedrag vertonen, hebben die herverdelingen relatief weinig effect op de debieten van de overige tertiaire kanalen, welke niet betrokken zijn bij de herverdeling. Als er een verandering van 10% optreedt in het debiet in het secundaire kanaal, veranderen de aftappende debieten voor deze kanalen met maar 5%. Er zijn ook andere interventies mogelijk, zoals het verwijderen van zand uit de kanalen of het fixeren van het stroombed. Deze interventies zijn nodig om de de veiligheid van het kanaal te waarborgen en de maximale capaciteit van het kanaal te behouden, maar blijken vrij grove instrumenten te zijn om de waterverdeling te verbeteren. Het effect van dergelijke interventies is niet specifiek genoeg.

Verzouting is bestudeerd in een aantal bebouwde velden om het effect van irrigatie op de zouthuishouding en gewastranspiratie te analyseren. Een gecombineerd bodemwater - stoffentransport model voor de onverzadigde zone, SWAP93, gebaseerd op de Richard's vergelijking en op de convectie-dispersie vergelijking, is gecalibreerd en gevalideerd voor een aantal representatieve bodemtypes, varierend van een leemzand tot een kleileem. Een gevoeligheidsanalyse met behulp van het model laat zien dat de gewasfactoren en het verzadigde bodemvochtgehalte θ_s gevoelige parameters zijn, die van grote invloed blijken op de water- en zoutbalans en die dus nauwkeurig bepaald moeten worden tijdens een calibratie. De worteldiepte, de Boesten factor en de verzadigde doorlatendheid K_s zijn relatief ongevoelige parameters in de huidige omstandigheden. Het model is ook gebruikt om het effect van de kwantiteit en kwaliteit van het irrigatiewater op de verzouting en transpiratie te beoordelen. Dit is gedaan voor alle representatieve bodemtypen en al of niet in een situatie met een nabije grondwaterspiegel. Een parabolische relatie (negatieve coefficient) met afnemende tangens is gevonden tussen de irrigatiekwantiteit en de totale hoeveelheid zouten in het profiel. Een toename van het aantal zouten in het irrigatiewater leidt tot een parallelle curve, maar met hogere zouthoeveelheden. De relatie tussen de kwantiteit en de relatieve transpiratie, T_{act}/T_{pot} levert ook een parabool op (met positieve coefficient) met afnemende gradiënt. De invloed van de kwantiteit en kwaliteit van het irrigatiewater op de relatieve transpiratie is echter relatief veel kleiner dan op de verzouting. De bevindingen van deze analyses zijn om twee redenen belangrijk. Ten eerste laat het zien dat beheersmaatregelen gericht op het veranderen van de kwantiteit en kwaliteit van het irrigatiewater, welke de boeren ter beschikking staan, zin hebben vanwege de grote invloed daarvan op de verzouting. Ten tweede blijken bodemtype en de aanwezigheid van een nabije grondwaterspiegel ook van grote invloed te zijn op de verzouting. Met de bestaande verscheidenheid in beide factoren en in de grondwater kwaliteit, ontstaan er dus mogelijkheden voor positieve resultaten van een herverdeling van kanaalwater.

Tenslotte is het model gebruikt om het effect van andere maatregelen, die boeren nemen om verzouting tegen te gaan, te beoordelen. Maatregelen zoals het veranderen van de irrigatie frequentie of het toedienen van een grote irrigatiegift van goede kwaliteit voor aanvang van het seizoen blijken effect te hebben op de verzouting, maar deze effecten zijn veel kleiner dan die van irrigatie kwantiteit en kwaliteit.

Een regressievergelijking (4.18) is ontwikkeld tussen de *sodificatie* aan de ene kant en de kwaliteit van het irrigatiewater (SAR_{iw}) en textuur aan de andere kant op basis van veldgegevens. De vergelijking is vervolgens geverifieerd voor een aantal andere velden, waarbij kan worden geconstateerd dat deze vergelijking een betere voorspelling van de *SAR* doet dan bestaande empirische vergelijkingen, met een gemiddelde fout van 1.5 bij *SAR* waarden van rond de 10-15. De voorspellingen zijn gecontroleerd met de waarden die gevonden werden in het studiegebied met behulp van een geo-chemisch model, GYPSOL, waarbij de uitkomsten met elkaar in overeenstemming blijken. De analyses laten verder zien dat sodificatie en bodemdegradatie redelijk snelle processen zijn. Binnen een groeiseizoen vertonen de bovenste bodemlagen verschijnselen van verslemping en verharding van de bodem. Sodificatie blijkt al tot bodemdegradatie te leiden bij *ESP* waarden van 4%, waarschijnlijk door het feit dat de kleimineralen voornamelijk uit illieten bestaan.

De strategieën en bedrijfsvoering van boeren, gerelateerd aan verzouting en sodificatie, zijn bestudeerd in het grotere verband van de bedrijfsdoelstellingen en beperkingen. In een parallelle economische dissertatie analyseert Strosser (1997) de besluitvormingsprocessen van boeren ten aanzien van de gewasportefeuille en de acquisitie en verdeling van irrigatiewater als een functie van de bedrijfs- strategie en beperkingen, de omgevingsfactoren en de irrigatieaanvoer. Deze beslissingen zijn vastgelegd in modellen gebaseerd op lineaire programmering.

Een geintegreerde aanpak is ontwikkeld op basis van deze dissertatie en die van Strosser (1997). Dit is gedaan door een gemeenschappelijk platform te maken, waarbij fysische processen en de beslissingen die van invloed zijn op deze processen worden gekwantificeerd. Een gecombineerd model is ontwikkeld op basis van dit platform, welke getoetst is voor twee verschillende toepassingen. De eerste wordt beschreven door Strosser (1997), waarin de mogelijkheden voor het ontwikkelen van watermarkten en de gevolgen daarvan op de gewasopbrengst worden onderzocht. De tweede toepassing is in deze dissertatie beschreven en laat het effect zien van irrigatiewaterbeheer interventies op verzouting en sodificatie in een 14.000 ha groot secundair vak, bediend door de Fordwah Distributary.

