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TABLE OF CONTENTS

FOREWORD

Volume IV on Environmental Management of Irrigated Lands contains the eight papers that were presented at the National Conference on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan held at Islamabad, November 5-7, 1996. These papers are authored by the researchers of IIMI-Pakistan and by professionals in the organizations with which IIMI-Pakistan has been collaborating, comprising of: Director General, Soil Survey of Pakistan (SSoP); Director, Land Reclamation (DLR) of Irrigation Department, Government of the Punjab; and the Water and Power Development Authority (WAPDA).

SALINITY/SODICITY IN PAKISTAN:
Experiences and Findings

Dr. Ghulam Saeed Khan[1]

ABSTRACT

The problem of soil salinity/sodicity in the Indus plains has been known for long, but since the early 1950's, it has been ranked as the most serious constraint for agricultural production. It is undoubtedly one of the main soil problems but not the major one to limit agricultural productivity. Its gravity may be judged from the fact that about 6.3 x 10^6 ha of the total area of Pakistan is salt affected, out of which about 2.8 x 10^6 ha are affecting the agricultural land. The nature of the problem, though it looks simple, is factually quite complex. The immense amounts of money invested in reclamation endeavors with little success speak of the compexity. The common claim to have spectacular acheivements in that regard is controversial as the problem seems to be on the increase.

A systematic approach to survey, characterization and classification of salt affected soils is of prime importance for developing reclamation strategies and evolving appropriate management packages. The conventional salinity classification on the basis of severity i.e., slightly, moderately or strongly saline etc., is not of much practical value. An objective classification is better done on the basis of the problem status with respect to salinity, sodicity, permeability and physiography because all of these characteristics jointly determine their reclaimability.

Systematic studies by the Soil Survey of Pakistan (SSP) over the past quarter century have revealed that a sizeable area was already salt affected prior to introduction of the present irrigation system. The SSP have surveyed and classified all salt affected soils on the basis of their specific characteristics and relative ease of reclamation. The SSP have also observed that a few of the present agronomic and irrigation practices are adding to the problem of salinity/sodicity at an alarming rate.

INTRODUCTION

Salinity/sodicity is undoubtedly amongst the most severe soil problems facing the irrigated agriculture throughout the world and Pakistan is no exception. It has been known for long in the Indus plains, but since the early 1950's, ranked generally as the most serious constraint for agricultural productions and haunting the minds of planners and decision makers. The nature/complexity of this problem has, however, not been well understood in the past and, therefore, the improvement measures did not achieve the targeted results. The claim about spectacular achievements in this regards is controversial as the threat seems to be on the increase.

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Systematic/standardized surveys - characterization and classification of the salt affected (including those prone to this menace) is a pre-requisite for developing reclamation strategies and evolving appropriate management (agronomic) packages. The conventional salinity classification on the basis of severity (i.e. slightly, moderately or strongly saline etc.) is not of much practical value. An objective classification is better done on the basis of the problem status with respect to salinity, sodicity, permeability and physiography because all of these characteristics jointly determine its reclaimability.

METHODOLOGY

Systematic surveys of the almost whole country (about 87%) have been carried out since the mid-60's and information regarding the types of soil, their potential/ limitations, areal extent and geographic distribution have been documented in the form of reports and maps (Soil Survey Staff, 1967-85). Aerial photographs (1:40,000) and topographic maps (1:50,000 and 1:250,000) were used as base maps. Preliminary land units based on landform, drainage, topography, salinity/sodicity, erosional features and land use are delineated on the aerial photographs through stereoscopic interpretation. Through this basic study, supplemented by secondary information about climate, geology, hydrology and agriculture, broad outlines of soil patterns emerge. Regular surveys, ground checks/ truthing, start along transects across the various patterns of landform, drainage and topography. Soil observations are made by digging pits about 45 cm deep, followed by augering down to + 150 cm, at intervals ranging from meters to k, meters depending upon the complexity/heterogenety of the unit. The soils are described in accordance with the Soil Survey Manual (USDA, 1951) and during the course of the survey necessary amendments in the soil mapping legend and unit boundaries are made. Soil samples from each horizon of a modal profile of soil series (a distinct soil type) are taken for detailed laboratory analysis.

RESULTS/DISCUSSION

The surveys/investigations have resulted in the identification, characterization, classification and mapping of different types of salt affected soils alongwith other types. The following types are differentiated on the basis of physical, chemical and morphological characteristics coupled with their physiographic position in the landscape.

Saline-sodic (dense) soils

These soils have characteristics of dense (impervious), strongly sodic (pH > 9.5) B horizon and silt loam to silty clay texture. Electrical conductivity is comparatively low, specially where the groundwater is below critical depths. Presence of $CO_3^=$ in soil solution are indicative of virtual inactivation/elimination of Ca^{++}, dominance of Na^+ and concurrent abundance of the latter cation on the exchange complex. Such a situation invariably leads to structural degradation, increased bulk density and resultant reduced permeability. These soils are mostly found in old river terraces and in the subrecent plains and occupy higher parts of channel infills and margins of basins. In these soils, the process of sodication had been operative for a longer time resulting in severity of the problem to greater depths in the profile. Due to this severity of the problem, such soils are rated as class IVa in an earlier USDA capability classification system. These soils are mainly found in comparatively higher rainfall (semi-arid) areas (i.e. North and North-eastern Punjab).

Saline-sodic (porous/permeable) soils

These soils have almost similar characteristics as the preceding soils but differ in the severity of the problem. The sodication has not so advanced (pH < 9.5 but > 8.5), hence, the soil structure is not so degraded and the soils are still porous/ permeable. Physiographically, these soils generally occupy comparative lower sites on the margins of basins and old channels. These soils are mostly found in arid to semi-arid areas.

.Saline-sodic gypsiferous soils

These soils are similar to the preceding group except that these contain gypsum and occur in hyper-arid areas - Southern Punjab (South of Multan) and sporadically in Sindh.

Saline-gypsiferous soil

These soils have no sodicity problem (pH < 8.5). Chloride and sulphate of calcium and sodium dominate in the soil solution. These salts being hygroscopic, give the soil surface a damp/oily look, especially in the morning. These are mainly found in the hyper arid zone - Southern Punjab and Sind, including the Indus delta.

Intersparsed (Patchy) saline/sodic soils

These soils are generally under cultivation and characterized by the appearance of salts in patches. The problem is the least severe from all the preceding groups. The salt content of the surface (few centimeters) are high enough to adversely affect germination/growth of crops. Subsoils are usually normal or slightly saline/sodic. These soils generally occur on slightly higher parts (micro-relief differences).

The areal extent of the various types of salt affected soils is given in Appendix.1.

Source of Salts (Genesis)

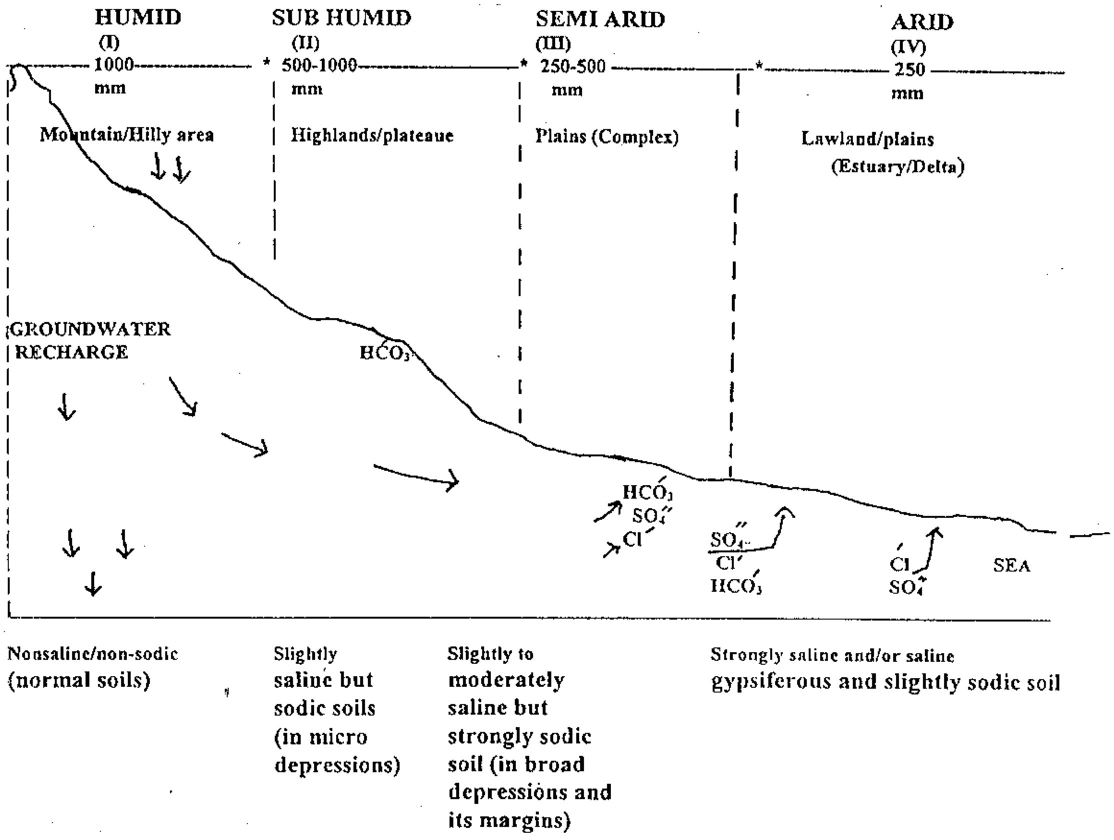
The primary source of salts in soils is their release by the weathering of minerals and subsequent redistribution (accumulation) through the evaporation of the soil solution. The increasing trend of salt accumulation in the upper layers of soil profiles is because of conditions facilitating accumulation of salts, such as shallow mineralized groundwater and the irrigation water combined with aridity. The rate of salt accumulation through the groundwater is mainly governed by the depth of water table and its degree of mineralization, hydraulic/capillary conductivity characteristics of soils, meteorological conditions and soil-crop (land use) management practices. According to Kovda et al., (1973) favourable climatic (hot and dry), geomorphological (vast depressions) and topographical (small relief depressions) are not sufficient to set up the salinization process unless combined with favourable geohydrological conditions. Salinization occurs only when the aforesaid features are found in combination with a high ground water table and where the ground water is stagnant and has little natural drainage.

Shallowness of the watertable is not always hazardous, but is rather a valuable asset if a sufficient volume of top soil is aerated for root growth and the water is constantly circulating, thus being sufficiently aerated and preventing salt accumulation. Similary critical depth of watertable cannot be interpreted in the traditional way if it is ensured that the downward water movement dominates in the cultivated top soil layer. Poor irrigation management can also result in salinization if the downward flux is not ensured. Even the so-called good quality canal water contains salts, which are continuously added to the soil. The appearance of salts on field banks and high spots (even clods) is the manifestation of these salts. The presence of saline patches in uneven or fallow fields, under deep water table conditions is the result of side seepage from neighbouring irrigated fields or from lower parts of the fields (Choudhri et. al, 1978).

Indiscriminate use of questionable quality groundwater, which is on the increase, is a real threat to the salinization and specially the sodication of soils. In the begining, this use seems very attractive, as its damages are gradual and usually un-noticed, but suddenly assume alarming proportions, resulting in abandonment. Though a recent study by IIMI (Kielin, 1996) indicates that now farmers have a fair sense of the problem caused by use of such waters, but that also after sufficient damage has already been done.

As a consequence of relatively mobility/solubility, Cl and SO_4 accumulate in the deeper parts of depressions or in terminal drainless lakes and $CO_3$and HCO_3on relatively elevated relief elements (Bazilevich, 1970). Bhargava and Bhattachargee (1982) observed that sodic soils encountered in the region with mean annual rainfall ranging from 550 to 1000 mm, while saline soils occured in regions having less than 550 mm annual rainfall. Bhargava (1986) reported that in a toposequence of sodic and saline soils, the sodic soils occupied elevated positions, whereas saline soils occured on the slopes and centre of basins. Khatib (1970) observed that in the river system, having its source in the mountains, the groundwater was deep and of less salinity in the upper streches due to coarse texture, high hydraulic conductivity and good internal drainage. As the river meandered downwards, the slope changed from steep to gentle and flat, texture became finer, hydraulic conductivity lowered, with consequent poor internal drainage resulting in shallow groundwater with high salt content, especially in basins. According to him, the type of salt found in groundwater also varied along the river course; this were mainly carbonates in the upper reaches, sulphates in central parts and chloride predominated in the lower parts. The following schematic diagram of the pedo-climatological zones elaborates the preceding observations in respect of our country.

SCHEMATIC DIAGRAM OF THE PEDO-CLIMATOLOGICAL ZONES



<u>Zones.</u>

I. Mountaneous/hilly area (outer Himalaya), it lowers and terminates at Margalla hills.
II. Start from Margala hills upto Gujrat area $HCO_3^{\prime} + CO_3^{\prime\prime}$ dominate in anions of soil solution.
III. Start from Gujranwala to Lahore/Kasur area uptil Patoki-$HCO_3^{\prime} + CO_3^{\prime\prime}$ followed by $SO_4^{\prime\prime}$ and than $Cl^{\prime}$.
IV. From Kasur (Patoki) to Multan (arid) and onward to sea coast (very arid)-$SO_4^{\prime\prime}$ and $Cl^{\prime}$ dominate.

HISTORICAL PERSPECTIVE

As indicated in the begining, all of the salinity/sodicity is not a recent phenomenon, attributed to the rise of the groundwater table with the introduction of the present irrigation system. Soil survey findings and historical records testify to this fact. At the time of canal colonisation (Wace,1934), sizeable patches of salt affected land were excluded from canal command areas (CCA). Only normal soils were allotted to farmers and the saline patches, small in size and occurring in intricate patterns within normal lands were included in the CCA. Time related soil morphologic properties recognized in the field (relative soil development and lime concretion) are primary keys used to understand differences in landscape age. Extensive saline sodic soils have been mapped, which are having well developed profiles and distinct lime concretions. Micromorphological studies (Khan,1993) have shown that the lime concretions (kankers) are not formed under the in fluence of a high ground watertable.

Pendall and Amundson (1990) have reported the age of these lime nodules to be 7080+-120Y B.P., which is conconsistent with the old river terrace (Late Pleistocene) age i.e. 12,000 years B.P, since 5000 years is a reasonable time for initiation of significant calcite deposition (Birkeand, 1984). The watertable, in certain of these areas, is neither within the critical depth, nor ever reported since the introduction of the present canal irrigation system. This indicates that favourable condition, including grandwater, which in the past were responsible for salt accumulation, have vanished and the salinity/sodicity had been preserved due to desert like condition, as also reported by Kovda etal (1973). However, the point should be made that where the watertable is deep in such soils, the surface appears salt free to the casual observer. Wherever the watertable has risen in the soils, due to the recent irrigation system, salt efflorescence has appeared on the surface.

CONCLUSIONS

- Proper understanding of the diverse nature of soils is a pre-requisite for formulation of sound land improvement plans, including irrigation and drainage. These plans must also keep in view the limited amount of surface water supplies and the questionable quality of groundwater, the relative economics of reclamation of different kinds of salt affected soils, and options of increased production by intensive cropping on good agricultural lands. In reclamation, priority must be given to patchy (Interspersed) salinity in the cultivated fields, because the farmers are applying water, seed, fertilizer, etc. without any benefit to such slick spots. Next, if still water is available in excess of the crops requirements, porous saline-sodic soils should be given priority. Reclamation of dense, saline-sodic soils should be given the lowest priority as presently this will be uneconomic.

- It is a hard fact that all arid countries in the world will have to use more and more water of poor quality and we will have to live with this because in almost all countries there is more good land available than good water resources. In view of the pressure on the land, we must learn how to live with water of poor quality. Admittedly, there is no escape from the use of poor quality groundwater, but this must not be indiscriminately used. This message must be spread quite effectively and efficiently through various media and the support services.

- Soil maps must be used for sustainable and environmentally sound land use planning/development propositions.

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App. I

EXTENT (Sq.Km.) OF SALINE/SALINE-SODIC SOILS OF PAKISTAN

A. SALINE/SALINE GYPSIFEROUS (DENSE)/SALINE GYPSIFEROUS (POROUS)

PUNJAB	SIND	BALUCHISTAN	N.W.F.P	PAKISTAN
1655 (5)	17154 (47)*	17253 (48)	-	36062

B. SALINE SODIC (DENSE)

PUNJAB	SIND	BALUCHISTAN	N.W.F.P	PAKISTAN
8412.00 (90)	869.00 (9)	22.00 (1)	-	9303.00

C. SALINE SODIC (POROUS)

PUNJAB	SIND	BALUCHISTAN	N.W.F.P	PAKISTAN
9779.00(69)	2608.00 (18)	1584.00 (11)	269.00 (2)	14240.00

D. SALINE SODIC GYPSIFEROUS (DENSE/SALINE SODIC GYPSIFEROUS (POROUS)

PUNJAB	SIND	BALUCHISTAN	N.W.F.P	PAKISTAN
1076 (30)	483 (14)	1926 (54)	75 (2)	3560

G.T:

20922 (33)	21114 (33)	20.785 (33)	344 (1)	63165

* Percentage of total Pakistan areas.

ADVANCES IN UNDERSTANDING THE IMPACT OF IRRIGATION MANAGEMENT ON SALINITY, SODICITY AND SOIL DEGRADATION IN PAKISTAN.

Marcel Kuper[1] *and Jacob W. Kijne*[2]

ABSTRACT

IIMI's research on irrigation-induced salinity in the Punjab, Pakistan, was started in late 1988. This paper reviews several aspects of the research by examining the research methodologies employed in the studies, and summarising the salient findings. Special attention is given to soil degradation and yield reductions arising from salinity and sodicity, induced by the tremendous increase in the use of groundwater for irrigation. The paper also lists a number of implementable recommendations for the management of the affected lands. Improved management of surface water supplies is shown to be a potential means for enabling farmers to better manage salinity.

The long term consequences of irrigation practices which depend for a large part of the irrigation supplies on pumped groundwater, were explored by simulation studies making use of existing computer models, such as SOWATSAL and SWAP, and also of an IIMI-developed spreadsheet approach. Simulations show that non-uniform field application of irrigation supplies results in higher soil profile salinities than in case of uniform applications. This observation is consistent with field observations of poor and patchy vegetative covers and points to the importance of adequate levelling of fields. Simulations indicated that a relatively small (10%) reduction in seasonal irrigation supply could result in a tripling of profile salinity. Precise control and allocation of irrigation water congruent with the evaporative demand of the crop, as well as the leaching requirements, is obviously important in the management of soil salinity, as is the quality of irrigation water available to farmers. The limitations of the modelling exercises are discussed. Some constraints are inherent in the type of models (e.g., restrictions on the depth of the groundwater table); others are due to non-availability of reliable data (e.g., soil hydraulic parameters, seepage losses), which are needed as input for the modelling.

Considerable progress has been made in understanding the physical and chemical processes that give rise to soil degradation under saline and sodic conditions. The usefulness of visual observations combined with measurements of residual alkalinity and exchangeable sodium percentage (ESP) is illustrated by field observations of soils in sample areas in the Fordwah/Eastern Sadiqia (FES) command area, supported by chemical analyses of soil samples. It was found that soils with an ESP value below 4% were not in danger of degradation due to sodicity; above 4% the hazard of soil structural degradation, as exemplified by the presence of surface crusts and hard layers, increased with the value of ESP. Soils with ESP values above 12% were seriously degraded. Generally, current practices lead to degradation of many irrigated lands, resulting in low infiltration rates and the likelihood of surface ponding of water. The effect of salinity and sodicity on crop yields has been studied for wheat and cotton, also in FES. The yield of cotton, more than of wheat, was found to be affected by the presence of sodium.

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Farmers in the Indus Basin have a rich experience in dealing with salinity related problems and are presently confronted with sodification and soil degradation. They have a clear idea about the causes of sodification, but are constrained in their implementation of remedies by a limited access to good quality irrigation water and other environmental constraints and by financial limitations. Interventions in the environmental constraints will, therefore, improve the degrees of freedom for farmers to manage salinity.

A relatively large number of surveys related to soils, salinity levels and groundwater tables have been undertaken for the Indus Basin, e.g., by the Soil Survey of Pakistan (SSP), WAPDA, and the Directorate of Land Reclamation (DLR). Attempts were made to develop methods for monitoring the salinity and sodicity status in the Indus Basin in a cost-effective way. The use of satellite imagery for the detection of salinity is discussed. The development of 'smart' sampling techniques for monitoring purposes has been initiated in collaboration with SSP and DLR. Various data bases are linked using a geographic information system (GIS). Preliminary results have yielded a classification of 5 soil types, several physiographic units, water qualities and groundwater depths, which form the basis for the sampling frame. GIS is also used to link visual observations of salinity with laboratory analyses.

INTRODUCTION

Traditionally, salinity has been associated with irrigated agriculture in the Indus Basin. Often, salinity was considered to be linked with waterlogging, which occurred due to the introduction of large-scale perennial irrigation. In the 1970s, researchers from the University of Agriculture, Faisalabad (UAF) and from the Soil Survey of Pakistan (SSP) demonstrated that the causes for salinity were much more diverse. Genetic salinity, due to weathering of parent material was shown to affect about 4.8 million ha of commanded area (Choudry et al., 1978). A second source of salinization was the rise of groundwater tables, displacing salts and bringing them into the rootzone through capillary rise. Finally, SSP warned about the imminent threat of salinization through the use of poor quality groundwater (Choudry et al., ibid).

Another important finding was the distinction that was made between salinity and sodicity. The WAPDA master survey showed that out of a total of 63,866 samples taken in the Indus Basin, 10.7% were saline, 23.6% saline-sodic and 3.5% sodic (Ghassemi et al., 1995).

Measures that have been taken in Pakistan to combat salinity have focused largely on vertical drainage through the Salinity Control and Reclamation Projects (SCARP). In addition to that, some horizontal drainage schemes have been implemented and a number of canals have been lined to prevent seepage (Ahmed and Chaudry, 1988). Researchers have also evaluated a number of farm practices, such as the application of gypsum and the cultivation of salinity-tolerant crops.

Recently, there has been a growing recognition by policy makers and researchers that much was to be gained by composing and testing a larger package of measures that would help farmers combat salinity and sodicity. This has led, for instance, to the formulation of the Fordwah/Eastern Sadiqia (South) project (FESS), where a large number of research institutes in collaboration with engineers of WAPDA and the Punjab Irrigation & Power Department are testing different measures in the first phase of the project in order to come up with practical recommendations on the implementation of irrigation and drainage measures in phase 2 of the project.

IIMI's research on salinity has focused on the potential contribution of irrigation management to provide a better means for farmers to manage salinity and sodicity. The principal hypothesis underlying IIMI's research on salinity is that management interventions in the Indus Basin Irrigation System would lead to the prevention of further land degradation and could mitigate the effects of salinity on crop production. An acceptance of this hypothesis would mean that in addition to drainage measures, irrigation management could provide a means of combatting the adverse effects of salinity and sodicity.

This paper provides a thematic overview of the salinity research that has been carried out so far by IIMI. Firstly, a number of modelling studies were conducted to assess the impact of irrigation and soils related parameters on salinization and sodification. We were particularly interested in the long-term consequences of present irrigation practices and in the identification of those irrigation variables that, if changed, would contribute to managing salinity and sodicity levels. Secondly, the effects of sodicity on soil degradation and on crops were determined. These problems are affecting the productivity and sustainability of irrigated agriculture and are of concern to policy makers and farmers alike. Since farmers are directly dealing with problems of salinity and sodicity and have a rich experience in mitigating their effects on soils and crops, they were solicited by IIMI in order to understand their perceptions of salinity and define their salinity strategies. If irrigation and drainage measures of the Government of Pakistan are to be capitalized on by farmers, we need to understand how to remove the environmental constraints of farmers so that they can better manage salinity and sodicity. Finally, the large spatial and temporal variability in salinity and sodicity has been emphasized. Measures that are developed to tackle salinity and sodicity need, therefore, to be site-specific. To accomplish this, information is required for a key number of parameters. This is at the core of the last thematic focus of IIMI: determining the salinity and sodicity status and risks over large areas.

SYNTHESIS OF THEMATIC STUDIES

I. MODELLING THE PROCESSES OF SALINIZATION AND SODIFICATION

In 1989, the salinity of tubewell water was started to be identified as a key factor in the water and salt balances of fields conjunctively irrigated with canal and tubewell water. It was then that attempts were made to model these balances. Modelling makes it possible to simulate situations which are impractical to measure in the field or would take far too long to monitor in reality. IIMI was particularly interested in predicting the long term consequences of irrigation with undiluted tubewell water of questionable quality, a practice that was found to occur quite extensively in the tail reaches of watercourse command areas in the study areas. Also, IIMI was interested to identify those management variables that would, if changed, contribute to keep salinity and sodicity within permissible limits.

Simulation of salt and water balances: SOWATSAL

The first study was conducted in the Upper and Lower Gugera Branch Canal commands, where the main cause for salinization was reported by farmers to be the use of poor quality groundwater. Due to an inequitable access to canal water, farmers (particularly those located in tail end watercourses) were forced to irrigate sometimes with undiluted tube well water. The aim of the study was to evaluate the impact of present irrigation practices on soil salinity.

Two computer models, one each for the water and the salt balance, were used for this purpose. These models, collectively referred to as SOWATSAL, were developed by Hanks at Utah State University, who together with his colleagues had used them successfully to simulate water and salt profiles under deficient irrigation when the initial water content and salt profiles were known.

In one study (Childs and Hanks, 1975) the influence of two levels of irrigation on relative yields was simulated over several years, using measured climatic and irrigation data as input. Other input data requirements of the models refer to basic properties of soils and plants. These include the relation of matric potential and unsaturated conductivity on soil water content; root depth during the season and fractional amount of active roots in a particular increment of depth; boundary conditions of potential evapotranspiration rate, rainfall and irrigation amounts; and the presence or absence of a watertable. IIMI simulated the water and salt movement into and out of the rootzone for three major crops grown in the sample areas, cotton during kharif, wheat during rabi and sugarcane during both seasons. The necessary input data had to be measured or assumed. Evapotranspiration rates were calculated from meteorological data obtained from the nearest weather station, and the initial water contents and salt concentrations in the profile were measured in the field. Sand and clay contents were determined from representative soil samples collected when watertable observation wells were installed in the sample areas.

This information, together with the measured saturated conductivities, was used to identify characteristic soil types based on soil data compiled by Wosten and Van Genuchten (1988). The required soil physical parameters for the soils chosen for the modelling (i.e. sandy loam, silt loam and clay loam) were those characteristic for each soil type. The median irrigation applications for wheat grown in the Upper Gugera sample area, and for cotton and sugarcane in the Lower Gugera sample area, were used as input in the model.

Simulations were done with irrigation water of two salt contents, corresponding to the median electrical conductivity (EC) and the EC value exceeded by 25% of the water samples (respectively 2.1 and 2.5 dS/m), that farmers in tail-end watercourse command areas used for irrigation. The frequency distributions of EC and SAR, as for example presented in Figures 8.17 and 8.18 of Kijne and Vander Velde (1992), show the wide (and skewed) distribution of these two parameters. By choosing EC values for the simulations that are characteristic for farms in tail-ends of the command areas, a worst scenario approach is followed, but nevertheless one that is probably representative for a quarter to one-third of the farmers in the Upper Gugera command areas.

The mean EC value of tubewell water in five sample watercourses in the Upper Gugera command area range from 0.55 to 2.35 dS/m. Tubewells in the Lower Gugera and the Fordwah/Eastern Sadiqia (FES) command areas have mean EC values ranging from 0.9 to 1.48 dS/m and 0.61 to 1.93 dS/m, respectively (Kijne and Kuper, 1995). The high spatial variability of tubewell water quality is illustrated for the FES area by the average EC value of 3.49 dS/m for the sample tubewells in the command area of the Fateh Watercourse 184R (a tail watercourse), which was for a while included in the set of sample watercourses.

Output of the model included the leaching fractions for the three crops, three soil types and two salinity levels of the irrigation water. The simulations indicated that the leaching fractions ranged from 2% for wheat on the clay loam to 47% on the sandy loam, and that the change in profile salinity, expressed as the ratio of profile salinity before and after the growing season, varied according to the salinity of the irrigation water and the leaching fraction. In all but one of the model runs for wheat, the profile salinity was lower after the rabi season, while it increased for all runs for cotton and all but one of the runs for sugarcane. The largest increase in profile salinity was found for sugarcane grown on the silt loam soil with irrigation water of 2.5 dS/m, i.e., an increase of 1.7 times in a single season.