De toepassing voor de Fordwah Distributary laat zien dat het model het bestaande areaal aan landbouwgewassen redelijk goed voorspelt met een onnauwkeurigheid van 17-25%. Het gebruik van grondwater wordt overschat, doordat de economische modellen nog niet gecalibreerd waren voor de tertiaire vakken. Strosser (1997) laat zien dat het grondwatergebruik na calibratie zeer realistisch wordt voorspeld met een onnauwkeurigheid van ongeveer 10%. In de bestaande situatie wordt 25% van het areaal, i.e. 3300 ha, bedreigd door sodificatie met een *SAR* hoger dan 13. Beheersinterventies gericht op het verschaffen van extra water voor gebieden met bestaande zoutproblemen blijken niet erg effectief te zijn, aangezien het risico voor toekomstige verzouting en/of sodificatie niet in aanmerking werden genomen. Door een analyse van de bestaande irrigatiepraktijken en de lange termijn effecten daarvan op de verzouting en sodificatie met behulp van de geintegreerde aanpak, kunnen betere interventies geformuleerd worden. Simulaties laten zien dat het areaal dat op dit moment wordt bedreigd door sodificatie met 40%, i.e. 1400 ha, kan worden gereduceerd door een herverdeling van water, mogelijk gemaakt door beheersinterventies in het hoofd- en secundaire kanaal.

De analyse heeft de sterke en zwakke punten van het gecombineerde model als onderdeel van de geintegreerde aanpak naar voren gebracht. Deze aanpak verschaft inzichten in het huidige functioneren van het irrigatiesysteem en in het effect van beheersinterventies in het hoofd- en secundaire kanaal op verzouting en sodificatie. De nauwkeurigheid van de voorspellingen kan verder worden gecontroleerd, maar dit lijkt niet de meest noodzakelijke stap voor de toekomst. Voorspellingen zouden niet op hun absolute waarden moeten worden beoordeeld, aangezien er in een complex systeem altijd onvoorziene gebeurtenissen zullen plaats vinden. Deze voorspellingen zouden veel meer moeten worden beoordeeld op de informatie die ze voorzien aan actoren, zoals de waterschappen, voor wat betreft het relatieve effect van beheersinterventies op verzouting en sodificatie, zodat deze actoren beter zijn voorbereid op toekomstige gebeurtenissen (wat-als scenarios).

Algemene toepassing van een geintegreerde aanpak in irrigatiewaterbeheer

Het gebruik van de geintegreerde aanpak: toekomstverwachtingen

De geintegreerde aanpak is getest in twee casestudies, welke waardevolle inzichten hebben verschaft in het functioneren van het irrigatiesysteem, in het effect van beleids- en beheersinterventies en in aspecten gerelateerd aan het ontwikkelen en toepassen van een geintegreerde aanpak. De belangrijkste stap voor de toekomst is het verdere gebruik van de ontwikkelde aanpak. In samenwerking met de actoren in het irrigatiesysteem kunnen verschillende scenario's worden geformuleerd en gesimuleerd met het huidige gecombineerde model. Dit kan de basis vormen voor toepassingsgerichte discussies met de actoren om het functioneren van het huidige systeem te verbeteren in een meer actiegerichte fase. Een dergelijke toepassing kan de conclusies van de beide case studies enerzijds versterken ten aanzien van de pertinentie van een geintegreerde aanpak en kan anderzijds leiden tot een bijstelling van bepaalde aspecten in de geintegreerde aanpak. Gebaseerd op de huidige ervaringen kunnen al een aantal verbeteringen worden aangegeven. Ten eerste zullen analyses van de terugkoppelingen tussen verschillende processen, zoals de invloed van verzouting op de beslissingen van boeren, kunnen worden toegevoegd aan de aanpak. Ten tweede zal het draaien van verschillende scenario's vergemakkelijkt moeten worden. Daarnaast kunnen verbeteringen in het modelleren van individuele processes worden overwogen, bijvoorbeeld het inbrengen van een geo-chemisch model of het analyseren van een groter aantal bedrijfsbeperkingen van boeren. Deze verbeteringen kunnen relatief gemakkelijk worden aangebracht door de modulaire opzet van het gecombineerde model. Tenslotte, zal een diepergaande nauwkeurigheidsanalyse moeten worden uitgevoerd. In de huidige configuratie blijken fouten niet te worden geamplifieerd, hetgeen uiteraard een goede zaak is. Dit fenomeen zou echter beter moeten worden geanalyseerd en getest voor een groter aantal scenario's. Benadrukt moet echter worden dat al deze verbeteringen op zich wenselijk zijn, maar dat de eerste prioriteit zal moeten liggen bij het gebruik van het huidige model binnen het grotere geheel van de geintegreerde aanpak.

Procesmatige aspecten

Een geintegreerde aanpak wordt als concept door vele onderzoekers toegejuicht, maar blijkt nog zeer weinig te worden toegepast. Dit wordt waarschijnlijk veroorzaakt door problemen in de uitvoering. Verschillende disciplinaire teams moeten daartoe hun onderzoek coordineren en hun onderzoeksdoelstellingen en methodologieën harmoniseren. Daarnaast worden deze teams beperkt in de onderzoekskeuzes door het inter-disciplinaire verband. Dit houdt verband met practische aspecten, zoals de keuze van het onderzoeksgebied, het bemonsteringsschema en de tijdsplanning van het onderzoekstraject. Het is wellicht ook gerelateerd aan de keuze tussen de relatieve zekerheid van een disciplinaire uitkomst en de onzekerheid van wat een geintegreerde aanpak zal bieden. De uitgevoerde case studies laten echter zien dat het zeer wel mogelijk is om disciplinair en geintegreerd onderzoek naast elkaar uit te voeren.

In de diepte of in de breedte ? Om tot een succesvolle integratie te komen, zou deze zover mogelijk bovenstrooms in het onderzoekstraject plaats moeten vinden. Het combineren van onderzoeksresultaten en modellen levert waardevolle informatie op en moet niet tot het laatst worden bewaard, waarbij men tot de ontdekking komt dat bepaalde belangrijke relaties niet zijn bestudeerd. Het is aan te raden om een gecombineerd model op te stellen in de aanvangsfase van het onderzoek in de context van de geintegreerde analyse, zelfs als dit model zeer gesimplificeerd is. Dit model kan dan vervolgens worden aangepast en verbeterd, want het geeft al in een vroeg stadium signalen af ten aanzien van de processen welke moeten worden bestudeerd, de zwakke punten van een aanpak, en de variabiliteit van belangrijke procesvariabelen. De geintegreerde aanpak moet echter voldoende ruimte laten voor de disciplinaire teams om hun studies uit te voeren, omdat voldoende diepgang in de bestudering van belangrijke processen moet worden bereikt. De waarde van de geintegreerde aanpak hangt af van de rigueur van de samenstellende delen. Het is moeilijk om de balans tussen diepte en breedte te vinden en te handhaven.

Bij de uitvoering van een geintegreerde aanpak is het informatiebeheer van groot belang. Bij een onderzoek dat zich in verschillende ruimte- en tijdschalen afspeelt en waarbij de resultaten van het ene proces gebruikt worden om een ander proces te analyseren, moeten afspraken worden gemaakt over gemeenschappelijke ruimte- en tijdstappen, en gemeenschappelijke gegevensbestanden.

Heterogeniteit en variabiliteit

De ruimtelijke heterogeniteit van fysische factoren en de temporele variabiliteit van verschillende processen, alsmede de diversiteit in boerenbedrijven, zijn inherent aan de analyse van irrigatiesystemen. Dit is een nadeel omdat het diepgaande (geo-) statistische analyses vereist van de ruimtelijke en temporele ordening in een systeem, hetgeen een groot aantal gegevens vergt. Het betekent ook een nadeel voor beleidsmakers en voor de waterschappen, die graag met interventies zouden komen met een uniforme uitwerking.

De heterogeniteit/variabiliteit kan echter ook gezien worden als een voordeel dat grote vooruitzichten biedt. Het is een sterk punt omdat het systeem beter bestand is tegen ongunstige externe omstandigheden en het biedt vooruitzichten omdat er in potentie mogelijkheden bestaan om tot een herverdeling van goederen te komen, zulks met wederzijds voordeel. Dit wordt geillustreerd in beide casestudies. Strosser (1997) laat zien dat door gebruik te maken van seizoensinvloeden, een herverdeling van water zal leiden tot een algemene verhoging van de gewasproductie. In deze dissertatie wordt aangetoond dat bij een heterogeniteit van de kwaliteit van het grondwater en bodemtypes, een herverdeling van water kan leiden tot een afname van het areaal dat wordt bedreigd met verzouting en sodificatie. *De uitdaging ligt dus in het begrijpen en kwantificeren van de bestaande heterogeniteit/variabiliteit teneinde deze te gebruiken bij het formuleren van nieuwe beleids- en beheersinterventies.*

Interventies

De beleids- en beheersinterventies die zijn geanalyseerd in de beide case studies beslaan een breed kader. Terwijl in de studie van Strosser (1997) voornamelijk de beleidsinterventies worden geanalyseerd, zijn in deze dissertatie meer de beheersinterventies geevalueerd. In de praktijk hebben beleidsmakers en waterschappen uiteraard de keuze in het toepassen van een combinatie van dergelijke ingrepen. Een logisch vervolg op de beide casestudies is dus een geintegreerde analyse van deze ingrepen. Dit is zeer wel mogelijk vanwege de uitgebreide analyses die zijn uitgevoerd en de configuratie van het huidige gecombineerde model, die het mogelijk maakt een groot aantal variabelen te veranderen. Het uitvoeren van een geintegreerde analyse van de complementariteit van de verschillende ingrepen zal tevens een afweging mogelijk maken van de effecten van deze ingrepen op de gewasopbrengsten en de duurzaamheid van de geirrigeerde landbouw.

Overdraagbaarheid

Het feit dat de ontwikkelde geintegreerde aanpak de complexiteit van een irrigatiesysteem goed benadert en dat een groot aantal interventies kunnen worden geevalueerd, maakt de aanpak ook interessant voor toepassing in andere gebieden, of eventueel bij andere vraagstukken. Bij deze toepassing moet echter goed in de gaten worden gehouden dat niet alleen de modellen worden overgedragen. Het zijn juist aspecten als diagnose, identificatie van relevante processen en parameters, en discussies met actoren, die van groot belang zijn voor het uiteindelijke nut van een geintegreerde aanpak. Deze fasen van het onderzoek bieden namelijk inzichten voor een goed begrip van de fysische en menselijke relaties. Op deze manier kan de aanpak gericht blijven op begrip van het huidige functioneren van een systeem en op het voorbereiden van de toekomst door het effect van verschillende interventies te vergelijken.

RÉSUMÉ ET CONCLUSIONS

Une approche intégrée a été développée pour évaluer l'impact, a priori, d'interventions en matière de politique et de gestion dans le contexte de l'agriculture irriguée. Cette étude a utilisé cette approche pour un système irrigué au Pakistan, testant les effets d'interventions dans la gestion de l'irrigation sur la salinité des sols, la sodicité et la transpiration des cultures. Une étude parallèle a permis de vérifier l'approche en analysant l'impact des changements de politique sur le développement de marchés de l'eau et sur la production agricole dans la même zone (Strosser, 1997). Les résultats et conclusions de la présente étude sont résumés dans la première partie. Les leçons tirées de l'approche intégrée appliquée aux deux études de cas sont discutées dans la deuxième partie.

Interventions dans la gestion des systèmes d'irrigation pour un meilleur contrôle de la salinité et de la sodicité: leçons tirées d'une étude de cas au Pakistan.