A limited validation of the SOWATSAL model was carried out for two sugarcane fields in the Pir Mahal command area, and also for an entire watercourse command (Kuper and Van Wayjen, 1993). The simulation correctly predicted a decrease in salinity in one of the sugarcane fields which was over-irrigated (relative water supply, RWS, of 1.65), and an increase for the other field with RWS of 1.0. It was found that simulations with non-uniform field applications better predicted salinity changes, whereas when uniform field application of the irrigation supply was assumed, the changes in soil salinity were exaggerated. The assumed non-uniformity of application does not represent the actual field situation, but is a convenient mathematical way to take into account the combined effects of preferential flow paths and actual (but not measured) non-uniformity in field application. Generally, simulations of water and salt balances of cotton fields were better than those for wheat fields, perhaps because the pre- sowing irrigation of the wheat fields was not adequately accounted for in the simulations.

Simulations with SOWATSAL for a RWS of 0.94 during kharif and 1.31 during rabi (i.e. leaching of salts during rabi and accumulation of salts in the root zone during kharif), and assuming non-uniform water application, show that higher final soil profile salinity levels are reached than in the case of uniform field application (Kuper and Van Wayjen, 1993). This is an important conclusion, supported by field observations, that salinity in most fields occurs in patches. An obvious remedial action is thus to improve on the uniformity of field applications through levelling of the fields.

The time to reach equilibrium salt levels in the root zone was found to be far longer when non-uniform field application was assumed than with uniform application. The best that can be concluded from this set of simulations is that under actual field conditions, but with a yearly repeated cropping pattern, it may take more than ten years for a stable salinity profile to be established. Finally, according to the simulations, salt accumulation in the root zone nearly tripled for a ten percent reduction in the annual RWS. Hence, it seems unlikely that stable salt profiles will ever be established under actual farming practices where farmers from year to year change crops and apply different amounts of water (varying RWS) on most of their fields.

Simulations of salt and water balances: a spreadsheet approach

The results of the first set of simulations with SOWATSAL can be compared with those of the salt and water balance analysis, using the spreadsheet approach described by Kijne (1996). The same supply of irrigation water with EC of 2.1 dS/m, and of rain as used in the earlier simulation, applied to wheat during rabi, gives according to the spreadsheet analysis an increase in rootzone salinity of 3%, with a leaching fraction of 13%. The results of the comparable SOWATSAL simulation were a decrease in soil salinity of 35 to 58%, for a leaching fraction of 28 and 47% (silt loam and sandy loam, respectively).

A similar simulation for cotton during kharif using the spreadsheets gives an increase in rootzone salinity of 3% and leaching fraction of 15%, compared with the SOWATSAL results of an increase in profile salinity of 20 and 80%, for leaching fractions of 26% and 4%, respectively, for silt loam and sandy loam. The spreadsheet approach gives as recharge to the groundwater during rabi -158 mm, and during kharif -280 mm. In other words, the results indicate that large amounts are pumped from the groundwater, and in excess of the recharge to groundwater of seepage from canals and deep percolation from fields. It should be kept in mind that the simulation is representative for the situation of tail-end farms, where the dependence on pumped groundwater is far greater than in the head and middle reaches. The order of magnitude of salt accumulation and leaching fractions, as obtained with the spreadsheet approach, appears more likely than the SOWATSAL results.

Modelling the effects of irrigation application on soil salinity and crop transpiration: SWAP

Once the general trend of salinization was known, IIMI wished to explore the opportunities for management interventions. Two principal questions were formulated:

- what are the management variables that influence salinization; and
- and how does the physical environment interact with these variables.

In collaboration with Wageningen Agricultural University, a state-of-the-art solute transport model, SWAP93, was used to study the water and solute transfer in the unsaturated zone for the predominant soil types in the sample areas of FES. A careful calibration and validation process made it possible to carry out a sensitivity analysis of the impact of various environmental parameters and management variables on salinization (Smets, 1996). The effect of environmental parameters on salinization needs to be considered to ensure that the possible management interventions take cognizance of the existing physical conditions and its limitations.

The following environmental parameters were studied:

* soil hydraulic parameters. These parameters, referred to as Van Genuchten-Mualam (VGM) parameters, describe the soil hydraulic functions of soil moisture content, pressure head and unsaturated hydraulic conductivity. They depend on the physical characteristics of the soil, such as texture, pore density and pore sizes.

- root depth and distribution.
- groundwater table depth.

Since the soil hydraulic functions determine to a large extent the movement of water and solutes through the unsaturated zone, the VGM parameters have a considerable impact on the outputs of simulations by the SWAP93 model. These parameters can best be calculated through a mathematical process from the saturated hydraulic conductivity measured in the field and the saturated moisture content measured in the laboratory (Smets, 1996).

The reference evapotranspiration (e.g. obtained from the Penman-Monteith relations) and the ratio of bare soil evaporation and crop transpiration are important parameters. Climatic data are readily available, but the values of the crop factors can be questioned as general values reported in the literature (e.g., FAO publication 24) have been used.

Root depth and root distribution were shown to influence the transfer of water and solutes, but the impact was less pronounced than for the VGM parameters. This applies to the conditions for which the model was used, where the groundwater table is at 2.5m or more below the soil surface. A standard root distribution was adopted from the literature, while the rooting depth was measured in the field.

Groundwater tables influence the movement of water and solutes in the rootzone when they are within 2-3 meters of the soil surface. Their presence at a shallow depth affects the leaching of salts and can contribute to salinization of the rootzone when a downward flux is not maintained. Contrary to some other simulation models that were used, SWAP93 takes the groundwater tables into account, which facilitates its application under Pakistani conditions.

The impact of various changes in the environmental parameters on crop transpiration and salinization is illustrated in Table 1. Two indicators are used:

- relative transpiration (RT), which equals the actual transpiration over the potential transpiration; and
- salt storage change (SSC), which is the increase in salt volume in the soil profile over the initial salt volume.

Table 1. The effect of environmental parameters on crop transpiration and salt volume.

	value reference scenario	new value	RT	SSC
reference scenario			0.91	-0.20
increase k_s	12.0	36.0	0.91	-0.27
decrease $\boldsymbol{\theta}_s$	0.38	0.34	0.89	-0.17
decrease n	-1.0	1.2	0.86	-0.25
increase rooting depth	110 cm	150 cm	0.93	-0.15
increase crop coefficients		125%	0.82	-0.16
groundwater table at 2m	free drainage		0.93	-0.27

SSC is here the change in salt storage with respect to the reference scenario

Source: Smets, 1996

in which:

k_s is the saturated hydraulic conductivity (cm/day)
θ_s is the saturated soil moisture content (cm^3/cm^3)
n is a dimensionless VGM parameter, representing the width distribution of pore sizes (-)

The simulation shows that increasing the hydraulic conductivity mainly affects the salt volume. Water availability, however, is more affected by a change in the moisture content at saturation than in the hydraulic conductivity. Crop coefficients, functions of crop height, canopy cover, length of the growing season and climatic conditions, were increased by 25%. It increased the potential and - to a smaller extent - the actual evapotranspiration, resulting in a smaller leaching fraction and thus a higher final salt volume. RT is reduced because the increase in potential evapotranspiration exceeds the increase in the actual one. Simulation shows that salinity decreases more when the groundwater table is at 2m than when there is free drainage. The water content in the profile is lower (and hence the unsaturated conductivity is less) under free drainage, because of the downward flux in the rootzone when enough irrigation water is applied. Simulations with another field where less water was applied showed an increase of salinity when the groundwater table was at 2m due to capillary rise.

The management variables tested in SWAP93 were all irrigation related, i.e., amount, quality and frequency. These variables were initially tested for one year, i.e. two crop seasons of cotton and wheat consecutively. The long term effects were then evaluated for a few scenarios through 10 year simulations. The reference scenario was based on management practices recommended by the Agricultural Department for the study area. The results of the simulations are given in Table 2 only for the cotton season.

Table 2. The effect of irrigation management variables on crop transpiration and salt volume for the cotton crop, results of three simulations for one crop season.

variable	reference value	tested value	RT	SSC
quantity	80 cm	53.3 cm	-0.16	+0.37
frequency	8 applications	11 applications	+0.07	-0.05
quality	EC = 1.5[3]	EC = 3.0	-0.04	+0.16

The values of RT and SSC are the change in these parameters with respect to the reference value

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[3] The EC of the pre-soaking irrigation was 0.2

The effect of applying less irrigation water is especially pronounced in mid-season when the potential transpiration is highest. Since this coincides with the sensitive stage of the cotton crop, a reduction in yield is expected. The irrigation system is under much stress during this period, as all farmers want to irrigate their crops. Irrigating more frequently, while maintaining the total application at the same level as in the reference situation, increased crop transpiration as the rootzone is wetter. This is particularly pronounced on sandy soils because of their lower soil moisture retention. More frequent irrigations with less water means that less salt is leached from the rootzone. As the EC_e levels are relatively low, the osmotic effect of salts on the root water uptake is not very pronounced after one year of simulation. A build-up of salts is shown to occur, however.

Long-term simulations were done to study the trend in salinization under current and alternative practices. The results are presented in Table 3.

Table 3. The effect of irrigation management variables on crop transpiration and salt volume for cotton on a sandy loam, results of 10-year simulations.

variable	reference value	tested value	RT	SSC
quantity	148 cm annually	95 cm annually	-0.26	+3.29
quality	EC = 1.0	EC = 3.0	-0.03	+1.33
quality quantity	EC = 1.0 148 cm annually	EC = 3.0 95 cm annually	-0.31	+5.28

RT and SSC are the change with respect to the reference

A reduction by 40% in the quantity of water applied has a tremendous impact: the amount of salts in the profile increase and at a later stage crop transpiration is much reduced. A smaller reduction in irrigation supply, of say 20%, still causes a noticeable reduction in crop transpiration--RT was reduced by 9% after 10 years. Irrigating with water that is three times as concentrated as the reference increases salt storage notably, but doesn't have much effect on the crop transpiration. Irrigating with less water and of greater salt concentration, a situation that is sometimes observed in the field when the access of farmers to canal water is reduced, has a dramatic effect on both salt storage and crop transpiration, as shown in Table 3.

Using a geo-chemical model to estimate the effect of irrigation practices on sodification

After these modelling studies were completed, the understanding of the sodification process was still incomplete. This restricted the ability to recommend changes in management practices to address this important problem. However, based on farmers' interviews and laboratory analyses, the hypothesis was arrived at that the importance of sodicity and the resulting soil degradation, may well exceed that of salinity *per se* (Kijne and Kuper, 1995). Given the limitations inherent in the solute transport models, the use of a geo-chemical model seemed desirable. In the last few years, these models have started to become available as research tools. Based on a methodology developed by Marlet in Niger (Marlet, 1996), a study was initiated in the Chishtian Sub-division to define the processes of salinization and sodification for the Pakistani situation and confirm the current trend of these processes through a modelling study.

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 gypsum is likely only on non-cultivated fields at high EC levels and with a negative RSC. In case of a positive RSC, a process of alkalization takes place with precipitation of calcite and possibly a Mg based mineral such as sepiolite (Condom, 1996). The precipitation of calcite could partly explain why solute transport models overestimate the leaching of salts, if salts are stored in the soil matrix. The exchange of ions in soil solution with the exchange complex of the soil is also important.

Both processes are considered in the Marlet (1996) model, which was derived from the GYPSOL model (Vallès and Bourgeat, 1988 in Marlet, 1996). Laboratory analysis defined the model parameters by determining the cation exchange capacity (CEC), the ions to be modelled, the minerals making up the solid matrix and the main exchange processes between soil solution and exchange complex. The principal ions were shown to be Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-} and Si^{4+}. The alkalinity is calculated by subtracting the anion concentrations from the cation concentrations. The principal exchanges were taken to be Ca^{2+}-Na^+, Ca^{2+}-Mg^{2+} and Na^+-Mg^{2+} (Condom, 1996). Then, a calibration and validation procedure was undertaken, whereby the soil solution obtained from the soil samples was concentrated and its composition analyzed and compared with simulated results.

The effect of applying water of various qualities, defined by concentration (EC) and composition, on soil salinity and sodicity was evaluated by simulating the mixing of these waters with a soil and then concentrating the soil solution. In this manner, the conditions under which processes of salinization, alkalization and sodification occur could be quantified (see table 4).

Table 4. Identification of salinity processes as a function of the chemical composition of irrigation water.

Composition indicators		low EC	high EC
CSG-RA < 0	RSC < 0	salinization	salinization
CSG-RA > 0	RSC < 0	salinization	alkalization sodification
	RSC > 0	alkalization sodification	alkalization sodification

Source: Condom (1996)

The model was then linked with a solute transport model (Lafolie, 1991 in Condom, 1996), the inputs of which were based on results of earlier work with SWAP93 (Smets, 1996). The application of water of different qualities was simulated, while irrigation supplies were maintained at the same level. The simulations indicate that alkalization does not occur in cultivated fields within the simulation period, because of the large amounts of divalent ions on the complex. A longer-term simulation would be required to estimate the likely impact over a longer period. The amount of sodium on the complex, expressed as Exchangeable Sodium Percentage (ESP), was found to increase sharply during the simulation period for irrigation water qualities that are presently used in the study area. This important finding confirms and explains the observations of farmers that soil degradation as a result of irrigation with poor quality water can occur rapidly, even after a few irrigations. The increase in ESP happens initially only in the upper layers of the soil. The results are summarized in Table 5.

Table 5.

	water quality	EC[4] (dS/m) at 10 cm	ESP (%) at 10 cm	RSC (meq/l) at 10 cm
canal	EC = 0.2 SAR= 0.2 RSC= -1.6	< 1	2	- 2
TW 1	EC = 1.4 SAR= 6.3 RSC= -0.9	~ 4	21	-16
TW 2	EC = 0.8 SAR= 7.7 RSC=+2.7	~ 2	20	-10
TW 3	EC = 1.3 SAR= 8.2 RSC=+2.2	~ 4	25	-10

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[4] The electrical conductivity is calculated based on the sum of the cations (Condom, 1996).

Discussion and conclusions

All models have several important limitations, which together suggest that the results of the simulation are indicative of the direction rather than the magnitude of the changes that occur under the specified conditions. Some of the limitations arise from the non-availability of the necessary data. A case in point is the lack of information about the hydraulic characteristics of the sample soils. Soil water retention curves are not available for the sample soils and had to be deduced from similarly textured soils reported in the literature. Although IWASRI has been involved in measuring these relations in the field and laboratory using standard measurement techniques, the considerable spatial variability in soil parameters makes these efforts quite difficult. In the meantime, the use of hydraulic parameters reported in the literature for similar soils is appropriate for modelling purposes. Also, particularly in the earlier modelling efforts, the limited set of measured salt and water content profiles at the beginning of the season did not fully take into account the considerable spatial and temporal variation that is found in these parameters. With respect to the spreadsheet approach, the values of some parameters, such as the seepage losses during conveyance of the irrigation water, the field efficiency, and the effectiveness of rain, had to be estimated.

Other difficulties with models, however, are due to limitations in our understanding of the processes, e.g., the decline in evapotranspiration rates at the end of the growing season, for example for cotton. Also, the simulation of the effect of fallow on the water and salt balance is notoriously difficult.

Some limitations in the modelling exercises are the result of the particular design of the model. For example, SOWATSAL is not capable of modelling a watertable depth that varies during the growing season Hence, the component of the crop water supply obtained from capillary rise is not obtained when this model is used. As was pointed out by Van Wayjen (1996), when under-irrigation takes place (for example, a relative water supply, RWS, of 0.67, thus only two-thirds of the evaporative demand of the crop is met by irrigation and rainfall), capillary rise can contribute up to 12% of the crop transpiration requirement, particularly for deep rooting crops such as cotton, and depending on the soil type. With less irrigation (i.e., more under-irrigation, RWS of 0.5) and a groundwater depth of 2 m., the contribution from capillary rise can amount to 20% of the demand. This probably wasn't much of an issue for the sample sites in Upper and Lower Gugera, where the watertable depths were found to be between 3 and 8 m (e.g., see Kuper and Van Wayjen, 1993). Typically, RWS values are relatively high, ranging from 0.9 to 1.6 in Upper Gugera (Vander Velde and Johnson, 1989), compared with at least 0.85 in FES, with only one watercourse in the FES area having a RWS of 0.77 (e.g., see Van Wayjen, 1996). However, it would be of considerable importance in areas with (periodically) high watertables.

SWAP93 was successfully calibrated/validated as demonstrated by the degree of conformity between predicted and measured salinity levels. However, the model does not take into account exchange reactions between the exchange complex and the soil solution, or the precipitation of ions. Salinity levels can, therefore, not be accurately predicted. Solute transport models should preferably be used together with a study of the geo-chemical processes, as was done when Condom (1996) carried out his model studies, which contributed greatly to the understanding of the underlying geo-chemical processes, .

Although the magnitude of the changes in profile salinity differ substantially in the various simulation attempts, the direction of the changes is beyond doubt. Current practices give rise to increased soil salinity and, perhaps of even greater importance, to the accumulation of sodium salts with its concurrent soil degradation. The simulations have pointed at the importance of RWS, and hence of leaching fractions, of soil types and depth of the watertable in the build-up of rootzone salinity. Also, the importance of uniform field applications of irrigation water on the rate of salt accumulation in the rootzone is clearly demonstrated. Furthermore, modelling indicates that groundwater withdrawal during kharif is probably 1½ to two times as much as during rabi.

II. SOIL DEGRADATION

The permeability of a soil column was first demonstrated in the 1950's as a function of both the exchangeable sodium content and the total electrolyte concentration (TEC) of the percolating solution. Basically, the higher the sodium concentration, expressed as the sodium adsorption ratio (SAR), and the lower the TEC of the percolating solution, the greater the reduction in hydraulic conductivity (HC). Quirk and Schofield (1955) proposed the concept of a 'threshold' concentration, which was defined as the concentration required to maintain soil permeability at an acceptable level relative to that measured with a strong salt solution for any particular value of SAR. Soils exhibit a behaviour that qualitatively corresponds with the threshold concept, but apparently each soil has its own unique threshold behaviour as other soil properties, such as clay content and mineralogy of the clay fraction, organic matter content and bulk density strongly influence the permeability of the soil.

Swelling and dispersion of clays have been proposed as the major mechanisms contributing to the reduction in HC as TEC is reduced. Particularly, clay dispersion is very sensitive to changes in exchangeable sodium percentage. It has been argued that in heavy textured soils, the swelling of clays is the main cause of the reduction in HC, whereas in the lighter textured soils, clay dispersion and movement predominate, resulting in the irreversible sealing of soil pores. When Na-affected soils are exposed to rainfall or irrigation water of low TEC, permeability is reduced because the ambient concentration in the soil solution is not sufficient to prevent swelling and clay dispersion. This is obviously occurring in irrigated soils in Pakistan, where groundwater and nearly pure canal water are used intermittently to irrigate the lands. Sumner (1993) has argued that parts of the clay fractions of soils which would not normally be considered to be sodic can be dispersed simply by the velocity of water of low TEC passing through the soil. He suggests that in sandy soils these colloids can be moved over great distances, but that they get trapped where the pores become narrow, blocking the pores and consequently reducing HC. Hence Sumner's view that soil physical properties of a particular soil are a continuous function of Na saturation and TEC (expressed as electrical conductivity of the soil solution, EC), and are moderated by clay mineralogy, texture and organic matter; thus, in fact, diminishing the importance of the threshold concept.

Recently, Condom (1996) has reviewed the geo-chemical reactions involved in salinisation, sodification (soil degradation associated with the presence of sodium ions in the soil solution), and alkalisation (soil degradation associated with the presence of anions, especially carbonates and bicarbonates), and identified the determinants in the accumulation of sodium salts and carbonates and bicarbonates (i.e., alkali salts) in the rootzone. A particularly important parameter is the residual alkalinity (RA), defined as the difference between the total anions, such as carbonate, bicarbonate, hydroxyl and sulphate ions, and the calcium and possibly magnesium ions in the soil solution. The concentration of these ions in solution depends on the solubility of certain calcium and magnesium containing minerals, which is in turn pH dependent. For most of the soils, alkalinity is mainly due to carbonate and bicarbonate ions. Between a pH of 6 and 10.3, the proportion of carbonates in the soil solution is negligible, which simplifies the concept of alkalinity in most soils to the presence of bicarbonate ions. Three parameters are used to describe RA, dependent on which minerals are considered. The first term, residual alkalinity on the basis of calcite (C-RA), is the difference between carbonate and bicarbonate ions and Ca. The second, residual alkalinity on the basis of calcite and sepiolite (RSC, or residual sodium carbonate) considers the presence of Ca and Mg. The third, RA on the basis of calcite, sepiolite and gypsum (CSG-RA), expresses RA as the difference between carbonate, bicarbonate and sulphate ions and Ca and Mg.

In brief, the main processes involved in salinisation are the following. If RA of the soil solution is negative, and many salts are present, the soil is saline. Due to precipitation of ions, and hence formation of minerals, the absolute amounts of Ca, Mg and of the bicarbonate ions will be reduced, but the concentrations of these ions in the soil solution will remain the same. If Na is present in large amounts, it may eventually predominate on the exchange complex, and sodification would occur. However, when RA is negative, sodification is a slow process.

When RA is positive, precipitation of Ca and Mg causes a fast drop in Ca and Mg concentration, and hence an increase in alkalinity. This is the process of alkalisation. When the soil solution becomes more concentrated due to evaporation and plant water uptake, Na is soon the predominant ion in the soil solution and through cation exchange also on the exchange complexes of the soil matrix. This is the process of sodification, which occurs rapidly when RA is positive. Once Na predominates on the exchange complex, the soil is sodic. This type of soil is unstable and becomes degraded: it loses its structure due to mechanical effects, such as the impact of rain drops and tillage, and the clay minerals disperse as a result of geo-chemical processes.

Condom (ibid.), using a number of field indicators, such as 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, recorded the occurrence of soil degradation in the FES sample areas. He reported two different types of soil degradation: the formation of surface crusts and the formation of hard layers in the profile. A surface crust is a superficial, thin and hard layer consisting of fine particles, which differs physically from the underlying layers. Two types were distinguished: those due to dis-aggregation of soil particles and those consisting of layers of fine particles that were deposited on the surface when covered by water ('deposited crust'). Black surface salinity (locally called 'kala kalar') was often found in fallow land, and is always found in the presence of a surface crust. Also, poor vegetative cover is probably associated with the presence of these crusts and hard layers. When samples from these crusts and hard layers were later analysed in the laboratory, it was found that they differed much in their chemistry. All three processes, salinisation, alkalisation and sodification, took place in the sample area, and the analysis of representative soil samples has helped to identify the minerals that play a role in the salinisation processes. The value of RSC, and particularly its sign, positive or negative, helps to distinguish the geo-chemical processes that are likely to occur.

Condom (1996) in his lucid paper has also shown that exchangeable sodium percentage (ESP, the degree to which the exchange complex of the soil is saturated with Na, an indicator that can be calculated from the sodium adsorption ratio, SAR) is also an important parameter in the characterisation of the degree of sodification. The threshold value of ESP above which sodium saturation becomes harmful was set in 1954 by the US Salinity Laboratory at 15%. More recently - as was mentioned above - several research studies have thrown doubt on the existence of a threshold value, and if there is one at all, recent studies put it at a much lower value, e.g., 5%. Condom (ibid.) found that some of the samples taken from crusted soils exhibited quite low ESP values, and lower than ESP's of samples taken from non-crusted soils. 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 categorised on the basis of ESP, as follows:

- soil with a ESP below 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 would certainly have surface crusts and hard layers
- soil with ESP above 12%: the soil shows serious signs of degradation.

Infiltration rates

Thus, the main causes of soil degradation are swelling and dispersion of clay particles, and 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, ibid.), the infiltration rate (IR) 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 IR were observed even at SAR values of 3 when the TCC was below 5 $mmol_c$/L (equals an EC of 0.5 dS/m). Oster and Schroer (1979) also demonstrated that irrigation, by alternating water with SAR_c = 19.9 with distilled water, resulted in very low IR values (0.3 mm/hr). These data indicate that alternating irrigation water and rain has a greater deleterious effect than irrigation waters containing some salts on its own. This was confirmed for the sample watercourses in Upper and Lower Gugera command areas for which it was reported that 40% of the hydraulic conductivity determinations, done with a Guelph permeameter, gave a zero reading. Also many of the infiltration tests carried out in cultivated fields with a double ring infiltrometer gave zero or very low infiltration rates.

Thus, it appears likely that also the infiltration rates of most of IIMI's sample soils in the eight watercourse command areas of the Fordwah/Eastern Sadiqia area are low. The soils are known to be low in organic matter content and the occurrence of surface crusts and hard layers is now well documented. This makes it difficult to know what the basic infiltration rate would be without the unfavourable balance of cations and the effect of low EC.

SSP measured infiltration rates

The Soil Survey of Pakistan in the report entitled "Detailed Soil Survey of Eight Watercourses in Chishtian and Hasilpur Tehsils" (1995) gives basic infiltration rates obtained with ring infiltrometers in 12 tests done in the command areas of FD14R, FD130R, AZ 20L, AZ 63L and AZ111L. The ECe and SAR values of the soil samples are also given. Several of the infiltration tests were carried out in highly saline-sodic sites: ECe of 45.2 and SAR of 100.2 (with an IR of 2.5 mm/hr), ECe of 25.4 and SAR of 58.8 (IR is 2.2 mm/hr), both in AZ111, and ECe of 44.5 and SAR of 253 (IR is 1.8 mm/hr), and ECe of 3.74 and SAR of 27.1 (IR is 9 mm/hr), both in AZ20. The first mentioned site was on barren land. The others were not marked as fallow or barren in the report, but the values appear to fall outside the common range for culturable land. IR values which are probably more representative for cultivated conditions ranged from 0.9 to 3 mm/hr. These values are 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. Not enough samples remain for a statistical analysis of the relation between infiltration rates and EC or SAR values of the soil samples. This is unfortunate, but probably SSoP has many field measured data of infiltration rates from which such relations could be determined.

Conclusions

From the present analysis, it appears obvious that the infiltration rates and the hydraulic conductivity of soils in the Fordwah/Eastern Sadiqia area, and for that matter elsewhere in the irrigated lands of Punjab, are adversely affected by the presence of sodium on the exchange complex and in the irrigation water. The extent to which the soils are affected, however, is difficult to establish on the basis of the limited available field observations of infiltration rate and hydraulic conductivity. The ratio of SAR over EC appears to play a major role in this respect. EC values can be approximated in the field (e.g., EM 38), but there doesn't seem to be an easily measurable proxy for the SAR value. For the determination of SAR one remains dependent on laboratory determinations.

However, considerable progress has been made in understanding the underlying geo-chemical processes and in identifying the key parameters of residual alkalinity (RSC) and exchangeable sodium (ESP). Using the crucial test of negative versus positive values of the RSC, and the ESP value of 4% will help to recognise the potential hazard of structural and chemical degradation of the irrigated soils in Pakistan. The usefulness of visual observation of soil degradation has also been established.

Further work needs to be done to confirm and quantify the expected relation between final infiltration rates and the SAR (or ESP) and EC values of the top soil, based on actual field determinations in the predominant soil types of the FES area. Until these additional studies have been carried out, quantitatively predicting the effect of using different quality irrigation waters on infiltration rates, and/or hydraulic conductivities in field situations is not possible. From a practical point of view, one would be interested in a method of prediction if it involves a few parameters that can easily be measured in the field. If predictions can only be made on the basis of a large number of parameters, for example including soil organic matter, free iron oxides, etc., its practical value would be small.

Perhaps, at present, more important than this quantification is the awareness that soil degradation is clearly associated with the use of tubewell water for irrigation. There are indications in some command areas, but not in others, that the quality of pumped groundwater tends to decrease towards the tail end of the systems. This simple spatial pattern is clearly disturbed when there are obvious areas of groundwater recharge elsewhere in the command area (e.g., because of close proximity to river bends, link canals or other main canals). The degree of the soil structural degradation due to salinity and sodicity should and can be established more precisely. The relation of soil structural degradation and relative water supplies, the fraction of irrigation water derived from tubewells and its quality, the cropping intensity and percentage of water-demanding crops, as they change in the command areas of distributaries, may throw some light on the determinants of water quality with respect to soil degradation. This knowledge would help in developing strategies for improving irrigation practices that may prevent or mitigate the current process of soil degradation.

III. THE EFFECTS OF SALINITY AND SODICITY ON CROPS

In general, three direct effects of salinity and sodicity on crops are identified. First of all, an increase of the osmotic potential, which means that plants have to make more effort to extract water from the rootzone. Secondly, certain specific ions (boron, chloride, 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).

Indirectly, 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 adverse effect of sodicity on crop yields was demonstrated in a study on the relationship between farmers' practices and cotton production (Pintus, 1995; Meerbach, 1996). A crop production function for cotton was developed on the basis of field observations for over 60 fields, which showed a high correlation between predicted and observed yields with an R^2 of 0.87. The function showed that an SAR in the upper layers of the soil that exceeds 8 reduces the yield of cotton. An SAR of 12, for instance would reduce the yield by 336 kg, which is more than 10% of the maximum yield obtained in the area. However, the crop production function that was developed for wheat, which also closely matched observed values, showed no such direct link between yield and sodicity. Apparently, the SAR levels that were observed in the field do not affect the wheat yield. Both for cotton and wheat no direct link could be proven between the EC_e and the yield.

IV. FARMERS' SALINITY MANAGEMENT

Farmers in the Indus Basin have a long experience in dealing with problems of salinity and sodicity. It is, therefore, surprising that not much literature is available on how farmers cope with salinity, as so many papers were written about salinity in the Indus

Basin. A first attempt of documenting farmers' practices related to salinity management revealed that farmers were using tubewells as a means 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 tubewell water, farmers often succeed in keeping the salinity of the irrigation water below an EC of 1.15 dS/m.

It was, however, only after IIMI had made further progress in understanding the farming systems in the Punjab that a more thorough study of the relationship between farm strategies and farmers' salinity management could be undertaken. Firstly, existing farmers' practices were documented, which revealed that farmers utilized about 30 practices to reduce or control salinity and sodicity levels, or to reduce the effect of salinity and sodicity on crop yields (Kielen, 1996a). These practices were formed on the one hand by the overall farm strategies of farmers and on the other hand by the understanding farmers have of the processes of salinization and sodification. A good comprehension of both was thus required in order to understand why farmers manage salinity the way they do, and to understand the constraints farmers face in dealing with salinity. Only then can appropriate interventions be formulated which effectively help farmers to cope with the adverse effects of irrigation. Interestingly, a complete analysis of farmers' salinity strategies was only possible once a thorough understanding of the farming systems was gained through economic studies (e.g. Rinaudo, 1994).

On the basis of the work of Kielen (1996b), the following salinity strategies were identified:

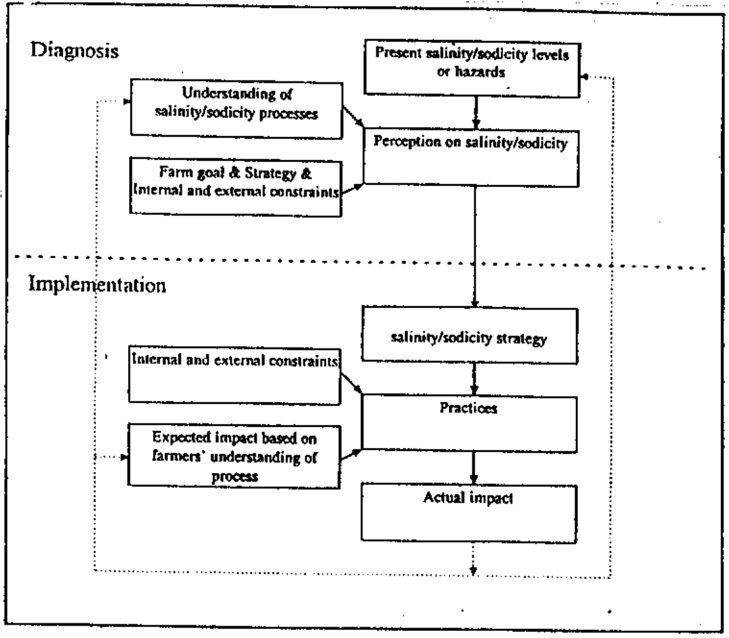
- mitigate the effects on crop yields;
- reduce/prevent salinity/sodicity; and
- no salinity strategy.

A large group of farmers is unable to reduce/prevent salinity and sodicity, because of financial constraints, being tenants or faced with extreme physical limitations, such as shallow groundwater tables or no access to good quality water. Even then farmers often try to lessen the effects of salinity and sodicity on crops, for instance, by increasing the frequency of irrigation to have a wetter soil profile. The practices that farmers adopt are generally low cost ones, such as selecting a better tubewell from which irrigation water is purchased and construction of furrows. Farmers with a better financial position and who are involved in an intensive, high investment type of farming, are generally more inclined to go one step further in attempting 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 practices of the previous group, these farmers also implement higher cost solutions, such as the application of gypsum.

Farmers who do not appear to have a clear salinity 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 a 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 and often serious financial problems, who 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.

In the description of the farm strategies, it was indicated already that farmers' understanding of salinity plays a role in defining their salinity strategy and thus in the practices they implement. It was, therefore, necessary to add to the research a study of farmers' perceptions to assess how farmers evaluate soil salinity and sodicity, what they think has caused the problems and how they expect the process of salinity and sodicity to evolve over time. In Figure 1, the decision-making process of farmers with respect to salinity and sodicity is represented to facilitate the analysis. An important feature of the figure is the *a posteriori* or empirical approach is followed by farmers. Based on their own or observed experiences of the impact of certain practices, farmers not only learn how to cope with salinity and sodicity, but also gain in understanding of the dynamics and causes of it. This helps them to better deal with salinity in the future.

Figure 1. Representation of the decision-making process of farmers in dealing with salinity and sodicity.



source: Kielen, 1996a

The first output of the research was a definition of the classification farmers use for soil salinity and sodicity (Kielen, 1996b). 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, i.e. reduced intake rate, surface crust or hard layers, and the effects on crop growth, e.g. germination problems. A vernacular terminology is used by farmers to define and classify these phenomena, (see Table 6).

Table 6. Farmers' soil salinity and sodicity classification.

Classes	Characteristics
chitta kalar	white (chitta) surface crust
kala kalar	black (kala) appearance with hard upper soil layer
zacht	hard layers in the profile
kalar shoor	white salts at the surface, extremely difficult to cultivate
sam	waterlogged soils

Interestingly, this classification does closely correspond with the criteria defined by USDA, where an EC_e of 4 dS/m and an ESP of 15 are assumed to distinguish between non-saline and saline, and non-sodic and sodic soils. At EC_e levels of 2.4 dS/m and higher, farmers already observe *chitta kalar* to occur, while *zacht* happens at SAR levels as low as 6. Also, the distinction between salinity and sodicity is not as straightforward as defined in the USDA classification. Sometimes, sodic and saline soils are grouped together by farmers in their classification, as they judge the effect of salinity and sodicity on soils and crops.

Causes identified by farmers for the present salinity and/or sodicity status relate mainly to the use of poor quality irrigation water, the presence of high water tables and to genetic salinity. The importance of the quality of irrigation water is expressed in the classification of irrigation water used by farmers. Generally, irrigation water is evaluated for its effect on soils and crops: the water of tubewell x causes *zacht* or a hard layer in the profile. The classification seems to be in line with the FAO classification of Ayers and Westcot (1989), which emphasizes the risk of reduced infiltration rates with waters of low salt concentration and a relatively high amount of sodium (expressed as an

SAR), although threshold values differ (Kielen, 1996b). According to farmers, tubewell water with an RSC greater than 0.8 and an EC greater than 0.8 dS/m causes hard layers in the soil. Observed sodification processes, which evolve over several cropping seasons, could well be explained if an alkalinity indicator (e.g. RSC) would be taken into account.

How farmers react to changes in water supply is more difficult to establish. We would like to know this as a hypothesis of IIMI's research in this area is that redistribution of good quality canal water would help those farmers who are most in need of measures to deal with salinity. A historical analysis was carried out to find some evidence of farmers reactions. Generally, a reduction in canal water supply leads to substitution of groundwater for canal water, as farmers try to maintain their cropping intensities and pattern. Farmers then observe rapid soil degradation (i.e. formation of soil crusts, hard layers and reduced intake rates) and try to deal with this through the practices described above. An increase in canal supplies, on the other hand, has been shown to lead to increases in cropped area, also by a reclamation of salinity/sodicity affected land, and a shifting to crops with higher water requirements, like rice. Especially those farmers presently unable to deal with salinity and especially sodicity through costly methods (e.g. the application of gypsum), are helped by increased canal water supplies.

V. DETERMINING THE SALINITY AND SODICITY STATUS OVER LARGER AREAS

In the Indus Basin, a relatively large number of surveys related to soils, salinity levels and groundwater tables have taken place. The most important ones are:

- the soil classification and mapping for the entire Indus Basin at the reconnaissance level by the Soil Survey of Pakistan;
- salinity and sodicity status, as well as groundwater tables, for the Indus Basin by the WAPDA Master Planning survey; and
- yearly visual observation of the salinity status by the Directorate of Land Reclamation.

The question of how the salinity and sodicity status in the Indus Basin can be monitored regularly, making use of the information that is already available, prompted IIMI to investigate ways to develop a methodology to do this. Basically, two different ideas were developed and implemented.

Firstly, new techniques involving satelite imagery have been tested around the world to detect salinity. This was applied to the Chishtian Sub-division, relating the vegetation and brightness indexes obtained from SPOT XS images to salinity levels observed in the field (Tabet, 1995). The classification that was developed allows us to distinguish between highly salinized areas, which are generally barren and subject to genetic salinity, and non-saline areas. Areas that are affected by relatively low levels of salinity are more difficult to identify. Research will continue to improve the results obtained through this method by using several images at different stages of crop development and by better relating visual observations of salinity, soil degradation and crop stand to soil analyses (Vidal et al., 1996).

Secondly, a better understanding of the processes that lead to salinity and/or sodicity by identifying the determinant parameters, such as the groundwater quality, soil type, depth to groundwater table, would enable the construction of a "smart" sampling frame making use of the already available information. This was tested in two studies that were undertaken in collaboration with the Soil Survey of Pakistan (SSP) and the Directorate of Land Reclamation (DLR), respectively.

The SSP-IIMI study had as an objective to assess the salinity and sodicity status, as well as the risk for further salinization/sodification, and the development of a methodology to assess this in the most efficient manner. SSP prepared a soils map for the entire Chishtian Sub-division on the basis of a field survey, which facilitated also a good understanding of the physiography of the area. A field survey also yielded the groundwater qualities used by farmers. This information was linked with depth to groundwater table data that was already available using a Geographic Information System (GIS).

Table 7. Information collected for the SSP-IIMI study on salinity and sodicity risks

Data	Source
soils	survey SSP
physiography	survey SSP
groundwater table depth	WAPDA-SMO
groundwater quality	survey IIMI

On the basis of the range of these parameters and their spatial distribution, a classification was made of 5 soil types, two physiographic units, three water qualities and two groundwater table depths, which formed the basis of the sampling frame. The results of the salinity and sodicity survey are awaited and will be reported on shortly in an SSP-IIMI publication.

The DLR-IIMI survey had as an objective to better relate visual salinity observations with laboratory analyses. A visual salinity survey was undertaken in 1996 for the entire Chishtian Sub-division based on the classification that is traditionally used by DLR. The spatial distribution of salinity was linked with groundwater table depth and quality data using a GIS in order to identify areas that urgently need additional fresh water resources in order to mitigate salinity (Asif et al., 1996). The comparison of visual observations with laboratory analyses and possibly satelite imagery remains still to be undertaken.

SUMMARY AND DISCUSSION

The results presented in this paper answer partly the questions that are implied by the definition of IIMI's principal research hypothesis. An important conclusion of the research is that a modified access to canal water can help farmers deal with salinity and sodicity. It was shown that the quantity, quality and frequency of irrigation have a pronounced impact on the processes of salinization and sodification. Also, it was demonstrated that soil degradation, such as the formation of surface crusts and hard layers, takes place at relatively low levels of sodicity, i.e. an ESP of 4%. Sodicity was shown to have an adverse effect on cotton yields in the present situation, while the research has not been able yet to do the same for other crops like wheat, sugarcane and rice.

This means that in the conjunctive use environment of the Indus Basin a redistribution of canal water, targeting the deliveries where they are required in quantities that are required, would not only lead to more degrees of freedom for farmers to prevent further soil degradation, but would enable them also to mitigate the effects of salts on crop production. Traditionally, extra supplies were allocated to farmers to reclaim areas affected by genetic salinity and sodicity, but the tremendous pressure on canal water has seriously undermined this practice. In the more than 1 million ha Bahawalpur irrigation zone, for instance, no supplies have been sanctioned for reclamation for the past three years.

The methodology that has been developed has allowed an evaluation of the short-term, as well as the long-term effect, of irrigation water qualities on soil salinity and sodicity for different soil types. The effect of the alkalinity (carbonates and bicarbonates, principally) of irrigation water, expressed as the RSC, as well as the concentration (EC) of the water on sodification was demonstrated. The experience of some researchers indicate that the use of gypsum in case of alkaline water is not sufficient to prevent soil degradation (Dr. Ghafoor, UAF, personal communication). Existing "safe" RSC limits of water quality seem to be rather high. If groundwater is not used in conjunction with canal water, the limit should be adjusted downwards to 0.

Sodification, as well as soil degradation, were also shown to occur within the time span of a few irrigations. The swiftness of these processes was confirmed by farmers, who were shown to be very ingenious in adopting farm practices to control salinity or to mitigate the effect of salinity and sodicity on crop yields. Studying these practices provides useful indications about the types of measures that work. A comparison of these practices over a larger area, where farmers are confronted with different soils, groundwater qualities, groundwater table depth and access to canal water, allows insights under which conditions these measures work. In addition to that, the importance of the different environmental constraints becomes evident, which is useful when defining large scale irrigation and drainage interventions. For all of these reasons, IIMI's research has focused on farmers' fields.

Studies of SSP and the University of Agriculture, Faisalabad emphasizing the spatial variability of status, causes and dynamics of salinity in the Indus Basin (Muhammad, 1975; Choudri et al., 1978), are confirmed by results of the studies reported in this paper. This implies that irrigation and drainage interventions addressing salinity will impact differently depending on the environmental parameters, such as the groundwater quality, soils and groundwater tables. In addition to that, farming systems research has provided evidence of the heterogeneity of farm and salinity strategies in the Punjab, explaining the fact that salinity strategies of farmers are not the same. Farmers will, therefore, react differently to changes in the physical environment, e.g. the provision of extra canal water. The research shows that especially those farmers facing large environmental constraints and having little resources will benefit from a redistribution of canal water.

The studies showed that it is possible to identify and map areas affected by genetic salinity, which are not cultivated, through remote sensing. Identifying cultivated salinity and sodicity affected areas is much more difficult, although research continues on the use of remote sensing for salinity monitoring. Perhaps, it is easier to determine the status and risk of salinity and sodicity by collecting information on those parameters that are causing salinization and sodification, such as the groundwater table depth, groundwater quality, canal water distribution and soils. Some of these parameters are regularly collected by agencies such as SMO. With some additional data and a tool to combine these different layers of information, this would perhaps suffice for monitoring salinity and sodicity. The development of such a monitoring protocol is currently being tested in a collaboration with SSP, using a geographical information system (GIS).

POLICY AND MANAGEMENT IMPLICATIONS

The objectives of an equitable canal water distribution and a productive and sustainable irrigated agriculture do not necessarily agree with eachother. A redistribution of canal water, providing it in the right quantities at the right locations, could much contribute to managing salinity and sodicity, but may be difficult to implement if no additional water is made available for the canal systems. However, given the clear evidence of the impact of canal water distribution on salinity and sodicity and on crop production, it seems time to clarify the targets of the irrigation agencies and exact their contribution to the campaign for a sustainable irrigated agriculture. This is all the more urgent since even their traditional contribution to this campaign, the sanctioning of reclamation supplies, is under serious threat.

In the light of this statement,we can identify a number of management implications for salinity and sodicity management:

1. Farmers at different locations in the Punjab are using a mix of irrigation water that contains too many salts, leading to salinization and sodification. Also, farmers in different parts of the Punjab have been shown to overpump the aquifer, leading to a drop in groundwater tables. If the government wants to maintain present cropping intensities at 130% and keep irrigated agriculture sustainable, new water resources should be made available through the construction of storage facilities. In the meantime, a redistribution of canal water can address the most urgent problems in the canal commands. The alternative can only be a further soil degradation or interventions that would target reducing cropping intensities, which has tremendous social implications.

2. The contribution of researchers to Pakistan's salinity management is not only the provision of answers to questions about the causes and remedies of salinity and sodicity, but also to provide tools that can be used by policy makers and line agencies as a basis for discussion. They can then formulate scenarios, e.g. the implementation of a drainage scheme or the reallocation of canal water, and assess the likely impact on salinity and sodicity, preceeding the field implementation. In this way, a sensitivity to the complexity of the issues and potential improvements can be more easily transferred to policy makers and line agencies alike.

3. Information sharing in the common cause of salinity management between agricultural, irrigation and water development government departments, will be crucial for a successful salinity control. On the one hand, salinity-prone areas can be commonly targeted, while on the other hand,the best alternative for salinity management can be selected. In order to avoid that this remains a recommendation, of which there have been many in the past, it is necessary to initiate concrete collaborative projects involving Irrigation and Agricultural Departments as well as WAPDA. The FESS project is probably an excellent location to try out this approach, provided a clear message is provided to the various agencies regarding the necessity of joining hands.

4. Presently, tools are available to determine the water and salt balances for canal command areas by making use of available information with different agencies (SMO, SSP) and adding a few layers of information. In this way,those irrigated areas that run a serious risk of salinization and especially sodification can be identified in order to determine the required quantities of canal water per canal command. In order to do this, agreement has to be reached between policy makers, line agencies and researchers on the configuration of the tool and the validity of the outcomes.

5. If extra water is made available, areas affected by genetic salinity can be reclaimed by farmers, provided the soil structure is not too dense. In the Chishtian Sub-division, they have reclaimed thousands of acres in this way. Whether or not this reclamation process can be sustained depends largely on the quantities of canal water available, as well as the amount of groundwater that can be safely used for irrigation. Standards of water quality have been evaluated for their effect on soil degradation and crop yield.

6. Farm and irrigation practices can contribute much to maintaining a good salt balance. Land levelling, frequency of irrigation, application of chemical amendments, green manuring and the production of salt tolerant crops and varieties are some of the options that have been shown to be successful both at research farms as well as on farmers' fields. An understanding of farmers' constraints and strategies, combined with the technical knowledge of how to deal with salinity, needs to be made explicit. In this way, management interventions can be targeted at the right level. The recommendation to use gypsum, for instance, is not useful for farmers, if they do not have access to it on the market, for which an intervention at a higher level would be required.

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USE OF GEOGRAPHICAL INFORMATION SYSTEMS TO DEVELOP RECLAMATION PROGRAMS TO MITIGATE SALINITY IN PAKISTAN: EXAMPLE FROM THE CHISHTIAN SUB-DIVISION[1]

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ABSTRACT

Salinity has always been an important issue for irrigation managers and policy makers in Pakistan. With 25 percent of the irrigated areas of the country currently affected by salinity, specific interventions are required to mitigate this problem. To provide extra canal water supplies to salinity affected areas is one of the possible interventions that is part of the mandate of the Directorate of Land Reclamation of the Punjab Irrigation & Power Department. The present paper focuses on the methodology currently used by the Directorate of Land Reclamation to develop reclamation programs. In the context of a collaboration between this Directorate and the International Irrigation Management Institute, several improvements are proposed to complement the traditional salinity survey undertaken by field staff of the Directorate of Land Reclamation. These improvements include the use of Geographical Information Systems for spatial analysis of salinity in a given canal command area, along with the integration of irrigation related information such as soil types, irrigation water supplies, ground water quality in this analysis. This spatially referenced information is also used to prioritize areas for reclamation. The improved methodology is tested in the command area of one secondary canal of the Fordwah Branch Canal Irrigation System, South-Punjab, Pakistan. The results presented illustrate the added-value of the use of Geographical Information Systems for the development of reclamation programs. The conclusion part of the paper discusses follow-up activities for the operationalization of the improved methodology.

INTRODUCTION

The International Irrigation Management Institute (IIMI) started research activities on the use of Remote Sensing (RS) and Geographical Information Systems (GIS) for irrigation management in 1992. Initially, efforts focused on the development of the GIS capability only, for mapping of secondary and primary information mainly in the Rechna Doab area where IIMI had some field sites, and also for spatial analysis of this information using simple models and GIS capabilities.

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[1] This paper is an extended version of the paper by Asif et al. (1996) presented at the 17th Asian Conference on Remote Sensing, Colombo, Sri Lanka, November 1996.

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This effort has been carried on with a comprehensive analysis of salinity issues in the Rechna Doab area (Gauhar et al., 1996). At the same time, new research activities have been developed in the Chishtian Sub-division and includes remote sensing activities using SPOT and Landsat satellite images. These activities are part of a research collaboration with Cemagref, a French research institute for agricultural and environmental engineering. The different research issues included in the research program implemented in the Chishtian Sub-division include:

(i) GIS for watercourse level management: the main objective is the understanding of water management activities (mainly allocation and distribution) within the watercourse command area and of their impact on irrigation system performance. The analysis includes the identification of factors that may influence irrigation system performance, such as farm characteristics, physical variables (water-table depth, soil type, etc) and also spatial variables such as distance from the head of watercourses or distance from tubewells.

(ii) GIS for the assessment of irrigation system performance: a spatial database has been developed for the whole command area of the Chishtian Sub-division. The GIS, complemented by statistical techniques, is used to analyse the spatial variability of physical characteristics, irrigation water supply and agricultural production.

(iii) RS for land use mapping and crop identification: satellite imagery offers a potential to assess performance in large irrigation systems. Initial efforts have targeted crop related parameters such as cropping intensity and cropping pattern. The research focus has recently shifted towards the development of appropriate methodologies to assess cropping intensity and cropping pattern at any level of the irrigation system and for a given accuracy.

(iv) RS for salinity monitoring: salinity information in Pakistan is scanty and rather old. For problems of implementation of appropriate surveys, the last large-scale salinity survey was undertaken in 1976-77. And the information collected in this survey is still used to allocate financial resources in the irrigation and drainage sector. The methodology developed has been able to identify highly saline areas. However, difficulties have been encountered in distinguishing different levels of salinity in cropped areas.

Initially, IIMI's efforts have focused on the development of a research and analytical capability. More recently, the development and strengthening of collaboration with Pakistan research and monitoring research institutes has become more important in the context of transfer of technologies and methods to local partners. Different degrees of collaboration have been developed: **(i)** sharing of information and preparation of maps with secondary data collected by the SCARP Monitoring Organization; **(ii)** assessment of the usefulness of the GIS for activities of the Directorate of Land Reclamation (DLR) of the Punjab Irrigation & Power Department, with DLR providing the field expertise and IIMI the GIS expertise; **(iii)** development of joint research activities for the assessment of salinity in a large irrigation system with the Soil Survey of Pakistan; and **(iv)** training and technical assistance in the use of GIS/RS provided to the Watercourse Monitoring and Evaluation Directorate (WMED) of WAPDA as part of the Fordwah Eastern Sadiqia (South) Irrigation and Drainage Project.

The present paper focuses on the collaboration with the Directorate of Land Reclamation. The main purpose is to illustrate the methodological part of this collaboration, that has been initiated in the Chishtian Sub-division in January 1996.

THE ROLE OF THE DIRECTORATE OF LAND RECLAMATION

The Directorate of Land Reclamation (DLR) of the Punjab Irrigation & Power Department was formed in 1945 to allocate extra canal water supplies for the reclamation of saline fields. The main activities undertaken by DLR include: **(i)** assessing the extent of salinity and waterlogging in canal command areas; **(ii)** planing, organizing and monitoring the allocation of extra canal water supplies (also called reclamation shoots) to salinity affected areas, in coordination with the operating staff of the Punjab Irrigation & Power Department; and, **(iii)** conducting research on soil and water related issues to identify (and test) options that would tackle waterlogging and salinity in an effective way (Directorate of Land Reclamation, 1996; Bandaragoda and Rehman, 1994). To undertake these tasks, DLR has field staff in almost all canal circles of the Punjab and staff in its head office in Lahore, along with appropriate laboratory facilities for soil and water testing.

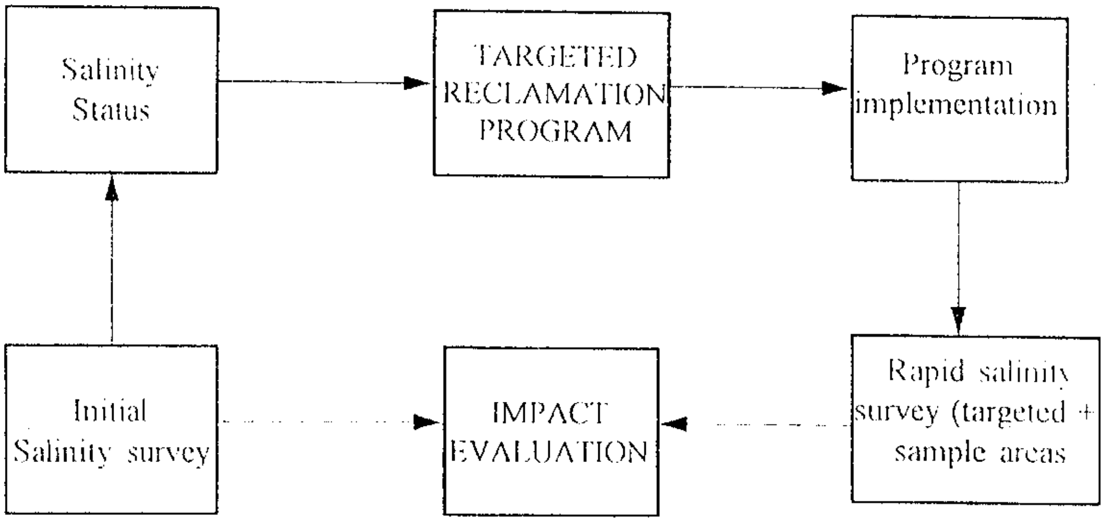
Salinity assessment is made through visual salinity surveys undertaken during the months of December, January and February when salinity is the most visible. Salinity information is collected at the level of the field or *killa* (basic administrative unit of the irrigation system with dimensions 67 m x 60 m) and classified according to specific classes as defined in Table 1.

Table 1. Salinity classes used by DLR in visual salinity surveys.

Salinity and land status	Salinity class (local name)	Characteristics of salinity class
Uncultivated and saline	*Thur Kohna*	Saline area that has never been cultivated since the advent of canal irrigation
Formerly cultivated and saline	*Thur Panjsala*	Saline area that has gone out of cultivation more than 5 years ago
	Thur Nau	Saline area that has gone out of cultivation within the past 5 years
Cultivated and saline	*Thur Juzvi*	Visually salinity affected area with more than 20 percent affected by salinity but still under cultivation
	Thur Tirk	Salinity not visible but affecting cotton crop (incomplete opening of bowls)

Based on the visual salinity information and also on rough estimations of water-table depth, DLR staff identify areas for which reclamation shoots are required and prepare reclamation programs that specify watercourses that will receive extra canal water supplies for reclamation. These programs are submitted to, and discussed with, concerned staff of the Punjab Irrigation & Power Department for finalization of the reclamation program. The implementation of these programs includes the installation of reclamation shoots (pipes) at the head of tertiary units for the high flow summer season only, when water is in excess in the rivers. Also, new allocation schedules for canal water within a given tertiary canal command (or warabandi schedules) are developed to account for extra supplies to saline areas. Soil samples are also taken by DLR staff for laboratory analysis. Results of the soil analysis are used to advise farmers about soil management and chemical amendments. These results will also be compared with results of soil analysis taken after 3 years of reclamation supplies for impact assessment (Directorate of Land Reclamation, 1996). The basic methodology followed by DLR is summarized in Figure 1.

Figure 1. Development of reclamation programs: the DLR approach.