La salinité et la sodicité au Pakistan

Traditionnellement, la salinité a été associée avec l'agriculture irriguée dans le Bassin de l'Indus. Trois causes principales peuvent être identifiées: (1) matériaux d'origine marine, (2) stagnation d'eau ("waterlogging") et la montée des nappes phréatiques dus à l'introduction de l'irrigation à grande échelle, qui entraîne les transferts de sels dans la zone racinaire par montée capillaire, et (3) l'utilisation d'eau de profondeur de qualité médiocre en provenance des forages. Les deux premières causes ont été largement étudiées et pourraient, dans ce cas, ne pas constituer le problème majeur. Les paysans ont réussi à mettre en culture de grandes superficies affectées par la salinité et/ou la sodicité d'origine ancienne. Aussi, la baisse des nappes phréatiques dans une grande partie du Pendjab rend le problème de waterlogging lié au contrôle de la salinité moins préoccupant. La salinité, liée à l'utilisation d'eau de profondeur de faible qualité, en complément de l'eau de canal, est un phénomène relativement récent qui est devenu important en raison du développement massif des forages. Cette menace n'a pas encore été prise sérieusement en considération et il est nécessaire que la recherche puisse évaluer l'importance de ce problème et les possibilités d'amélioration.

L'eau de canal, qui est d'excellente qualité, représente une valeur inestimable pour les paysans qui doivent faire face à des problèmes de salinité et/ou de sodicité. Avec l'eau de canal, ils peuvent récupérer les terres affectées par la salinité héritée, tant que l'utilisation conjointe d'eau de canal permet d'atténuer l'effet de l'eau de qualité médiocre des forages. Les ressources en eau de surface ne sont pas illimitées et les paysans devront utiliser l'eau des forages en complément de l'eau de canal pour maintenir les intensités culturales actuelles. Cependant, puisque tous les paysans ne sont pas confrontés aux mêmes conditions physiques tels que la qualité de l'eau de profondeur et les types de sol, une redistribution de l'eau de canal pourrait réduire le pompage dans les zones où la qualité de l'eau est la moins bonne ou dans celles où les sols présentent un risque de salinisation. Ceci conduit à affirmer que *la reallocation de l'eau de canal, en la rendant disponible dans les zones avec les plus fortes contraintes environnementales, contribuera à minimiser la salinité et la sodicité, et à atténuer leurs effets sur les sols et les cultures.*

Les objectifs de cette étude ont donc été énoncés comme suit :
- Définir les opportunités d'interventions dans la gestion du système d'irrigation et évaluer l'impact sur la distribution de l'eau de canal;
- Evaluer l'impact de l'offre en eau de canal au niveau de l'exploitation et de la parcelle sur la salinité et la sodicité des sols, et l'effet probable sur la production agricole; et
- Développer et utiliser une approche intégrée pour évaluer l'impact de changements dans la gestion du système d'irrigation sur la salinité, la sodicité et la production agricole.

Méthodologie

Actuellement, il n'existe pas d'outil ou de méthodologie pour examiner les possibilités de changement dans la distribution de l'eau, et pour évaluer l'impact de ces changements sur le renforcement des capacités des paysans à contrôler la salinité et la sodicité. Le développement de tels outils est nécessaire afin de permettre aux décideurs et gestionnaires d'évaluer l'impact de changements dans la gestion et de déterminer si une meilleure gestion de l'irrigation peut réduire les besoins en travaux coûteux sur les infrastructures.

Cette étude présente deux axes de recherche: une analyse de la gestion du système d'irrigation orientée vers les interventions ; et une étude, axée sur le processus, de la salinité et de la sodisation ?? au niveau de l'exploitation et de la parcelle. Ces études ont été combinées en développant et en rendant opérationnelle une approche intégrée, qui traduit les effets de changements dans la gestion de l'irrigation sur le développement de la salinité et de la sodicité, et sur la transpiration. L'étude a été menée dans un système d'irrigation de 75000 ha, la sous-division de Chishtian, qui constitue une partie du Bassin de l'Indus pakistanais. La zone d'étude est localisée dans le sud-est du Pendjab, où le coton et le blé sont les principales cultures en été et en hiver respectivement. Le climat est (semi -) aride avec une évaporation annuelle dépassant largement les pluies.

Résultats de l'étude

Un outil a été développé pour simuler les écoulements de l'eau dans les canaux et quantifier l'impact des changements au niveau du canal principal et primaire sur la distribution d'eau aux unités tertiaires. L'outil consiste en un modèle hydraulique en régime transitoire, SIC - Simulation des Canaux d'Irrigation - basé sur les équations de St. Venant, lié à un module prenant en compte les décisions opérationnelles de l'agence d'irrigation tant au niveau *tactique* (exécution) qu'au niveau *stratégique* (définition des objectifs). Les règles opérationnelles en vigueur au niveau du canal principal ont induit une distribution inéquitable de l'eau et une incertitude pour les utilisateurs quant à la date d'obtention de l'eau. Le retour aux règles officielles n'est pas une solution car les simulations montrent qu'il est impossible de les mettre en place. Ces règles supposent une offre maximale pour tous les canaux secondaires pendant les périodes de priorité opérationnelle du système d'irrigation concerné, alors que tous les canaux secondaires suivent une rotation lorsqu'il n'y a pas de priorité. L'application de la première règle est impossible en raison d'une arrivée d'eau insuffisante même lors des périodes de priorité opérationnelle, et la seconde règle n'est pas d'usage facile car les petits canaux secondaires ne sont pas en mesure d'absorber les fluctuations relativement importantes de débit dans le canal primaire. Les règles opérationnelles en vigueur sont plus pratiques mais ont des répercussions négatives sur la distribution d'eau. Il est possible d'améliorer la distribution de l'eau au niveau du canal principal en adoptant des règles opérationnelles alternatives. Ceci peut se faire en mettant en place une rotation au cours de la saison, concernant essentiellement les canaux secondaires les plus importants, tout en maintenant des périodes fixes de distribution de 8 jours. Ceci est bénéfique pour les paysans qui partagent l'eau selon des tours d'eau fixes, qui couvrent une période de sept jours. Ainsi, une distribution équitable de l'eau, le principe officiel pour l'irrigation au Pakistan, peut être restaurée. Pour le canal principal de la zone d'étude, la Branche Fordwah, le ratio inter-quartile modifié pourrait diminuer de 1.9 à 1.4. En d'autres termes, les 25% de la zone les plus favorisés obtiennent 1.4 fois l'offre en eau du quart le plus défavorisé contre presque le double. Ceci pourrait encore être amélioré si les petits canaux secondaires sans vannes en étaient pourvus ou en prenant en compte les canaux secondaires plus petits dans la rotation. Des investissements dans le système de communication ou des interventions en amont de la zone d'étude pour stabiliser l'arrivée d'eau seraient alors nécessaires. Un autre changement consisterait à redistribuer l'eau aux canaux secondaires avec un risque élevé de salinité et sodicité. Les simulations ont montré qu'une augmentation de 6% de la quantité d'eau délivrée dans le distributeur Fordwah, qui était récupérée par une diminution de l'offre de plus de 12% dans le distributeur Masood, n'affectait pratiquement pas les autres canaux secondaires de la zone d'étude.

L'infrastructure physique existant au niveau des canaux secondaires, concernant en particulier les prises tertiaires, induit une distribution inéquitable de l'eau, avec un *coefficient de variation spatiale* du ratio entre offre effective et offre autorisée/théorique variant de 0.3 à 0.8 pour tous les canaux. Il est possible de modifier la distribution de l'eau actuelle en changeant la dimension des prises d'eau tertiaires. Dans le cas du distributeur Masood, le coefficient de variation a été réduit à 0.1. De plus, l'eau peut être redistribuée à des prises tertiaires spécifiques, par exemple pour le contrôle de la salinité, en changeant les dimensions des prises. Les effets secondaires sur d'autres prises sont assez limités en raison du comportement hydraulique sub-proportionnel de ces prises. Un changement de 10% du débit dans un canal secondaire entraîne un changement de seulement 5% du débit de sortie des prises tertiaires. Les interventions globales tels que le curage ou la réduction de la largeur des canaux, sont en général nécessaires pour arrêter les débordements et maintenir la capacité de transport du canal, mais c'est souvent un instrument grossier d'intervention sur la distribution de l'eau car les principaux problèmes concernent des prises spécifiques.

La salinisation a été étudiée dans les parcelles des paysans afin d'évaluer l'effet des pratiques d'irrigation sur la salinité, la sodicité et la transpiration des cultures pour différents types de sols. Un modèle intégrant le transfert de l'eau du sol et de solutés, SWAP93, basé sur les équations de Richards et l'équation de convection-dispersion, a été calibré et validé pour des types de sols représentatifs, plutôt limoneux-sableux.

Une analyse de sensitivité a été effectuée avec le modèle. Les caractéristiques des plantes et la teneur en eau du sol saturé θ_s se révèlent être des paramètres importants influençant la balance en eau et sels. Ils doivent donc être déterminés précisément pour le calibrage et la validation du modèle. La profondeur racinaire, facteur de Boesten et la conductivité hydraulique saturée K_s sont des paramètres beaucoup moins sensibles dans les conditions données. Le modèle a aussi été utilisé pour évaluer l'importance relative de la quantité et de la qualité d'irrigation pour la salinité des sols et la transpiration. Une relation curvilinéaire avec une tangente décroissante a été établie entre la quantité d'irrigation et la salinité du sol. Des augmentations de la conductivité électrique (*CE*) de l'eau d'irrigation conduisent à une courbe qui est parallèle à la courbe d'origine mais avec des niveaux de salinité plus élevés. La transpiration relative T_{act}/T_{pot} est aussi une fonction curvilinéaire avec un gradient décroissant de la quantité d'irrigation. Cependant, l'impact relatif de réductions de la quantité d'irrigation ou d'augmentation de la *CE* de l'eau d'irrigation sur la transpiration est plus faible que sur la salinité du sol. Les relations entre la salinité et la transpiration et la quantité et la qualité d'irrigation ont été déterminées pour tous les types de sols représentatifs dans des conditions de drainage libre et pour une nappe phréatique d'une profondeur de 2 mètres. Les résultats de ces analyses sont importants pour deux raisons. Premièrement, cela montre que les changements de quantité ou de qualité de l'irrigation influencent considérablement la salinité du sol et la transpiration. Les changements dans la gestion du système d'irrigation sont donc des instruments importants pour le contrôle de la salinité. Deuxièmement, les paramètres environnementaux, tels que le type de sol ou la profondeur de la nappe phréatique, jouent un rôle important dans les processus concernant la balance en eau et en sels. Compte tenu de l'hétérogénéité de ces paramètres et de la qualité de l'eau des nappes, la redistribution de l'eau de canal est susceptible d'avoir un effet positif. L'impact des pratiques d'irrigation des paysans en présence des contraintes physiques (quantité et qualité d'irrigation, profondeur de la nappe, qualité de l'eau de la nappe et type de sol) a été analysé. Des mesures telles que l'application d'une importante irrigation avant le semis ou le changement de la fréquence des irrigations peuvent influencer la salinité du sol dans une certaine mesure, mais les effets sont beaucoup plus faibles qu'avec les changements de qualité ou de quantité de l'irrigation.

Le processus de sodisation a été étudié et une régression (équation 4.18) a été établie pour la zone d'étude afin de quantifier le risque de sodisation en fonction de la qualité de l'irrigation (SAR_{iw}) et la texture du sol. L'équation a été vérifiée pour d'autres points observations et elle permet une meilleure prédiction du risque de la sodisation que les formules empiriques existantes, avec une erreur standard de l'estimateur de *SAR* à 90 cm de profondeur d'environ 1.5. Les prédictions ont aussi été confrontées aux résultats d'un modèle géochimique, GYPSOL, qui montre une bonne correspondance entre les deux séries de résultats. Il a ensuite été montré que les problèmes de sodisation et de dégradation des sols sont des processus relativement rapides. Au cours d'une saison d'irrigation, les couches supérieures montrent des signes tangibles de dégradation de leur structure, comme les croûtes de surface et les zones indurées dans le profil. La sodisation conduit à la dégradation de la structure des sols pour des niveaux d' *ESP* aussi bas que 4%, en raison de la nature feuilletée des argiles (illites).