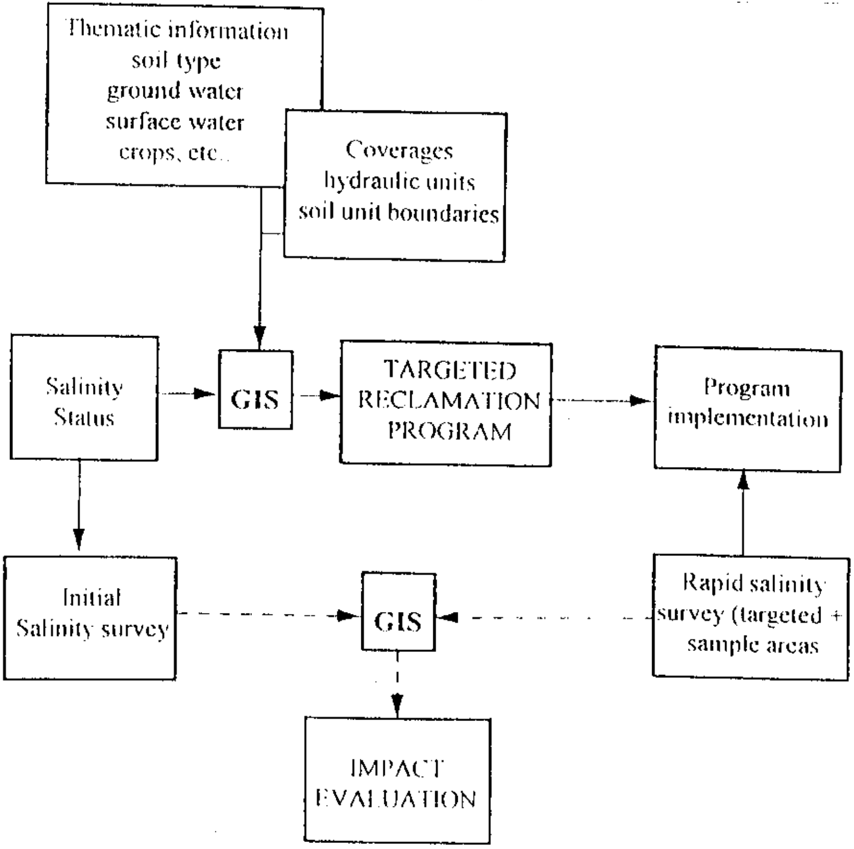
The method used by DLR to assess salinity and allocate extra canal water supplies to reclaim saline areas has been recently questioned on several grounds (see Bandaragoda and Rehman, 1992) including: **(i)** the lack of rigorousness of this (rapid) salinity assessment; **(ii)** the use of salinity information only without including other parameters such as soil type, ground water quality, canal water supplies, etc, that may explain current salinity status and influence the reclamation process; and, **(iii)** the focus on canal water supplies only to assess irrigation water availability for reclamation shoots, while suitable tubewell water may also be considered.

In the context of the development of new technologies for the monitoring and analysis of environmental variables, DLR is currently considering upgrading its capabilities for salinity assessment. New technologies of potential interest for DLR include the use of the EM38 to assess salinity levels, the use of satellite imagery for salinity monitoring, or the use of new computer hardware and software for analysis of salinity related information and development of reclamation programs. The present paper focuses on one specific effort undertaken jointly by DLR and IIMI, i.e. to test the potential for GIS to improve the development of reclamation programs in Pakistan.

OBJECTIVES AND METHODOLOGY

The main objective of the present paper is to present the results of the application of an improved methodology **to analyse the spatial distribution of salinity within the command area of irrigation systems, to identify factors that explain the current distribution of salinity, and to develop targeted reclamation programs to allocate (extra) canal water supplies to priority areas.** The proposed methodology relies on the capability of the GIS that has been developed in the present study using the ARC/INFO software. The different steps of the improved methodology are summarized in Figure 2.

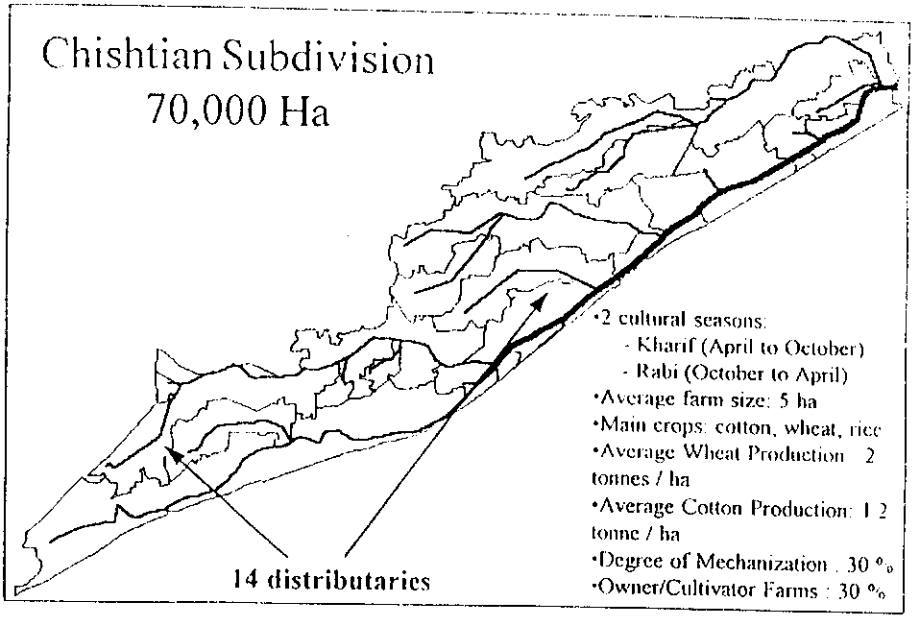
Figure 2. Using GIS for the development of reclamation programs.



The similarities between Figure 1 and Figure 2 should be noted. In order to reduce the potential difficulties while implementing proposed changes within DLR, the improved methodology builds on the existing steps currently undertaken by DLR to develop reclamation programs. The GIS is critical at two stages of the process for developing reclamation programs. First, the GIS is used to integrate supplementary information for the identification of areas for reclamation shots. To do this, specific coverages are digitized, and thematic information attached to these coverages. Second, the GIS provides an appropriate structure for the evaluation of the impact of reclamation programs after their implementation. Salinity information collected to assess the impact of the reclamation program can be easily stored into the spatially referenced database. And the GIS offers analytical capabilities for the identification of areas with reduced, unchanged or increased salinity levels.

The initial steps of the methodology (from visual salinity survey to the identification of priority areas for reclamation) have been tested in the Fordwah Distributary (secondary canal) command area of the Chishtian Sub-division, South-Punjab, Pakistan (see Map 1), where IIMI is implementing a comprehensive research program on irrigation system performance.

Map 1. The Chishtian Sub-division of the Fordwah Canal Irrigation System



The total command area of the Fordwah Distributary is equal to 16,000 hectares, with cotton, rice, sugarcane and fodder being the main crops cultivated during the kharif (summer) season, and wheat, sugarcane and fodder being the main crops cultivated during the rabi (winter) season. The design discharge at the head of the Fordwah Distributary is equal to 4.5 m^3/s, distributed to 113 tertiary units or watercourses. Canal water supplies are complemented by ground water pumped by more that 1,200 private tubewells. The information collected and used in the present study relate to the *kharif* (summer) 1995 and *rabi* (winter) 1995-96 seasons. This information is summarized in Table 2.

Table 2. Basic information stored in the GIS.

Information	Basic unit	Source*
Soils		
. Basic characteristics	. soil unit	SSOP
. Salinity	. killa or field	DLR
Ground water		
. Tubewell water quality	. sample tubewells (values averaged at the watercourse level)	IIMI
. Tubewell density	. watercourse command area	IIMI
. Water-table depth	. water-table class units	SMO
Surface water		
. canal water supply	. monthly canal water supply at the watercourse head (results of simulation with hydraulic model SIC**)	IIMI

* : DLR = Directorate of Land Reclamation, Punjab Irrigation & Power Department
SSOP = Soil Survey of Pakistan
IIMI = International Irrigation Management Institute
SMO = SCARP Monitoring Organization, Water & Power Development Authority

** : The hydraulic model SIC estimates daily canal water supplies at the watercourse head (the Jiwan Minor being considered as one unit) based on the daily discharge measured at the distributary head.

SALINITY ASSESSMENT IN THE FORDWAH DISTRIBUTARY

Salinity collected through a visual salinity survey at the killa level has been stored in the spatial database. The information is then available for any area of the Fordwah Distributary command area. As an example, Map 2 illustrates the spatial distribution of this information for one given watercourse of the Fordwah Distributary, the Fordwah 33-R Watercourse. This information has been extracted from the database, along with the corresponding watercourse coverage developed for the Fordwah Distributary. Overall, 30 percent of the watercourse is classified as uncommanded, 51 percent is classified as salt free and 19 percent is classified as *Thur Juzvi*. A rapid look at the information displayed highlights that salinity within the watercourse command area does not display a clear spatial distribution pattern[6].

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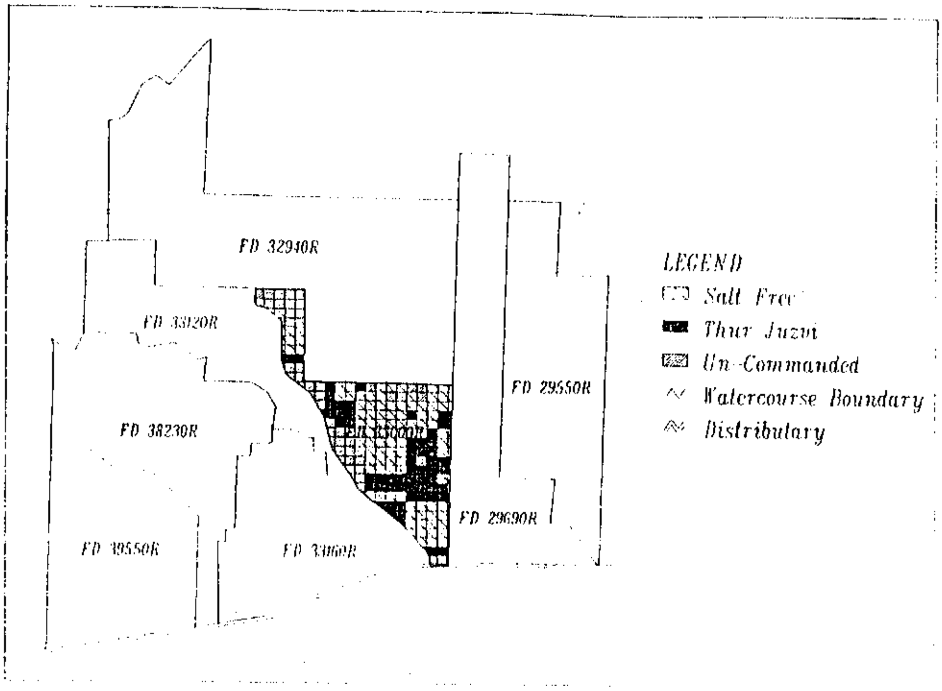
[6] For example, no clear trend can be observed from the head to the tail of the watercourse command area.

Map 2. Killa level salinity for the Fordwah 33-R Watercourse.



The information is then aggregated at the level of the square (one square is equivalent to 25 killas) for mapping at higher levels of the irrigation system. Map 3 presents the squares that are predominantly salt free in the Fordwah Distributary command area. Out of the total command area of this distributary, the percentages under different salinity classes are as follows: 1 percent under *Thur Kohna*; 0.1 percent under *Thur Panjsala*; 0 percent under *Thur Nau*; 9.1 percent under *Thur Juzvi*; and 0.1 percent under *Thur Tirk*. These figures show that salinity seems less problematic in the Fordwah Distributary command area as compared to other irrigated areas of the Punjab. It also shows that *Thur Juzvi* (i.e. visually salinity affected area with more than 20 percent affected by salinity but still under cultivation) is the most common form of salinity in the area. Map 3 also highlights that salt free areas are mainly located in the middle reach of the distributary and that salinity is mainly a problem for tail and head watercourses[7].

Using the boundaries of the watercourse command areas that have been digitized in the GIS, the percentage of salt free areas at the watercourse level is estimated and presented in Map 4. Totally, and as presented in Figure 3, 16 percent of the watercourses along the Fordwah Distributary have more than 50 percent of their command area affected by salinity (*Thur Juzvi*).

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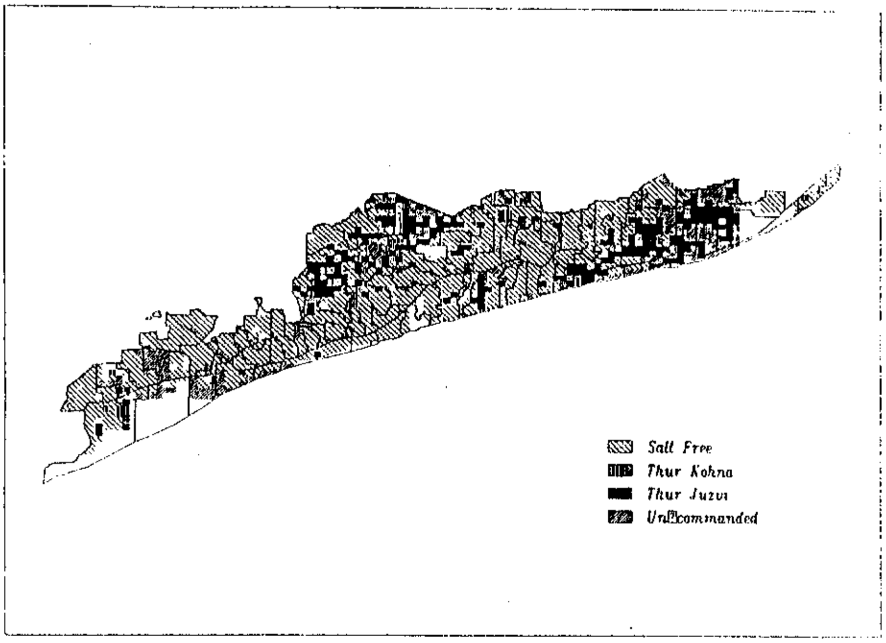
[7] Similarly to what has been said for salinity within the watercourse command area, this result stresses the complexity of the spatial distribution of salinity within the irrigation system that cannot be simplified by a simple head-tail trend.

Map 3. Predominantly salt free area at the square level for the Fordwah Distributary command area.



Map 4. Importance of salt free area at the watercourse level along the Fordwah Distributary.

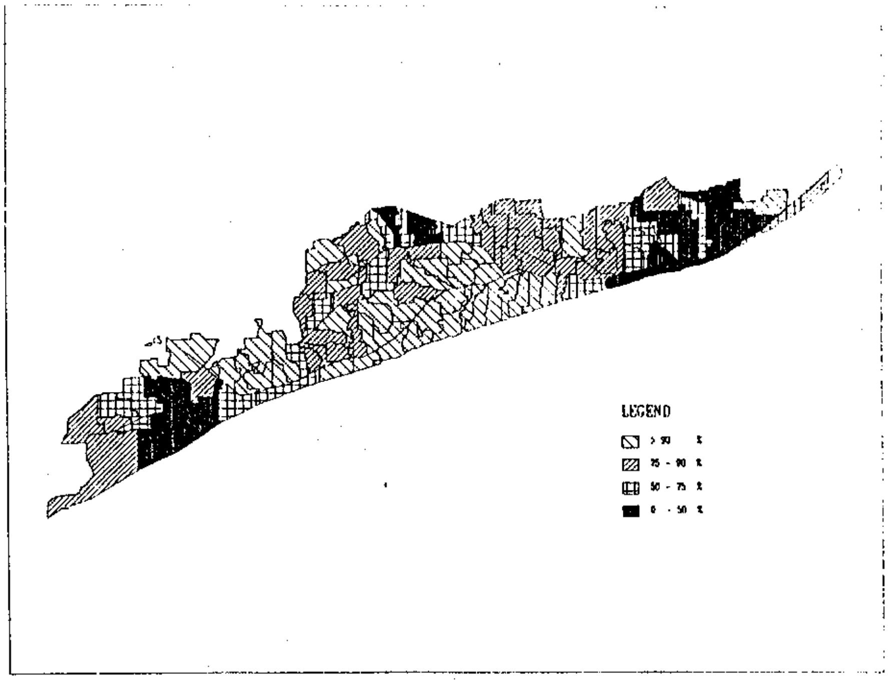
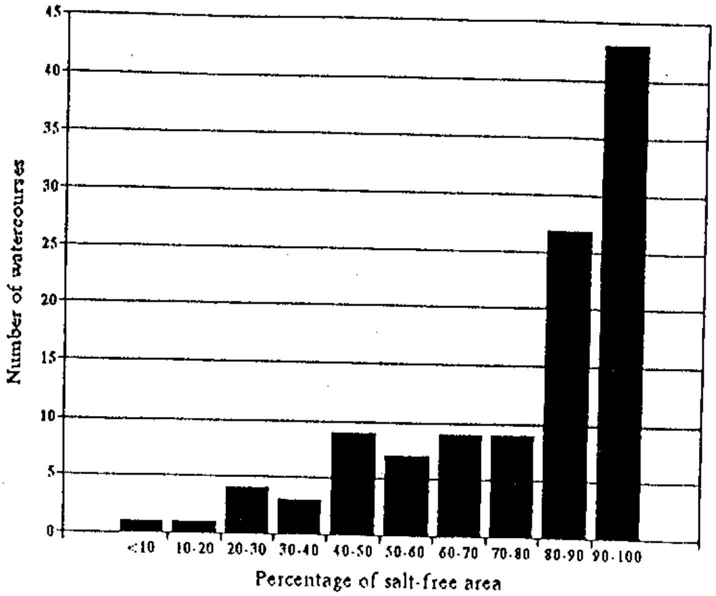


Figure 3. Frequency distribution of watercourses per class of percentage of salt free area for the Fordwah Distributary.



As specified in Table 2, the following irrigation related information has been collected and stored in the spatial database: (i) soil characteristics (physiography and texture classes) and visual salinity; (ii) tubewell density (number of tubewells divided by total command area) at the watercourse level; (iii) quality of ground water pumped by private tubewells (in terms of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC)); (iv) water-table depth; and, (v) canal water supplies at the watercourse head (expressed by the Delivery Performance Ratio (DPR) of the actual discharge over the design discharge). Watercourse level values are computed for each set of information and stored in the database for further statistical analysis to identify factors that may explain current salinity levels within the Fordwah Distributary command area.

Regression analysis shows that salinity is significantly related to canal water supplies (lower percentage of salinity for watercourses with higher canal water supplies) and soil texture (lower salinity for sandy soils). However, factors such as groundwater quality, soil physiography and water-table depth do not show any significant relationship with the percentage of area under different salinity classes. Overall, the coefficient of correlation R^2 remains very low (around 0.1)[8].

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[8] The very low R^2 may be explained by the limited number of variables used for the analysis, or the level of analysis considered (i.e. the watercourse command area). However, the very low level of salinity in the area is probably the main problem that makes it difficult to identify the factors that explain salinity levels. Further analysis is currently underway to better understand the factors explaining salinity levels.

USING GIS TO PRIORITIZE AREAS FOR RECLAMATION

Using the salt free area as a decision variable and 50 percent as a threshold value (i.e. watercourses with a salt free area of less than 50 percent are selected for the reclamation program), it is possible to identify watercourses for reclamation purposes and allocation of extra canal water supplies by the Punjab Irrigation & Power Department. Using the GIS, 19 watercourses are selected for the reclamation program. As already specified above and presented in Map 4, these watercourses are mainly located along the upper reach and lower reach of the Fordwah Distributary.

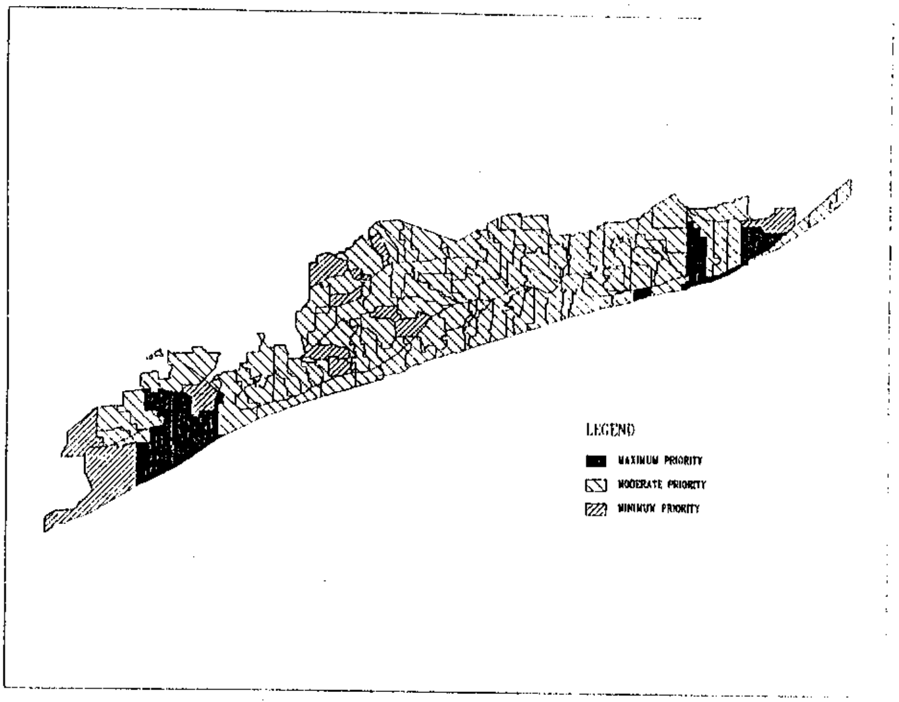
In a context of increasing water scarcity, however, it may be difficult for the Punjab Irrigation & Power Department to allocate extra canal water supplies to all of the watercourses identified. Thus, priorities are to be made between these 19 watercourses. In order to reduce the number of watercourses for reclamation, supplementary information stored in the spatial database is included in the selection process. The selection process is illustrated using canal water supply information, ground water quality information and a set of selection rules as summarized in Table 3.

Table 3. Criteria for the selection of watercourses for a targeted reclamation program.

Priority	Criteria Used
Maximum Priority	**Case I** - Groundwater Quality: EC > 1.45 or SAR > 10 or RSC > 1.25 and - Simulated vs Design Discharge < 100% - Non-Saline Area <= 50% **Case II** - Groundwater Quality: EC > 1.45 and SAR > 10 and RSC > 1.25 and - Non-Saline Area <= 50%
Moderate Priority	All cases other than Max. and Min. Priority
Minimum Priority	**Case I** - Groundwater Quality EC < 1.45 and SAR < 6 and RSC < 0 and - Non-Saline Area > 50% **Case II** - Simulated vs Design Discharge >= 100 - Non-Saline Area > 50%

Applying these rules within the structure of the GIS, priority areas for reclamation are identified and presented in Map 5. Totally, 9 watercourses have been selected for reclamation. The comparison between the watercourses selected using the salinity threshold criteria only (Map 4) and watercourses selected using the criteria presented in Table 3 highlights that watercourses excluded from the initial reclamation program are located in the middle reach of the Fordwah Distributary.

Map 5. Identification of watercourses for reclamation using salinity, canal water supply, and ground water quality information for Fordwah Distributary.



DISCUSSION AND CONCLUSIONS

The main purpose of the paper is to illustrate the potential of GIS for the development of targeted reclamation programs in irrigation systems in Pakistan. The GIS provides a proper structure for the storage of spatially referenced data. This facilitates the computation of watercourse level indicators using information that has been collected at different scales of the irrigation system (at the killa level, for example). It also provides an appropriate way to incorporate variables other than salinity for the identification of target areas for reclamation shoots.

The analysis presented so far uses the watercourse as the basic level of analysis. For watercourses that have been selected for the reclamation program, more detailed analysis is possible using the GIS, as salinity is available at the level of the killa and spatially referenced in the GIS database.

The analysis of salinity information within the command area of a given watercourse can retain the killa as the basic unit of analysis. However, for the analysis of larger areas, such as the command area of a distributary, limits in hardware and software[9] are rapidly reached for the manipulation of a large killa database (more than 400,000 cells required to store information for the 40,000 killas of the Fordwah Distributary!).

The maps obtained with the GIS provide a good support for discussion and communication with irrigation managers that will implement the reclamation program. When canal water supplies are limited, the GIS provides an effective way to rapidly identify watercourses with higher priority. Maps presenting the information at the killa level for specific watercourses will also facilitate discussions between DLR staff and farmers for the development of modified warabandi schedules that take into account reclamation requirements.

The database created in the GIS provides an appropriate structure for the collection of information at the end of the reclamation program (usually three years of extra canal water supplies are allocated to targeted watercourses). Information collected at the end of the reclamation program will be entered in the database and analyzed spatially using the GIS. The comparison between salinity survey information *before* and *after* the reclamation program will be undertaken to identify areas that have been successfully reclaimed. Special attention will be given to areas that may have recorded an increase in salinity as this may lead to the identification of factors that influence salinity but have not been included into the initial analysis.

The results presented in this paper have been obtained in the context of a collaboration between DLR and IIMI. The next step will be the development of a targeted reclamation program for the Chishtian Sub-division as a whole (total 67,000 hectares) with refinement of the criteria selected for defining priority areas and discussion of the methodology and results with operating staff from the Punjab Irrigation & Power Department.

The analysis presented in this paper proposes simple changes in the methodology currently applied by the DLR, in order to facilitate the potential implementation of these changes. At present, and although proposed changes in the methodology for identifying areas for reclamation are rather modest, the operational use of the methodology by DLR staff will already require significant changes. DLR does not have the appropriate software and hardware capability to

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[9] The PC ARC/INFO software that has been used in the present study can not manage more than 100,000 features in one coverage. Two options are available to bypass this limit: whether slicing the irrigation system into sub-systems with sizes more compatible with the limitations of the software, or to aggregate the salinity information at the level of the square (or higher levels of the irrigation system).

undertake such an analysis. Also, trained staff will be required for using these hardware and software[10]. And surveys undertaken by DLR would need to be amended to include other irrigation related information (or to collect secondary information available with other government agencies). A proper evaluation of the usefulness of the GIS will be undertaken at the end of the study in the Chishtian Sub-division to assess whether DLR should embark on the implementation of these changes.

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[10] One DLR officer has recently been trained in the use of the PC ARC/INFO software.

THE APPLICATION OF AN INTEGRATED APPROACH TO ASSESS THE IMPACT OF CHANGES IN IRRIGATION MANAGEMENT ON SALINITY, SODICITY AND AGRICULTURAL PRODUCTION: PRELIMINARY RESULTS

Pierre Strosser, Marcel Kuper, Zaigham Habib, Khalid Riaz and Gaylord V. Skogerboe[1]

ABSTRACT

The paper presents an integrated approach currently developed by the International Irrigation Management Institute (IIMI) in Pakistan in collaboration with the French research institute Cemagref to assess the impact of interventions in irrigation management on salinity and agricultural production. Issues of irrigation, salinity and agricultural productivity are interrelated, but are often analyzed thematically and managed separately. The rationale behind IIMI's study on integrating research results and methodologies is that the functioning of irrigated agriculture is more that the sum of these three issues and that links between issues need to be determined. The approach includes an analysis of the spatial variability of important parameters within the irrigation system that is expected to influence the links between water, salinity and production. Also, a platform or tool that integrates hydraulic, economic and solute transport models with a spatial database is developed in order to estimate the impact of interventions on water deliveries, farmers' decisions regarding crop choices and groundwater use, and salinity and crop production. The results of the simulation are not accurate predictions because of known inaccuracies of models and the complexity of interactions between human behaviour and bio-physical processes. However, the results are required for the different actors involved in irrigated agriculture, as they answer what-if questions and facilitate decision making. The integrated approach is presently applied in the Chishtian Sub-division of the Fordwah/Eastern Sadiqia Irrigation System and preliminary results and conclusions are presented in this paper. IIMI's experience in the application of an integrated approach in the Chishtian Sub-division needs to be captured in implementable recommendations, since integration of research issues is also part of the current Fordwah/Eastern Sadiqia (South) (FESS) Irrigation and Drainage Project. In this project, the Government of Pakistan has proposed to look at issues of irrigation, drainage and salinity in an integrated manner, where 13 research and monitoring organizations are investigating the feasibility of measures to alleviate salinity problems and increase agricultural productivity. The final conclusions of the application of an integrated approach in the Chishtian Sub-division will be presented at a workshop in the framework of the FESS Irrigation and Drainage project in 1997.

INTRODUCTION

Two important phenomena that affect policy planning and interventions in the irrigation sector are currently taking place simultaneously in Pakistan. The first phenomenon relates to water resources themselves. The last 20 years have recorded a drastic increase in the pressure on water resources, as illustrated by the increased population, changes in cropping intensities and cropping pattern, and mining of groundwater of good quality in many canal command areas (NESPAK, 1991; Ullah, personal communication). And although the demand for water from the other sector

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of the economy is still rather low in terms of percentages of the total water used (World Bank, 1994), the demand from these sectors is expected to increase and to add to existing pressures on water resources, especially for good quality water.

The second phenomenon relates to macro-economic policies and the economic development of the country. Financial resources are becoming scarce in the context of structural adjustment and service of the external debt. Also, and although the agricultural sector is still of first importance for Pakistan (in terms of employment or exports for example), the competition from the other sectors of the economy has also increased for the allocation of scarce financial resources.

Irrigation sector policies in 1996 are to be seen in the context of these two issues. On one side, there is a need to allocate water resources in the most productive and sustainable way. On the other side, it is important to identify the "best" and more cost-effective options to achieve objectives. For long, to increase the supply of water available at the farm gate has been the favoured option (whether at the source with the construction of dams, or within the irrigation system by reducing losses or tapping groundwater resources). But these options have proven to be costly (and increasingly costly) and may not be possible (or even appropriate) anymore. Also, there is an increasing need to manage not only the supply of water but also the demand for water.