Les pratiques et stratégies des paysans liées à la salinité et à la sodicité ont été étudiées dans le contexte plus large des objectifs et contraintes de l'exploitation. Dans une étude parallèle, Strosser (1997) a étudié les processus de prise de décision des paysans concernant les choix de cultures, l'obtention et la distribution de l'eau, en fonction de la stratégie, des contraintes des paysans, et de l'environnement physique et de l'irrigation. Les décisions des paysans ont été représentées dans des modèles de programmation linéaire (LP).

Une approche intégrée a été développée sur la base de cette étude et de celle de Strosser (1997) grâce à une base commune permettant de quantifier les processus physiques et les décisions humaines qui gouvernent ces processus. Un outil commun a été élaboré et appliqué à deux études de cas. La première décrite par Strosser (1997), teste la faisabilité de développer des marchés de l'eau et leur impact sur la production agricole. La deuxième étude de cas, décrite ici, concerne l'évaluation de l'effet des changements dans la gestion de l'irrigation sur la salinité et la sodicité d'une région de 14000 ha, appartenant au distributeur de Fordwah.

L'application à la situation actuelle dans le distributeur Fordwah montre que les prédictions des intensités culturales sont correctes, entre 17 et 25%. Le pompage par les forages était surestimé car les modèles économiques de programmation linéaire n'étaient pas encore calibrés au niveau des unités tertiaires. Strosser (1997) montre qu'après calibrage/validation, un niveau de pompage plus réaliste peut être prédit avec une erreur d'environ 10%. Dans la situation actuelle, il existe un risque considérable de sodisation pour 3300 ha soit 25% de la superficie du distributeur Fordwah, avec un *SAR* supérieur à 13. Les changements dans la gestion des canaux qui fournissaient des quantités d'eau additionnelles aux zones affectées par la salinité ne se sont pas révélés très efficaces, puisque le risque de sodisation future n'était pas pris en compte. Après un diagnostic des tendances futures avec le mode d'irrigation en vigueur en utilisant l'approche integrée, les interventions dans la gestion des canaux ont été définies afin de réduire le risque de salinité et de sodicité. Des interventions ciblées dans la gestion des canaux au niveau principal et secondaire peuvent permettre d'améliorer le contrôle de la salinité par les paysans. La zone à risque de sodisation élevé est réduite de presque 1400 ha.

L'analyse a montré les forces et faiblesses du modèle intégré en tant qu'élément de l'approche intégrée. L'approche permet de comprendre le fonctionnement d'un système d'irrigation et l'impact de changements dans la gestion de l'irrigation sur la salinité et la sodicité des sols. La précision des prédictions peut être établie pour la situation actuelle par un processus de vérification, mais cela ne constitue pas une étape indispensable. L'examen des prédictions pour le futur ne devrait pas se focaliser sur les valeurs absolues car il existe probablement des événements imprévus. Ces prédictions devraient plutôt être utilisées pour l'information qu'elles fournissent aux acteurs, tels que les gestionnaires, sur l'effet relatif d'interventions dans la gestion sur la salinité et la sodicité afin que ces acteurs soient mieux préparés pour les éventualités futures.

Application générale de l'approche intégrée à la gestion de l'irrigation

Utiliser l'approche intégrée: perspectives

L'approche intégrée a été testée pour deux études de cas, et a permis d'améliorer la compréhension du fonctionnement d'un système d'irrigation, de l'effet d'interventions dans le système, et des problèmes opérationnels d'une approche intégrée. La suite la plus importante de ces études concerne l'utilisation de l'approche développée. Différents scénarios devraient être formulés et simulés en utilisant l'outil combiné en collaboration avec les acteurs du système d'irrigation concerné. Ceci pourrait constituer la base de discussions permanentes entre acteurs pour améliorer la performance du système lors d'une phase plus opérationnelle. Le succès de la mise en oeuvre de l'approche viendrait renforcer les arguments de cette étude en faveur de la pertinence de l'approche intégrée et pourrait aboutir à l'identification d'autres perfectionnements nécessaires. Des améliorations dans l'analyse et les outils peuvent être identifiées sur la base de ces expériences. Premièrement, des boucles de rétroaction entre les différents mécanismes, comme l'impact de la salinité sur les stratégies des paysans, devraient être inclues dans l'approche. Ensuite, le logiciel pourrait être amélioré pour faciliter l'exécution de scénarios multiples. De plus, l'amélioration des modèles individuels ou des analyses devrait être considérée. Ceci concerne, par exemple, l'incorporation d'un modèle géochimique ou la prise en compte d'une gamme plus large d'objectifs et de contraintes pour les ménages dans la modélisation des décisions des paysans. L'interface entre différents modules et mécanismes nécessite un examen. Enfin, une analyse plus détaillée de transfert des erreurs entre les modèles devrait être étudiée. Avec la configuration actuelle, les boucles d'itération n'ont pas amplifié les erreurs des modèles individuels. Ce phénomène devrait être analysé et testé pour un plus large éventail de scénarios. Bien que ces améliorations soient souhaitables, la priorité devrait être l'utilisation de l'outil combiné avec la configuration actuelle, dans le contexte général de l'approche intégrée.

Le processus

Une approche intégrée est souvent préconisée mais peu appliquée en raison, probablement, des difficultés de mise en oeuvre. Des équipes pluri-disciplinaires doivent coordonner leurs recherche et donc harmoniser leurs objectifs et méthodologies. De plus, certains choix nécessaires dans la recherche seront contraints par d'autres disciplines. Ceci concerne des détails pratiques tels que le choix de la zone d'étude, la méthode d'échantillonnage, et le planning. Cependant, les études de cas discutées ici ont montré que la recherche "disciplinaire" et le développement d'une approche intégrée peuvent coexister.