Several interventions are currently proposed and discussed in various fora to tackle performance and sustainability issues in the irrigation sector in Pakistan. These interventions range from technical interventions (for example, construction of sub-surface drainage system, or lining of secondary canals) to institutional interventions (for example, strengthening a given government department, or increasing farmers' participation in irrigation management). More and more often, projects combine both technical and institutional aspects.[2]

In the general context of increasing scarcity of water and financial resources, it is important to compare the options proposed and understand their potential impact before starting any implementation. In fact, impact is to be looked at not only in its narrow definition of productivity and sustainability, but also in terms of equity or any other objectives seen as relevant by the different actors involved in irrigation management. Also, social acceptability and administrative feasibility of projects are to be assessed. It is clear that a large number of objectives cannot be satisfied at the same time, and that policy decisions are to deal with trade-offs between objectives to select among different interventions.

To make proper decisions, policy makers need information on the different options considered along with their expected impact on distinct performance indicators. At present, there is a lack

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[2] The combination between these aspects is specified in most of the project feasibility and appraisal reports. However, it is not clear whether institutional components are mainly included in project proposals to increase their chances of funding and meet requirements from donor agencies. Failures in the implementation of institutional components in past projects or programs raise the issue of the implementability of most of the proposed institutional changes.

of such information in Pakistan, and also no clear responsibility of any actor to systematically provide this information[3]. The Indus Basin Model (and its revised version) is one of the rare examples of the development of an approach (in this case a computer model) to assess the impact of interventions at the Indus Basin Level on water balance and agricultural production at the canal command area. However, the model has been rarely used, and mainly for specific studies or one-time planning efforts (see for example, the Water Sector Investment Plan, WAPDA, 1990), but does not provide information in a systematic manner as part of a well-established planning process.

Although the political interference within the policy decision process is acknowledged, there is a need for more (accurate) information on the present situation (what is the performance of the system todate) and also information on the expected impact of proposed interventions. The second point requires proper approaches and methodologies, and maybe also a different and less compartmental way to look at irrigation system management. Methodologies to assess the impact of different options and projects is required, keeping in view the complexity of the irrigation system, but also the diversity of objectives that are found among actors involved in the management of this system. Different options are to be analyzed and compared to obtain a better understanding of trade-offs between proposed interventions. And a common framework or platform is required to analyze and discuss interventions.

STATEMENT OF THE PROBLEM

The main issue relates to the requirements for developing and implementing such a common platform or approach that would help in investigating innovations for irrigation system management and assess their expected impact on the performance of the system. The objectives of such an approach, the potential users of the approach (or of the information obtained from this approach), and its practicality and operationalization are important questions that need to be addressed.

The objective of such an approach is to be able to take into account part of the complexity of the irrigation system to assess existing problems, to identify options for change that would solve these problems, to estimate the impact of these options on key indicators, and to prepare information to be used for taking decisions about development and implementation of these options in a real world. Such an approach does not necessarily imply an accurate predictive capability (although this accuracy may be required and obtained in some cases). However, the approach provides a platform for discussion between different actors and people coming from different disciplines.

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[3] Often, the initial justification of individual projects is done by consulting firms that are hired to prepare feasibility reports. However, estimates of project impact are often very crude. Also, the link between the different components of irrigation systems is rarely analyzed, partly because of the lack of information, but mainly because of the lack of a systematic and proper approach.

Part of the appraisal procedure of such an approach focuses on its potential users as it has important repercussions for the development of the approach itself. For whom do we try to obtain more information on issues in irrigation system managements? Which actor is interested by gaining a better understanding of the impact of interventions in irrigation management on irrigation system performance? And for which purpose? The information obtained may be used by policy makers for designing new policies for the irrigation sector, irrigation managers to implement and evaluate interventions, farmers to lobby for specific government interventions, etc. Obviously, the methodology developed cannot satisfy all the demands of these actors in terms of the aspects of irrigation management that are important for each actor, in terms of the information required to address a large range of complex issues, or for the selection of performance indicators to assess the impact of specific interventions.

Some of the difficulties in developing a common platform relates to the complexity of irrigation systems themselves. To analyze this complexity, the assessment procedure to identify requirements for the approach is required at early stages. To look at complexity does not necessarily imply studying each and every part of the irrigation system in great detail. Rather, it means investigating the irrigation system as a whole, and understand it in terms of:

(i) its general **structure**: by structure, we do not restrain to the hydraulic network as defined by hydraulic engineers, but the individual decisional and bio-physical processes taking place within the irrigation system. Examples of these processes are summarized in Apppendix I.

(ii) the **actors** involved in decisional processes: who takes a decision, for which objective, within which **time** frame, and at which **(spatial)** level of the irrigation system (field, watercourse, village, etc).[4]

(iii) the **links** between the different processes identified (direct link, feedback loop, etc). The higher the number of links between processes and actors, the higher the complexity of the irrigation system considered.

For each process or component, specific information may be collected. Also models with different levels of complexity[5] can be developed to understand processes and changes in the output of processes as a result of modifications in key variables. However, priorities are to be established and the most important processes only are to be selected for further investigation. This choice is based on: (i) the analysis of the main issues existing in the system considered; (ii) the potential users of the information to be provided (objectives, tasks performed, process

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[4] This information is also required to discuss interventions and identify implementation plans with higher chances of success.

[5] From complex simulation models that describe processes to more simple statistical relationships that do not investigate the process *per se* but establish a relationship between input and output of the process (Black Box approach).

considered, information required, indicators used, etc); and also, (iii) the time available and skills of people involved in the development of such a platform or approach.

Although there is a clear agreement on the need to obtain better information on different processes, on their output and on potential impact of irrigation management scenarios, little effort has been made in the direction of developing and implementing such an approach in the context of Pakistan. In fact, and along with a better assessment of potential users and information requirements, the questions: what to do and how to do it, are still to be answered. Also, the related question: who will/can/must do it is to be answered. For the International Irrigation Management Institute (IIMI) in Pakistan, researchers and research institutes have an important role to play in developing such approaches and providing information to support decisions taken by policy makers and agencies. However, this may require changes in the existing links between researchers and potential users of information[6], and also the development of a different attitude for improved integration of research activities between disciplines.

In early 1996, IIMI started working on the development of an approach/methodology to assess the impact of interventions on irrigation system performance. Based on the main constraints for irrigated agriculture in the Indus Basin Irrigation System, and also in line with the current objectives defined by policy makers and donor agencies for irrigation sector policies (i.e. productivity and sustainability), the main issues investigated in this approach focus on the link between water, agricultural production and environmental variables such as salinity and sodicity.

The main objectives of IIMI's research is to develop an approach (see next two sections for a description of the main elements of the approach developed by IIMI), to apply it in one irrigation system, and then evaluate the approach and results obtained from the scientific and practical points of view. An important element of the evaluation will also be the usefulness for potential users of the information obtained as a result of this approach. Research activities have been undertaken in the Chishtian Sub-division of the Fordwah Branch Irrigation system, South-Punjab, an area where IIMI has been working for the last 5 years in the context of the project *Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan* funded by the Government of The Netherlands. The main characteristics of the Chishtian Sub-division are summarized in Map 1.

Most of the research activities that have provided some input into the development of this approach have been undertaken separately in the context of specific (but inter-related) research components involving collaboration with various line agencies and research institutes (for example, the collaboration with the Punjab Irrigation & Power Department on Decision Support Systems, or the collaboration with Soil Survey of Pakistan for the assessment of salinity hazards in the Chishtian Sub-division).

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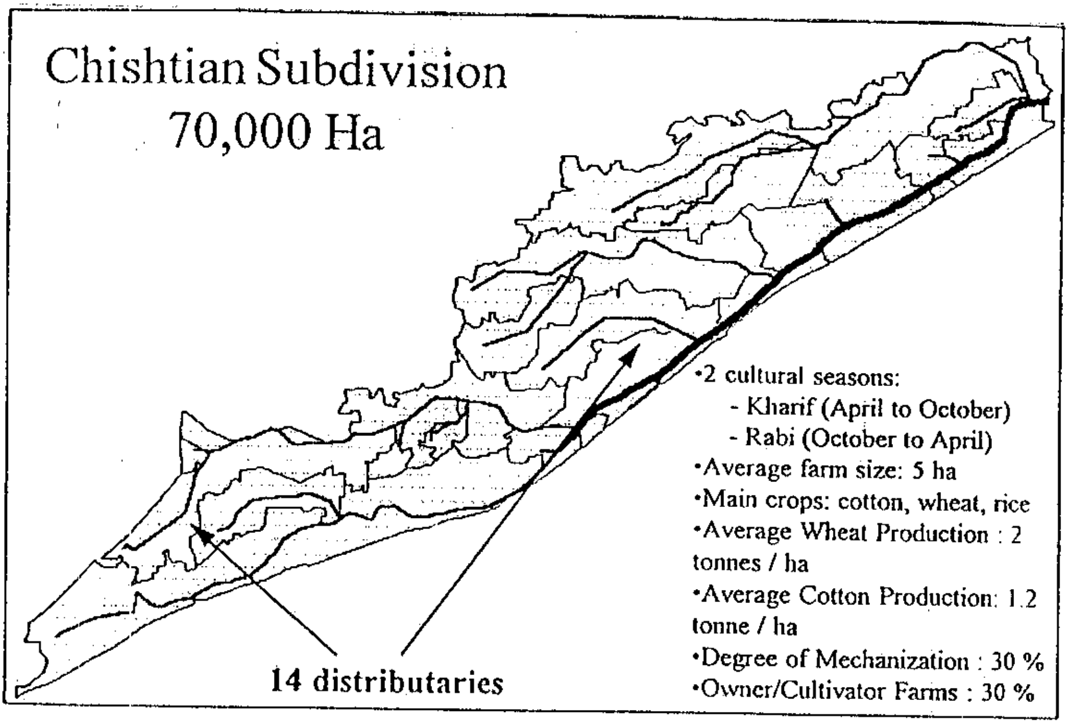
[6] Too often, researchers work in isolation from potential users of their results. Also, little extension effort is made to disseminate research results to these potential users or clients (whether farmers, irrigation managers, policy makers or other researchers).

Integration has taken place at the planning stage. But it is only recently that integration in itself has become an effective component of research activities with researchers from different disciplines being involved jointly in the assessment of irrigation performance in the Chishtian Sub-division and the development of links between different research results.

Map 1. Main features of the Chishtian Sub-division.



THEMATIC STUDIES: BASIS OF THE INTEGRATED APPROACH DEVELOPED

As specified in the previous section, initial research efforts have focused on the understanding of individual processes. The main issues analyzed relate to water, agricultural production and salinity and sodicity[7]. The following paragraphs summarizes the three main thematic studies that have been developed in the Chishtian Sub-division, i.e. hydraulics, economics and environmental studies.

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[7] As there is no waterlogging in the area under study, no specific research component has been developed to investigate groundwater related issues. However, groundwater characteristics are considered when analyzing salinity (groundwater quality), agricultural production and farmer's decisions (access to tubewells and total tubewell operation).

Hydraulics

The main objective of the hydraulic component is the monitoring and evaluation of current canal operations, and the identification of potential improvements in collaboration with irrigation managers. The assessment of the current water supply performance is undertaken using information collected by the Irrigation Department and IIMI staff through regular monitoring of water flows at given points within the canal network in the context of the Irrigation Management Information System (IMIS) program.

Also, simulation tools have been developed to assess the impact of maintenance and operation on water supply performance. In this context, the hydraulic model Simulation of Irrigation Canals (SIC) developed by Cemagref has been applied at the Fordwah Branch level (main focus on operational rules, see Litrico (1995)) and at the Fordwah distributary level (main focus on maintenance activities, see Hart (1996)). More recently, efforts have been made to develop simplified methodologies to calibrate and use the SIC model with still a good accuracy of simulation results. The methodology has been developed and tested in two distributaries (Visser, 1996).

Economics

The economic component developed for the Chishtian Sub-division in the context of the collaboration with Cemagref focuses on the analysis of the impact of changes in water supply on farmer's decisions and agricultural production. Two levels of analysis have been investigated so far (see Strosser and Riaz, 1996).

The first level of analysis relates to farm level decisions. Studies have focused on the analysis of the impact of canal water supply adequacy and variability on cropping pattern and gross income. Linear Programming (LP) economic models are developed for individual farms, calibrated and validated, and run to assess the impact of water supply scenarios (Rinaudo, 1994). Indications of tubewell water use (influenced by tubewell pumpage costs and purchase price) are also obtained from the LP models. The economic models will be used to assess the impact of water market development and water pricing on agricultural production and productivity.

The second level of analysis focuses at the field level processes, looking at the impact of irrigation water use and other inputs on crop yields. This analysis has been undertaken for the two major crops grown in the Chishtian Sub-division, namely cotton and wheat (Pintus, 1995; Meerbach, 1996). The methodology developed investigates a mix of agronomic and economic aspects. Water use is looked at from two different perspectives: adequacy and timeliness. And production functions are developed for the two crops. These production functions are used to better understand farm practices and the potential for yield increases due to changes in irrigation water supply for different types of farms. Also, the production functions are used to compute water related parameters in the LP models.

Environment

Important environmental issues in the Chishtian Sub-division relate to the development of salinity and sodicity as a result of current irrigation practices (whether at the main system or farm level). As explained above, with water-table depths lower than 10 feet in most of the command area, no specific study has been developed to analyze groundwater issues. However, the quality of groundwater is an important variable that has been included in the analysis of salinity and sodicity.

Research studies have focused on salinity assessment within the Chishtian Sub-division (using for example, satellite imagery as summarized in Tabet (1995)), farmers' practices to mitigate salinity and sodicity (Kielen, 1996), and the dynamics of the processes analyzed and identification of factors that influence salinization and soil degradation. In this context, a solute-transport model, SWAP93, developed by the Wageningen Agricultural University, has been calibrated and validated (Smets, 1996). More recently, geo-chemical aspects have also been included in the context of the application of an hydro-geochemical model to local conditions (Condom, 1996).

Can the above mentioned issues be addressed with these three thematic studies?

It is clear that the analysis undertaken under each thematic study has provided a large amount of information and a good understanding of the main factors that constraint irrigation system performance in the Chishtian Sub-division. The point made here is that putting together this information, or summarizing research results in a common report, is not sufficient to properly understand for the whole Chishtian Sub-division the impact of changes in irrigation management on irrigation system performance in terms of water, agricultural production and salinity/sodicity. Also, simple links between the different optimization and simulation tools will not provide the appropriate information. Several reasons listed below explain why there is a need to undertake something different, rather than just putting results and models together.

First, the independent analysis of the different processes undertaken so far has not included the links between the different variables and processes analyzed. The same variable may be input in one process, parameter in a second process, and output in a third process. The complexity of the system analyzed requires a proper development and understanding of links between processes.

The second major weakness of the individual studies is their level of focus. The field level for the analysis of the impact of water supply on salinity; the farm level for the analysis of the link between canal water supply and cropping pattern; the watercourse level for investigating water allocation and distribution between farms, etc. Processes that take place at different levels of the irrigation system cannot be simply "put" together as such for integration of research results.

The third major weakness is the lack of understanding of the variability of factors that influence processes and their outcome. Soil and farm characteristics are highly heterogeneous within the

Chishtian Sub-division. And this variability is expected to have a significant influence on the analysis of the impact of water supply on salinity and agricultural production. Similarly, access to water resources within the Chishtian Sub-division is highly variable (see for example the variability in tubewell density and canal water supplies to sample watercourses illustrated in Strosser and Kuper (1995)). In some cases, sensitivity of model parameters will be required to check whether using a given model with less detailed information (but available at the Chishtian Sub-division level) still provides accurate results.

The main objectives of the following sections of this paper focuses on the efforts developed during the last 6 to 8 months to integrate the three thematic components and develop a so-called integrated approach.

FROM THEMATIC RESEARCH TO AN INTEGRATED APPROACH

At this stage of the paper, we would like to summarize again the overall objective of the integrated approach currently developed by IIMI. The main objective is **to assess the impact of interventions on irrigation management in irrigation system performance**. As already explained above, the approach selected has been called an *integrated approach* to stress the efforts made to link disciplines and levels of the irrigation system.

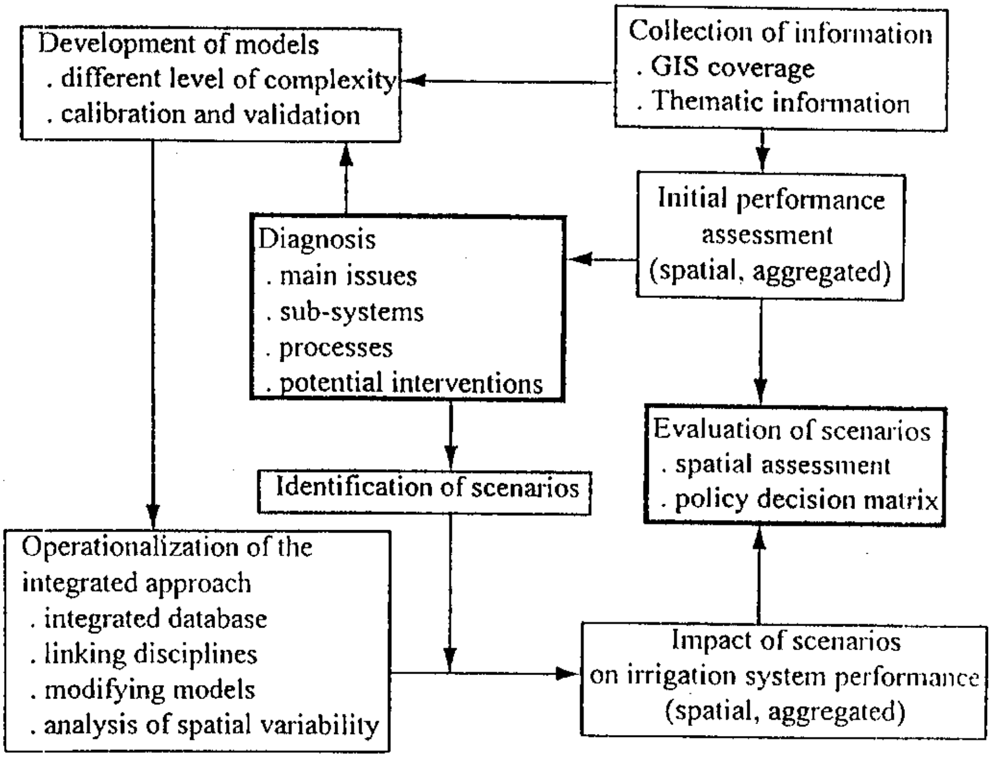
The users of the approach as identified by IIMI researchers falls into two categories:

> **(i) users of the information** obtained from the application of the approach: policy makers, planning departments of line agencies and donors are potential clients for this information.
>
> **(ii) users of the integrated approach** itself: initially, IIMI researchers will be the sole users of the integrated approach developed in the Chishtian Sub-division. However, lessons from its development and operationalization are expected to be shared with other research organization involved in irrigation management research in the context of the Fordwah/Eastern Sadiqia (South) Irrigation and Drainage project.

The main interventions that can be tested in the framework developed so far include: (i) changes in inflow at the head of the Chishtian Sub-division; (ii) changes in operational rules for the Fordwah Branch irrigation system; (iii) reallocation of canal water supplies among distributaries; (iv) maintenance activities for the four larger distributaries (whether desilting or remodelling of outlets); (v) lining of parts of the conveyance system (main, secondary, tertiary canal); (vi) changes in water charges (structure or level); and (vii) changes in agricultural input and output prices.

The overall methodology is presented in Figure 1. As already mentioned above, the areas of interest that have been included in the integrated approach include: water supply, salinity/sodicity and agricultural production. These elements of irrigation system performance are cited in numerous reports (whether planning, implementation or evaluation documents) and identified by the potential users of information obtained from the integrated approach as the main parameters to be investigated[8]. The main components of water supply performance that have been developed in the integrated approach relate to the equity of water supply (along and between distributaries), a century old objective for irrigation managers in Pakistan, but also related to adequacy and variability of these supplies.

Figure 1. Development of an integrated approach to assess the impact of irrigation management changes on irrigation system performance.



In order to support the analysis of scenarios for the Chishtian Sub-division, a comprehensive spatial database is required to support assessment of issues and understand the variability of key parameters involved in the processes analyzed. This database is link with various simulation and optimization models as presented in Figure 2. Also, facilities are provided to analyze the information obtained from simulations and compare actual situations and specific scenarios.

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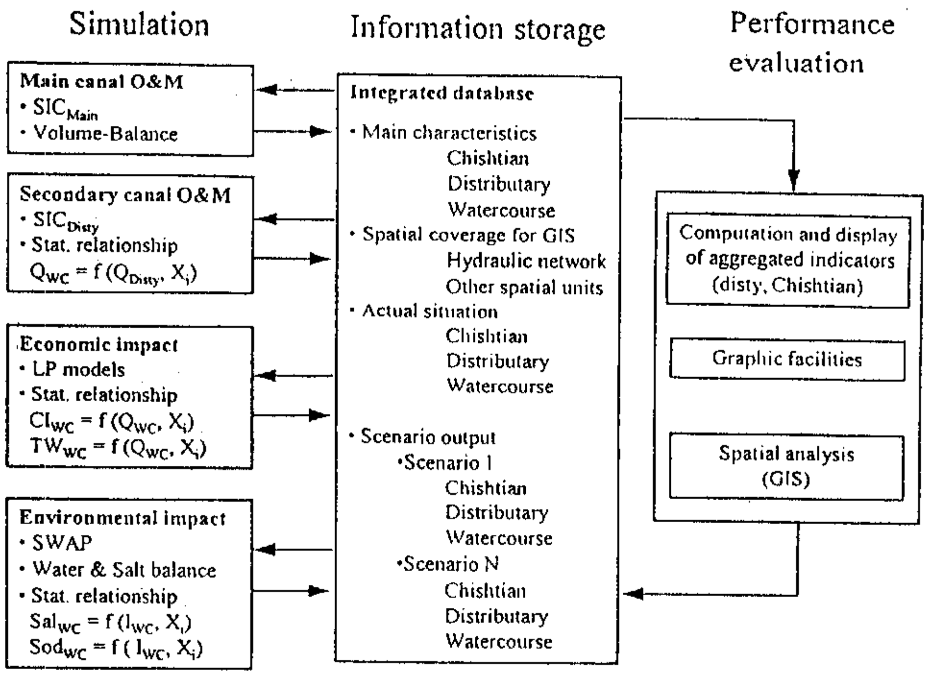
[8] Differences, however, exist between users in terms of the importance attached to each variable or set of variables.

Figure 2. Database and models to support the integrated approach.



As will be described below, different levels of complexity are proposed for each component of the integrated approach. The database and its management is central to the integrated approach. Also, simulation models are seen as specific (and separated) tools that help the user to progress in his understanding of the complexity of the irrigation system, and also facilitates his analysis of the impact of scenarios on specific aspects of irrigation system performance. Some of the elements of Figure 1 and Figure 2 are further detailed in the following sections describing specific activities undertaken as part of the application of the integrated approach in the Chishtian Sub-division.

FIRST APPLICATION IN THE CHISHTIAN SUB-DIVISION

Development of a spatial database using GIS

Important efforts have been devoted to the development of an appropriate database for the whole Chishtian Sub-division. The information collected at different levels of the irrigation system is stored in a spatially referenced database using a Geographical Information System (GIS). The information stored in the database (as presented in Appendix II) is used for several purposes.

First, it is used to describe and analyze the spatial variability of the different phenomenon and parameters analyzed. For example, the spatial distribution of salinity within the Chishtian Sub-division, or the heterogeneity of farming systems and cropping patterns among reaches of the irrigation system, or differences in access to irrigation water resources (surface water supplies and tubewells) of different qualities[9]. The analysis and assessment of the current status is undertaken with the data sets in their original spatial coverage (for example, soil types are analyzed at the level of the soil units).

Second, the information is used to adapt specific model parameters to local conditions, or to select the appropriate model calibration for different parts of the irrigation system. For example, the current salinity level is an important parameter that will be used for specifying the initial salinity values required for the SWAP model. Also, farm characteristics information throughout the Chishtian Sub-division is required to identify the types of farms and economic models to be used for a given watercourse command area.

Third, the GIS is used to aggregate and extrapolate information to obtain a watercourse level database for use in the simulation component of the integrated approach. The manipulation of information ranges from simple aggregation of information (for example, killa level salinity information may be averaged at the watercourse level) to allocation of values following simple decision rules (for example, one soil type only is allocated to each watercourse using the maximum area allocation criteria). Also, tubewell water quality information is extrapolated to watercourses with missing information (due to non-operating private tubewells at the time of the tubewell water quality survey).

To understand the spatial variability of parameters

Efforts have focused on understanding heterogeneity and variability within the Chishtian Sub-division for selected processes and parameters that influence these processes. The analysis of variability has been undertaken for a large number of physical and socio-economic variables, not independently one from each other, but jointly as some of these variables may be correlated with each other. The analysis leads to the identification of a limited number of combinations of these variables characterizing specific environments or well-defined patterns or groups. Each group still represents within-group variability for some variables, but is homogeneous for important parameters that intervene on the main process analyzed (i.e. on the transformation of a given input into an output). The effort of classification or pattern analysis has focused at three levels.

First, the analysis of soil types in terms of texture and physiography has led to the identification of 4 soil types that represent the various situations existing in the Chishtian Sub-division. The processes of classification has been based on expert knowledge in the context of the collaboration with the Soil Survey of Pakistan.

Second, farm level decisions have been analyzed and linked with farm characteristics. Based on the analysis of a sample of 280 farms in terms of farm strategies and constraints, 11 well defined

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[9] In terms of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonates (RSC).

farm groups have been identified using statistical classification techniques (Rinaudo, 1994). The main characteristics of the 11 farm types are summarized in Table 4 (for more information on the characteristics of these groups, see Rinaudo, 1996).

Table 4. Main characteristics of the 11 farm groups.

Farm group	Tractor owners	Tubewell owners	Cultivated area (in ha)	Area rented in (in % of cultivated area)	Yearly cropping intensity
1	No	No	4.1	45	140
2	No	No	4.7	55	130
3	No	No	5.8	55	140
4	No	No	4.4	65	135
5	No	No	4.5	70	160
6	No	No	6.0	75	140
7	No	Yes	1.5	10	180
8	No	No	3.5	30	120
9	Yes	Yes	8.2	30	155
10	Yes	Yes	4.3	20	145
11	Yes	Yes	42.5	60	130

Third, specific analysis is undertaken at the watercourse level to identify specific watercourse environments in terms of socio-economic characteristics and physical conditions. Although this analysis is not finalized yet, initial results using physical variables show that watercourses can be classified into a limited number of watercourse classes. Analysis of groundwater quality information, for example, has led to the identification of 8 tubewell water quality classes only, based on the Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonates (RSC)[10].

Adapting simulation and optimization models

As explained above, optimization and simulation models have been originally developed as part of different thematic research undertaken in collaboration with local partners. Thus, adaptation have been required to incorporate these models into the integrated approach.

To take into account the variability in soil types, the SWAP model has been calibrated for the 4 soil types characteristic of the Chishtian Sub-division. The differences between predictions obtained from simulations using the 4 SWAP models are illustrated in Figure 3. This figure emphasizes the different salinity levels obtained for different quantities of irrigation water applied on fields (and expressed in depth of water).

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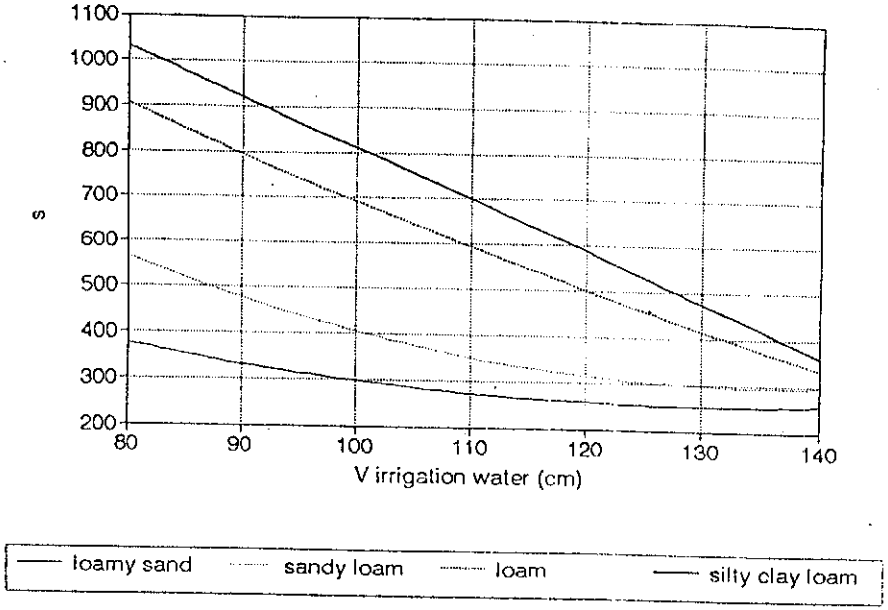
[10] The classification criteria developed by the Soil Survey of Pakistan for these three parameters would have led to around 100 possible classes...