Profondeur contre largeur ?? Le processus d'intégration doit commencer le plus en amont possible dans la démarche de recherche pour aboutir au succès. Combiner et lier des résultats de recherche et des outils peut apporter de précieux enseignements, et ne doit pas être une préoccupation de dernière minute quand apparaissent des lacunes dans les études de certaines relations. Il est recommandé de développer une approche intégrée simplifiée dans les premiers stades de la recherche, sur la base d'un cadre intégré. Ceci peut être ajusté ou remplacé dans la suite du processus. Cependant, une approche intégrée doit laisser suffisamment de latitude aux équipes de différentes disciplines pour mener leurs études car la recherche doit être suffisamment approfondie. La qualité de l'approche intégrée dépend de la rigueur individuelle des différentes parties. L'équilibre entre recherche disciplinaire et intégration est difficile à trouver.

De nombreuses difficultés concernant l'information apparaissent en mettant en oeuvre une approche intégrée. Les besoins en information sont importants, bien qu'ils puissent être limités par les analyses de sensibilité, et l'information doit être partagée par des groupes de personnes étudiant différents mécanismes à des échelles spatiales et temporelles variables. Pour ce faire, des étapes spatiales et temporelles communes doivent être définies et les bases de données doivent être standardisées.

Hétérogénéité et variabilité

L'hétérogénéité spatiale des paramètres physiques et la variabilité temporelle des différents mécanismes, ainsi que la diversité des exploitations sont inhérents à l'analyse des systèmes d'irrigation. C'est un inconvénient car ceci implique l'analyse de la structure spatiale et temporelle de l'information qui demande un jeu important de données et des techniques géo -statistiques avancées de classification et extrapolation. Pour les décideurs politiques et les gestionnaires de l'irrigation, ceci pause aussi un problème important car l'efficacité des interventions globales sont réduites.

Cependant, hétérogénéité et variabilité peuvent aussi être considérées comme une force et une opportunité; force car le système est mieux adapté aux chocs extérieurs et opportunité car l'hétérogénéité et la variabilité offrent des possibilités de redistribution des ressources. Ceci a été montré dans les deux études de cas. Strosser (1997) a montré qu'en utilisant la saisonnalité de l'irrigation, une redistribution de l'eau pouvait conduire à une augmentation de la production agricole. Dans la présente étude, on a pu montrer qu'une redistribution de l'eau pouvait permettre de diminuer considérablement la superficie affectée par la salinité et la sodicité en raison de l'hétérogénéité de la qualité de l'eau de la nappe et des types de sol. *Le défi consiste ainsi à comprendre et quantifier l'hétérogénéité et la variabilité existantes afin de l'utiliser pour définir des interventions en matière de gestion et de politique.*

Interventions

Les interventions en matière de gestion et de politique qui ont été proposées dans la présente étude et dans l'étude parallèle de Strosser (1997) couvrent un large éventail. La première étude est focalisée sur les interventions dans la gestion du système d'irrigation, i.e. les changements des règles opérationnelles de l'agence d'irrigation et les modofictions des caractéristiques des prises tertiaires alors que la seconde étude analyse les interventions concernant les politiques, tels que la fixation du prix de l'eau et le développement de marchés de l'eau. En pratique, les décideurs et gestionnaires peuvent choisir une combinaison de différentes politiques et/ou de changements dans la gestion. La complémentarité entre les interventions qui ont été analysées dans les deux études n'a pas été étudiée jusqu'à présent mais constitue une perspective intéressante de travail, d'autant plus qu'un grand nombre de variables, traduisant la complexité d'un système d'irrigation, ont été inclues dans les outils développés.

ABBREVIATIONS AND GLOSSARY

Abbreviations

AOSM	Adjustable Orifice Semi-Module
APM	Adjustable Proportional Module
ASCE	American Society of Civil Engineers
CCA	Culturable Command Area
Cemagref	French research center for agricultural and environmental engineering
DDL	Gouy-Chapman Diffuse Double Layer
DLR	Directorate of Land Reclamation, Punjab
FAO	Food & Agriculture Organization of the United Nations
FSL	Full Supply Level
GCA	Gross Command Area
GIS	Geographical Information System
IIMI	International Irrigation Management Institute
IWASRI	International Waterlogging and Salinity Research Institute
L	Loam
LF	Leaching Fraction
LP	Linear Programming
LS	Loamy Sand
M&R	Maintenance and Repair
NESPAK	National Engineering Services, Pakistan
OFRB	Open Flume with Roof Block
PID	Punjab Irrigation & Power Department
PWD	Public Works Department
R-index	Responsiveness Index
RD	Reduced Distance
RWS	Relative Water Supply
SBE	Sub-Engineer
SDO	Sub-Divisional Officer
SIC	Simulation of Irrigation Canals, hydraulic model
SiCL	Silty Clay Loam
SiL	Silt Loam
SL	Sandy Loam
SSP	Soil Survey of Pakistan
SWAP93	Simulation of transport processes in the Soil-Water-Air-Plant environment, hydro-dynamic model

USDA	United States Department of Agriculture
VGM	Van Genuchten-Mualem parameters
WAPDA	Water and Power Development Authority, Pakistan
XEN	Executive Engineer