Figure 3. Water-salinity relationship for different soil types (results of 10 year simulation, with initial EC_c = 3 dS/m).



The second process that is expected to vary significantly over the Chishtian Sub-division is the way a change in discharge at the head of a distributary is conveyed to the head of any given watercourse along the distributary. In order to account for the variability in situations, SIC models are developed for the largest distributaries using the simplified approach developed by Visser (1996). Also, specific links are established between the SIC model for the main canal and SIC models for the different distributaries, using the regulation module Gateman initially developed by Litrico (1995). Statistical relationships are established for other distributaries, as they record little variation in their head discharges over time. In the case of the Azim Distributary, as a result of the poor status of the distributary and of its outlets, it is not possible to calibrate even the simplified version of the SIC model. In this case also, a simple statistical relationship is used to predict the discharge at given points along the distributary based on the discharge at the head of the Azim Distributary.

Third, a simple volume-balance model is developed for the Fordwah Branch Canal. The main reason is that the SIC model developed can only be used for a certain range of inflows at RD 199. Below a certain discharge, a situation that is rather frequent during the Rabi season when non-perennial distributaries are not supplied with canal water, the SIC model cannot be used, and is replaced by the volume-balance model. Lastly, micro-economic models have been developed for each farm type. Thus, 11 farm models have been developed for the analysis of individual responses to changes in water supply adequacy and variability.

Changes in scale

An important aspect of the research undertaken so far relates to changes in scale. The main question is: what can be learned from the analysis of a given process at a given level of the irrigation system in order to understand a different level of the irrigation system? In fact, how to use results obtained at the field level for understanding of changes at the farm, how to use results obtained at the field and farm levels to understand issues at the watercourse level?

As a result of the analysis of decision processes taking place in the irrigation system, and also for operationalization of constraints that limit the possible number of distinct units that can be investigated simultaneously, the watercourse has been selected as the basic unit of analysis in the integrated approach (Garin et al., 1996). Thus, most of the changes in scale are targeted towards this level of analysis.

The understanding of physical processes at the field level has been used to calibrate the SWAP model for different physical conditions at the field level. However, as a result of the high spatial variability in salinity conditions within the watercourse command area, the SWAP model is to be adapted for use at the watercourse level. Further research, however, is required before obtaining appropriate watercourse-based SWAP models. Initial results have shown that the SWAP model in its present form is already useful to refine parameters required for more classical water and salt balance approaches at the level of the watercourse (van Waijjen, 1996) that have also been included in the salinity component of the integrated approach.

For farmer's decisions regarding agricultural production, the shift from the individual farm level to the watercourse level is rather straightforward. Individual micro-economic farm models are aggregated at the watercourse level by building a large matrix with the individual farm models along the diagonal of this matrix. Watercourse level constraints are added to the aggregated model, along with specific links between different farm groups that formalize exchanges between these groups. For example, links between water sellers and water purchasers have been included in the economic model aggregated at the level of the watercourse command area.

IMPACT OF PROPOSED INTERVENTIONS: SOME PRELIMINARY RESULTS

This section summarizes some of the results obtained so far in the operationalization of the integrated approach in the Chishtian Sub-division and the assessment of the impact of specific interventions on irrigation system performance. Along with the development and application of the approach, a specific research activity has been developed to tackle issues related to: (i) the level of complexity of specific models and of the structure of the system considered; and, (ii) the potential use of a simplified *integrated tool* (as opposed to the *integrated approach* as defined above) in the context of the analysis of complex irrigation systems and of the impact of changes in these systems. The initial lessons from this simplified approach are also summarized below, after a brief presentation of initial results obtained from the application of the integrated approach and the use of some models for the case of maintenance at the distributary level.

Impact of changes in water supply on cropping intensity and salinity

Initial results have been obtained with the application of parts of the integrated approach. Although the integrated approach has not yet been finalized, the efforts undertaken so far make possible the use of part of the integrated approach: assessment of main issues and definition of scenarios for change, analysis of the impact of some of these scenarios using simulation models or simple statistical relationships between input and output variables (black box approach).

The intervention that has been tested to illustrate the output and usefulness of the integrated approach relate to the maintenance of secondary canals that takes place every year during the month of January. A study undertaken by Hart (1996) has identified outlet dimensions as the main factor explaining the current inequity in canal water supply along the Fordwah Distributary. Interventions (whether official or not) that have modified outlet characteristics have led to a large discrepancy between actual and design conditions for most of the outlets off-taking from the Fordwah Distributary. The majority of interventions include modifying the size of outlets and changing the position of the outlet crest compared to the bed level of the distributary.

Based on the analysis of current water supply performance and of the assessment of the main factors that affect performance (using the SIC model calibrated for the Fordwah Distributary), a maintenance scenario is proposed and its impact on canal water supply at the watercourse head tested using the same SIC model. The proposed scenario targets the remodelling of outlets that present the largest discrepancy between design dimension/discharge and actual dimension/discharge. Totally, a remodelling plan for 9 outlets is proposed under the maintenance scenario.

As said above, the impact of this maintenance scenario on canal water supply is tested using the SIC model. Using simple watercourse level statistical relationships that relate cropping intensity and percentage of salinity free area to average seasonal canal water supplies[11], the impact of the modified water supply on cropping intensity and salinity is estimated. The output of the simulation is presented in 4 maps (Map 2 to Map 5) presented in the following page.[12] At this stage, the information presented is very simple, but is used to illustrate the potential for an integrated approach linking water, salinity and agricultural production parameters.

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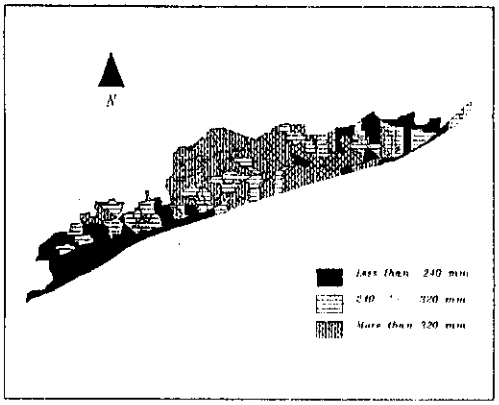
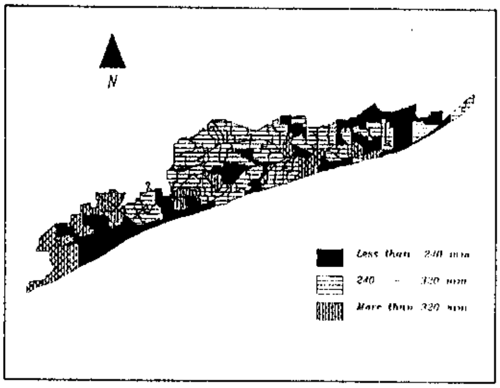
[11] These relationships have been developed using two data sets: (i) information collected by IIMI field staff for 18 sample watercourses and for 2 seasons; and (ii) information obtained for all of the watercourse command areas of the Fordwah distributary from the classification of satellite imagery information and from simulation results of the SIC model developed for the Fordwah Distributary.

[12] For one distributary only, the analysis of changes at the watercourse level does not require the GIS. However, the GIS becomes very useful when investigating the whole Chishtian Subdivision with 500 watercourses along 14 distributaries, and when looking simultaneously at different levels of the irrigation system as it provides facilities to rapidly aggregate and present information.

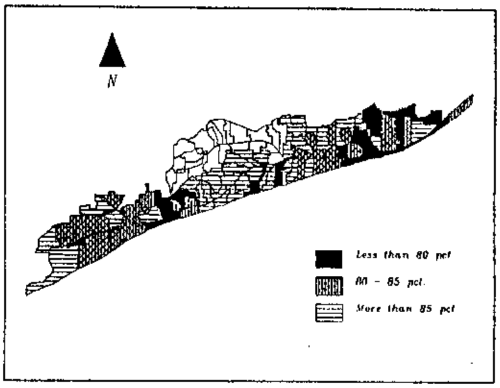
Map1.Current (estimated) water supply along the Fordwah distributary (in mm)



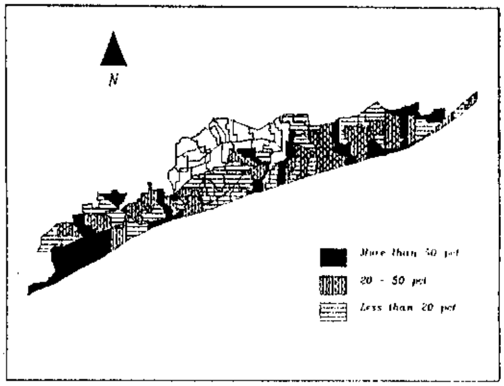
Map 2. Impact of outlet remodelling on canal water supply (in mm)



Map 3. Impact of changes in canal water supply on cropping intensity (in %)



Map 4. Impact of changes in canal water supply on percent of saline area



Development of a simplified approach

As highlighted in the section titled *Statement of the problem*, the level of complexity envisaged has been an important issue discussed during the planning and development of research activities. On one side, one would like to represent and analyze the complexity of the irrigation system as meticulously as possible. On the other side, too high of a complexity may lead to non-operational approaches due to high information and skills requirements. Thus, to start from the complexity of thematic studies may lead to too complex integrated approaches, without providing the required information in an effective way. As mentioned above, a related issue is the development of an integrated approach (that may include simulation and optimization models such as the one presented so far) versus the development of an integrated model that would automatically provide information on the impact of changes on the different performance indicators without allowing users to investigate the reasons for such levels of performance.

An effort has been made in 1996 (Belouze, 1996) to better assess the usefulness of a simplified integrated model. The main objective of this model is to identify within a short period of time important factors that affect the output of processes, to propose simplifications in the existing complex models, and to test a large number of scenarios (useful for the sensitivity analysis of the main parameters). The model has been developed using the MATLAB-SIMULINK software (Matlab, 1991) well adapted for the represention and modelling of complex systems.

The major model simplifications adopted by Belouze (1996) are the linearization of the SIC model (whether at the main canal or distributary levels), and the use of a water and salt balance at the watercourse level (van Waijjen, 1996). Also, automatic links have been developed between hydraulic, economic and salinity models at the main system, distributary, and watercourse levels.

To illustrate the feasibility of such an integrated model, a simplified structure of the irrigation system has been used as a case study, with only one main canal, 2 distributaries and 6 watercourses. The information used for building this simplified structure, however, has been collected from existing watercourses and distributaries. The simplified integrated model has been used to test specific scenarios of changes in inflow or operational rules (Belouze, 1996). Also, the stability of the overall model has been tested and refinements proposed for the operationalization of the overall integrated approach. In some ways, the simplified and integrated tool that has been developed as a result of discussion about complex system analysis and integrated approaches would have been required already at early stages of the research program. First, to refine the planning and implementation of process related research activities. Second, to identify key parameters that affect significantly the output of selected processes and for which information would be required for all watercourses of the Chishtian Sub-division.

CONCLUSIONS AND FOLLOW-UP

The approach presented in this paper combines water supply, agricultural production and salinity/sodicity issues for the assessment of the impact of changes in irrigation management on irrigation system performance. The approach will be finalized and evaluated by researchers and potential users of the information obtained through the approach during the first half of 1997. Already, benefits have been gained from the experience: a better understanding of the links between water, salinity and agricultural production; researchers developed in the analysis of complex issues; effective multi-disciplinary research; and the ability to compare interventions and assess trade-offs between different management options. The reactions obtained from the group of researchers and line department staff that attended the National Conference on *Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan* were also very positive and constructive, and showed a real (and lucid) interest for this type of approach.

In the course of the study, a simplified tool was developed to test the approach. This provided valuable insights into the stability of the approach and the links between different models. It is recommended that for future implementation of an integrated approach, a simplified tool or minimum configuration is constructed in the early stages of the research. In the Chishtian Sub-division, a comparison will be done between the outputs of the simplified and a more complex approach.

The integrated approach developed in this study has not specifically included groundwater, since groundwater tables in the Chishtian Sub-division are fairly deep. For future use of the approach in Pakistan, groundwater needs to be considered as an important part of the approach, e.g. with respect to long-term quality aspects. Present efforts of IWASRI, PCRWR and IIMI with respect to groundwater modelling could contribute to an integrated approach for future use.

The efforts required to integrate several thematic studies into a more integrated approach have been substantial. These efforts relate mainly to changing scales, spatial heterogeneity and interactions between physical processes and human decision-making. If an integrated approach were to be adopted and shared between several organizations, the coordination becomes an additional complicating factor. This ranges from practical issues, such as common or standardized data bases, to more institutional issues about sharing of responsibilities.

Due to the complexity of irrigated agriculture as a system and due to inherent problems of accuracies of simulating processes, the predictions of an integrated approach, which combines several models, should not be evaluated for their absolute values. The validation of the integrated approach is, therefore, much more related as to the fact as to whether or not the approach provides users with useful information to support decisions related to irrigation management. The potential users of the approach developed in Chishtian are policy makers, planners, irrigation managers and researchers. The use of the approach or tools should be distinguished from the use of the outputs of the approach, although it is recommended to provide users not only access to output but also to the tools itself.

Recently, IIMI has developed in collaboration with its French research partners a CD-ROM, which contains an interactive database structure. This means of dissemination could be an effective way to present the results of the research undertaken in the Chishtian Sub-division. Also, it would provide possibilities for a wide range of people to gain insights into the inter-related issues of irrigation, salinity and agricultural production.

The integrated approach that has been developed and tested in the Chishtian Sub-division is data-intensive, but efforts are underway to test the impact of different parameters on salinity, sodicity and agricultural production in order to minimize the data requirements for an integrated approach. An example is the development of a simplified procedure to calibrate a hydraulic, unsteady state model, which has reduced considerably the need for field surveys (Visser, 1996).

The Fordwah Eastern Sadiqia (South) project (FESS) has given a mandate to 13 organizations to formulate an integrated package of irrigation and drainage related interventions to prevent further land degradation. The integrated approach that has been developed and applied to Chishtian can offer the following contributions for the FESS project: **(i)** the assessment of salinity and sodicity over large areas in a collaboration between SSP, IWASRI, SMO and IIMI; **(ii)** the development of standardized databases that are geo-referenced; and **(iii)** the creation of a common platform to do a comparative analysis of the impact of various irrigation and drainage measures on agricultural production and salinity/sodicity.

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Appendix I

Selected bio-physical and decision processes in an irrigation system in Pakistan[13]

Sub-system	Main/Branch canal	Distributary	Watercourse	Farm	Field
Processes	Conveyance, distribution, scheduling, allocation to distributaries	Conveyance, allocation to watercourses	Conveyance, allocation and delivery of canal water to farms	Crop choices, allocation of irrigation water to specific crops	Crop production, salinization and sodification
Inputs	Canal water supply at the head of the main canal	Canal water supply at the head of distributary	Canal water supply at the head of the watercourse	Canal water supply at the farm gate	Irrigation water supply (quantity, timing, quality)
Characteristics	physical charac. of the canal, roughness coefficient, seepage losses	physical chara. of the canal, roughness coefficient, seepage losses	seepage losses, filling and drainage time of the watercourse, allocation of water turns to farmers	constraints on agricultural production (land, labour credit), technical coefficient for crop production, risk aversion	soil chara., initial salt content in the soil profile (sodium, calcium, etc)
Outputs	Canal water deliveries to distributary canals	Canal water deliveries to watercourses	Canal water deliveries to the farm gate	Cropping pattern and intensity, tubewell water use, participation in water transactions	Actual crop yield, final salt content in the soil profile, percolation to the aquifer
Models	SIC-Main	SIC-Disty	Watallo	Linear programming (LP) models	. SWAP . Sodicity functions . Production functions

Note: The SIC and SWAP software are developed by the Irrigation Division of Cemagref (France) and the Department of Water Resources of the Wageningen Agricultural University (the Netherlands), respectively. These models have been applied in Pakistan in the context of collaborations with researchers from these institutes.

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[13] The authors acknowledge the non-exhaustiveness of this table.

Appendix II

The elements of the spatial database developed in the Chishtian Sub-division

	Variable	Level	Source of information
Water	. Canal water supply	. Watercourse head	. Obtained from simulations (IIMI)
	. Groundwater quality	. Watercourse	. average of 3 values from tubewell water analyses (IIMI)
	. Tubewell density	. Watercourse	. tubewell survey (IIMI)
	. Water-table depth	. piezometers (point)	. seasonal monitoring (SMO)
	. Type of water allocation mechanism at the watercourse level (fixed or flexible)	. Watercourse	. Rapid farm survey (IIMI)
Soils	. Topography	. soil units	. Semi-detailed survey (SSoP)
	. Soil type	. soil units	. Semi-detailed survey (SSoP)
	. Salinity: (a) salinity classes (EC, SAR, RSC)	. (a) soil units	. (a) Semi-detailed survey (SSoP)
	(b) visual salinity classes	(b) *killa* (field)	(b) Visual salinity survey (DLR)
	(c) highly saline areas	(c) pixel	(c) satellite imagery (IIMI/Cemagref)
Social	. Origin of population (settlers versus locals)	. Watercourse	. Rapid farm survey (IIMI)
	. Presence of large landlords (Yes/No)	. Watercourse	. Rapid farm survey (IIMI)
Economics	. Number of farmers	. Watercourse	. Rapid farm survey (IIMI)
	. Number of tenants	. Watercourse	. Rapid farm survey (IIMI)
	. Machinery (tractor, tubewells)	. Watercourse	. Rapid farm survey (IIMI)
	. Main markets for agricultural products	. Watercourse	. Rapid farm survey (IIMI)
	. cultivated area	. Pixel	. Satellite imagery (IIMI/Cemagref)
	. cropping pattern	. Watercourse	. Rapid farm survey (IIMI)

DLR : Directorate of Land Reclamation, Punjab Irrigation and Power Department
Cemagref : French research center for water resources and environmental engineering
IIMI : International Irrigation Management Institute
SMO : SCARP Monitoring Organization
SSoP : Soil Survey of Pakistan

PREDICTING TEMPORAL VARIATIONS IN GROUNDWATER SALINITY OF PUMPED WATER IN RECHNA DOAB, PUNJAB, PAKISTAN

Muhammad Aslam[1]

ABSTRACT

The public and private tubewells are being effectively used for vertical drainage as well as for irrigation purposes in Pakistan. Currently, about 13,000 public tubewells having a discharge capacity of 60 to 150 liters per second are operational in various Salinity Control and Reclamation Schemes, in addition to over 300,000 private tubewells of about 30 liters per second pumping capacity installed by farmers. The salinity of groundwater supplies varies widely, with some supplies being too saline for irrigation. For good quality groundwater, tubewells serve the dual purpose of alleviating waterlogging and supplementing the canal water supply. The rapid development of private tubewells indicates the farmer's heavy dependence on pumped groundwater for their crop production, but a majority of the tubewells are pumping marginal to poor quality groundwater, use of which for irrigation reflects a gradual build-up of salinity and sodicity in the soil profile, thereby rendering the agricultural lands unproductive. There is a great need to manage properly the salinity of the groundwater resource for its sustained long-term use for irrigation.

This paper provides a discussion on tubewell development, conjunctive use environment, spatial groundwater quality variations, skimming well concept and the results of a model study carried out by employing a three-dimensional groundwater model, HST3D (Heat and Solute Transport in saturated 3-Dimensional Groundwater Flow System) in the Rechna Doab, Punjab. The groundwater salinity model provided the temporal variations in the salinity concentrations of pumped water by wells installed in the irrigation system. These predictions help in establishing groundwater management requirements for sustained use of the aquifer on a long-term basis. The issues and options related to groundwater irrigation are also discussed in this paper.

INTRODUCTION

To properly manage the problem of salinity in an irrigated area, it is important to manage the groundwater salinity problem, especially in areas where the aquifers have a saline water layer underlying a layer of fresh water that is being pumped for water supply. When these aquifers are pumped to withdraw fresh water, the encroachment of underlying salt water into the fresh water aquifer takes place. Eventually, the fresh water zone becomes contaminated and the pumped water is discharging saline water that is detrimental to crop production. The Indus Plain of Pakistan is a good example of this kind of aquifer in which the fresh water zone is underlain by a salt water zone.

In the Indus Basin there is a huge network of canals and watercourses to supply irrigation water to the irrigated areas. Seepage from the canals and watercourses and deep percolation from the farms are currently creating severe problems of waterlogging

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and salinity in Pakistan. These problems make it necessary to have a huge drainage system and reclamation measures. In order to lower the water table, groundwater is being pumped by deep and large capacity tubewells. This has resulted, however, in rapid deterioration of the groundwater quality. Soon after installation, the tubewells started pumping saline water due to their capacity being too large, so that encroachment of salt water from the underlying saline water occurred (McWhorter, 1980).

Clearly, to manage the waterlogging and salinity problems in such irrigated areas as the Indus Plain, it is important to skim the good quality groundwater in order to fulfill the drainage needs and also to supplement the irrigation water supply. An acceptable quality of fresh groundwater for irrigation is required on a long-term basis. Pumping of fresh water from above the saline water with a minimum of mixing within the aquifer requires an improved design and optimum operation of a skimming well. Skimming wells not only lower the water table for drainage purposes and supply water for irrigation, but they also minimize the mixing of fresh and salt waters in the aquifer.

For a careful and effective management of fresh water withdrawals in a saline environment, it is necessary to understand fully the mechanics of flow near the well that causes the upconing, which is the vertical upward movement of salt water in the form of a cone or mound from the saline water zone into the fresh water zone in response to pumping fresh water from the aquifer. In the present study, a three-dimensional groundwater model was applied to the Rechna Doab, which is the land between the Ravi River and Chenab River consisting of 2.3 million hectares of cultivated irrigated croplands. Considerable emphasis was placed on using the three-dimensional groundwater salinity model in order to predict the future trends in tubewell salinity discharges. A three-dimensional groundwater model was required because a vertical salinity gradient exists in the groundwater reservoir.

TUBEWELL DEVELOPMENT

SCARP Tubewells

A major program for the control of waterlogging and salinity began in the irrigated areas of Pakistan since the early 1960s, under which a number of Salinity Control and Reclamation Projects (SCARPs) have been launched. In these projects, about 13,000 high capacity (0.06 to 0.14 cubic meters per second, cumecs) deep (depth varies from 60 to 120 meters) SCARP tubewells were installed by WAPDA for vertical drainage and to supplement the irrigation supplies where the groundwater is usable. SCARP tubewells resulted in pumping of large quantities of groundwater from deep strata, which invariably is more saline, but they have made a significant contribution in lowering the water table in affected areas.

SCARP-I, which lies in central Rechna Doab, was the first project to control waterlogging and salinity in Rechna Doab. The gross area is about 0.49 Million hectares (Mha) and the culturable area is about 0.46 Mha. As of June 30, 1972, 2068 public tubewells with a total design capacity of 180 cumecs had been installed in the SCARP. Several schemes included in SCARP-I were operational in 1961, and all 12 schemes in SCARP were in operation by July 1962. There were 2073 public tubewells having a capacity of 130 cumecs in 1980-81. The high capacity public tubewells were installed along minors and distributaries not only to lower the water table, but also to supplement canal irrigation in fresh water zones and to pump out saline water in the saline zones. The main objective of the SCARP-I was to demonstrate the effectiveness of vertical drainage in reclaiming salt-affected soils in a large area. The plan was to lower the water table by pumping groundwater and to supplement the surface water supplies.

SCARP-IV originally planned to include most of Upper Rechna Doab, was reduced to two schemes in part because of a large antecedent increase in private tubewell development in the area. The Mangtanwala and Muridke Schemes lie along the northwest bank of the Ravi River between the river and SCARP-I and close to the Marala-Ravi Link Canal. The gross area of the schemes is 0.25 Mha, the culturable area is about 0.23 Mha and 935 public wells with a design capacity of 105 cumecs had been installed. All 311 wells in the Mangtanwala Scheme were in operation as of July,1969, but as of June 30, 1972, only 245 of the 624 wells in the Muridke Scheme were operational.

Under SCARP-V, in 1976, about 171 tubewells having a pumping capacity of 4.9 cumecs were installed in Shorkot Kamalia Project, which has a gross command area of 0.022 Mha, and in 1977, about 71 tubewells with a pumping capacity of 4.4 cumecs were installed in Satiana Pilot Project, which covers a gross command area of about 0.047 Mha.

Private Tubewells

The growth in numbers of private tubewells, in some parts of Punjab in the 1980s, has been explosive. Private tubewells increased five fold from 1965 to 1977. Pumping from the private tubewells lowered the water table and increased the water supply significantly. According to recent estimates, there are about 300,000 private tubewells to supplement surface water supplies. The rapidly growing exploitation of groundwater for irrigation by the private tubewells has greatly enhanced the vertical drainage effect of the SCARP tubewells. Currently, due to high operation and maintenance and other technical reasons, the SCARP tubewells are being handed over to the private sector through the SCARP Transition Program in fresh groundwater areas.

In Rechna Doab, private tubewells in operation as of June 30, 1971 were 31,900 out of which 25,100 were in Upper Rechna Doab and 6,800 were in Lower Rechna Doab. In SCARP-I there were about 310 private tubewells in 1964 and 4566 with average capacity of 0.03 cumecs in 1980-81. In Rechna Doab, IIMI's research on tubewell irrigation (1988-1989) undertaken in the command of Lagar distributary (Gross Command Area, GCA: 7450 ha, Cultural Command Area, CCA: 6,619 ha), off taking from Upper Gugera Branch Canal of the Lower Chenab Canal system, revealed that there are 399 operational tubewells out of which 368 are private tubewells and 31 are public tubewells. A comparison of the growth in private tubewell development for Punjab and the distribution of currently operational private tubewells in Lagar command by year of development is presented in Figure 1, which reflects the variation from year to year in the total number of tubewells installed and rate of installation in the 1980s. In late 1989, the overall density of private tubewells in Lagar's command area was about 5.5 wells per 100 ha of CCA. Between watercourse commands, private tubewells densities in Lagar's command area vary from 1.7 to more than 9.9 per 100 ha of GCA (Vander Velde and Johnson, 1992).

The development of private tubewells started in the mid-sixties in the commands of Mananwala Distributary (CCA: 26,800 ha) and its Karkan Minor (CCA: 9,400 ha) off taking from Upper Gugera Branch Canal of the Lower Chenab Canal system. The private tubewell development remained slow for the first 15 years. The average number of private tubewells per watercourse command area was lower than 2 until 1980. An explosive increase took place during the eighties. There were 70 private tubewells in 1985 (2.2 tubewells/100 ha) of CCA and 223 in 1990 (7 tubewells/100 ha of CCA) in the sample area (3180 ha of CCA) of 14 watercourses of Mananwala Distributary and Karkan Minor as shown in Figure 2. The aggregated tubewell density is equal to 7.6 tubewells per 100 ha (1992) for the sampled 14 watercourses of the two channels. The tubewell density among watercourses ranges from 1.5 tubewells per 100 ha for Karkan Watercourse 27L to about 13 tubewells per 100 ha for Mananwala Watercourse 71R as shown in Figure 3 (Malik and Strosser, 1993).

CONJUNCTIVE USE ENVIRONMENT

In Rechna Doab, IIMI's research findings of groundwater irrigation studies under the waterlogging and salinity project Phase-I (1989 -1993) in distributary canal commands served by Gugera Branch Canal in the Lower Chenab Canal (LCC) system in the Rechna Doab are discussed below.

In the Lagar Distributary command area, the average proportion of groundwater to all irrigation water available to farmers at the outlet was 67% for rabi season, and more than 80% for kharif. On the average, groundwater from public and private tubewells contributes about 70% of the total irrigation water used in irrigated agriculture in Farooqabad Sub-division.It was found that in Pir Mahal Distributary command during

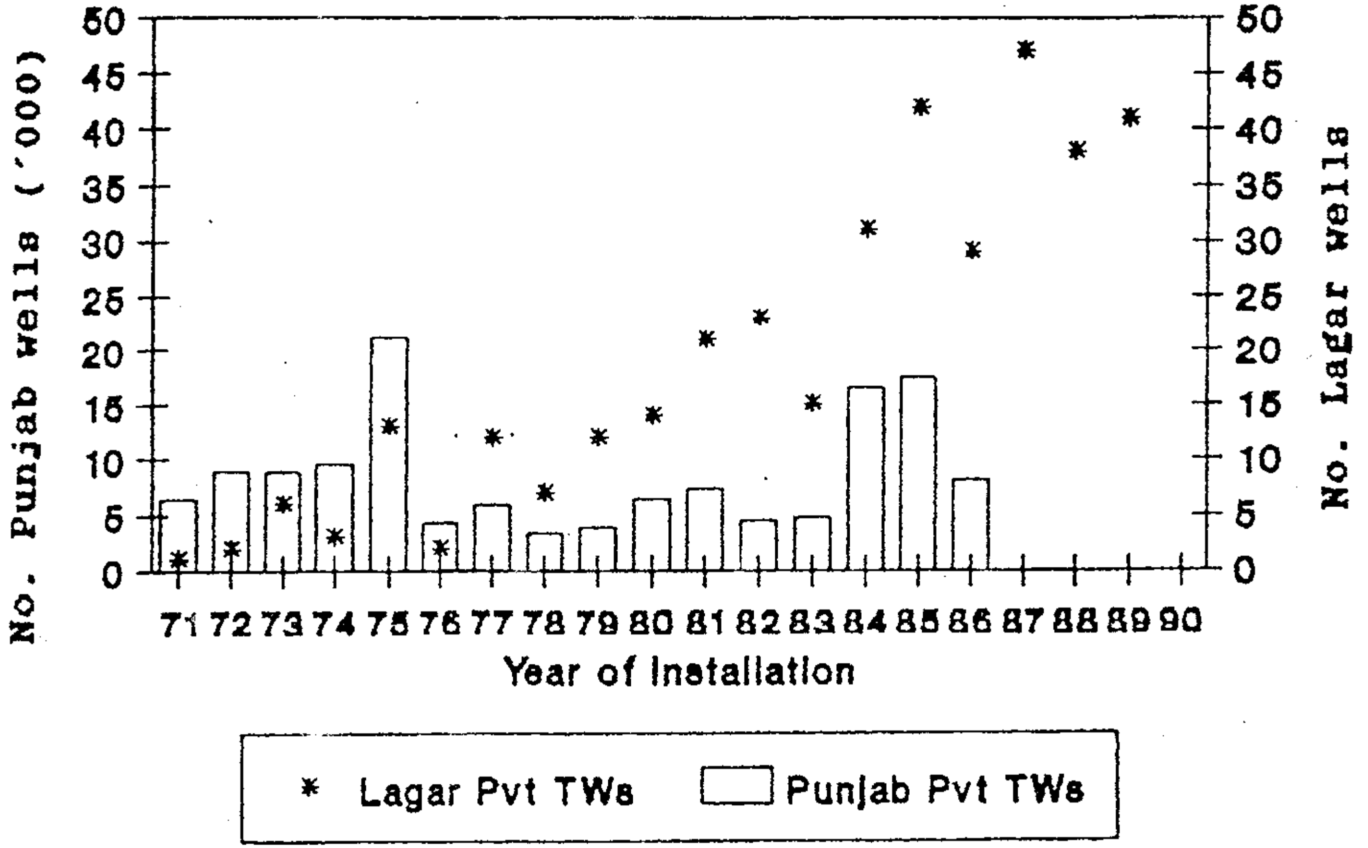

Figure 1. Private tubewell development: Punjab and Lagar Distributary.
(Source: Vander Velde and Johnson, 1992)

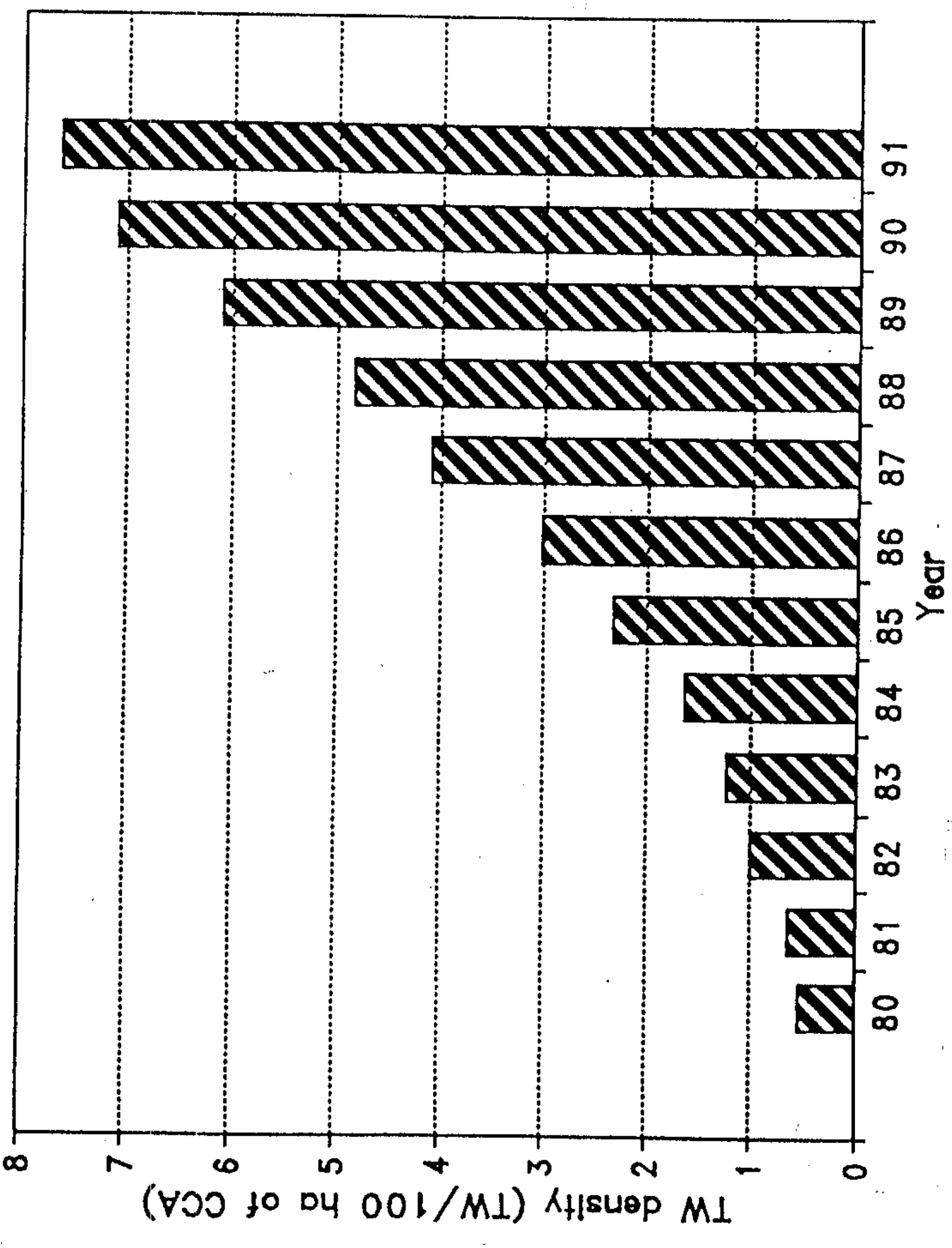

Figure 2. Private tubewell development in Mananwala Distributary Area.
(Source: Malik and Strosser, 1993)

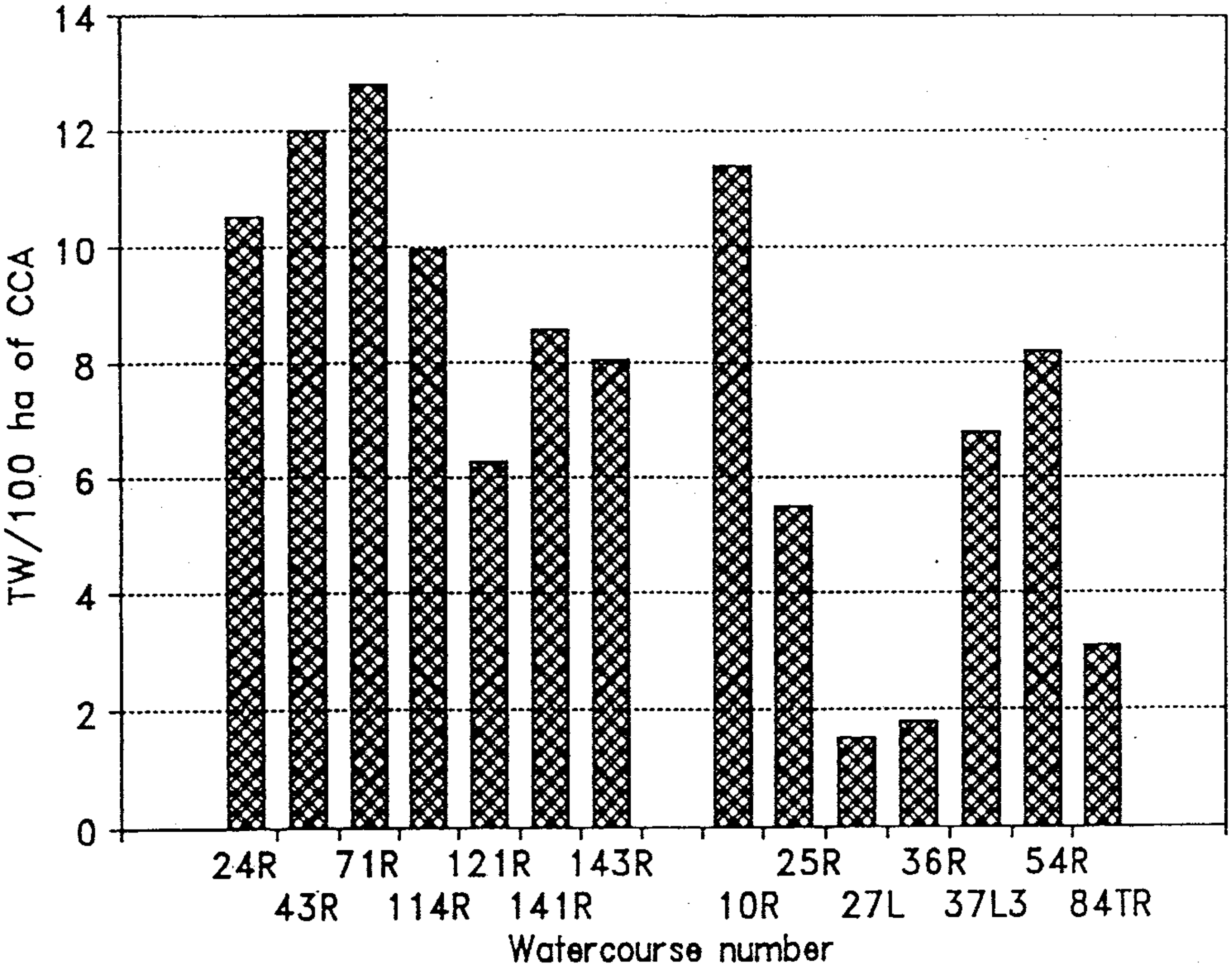

Figure 3. Private tubewell density in Mananwala Distributary Watercourses, (Source: Malik and Strosser, 1993)

kharif,1990, groundwater contributed 72 % of the total irrigation water used by farmers in the area (Kijne and Vander Velde, 1990). A majority of the tubewells are pumping marginal to poor quality groundwater, which reflects gradual build up of salinity/ sodicity in the soil profile (Vander Velde and Johnson, 1992). There is no institutional arrangements to manage the conjunctive use of groundwater (Bhatti and Kijne, 1992).

Murray-Rust and Vander Velde (1992) presented the results of an analysis of existing data on conjunctive use of surface and groundwater in secondary canals in Pakistan. Their main findings were: (1) groundwater accounts for between 70-90 % of all irrigation water in the three peak months of the hot season, declining to less than 50% of total water use in the cooler winter season; (2) cropping patterns show a consistent trend along each canal that reflects access to surface water. In the kharif season, both cropping intensity (80 to 60%) and percent under rice (50% to 33%) decline from head to tail, while cropping intensities of other crops remain more or less uniform. In rabi season, cropping intensities remain high (85-90%); (3) farmers are not aware of leaching requirements, which reflects a strong relationship between the percentage of increasingly poor quality groundwater used and levels of irrigation-induced soil salinity; and (4) no organization is collecting information on private tubewell use, even though it is contributing more than 50% to total irrigation water.

A tubewell operations study undertaken in the Mananwala Distributary and Karkan Minor command areas revealed that: (1) the use of groundwater is particularly important where farmers grow crops with higher water requirements and where tubewell owners have installed electric tubewells with relatively low operational and maintenance costs; (2) small farmers get groundwater through groundwater markets; (3) the dependence on groundwater supplies at the tail of the two channels has caused irrigation-induced salinity problems; and (4) tail watercourses have on average a lower irrigation water quality than the head and the middle watercourses (Malik and Strosser, 1993). It became clear that groundwater is contributing significantly to the total irrigation supplies for irrigated agriculture in many canal command areas of Punjab

GROUNDWATER QUALITY SITUATION IN RECHNA DOAB

Rechna Doab is located in the northeastern part of Pakistan as shown in Figure 4 and is part of the Punjab Plain, bounded on the south and east by the Ravi River and on the north and west by the Chenab River, and has a total area of about 28,500 square kilometers. The area is elongated, about 403 kilometers in length and 113 kilometers in width. The topographic slope of the doab is to the southwest, about 0.38 meters per kilometer at the upper part and about 0.29 meters per kilometer in the lower part.

Perennial canal irrigation began in the Rechna Doab in 1892 when the Lower Chenab Canal was put into operation. The Chenab River is the source of all canal irrigation water in this doab. The canal system is tremendous and waters are of excellent quality (TDS ranges from 150 to 250 ppm).

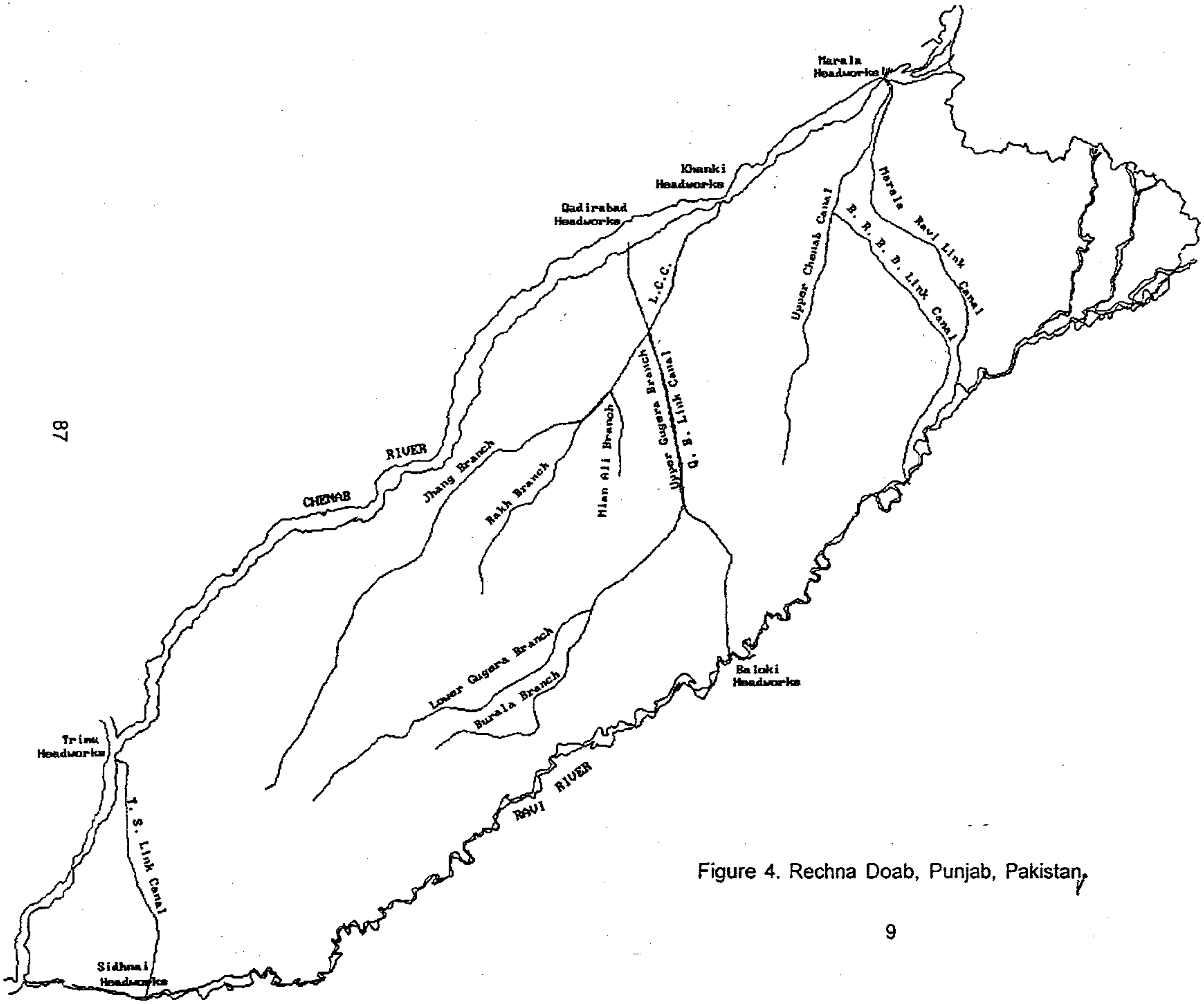

Figure 4. Rechna Doab, Punjab, Pakistan.

The problem of waterlogging and salinity was first noticed in the upper region of Rechna Doab a few years after the opening of the Lower Chenab Canal in 1892. At that time, salinity was attributed to the high water table conditions with groundwater as the source of salt. Investigations in deep water table areas, carried out later in 1937, brought to light that salts were originally present in the soil and that their movement towards the surface was caused not only by the rising water tables, but also by inadequate irrigation applications.

The groundwater is being developed on a large scale by means of tubewells due to the highly permeable unconfined groundwater aquifer of the Indus Plain. The groundwater salinity increases with distance from the rivers and with depth. The quality of groundwater in Rechna Doab is shown in Figure 5. According to one estimate, 1.7 million hectares of Rechna Doab lie over usable groundwater of which 1.36 million hectares contain fresh groundwater (TDS<1000 ppm) that may be used directly for crop production, while the remaining 0.34 million hectares have groundwater of intermediate salinity (TDS 1000-3000 ppm) which requires mixing with surface water to make it suitable for irrigation. There are 0.2 million hectares of CCA that lie over hazardous groundwater of TDS greater than 3,000 ppm that is not used for irrigation purposes (IDFCRC,1975).

The quality of deep groundwater in Rechna Doab was obtained from the chemical analyses of water samples collected from 183 meters deep test holes in 1957-1960. Fresh water zones, 24 to 32 kilometers wide, occur along the flood plains of the Chenab and Ravi rivers. The vertical depth extends to more than 300 meters. A test hole drilled near the confluence of the Chenab and Ravi revealed fresh water at a depth of 305 meters.

Upper Rechna is the largest area of fresh groundwater extending northeasterly from Sheikhupura towards the border of Jummu and Kashmir and extending laterally towards the Chenab and Ravi rivers. In most of these areas, groundwater contains 500 ppm TDS.

Saline zones are found in the *central and lower portion of the Rechna Doab.* Salt concentrations increase gradually moving southward to 3,000 to 5,000 ppm near the city of Faisalabad. The highly saline zone is restricted to the central doab containing 10,000 to 18,000 ppm near Shorkot Road.

Based on water quality data collected from test holes ranging in depth from 61 meters to 76 meters drilled in the *Shorkot Kamalia Unit*, the TDS content between 15 meters to 76 meters generally ranges from 250 ppm to 1,000 ppm and from 175 to 704 ppm in the fresh water zone and from 1,050 to 15,900 ppm in the marginal and saline zones of the area. The concentration of TDS in areas close to the Ravi and Chenab rivers ranges within 500 ppm. With increasing distance from the rivers, the TDS content increases upto 10,000 ppm or more in the central part of Rechna Doab (WAPDA,1979).

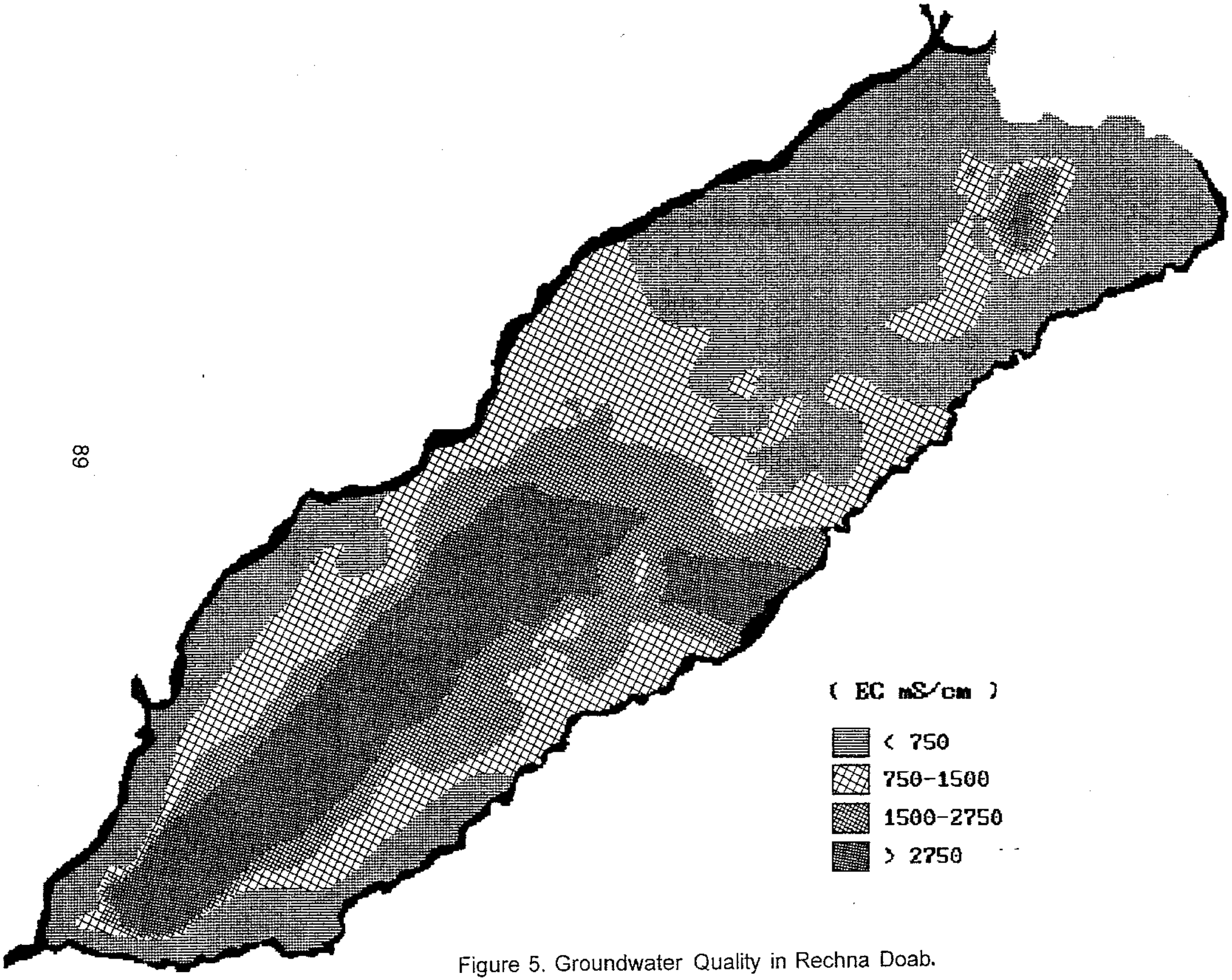

Figure 5. Groundwater Quality in Rechna Doab.

The deep groundwater quality of *Satiana Pilot Project* is poor containing EC values of 1,500 to 7,000 micromhos/cm and SAR values of 9 to 87. High salinity and sodicity makes the groundwater unfit for irrigation even with 1:1 dilution with canal water.

Changes in groundwater quality in SCARP-I have resulted from a variety of causes, most of which are directly or indirectly brought about by pumping. Disruption of hydraulic equilibrium and alteration of the natural flow regimen by pumping has caused changes in the quality of water pumped from wells over a period of time owing to the migration and mixing of waters of different chemical character.

When the SCARPs tubewells were put into operation in order to combat the waterlogging problem, groundwater quality started deteriorating, especially in the center of the doab, like SCARP-I where more than 2000 public tubewells were installed by WAPDA during 1957-1960. The use of poor quality tubewell water increased salts in the soil which rendered the land unusable for cultivation. The Scarp Monitoring Organization (SMO) of WAPDA has been evaluating the changes in groundwater quality in SCARP-I on the basis of classification criteria for irrigation usage given in Table 1.

Table 1. Groundwater Quality Classification for Irrigation Use.

Useable	EC	= 0-1500	micromhos/cm
	RSC	= 0-2.5	meq/l
	SAR	= 0-10	
Marginal	EC	= 1500-3000	micromhos/cm
	RSC	= 2.5-5	meq/l
	SAR	= 10-18	
Hazardous	EC	= more than 3000	micromhos/cm
	RSC	= more than 5	meq/l
	SAR	= more than 18	

The water quality analyses of 2,038 tubewells in SCARP-I collected during 1969-72 showed that 785 had marginal and 506 hazardous quality water. More than 60 percent of the tubewells in SCARP-I were pumping groundwater of marginal to hazardous quality. The inferior quality tubewell waters have caused adverse changes in the chemical and physical characteristics of the soils (IDFCRC, 1975).

SKIMMING WELL CONCEPT

The tubewell drainage for lowering the water tables and reclaiming the saline soils appeared the most economical solution due to the high transmissivity of the alluvial aquifer. Pumping of the required quantities of water for drainage by SCARP high-capacity deep tubewells have caused fast deterioration of groundwater quality in a large number of wells. This is due to the limited thickness of the fresh-water layer causing saline water from below the fresh-water zone to enter the well due to upconing. There is a need to optimize the abstraction of groundwater in order to meet the drainage requirements and the greater demand for irrigation water, while maintaining an acceptable quality of fresh groundwater for irrigation. Under these conditions, use of low-capacity shallow wells may help to augment canal supply and reduce waterlogging and salinity.

For exploiting thin fresh groundwater aquifers, the skimming well approach, under which fresh groundwater is extracted without disturbing the underlying saline groundwater, should be employed. A skimming well is a partially penetrating well in a thin unconfined layer of fresh water which overlies a saline water in an aquifer (Sahni, 1972). Skimming wells are designed to abstract fresh water from an aquifer in which the fresh water is underlain by saline water. The existence of saline water below the fresh water implies that tubewells installed for extracting fresh water may quickly become saline because of the saline-water upconing from below and entering the well screen. The depth and discharge of skimming wells have to be limited in accordance with the thickness of the fresh-water layer, the salt content of the fresh and saline water, the radial and vertical permeability, and the vertical recharge of the aquifer.

The research results of a study on fractional wells (less than 30 liters per second) carried out in the seventies indicated that fractional tubewells should be used in saline zones. In many cases, fractional tubewells having a capacity of only 6 liters per second should be used. This was a dramatic finding considering that most public tubewells have been installed in saline areas with capacities of 60 to 150 liters per second. The fractional tubewells technology has several socio-economic advantages because they can be installed by private individuals, and if small amounts of credit could be made available, then small farmers could also receive benefits from having a tubewell (Skogerboe et al., 1980).

The withdrawal of fresh groundwater overlying highly saline groundwater by means of skimming wells has been investigated jointly by the U.S. Geological Survey and WAPDA by means of electric analog simulation for various thicknesses of fresh water layers and varying well penetrations. The main finding of this study was that under unrestrictive thicknesses of the fresh water layers, skimming wells could produce useable quantities of fresh water (Bennett et al., 1968). The long-term behavior of skimming wells from a quality point of view needs to be investigated using a groundwater modelling study.

GROUNDWATER SALINITY MODEL

The analysis of groundwater flow and solute transport under variable fluid density conditions is a complex phenomenon, which requires the solution of two simultaneous non-linear partial differential equations that describe groundwater flow and solute transport through porous media. Many researchers have developed various groundwater flow and solute transport models to study the transport of solutes in a groundwater flow system. A finite-difference density-dependent groundwater flow and solute transport model, HST3D (Heat and Solute Transport in saturated 3-Dimensional Groundwater Flow System) developed by Kipp (1987) is adapted to simulating the solute transport in the groundwater flow system with pumping wells.