Glossary

Abiana	Water charges
Cheer	Labour (historically) provided by farmers in the winter months to prepare the (inundation) canals for the irrigation season
Chitta	White, in association with kallar
Distributary	Secondary canal
Doab	Land encompassed by two rivers, especially in the Punjab
Indent	Water demand for a canal or system formulated by the irrigation manager in terms of a discharge
Kallar	Salts
Kala	Black, in association with kallar
Kharif	Summer cropping and irrigation season
Kila bushing	Restriction of the width of a cross-section of a channel by inserting bamboo sticks and bushes to stimulate sediment deposition
Mogha	Tertiary outlet
Non-perennial	Label of canals that are entitled to water only during the summer
Partition	Under the Indian Independance Act of 1947, India and Pakistan, consisting of West Pakistan (present day Pakistan) and East Pakistan (now Bangladesh), obtained their independance. Through the Radcliff award Bengal and Punjab were partitioned or divided between India and Pakistan.
Rabi	Winter cropping and irrigation season
Rauni	Pre-sowing irrigation
Regime	Theory developed by British engineers Kennedy and Lacey, entailing the design of non-silting, non-scouring canals
Warabandi	Roster of water turns
Watercourse	Tertiary unit
Zacht	Hard layers in the soil profile

List of Main Symbols

Upper case

Symbol	Chapter	Interpretation	Unit
A	(3)	Wetted area	[m^2]
A_{sal}	(5)	Fraction of the *CCA* having an EC_e>4 dS m^{-1}	[-]
A_{sod}	(5)	Fraction of the *CCA* having an *SAR*>13	[-]
C_d	(3)	Discharge coefficient of the gate	[-]
C_r	(3)	Courant number	[m]
$C(h)$	(4)	Differential moisture capacity	[cm^{-1}]
CI		Cropping Intensity	[%]
$C\text{-}RA$	(4)	Residual alkalinity calcite	[-]
D	(3)	Water depth	[m]
D_{iw}	(5)	Depth of irrigation water delivered at the farm level	[mm]
D	(4)	Hydro-dynamic dispersion coefficient	[cm^2 d^{-1}]
D_e	(4)	Molecular diffusion coefficient	[cm^2 d^{-1}]
D_h	(4)	Mechanical dispersion coefficient	[cm^2 d^{-1}]
DPR	(3)	Delivery Performance Ratio	[-]
DT_{op}	(3)	Interval between two operations	[min]
E		Evaporation rate	[cm d^{-1}]
EC		Electrical conductivity	[dS m^{-1}]
ESP		Exchangeable sodium percentage	[%]
ET		Evapotranspiration rate	[cm d^{-1}]
F_c	(4)	Inverse leaching fraction	[-]
G_o	(3)	Opening before operation	[m]
G_o'	(3)	Opening after operation	[m]
H	(3)	Energy head	[m]
H_d	(3)	Downstream water level	[m]
H_u	(3)	Upstream water level	[m]
$K(h)$	(4)	Hydraulic conductivity	[cm d^{-1}]
$MIQR$	(3)	Modified Inter Quartile Ratio	[-]
P	(3)	Wetted perimeter	[m]
pH_c	(4)	Langelier index	[-]
Q	(3)	Discharge	[m^3 s^{-1}]
R	(3)	Hydraulic radius (*A*/*P*)	[m]

RSC		Residual Sodium Carbonates	[meq l^{-1}]
S	(3)	Sensitivity ratio	[-]
S	(4)	Salinity	[mg cm^{-2}]
SAR		Sodium Adsorption Ratio	[mmol l^{-1}]$^{0.5}$
$S(h)$	(4)	Root water uptake (sink term)	[d^{-1}]
S_f	(3)	Energy slope	[-]
S_r	(4)	Sink term for solute loss due to plant salt uptake	[g cm^{-3} d^{-1}]
$S_{x,y}$		Standard error of estimate	[-]
T		Transpiration rate	[cm d^{-1}]
T_{op}	(3)	Duration of an operation	[min]
V	(3)	Volume	[m^3]
V	(4)	Average pore water flow velocity	[cm d^{-1}]
V	(4)	Mean fluid velocity	[m s^{-1}]

Lower case

Symbol	Chapter	Interpretation	Unit
b	(3)	Breadth of an outlet opening	[m]
c	(3)	Celerity coefficient	[-]
c	(4)	Solute concentration	[g cm^{-3}]
cv_R		Spatial coefficient of variation	[-]
cv_T		Temporal coefficient of variation	[-]
g		Gravitational acceleration	[m s^{-2}]
h	(3)	Vertical depth of flow	[m]
h	(4)	Soil water pressure head	[cm]
h	(4)	Vertical depth of flow	[m]
k	(3)	Lateral in- (k=0) or outflow (k=1)	[m^2 s^{-1}]
k_{osm}	(4)	Crop specific coefficient	[-]
n	(3)	Manning's coefficient	[$m^{-1/3}$ s^{-1}]
n	(4)	Empirical coefficient, pore size distribution	[-]
q	(4)	Soil water flux (positive upwards)	[cm d^{-1}]
q_s	(4)	Solute flux	[g cm^{-2} d^{-1}]
t		Time	[d]
u	(3)	Power coefficient	[-]
v	(3)	Velocity (equals the discharge over the wetted area)	[m s^{-1}]
w	(3)	Top width of the wetted area	[m]
w	(3)	Width of the gate	[m]
x	(3)	Abcissa	[m]
y	(3)	Height of an outlet opening	[m]
z	(4)	Height (positive upwards, origin at the soil surface)	[cm]

Greek

Symbol	Chapter	Interpretation	Unit
α	(4)	Empirical coefficient, reciprocal of the air entry value	[cm^{-1}]
β	(4)	Boesten factor	[$cm^{1/2}$]
Δ		Difference	[-]
θ	(4)	Soil moisture content	[cm^3 cm^{-3}]
λ	(4)	Empirical coefficient, pore connectivity factor	[-]
μ		Arithmetic mean	[-]
π	(4)	Osmotic head	[cm]
σ^2		Standard deviation	[-]

Subscripts

Symbol	Chapter	Interpretation
act		actual
adj	(4)	adjusted
cw		canal water
d	(3)	downstream
dw	(4)	drainage water
eq	(4)	equivalent
i	(3)	intended
iw		irrigation water
osm	(4)	osmotic
pot		potential
r	(4)	residual
s	(4)	saturated
tw		tube well water
u	(3)	upstream

CURRICULUM VITAE

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1977-1983	Grammar school, "Stedelijk Gymnasium", Arnhem, The Netherlands
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