Groundwater Flow Equation

The major reasons for selecting a three dimensional groundwater model is for cases where a vertical salinity gradient exists in the groundwater reservoir. In many arid areas, higher salinity concentrations, which are also slightly more dense, are encountered at deeper depths in the groundwater reservoirs. In some cases, these higher salinity concentrations are largely the result of salts taken into solution from the underlying geologic formations, particularly when they are of marine origin. If pumping occurs, there is a high potential for salinizing the groundwater reservoir after a few decades unless the groundwater is carefully managed, which usually requires lower discharge capacity wells (e.g. fractional tubewells of perhaps only 10 liters per second in some areas of the Punjab in Pakistan as reported by McWhorter [1980]).

In the HST3D model, the groundwater flow equation, which is based on the conservation of total fluid mass in a volume element, coupled with Darcy's law for flow through a porous medium, is expressed as:

$$\frac{\partial(\epsilon\rho)}{\partial t} = \nabla\rho\frac{k}{\mu}(\nabla p+\rho g)+q\rho^{*} \tag{1}$$

Where p is the fluid pressure; t is the time; ϵ is the porosity; ρ is the fluid density; ρ^{*} is the density of a fluid source; k is the porous-medium permeability; μ is the fluid viscosity; g is the gravitational constant; and q is the fluid-source flow-rate intensity (positive for inflow and negative for outflow). In HST3D, the pore or interstitial velocity is obtained from Darcy's Law as:

$$\underline{v}=-\frac{k}{\epsilon\mu}(\nabla p+\rho g) \tag{2}$$

where $\underline{v}$ is the interstitial velocity vector.

Solute Transport Equation

The HST3D solute transport simulation is based on an advective-dispersive mechanism for solute transport. Ignoring adsorption, dissolution, production and decay of solute species, the mass of solute stored in a particular volume of solid matrix may change with time because of ambient water with a different concentration flowing in, injected water having a different concentration, change in the total fluid mass in the element, solute diffusion, or dispersion in or out of the volume.

In HST3D, the partial differential equation, which describes the solute transport in the porous medium, is expressed as:

$$\frac{\partial(\epsilon\rho w)}{\partial t} = \nabla\epsilon\rho D_s\nabla w+\nabla\epsilon\rho D_m I\nabla w-\nabla\epsilon\rho\underline{v}w-\lambda\epsilon\rho w-\rho_b R_{fs}+q\rho^* w^* \tag{3}$$

where w is the mass fraction of solute in the fluid phase; w^* is the mass fraction of solute in the fluid source; D_s is the mechanical dispersion coefficient; D_m is the molecular diffusivity of the solute; λ is the decay rate constant; R_{fs} is the transfer rate of solute from the fluid to the solid phase per unit mass of solid phase; ρ_b is the porous medium bulk density; and I is the identity matrix.

The groundwater salinity model was used in order to predict the future salinity concentrations of pumped water with time. A schematic diagram of the groundwater salinity model is given in Figure 6. The groundwater flow simulation portion of the groundwater salinity model uses input information on the physical dimensions of the aquifer in the study area, properties of the porous media, properties of the fluid, well data and recharge to the groundwater reservoir. This simulation provides predictions on the spatial and temporal pressure distribution in the aquifer, which reflects the movement of groundwater in the aquifer.

The solute transport portion of the groundwater model employs input data on initial salinity concentration distribution in the groundwater body, solute transport parameters, and the chemical quality of recharge water entering the groundwater. The solute transport subprogram predicts the salinity concentration distribution in the groundwater system of the area with time, as well as the temporal variation of salinity in producing wells present in the groundwater aquifer.

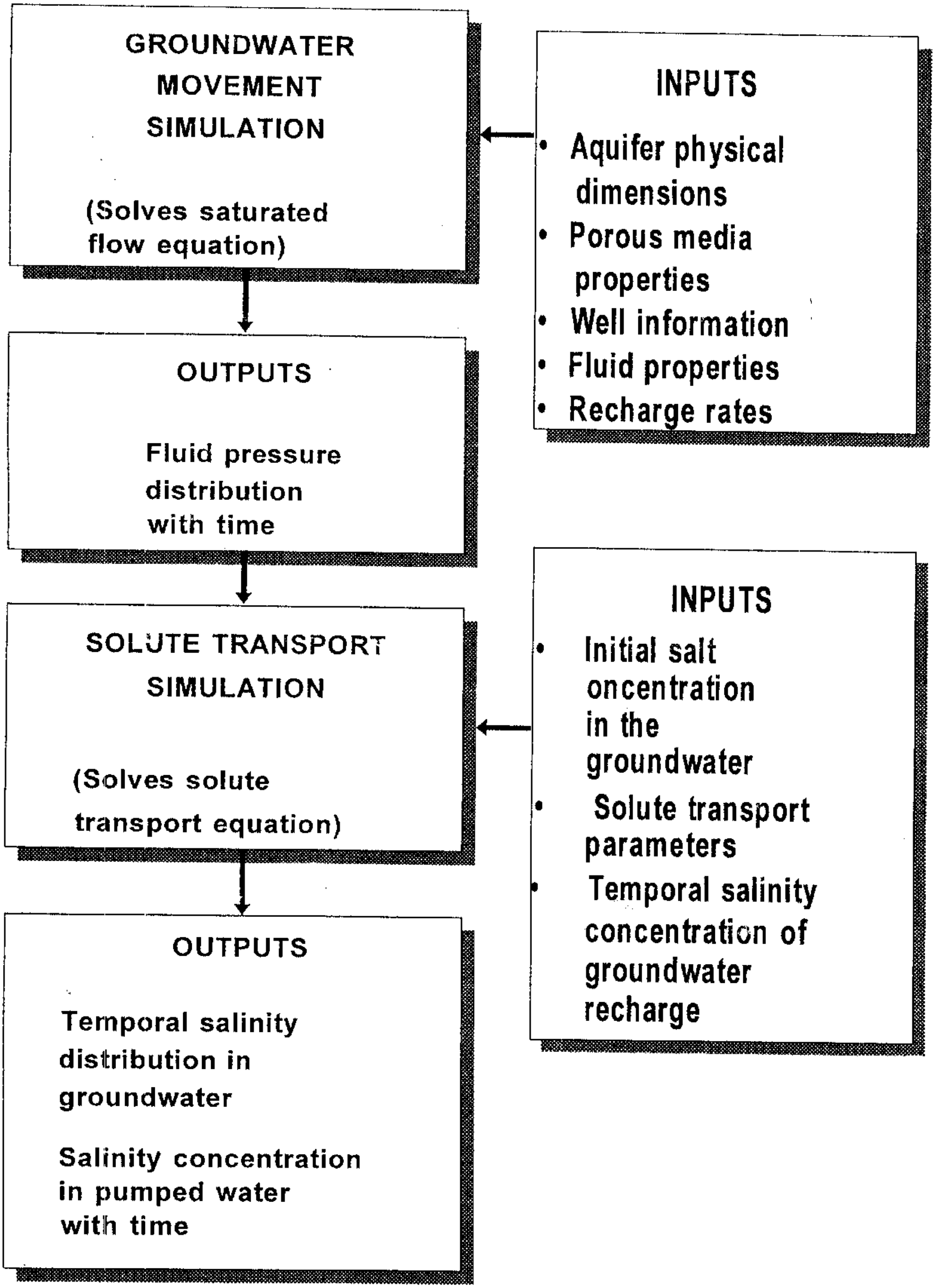

Figure 6. Schematic Diagram of the Groundwater Salinity Model.

PREDICTING FUTURE TUBEWELL SALINITY DISCHARGES

Computer models are invaluable predictive tools for studying the long-term groundwater salinity trends and impacts of various management alternatives upon groundwater salinity. However, extensive and reliable field data are essential for reliable model predictions. In the Rechna Doab study, an existing finite difference three-dimensional groundwater model, HST3D, that takes into account the vertical salinity gradient in the aquifer, was employed to predict the future long-term trends of groundwater salinity changes in pumped groundwater considering the existing and the reduced discharges of the producing wells.

For model calibration, the input data on areal extent, thickness, and other physical and chemical characteristics of the unconfined aquifer were obtained from published research. Information on historic salinity of the pumped groundwater and pumping well characteristics were obtained from SMO data sets.

As a first case, eight public tubewells of SCARP-I, namely, CK23 from the Chuharkana reclamation scheme, SH200 from the Sangla Hill reclamation scheme, SKT34 and SKT137 from the Shahkot reclamation scheme, and ZW137, ZW217, ZW241, and ZW337 from the Zafarwal reclamation scheme were selected for the groundwater modeling study. The various reclamation schemes of SCARP-I are shown in Figure 7. The abovementioned tubewells were selected due to the availability of a data base for a long time period and the presence of private tubewells surrounding them. The data base on groundwater quality from the SMO makes it easier to compare the observed values of salinity concentrations of pumped water with those simulated by the model. Understanding the behavior of groundwater salinity variation in public tubewells makes it easier to understand the behavior of quality changes in the private tubewells. An effort was made to select the tubewells whose water quality was deteriorating with time in order to study the behavior of salinity variation for pumped groundwater in each case. The water quality data of the eight selected tubewells for a period of 29 years (1960-1989) obtained from SMO of WAPDA are presented in Table 2.

Table 2. Water Quality Data for Selected SCARP-I Tubewells (TDS, ppm).

Tubewell Name	YEARS						
	1960	1965.	1970	1975	1980	1985	1989
CK23	486	461	896	832	896	-	-
SH200	2150	2180	2304	-	-	-	-
SKT34	2000	920	1820	-	628	1380	1040
SKT137	1600	1700	-	-	-	2060	-
ZW137	1920	2240	-	-	-	2400	-
ZW217	1197	1710	-	-	-	2360	-
ZW241	1280	1940	-	-	-	2496	-
ZW337	992	1120	-	-	-	2020	-

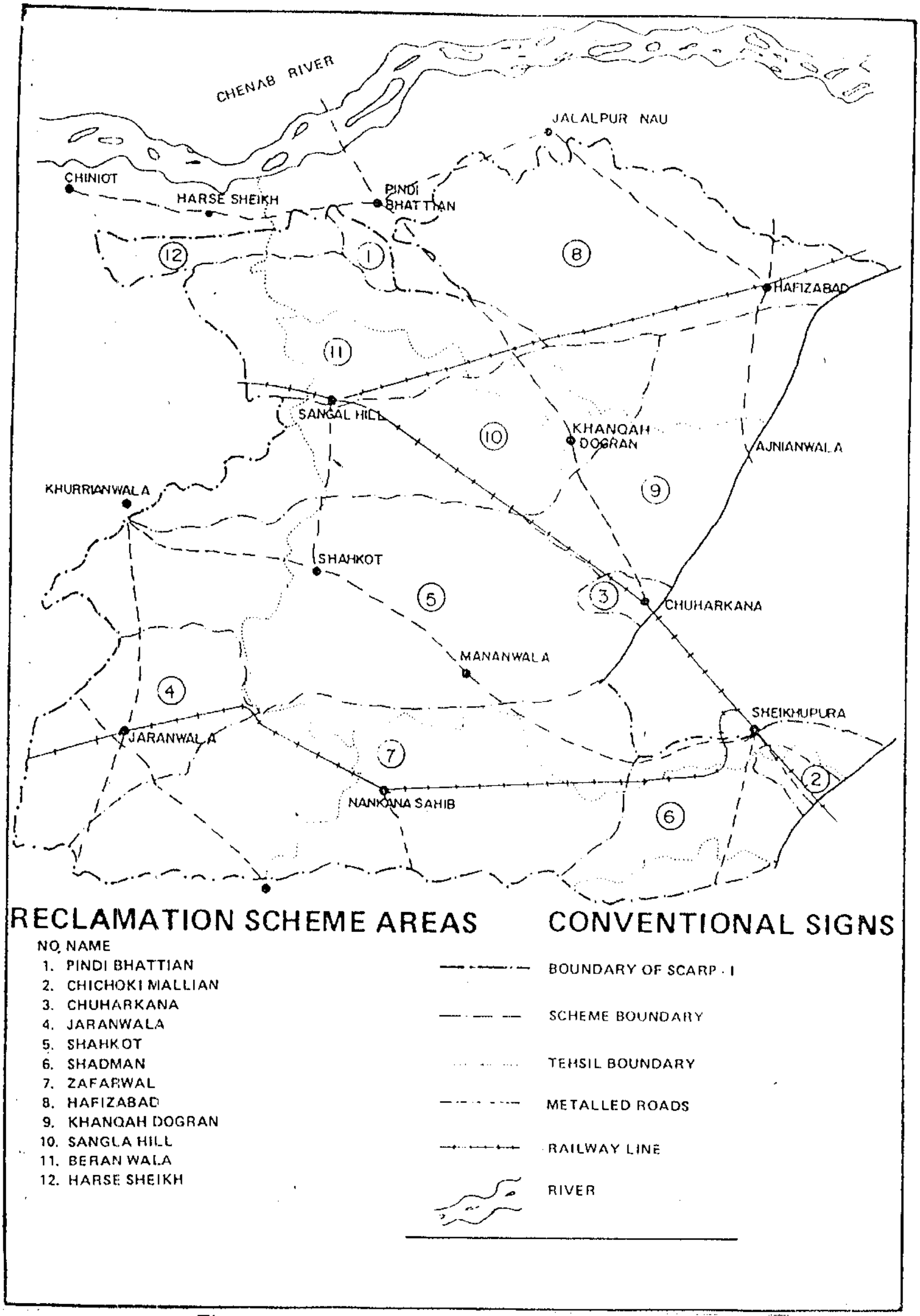

Figure 7. Reclamation Scheme Area of SCARP-I.
(Source: Awan, 1988)

The water quality values for CK23 and SKT34 tubewells given in Table 2 indicate almost the same trend (i.e., in some years the water quality is deteriorating while in others it is improving) which may be due to groundwater aquifer recharge resulting from heavy rainfalls and floods during those years. For some years, the groundwater quality data are missing. The water quality values for SKT137, ZW137, ZW217, ZW241 and ZW337 tubewells indicate an increasing trend in the salinity concentrations with time.

In order to investigate the temporal variation of pumped water salinity concentration from the selected 8 tubewells of SCARP-I on a local scale, the dimensions of the simulation regions were taken as 3000 meters (m) in the x-direction, 4000 m in the y-direction and 305 m in the z-direction. Seven equally spaced nodes were defined to discretize the region in the x-direction, nine nodes were distributed in the y-direction and ten nodes were used in the z-direction. The z-direction was oriented vertically upward. The lower and outer boundaries were assumed as no flow boundaries and the upper boundary was assumed to be an unconfined aquifer free surface. The areal recharge flux was set to - 6.2823E-9 m^3/m^2s with the negative sign denoting flux in the negative z-direction. The salinity concentration associated with the recharge flux was set at 300 ppm, which determines the amount of solute that enters through the free surface. The initial solute concentration in the simulation region ranged from 150 ppm to 5000 ppm from top to bottom of the region for Tubewell CK23, from 210 ppm to 5000 ppm for Tubewells SKT34 and ZW337, and from 210 ppm to 6000 ppm for SKT137, SH200, ZW137, ZW217 and ZW241. The discharge for Tubewell ZW337 was 70.80 l/s and the recharge flux was - 5.7990866E-9 m^3/m^2s. The values of initial salinity concentration in the aquifer were derived from the book on "Groundwater Resources of Pakistan", written by Nazir Ahmed, 1995. A fixed time-step of 60 days was used for a total simulation of 50 years.

The data on aquifer dimensions, physical properties of the fluid and porous media, solute transport parameters, and pumping wells are given in Table 3.

Table 3. Groundwater Model Input Data For SCARP-I Tubewells.

Porous medium and fluid physical properties	
aquifer thickness	305 m
aquifer permeability	1.2244898E-12 m^2
porous media porosity	0.25
porous media compressibility	0. pa^{-1}
fluid density	1,000 kg/m^3
fluid viscosity	0.0013 kg/m-s
fluid compressibility	0. pa^{-1}
temperature of region	20° C
longitudinal dispersivity	5.0 m
transverse dispersivity	5.0 m
Well information:	
well radius	0.13 m
well depth	102 m
pumping rate	84.96 l/s

The aquifer was assumed to be homogeneous and isotropic, though the model can also handle heterogeneous and anisotropic aquifers. Employing the required input data, the groundwater model was run for several times for a period of 25 years (1960-1985) in order to simulate the salinity concentration of pumped water and to have a reasonable match between the observed and simulated groundwater salinity. After achieving this agreement, the model was run for a period of 40 years (1960-2000) for CK23 and 50 years (1960-2010) for other tubewells in order to develop predictions on groundwater salinity beyond 1985.

For modeling purposes, six tubewells, namely, STN4, SNT6, STN9, STN12, STN32 and STN61 were also selected from the Satiana Pilot Project whose water quality data, whcih are available during 1981 and 1986, are provided in Table 4. The period of 1981-1986 was used for calibration of the model because groundwater quality data of pumped water were available for the selected tubewells for this period.

Table 4. Water Quality Data for Selected Satiana Pilot Project Tubewells (TDS, ppm).

Tubewell Name	YEARS	
	1981	1986
STN4	2560	2656
STN6	1293	2048
STN9	2086	2240
STN12	3840	3962
STN32	1024	1664
STN61	2240	2310

The same grid size was used for the selected tubewells as was employed for SCARP-I tubewells. The pumping capacity for all of the selected Satiana Tubewells was set equal to 78.8 l/s as found in the field and the recharge flux was equal to -5.7990866E-9 m^3/m^2s with its salinity concentration of 300 ppm. The initial solute concentration in the simulation region ranged from 210 ppm to 7000 ppm from top to bottom of the region for Tubewells STN4, STN6, STN9, STN32 and STN61, and from 210 ppm to 8000 ppm for STN12. The other required input information was from Table 3.

Various runs were made in order to have a reasonable match between the observed and simulated groundwater quality of pumped water for the study tubewells. Then, the model simulations were run to year 2010 in order to predict temporal salinity concentration changes in the pumped groundwater.

The model was also calibrated for a density of eight tubewells (STN29, STN30, STN31, STN43, STN44, STN 45, STN46 and STN47) over 3375 hectares of area within the Satiana Pilot Project. In this case, the dimensions of the simulation region were taken as 7500 m in the x-direction, 4500 m in the y-direction and 305 m in the z-direction. Sixteen equally spaced nodes were distributed in the x-direction, ten nodes were defined separately in the y- and in the z-directions. The same boundary conditions were simulated as assumed before. The areal recharge flux was set to - 1.2564688E-8 m^3/m^2s with its salinity concentration of 300 ppm. The initial solute concentration in the simulation region ranged from 100 ppm to 5000 ppm from top to bottom of the region for Tubewells STN29, STN31 and STN44, from 150 ppm to 5000 ppm for Tubewell STN30, from 700 ppm to 5000 ppm for STN43, from 400 ppm to 7000 ppm for STN45, from 200 ppm to 5000 ppm for STN46, and from 120 ppm to 5000 ppm for STN47. The discharge for all of the tubewells was 70.80 l/s.

The results of this modeling study for CK23, ZW217, STN9, STN12 and the 8 tubewells of Satiana Project are presented in Figures 8 through 17. Figure 8 reveal the change in salinity of pumped water in the range of about 270 to 1130 ppm, whereas Figure 9 indicates a range of salinity variation from 470 to 1240 ppm for Tubewell CK23. during the period of 1960 to 2000. Clearly, Figure 8 shows a lower salinity variation range and Figure 9 shows the higher prediction of salinity variation with time. These two figures indicate that the salinity concentration of pumped water could vary between these two ranges during the period of 1960 to 2000.

The impact of various discharges on salinity of pumped water is depicted in Figures 10 and 11 considering the cases of Figures 8 and 9, respectively. Figure 10 shows that the salinity concentration varies from 270 to 1130 ppm, 260 to 900 ppm, 260 to 770 ppm, 260 to 630 ppm, 250 to 450 ppm for discharges of 84.96, 56.84, 42.48, 28.32 and 14.16 l/s, respectively. Figure 11 indicates the salinity variation ranges from 470 to 1240 ppm, 470 to 1020 ppm, 470 to 910 ppm, 470 to 790 ppm, 470 to 630 ppm for discharges of 84.96, 56.84, 42.48, 28.32 and 14.16 l/s, respectively. The increase in salinity in percentage during the 1960 to 2000 period corresponding to discharge values in percentage of the maximum discharge was calculated from the results shown in Figure 10 (Case 1) and Figure 11 (Case 2). Figure 12 shows a plot of the percent increase in salinity concentration of pumped water versus the percent of the maximum discharge, resulting in two curves representing Case 1 and Case 2. These two curves provide a range of salinity concentration increase in pumped water corresponding to a particular discharge in percentage of the maximum discharge. For example, for a discharge value of 100 % of maximum discharge (84.96 l/s), the salinity concentration of pumped water will increase within the range of 163 % to 318 % during the period of 1960 to 2000. Likewise, if the pumping rate is only one-sixth (14.16 l/s) of the maximum discharge rate, the salinity of pumped water will only increase 25-80%.

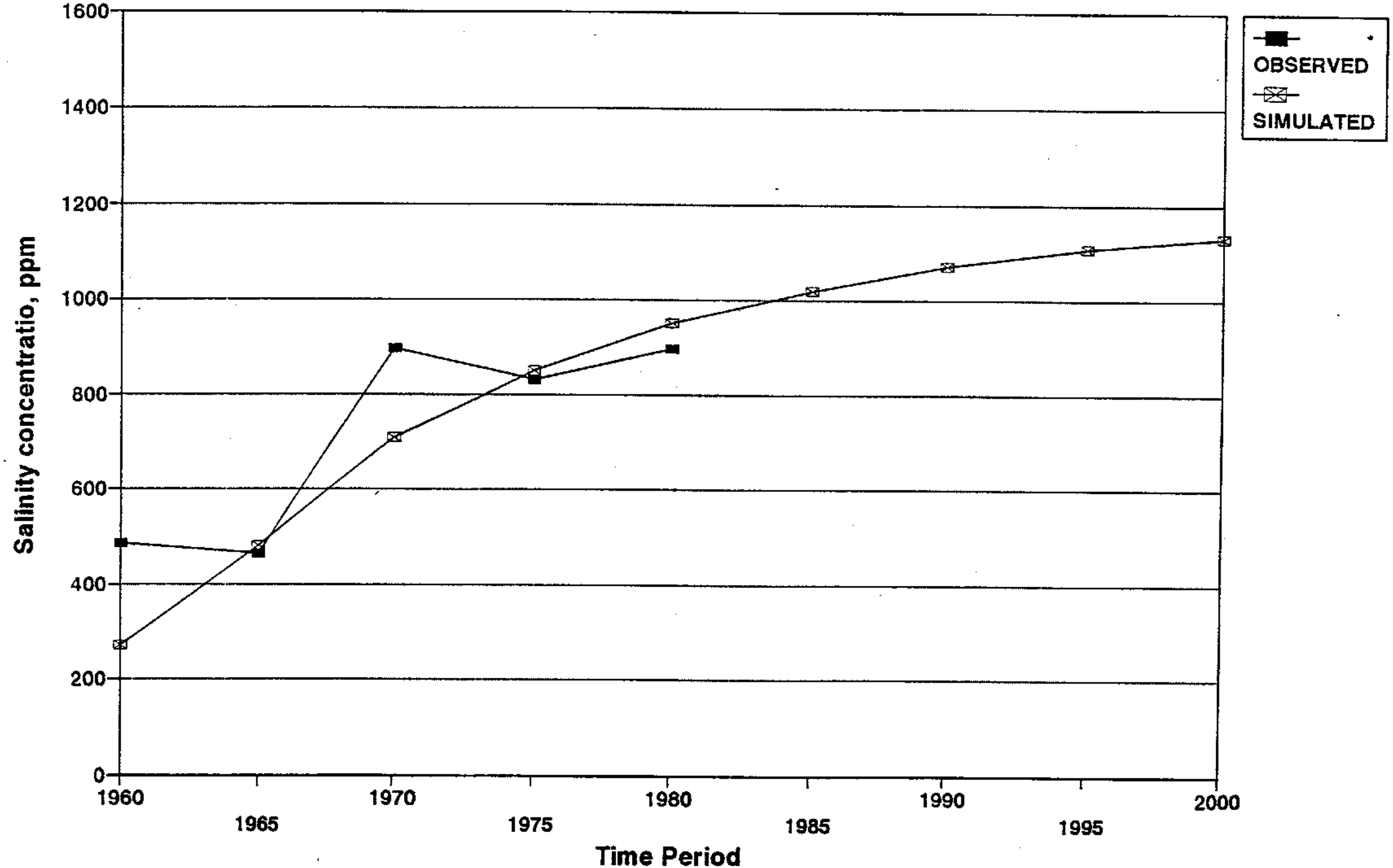

Figure 8. Observed and simulated groundwater salinity vs. time period for Tubewell CK 23 (siumlation without adjusting initial salinity in the aquifer).

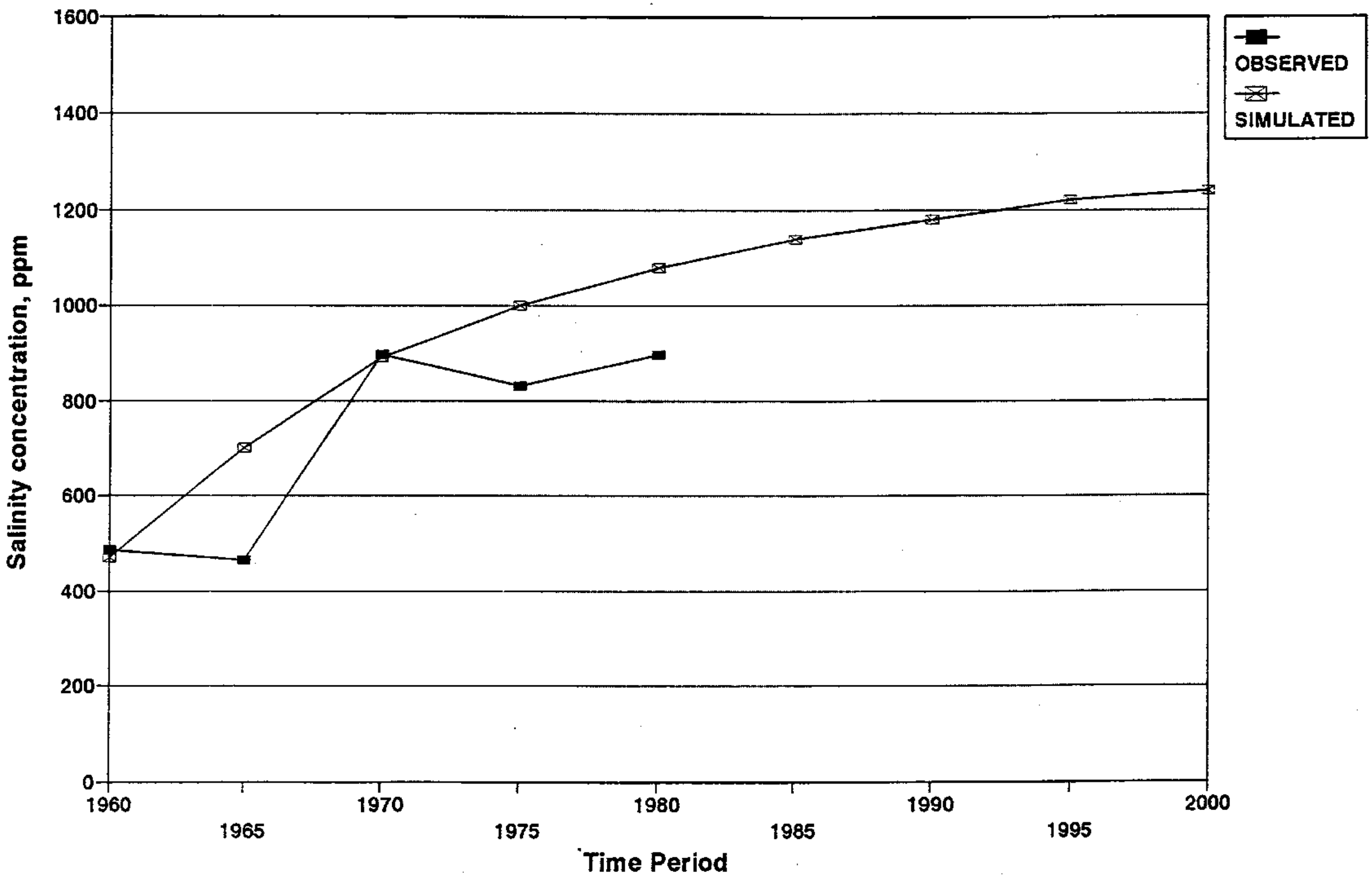

Figure 9. Observed and simulated groundwater salinity vs. time period for Tubewell CK23 (siumlation with adjusting initial salinity in the aquifer).

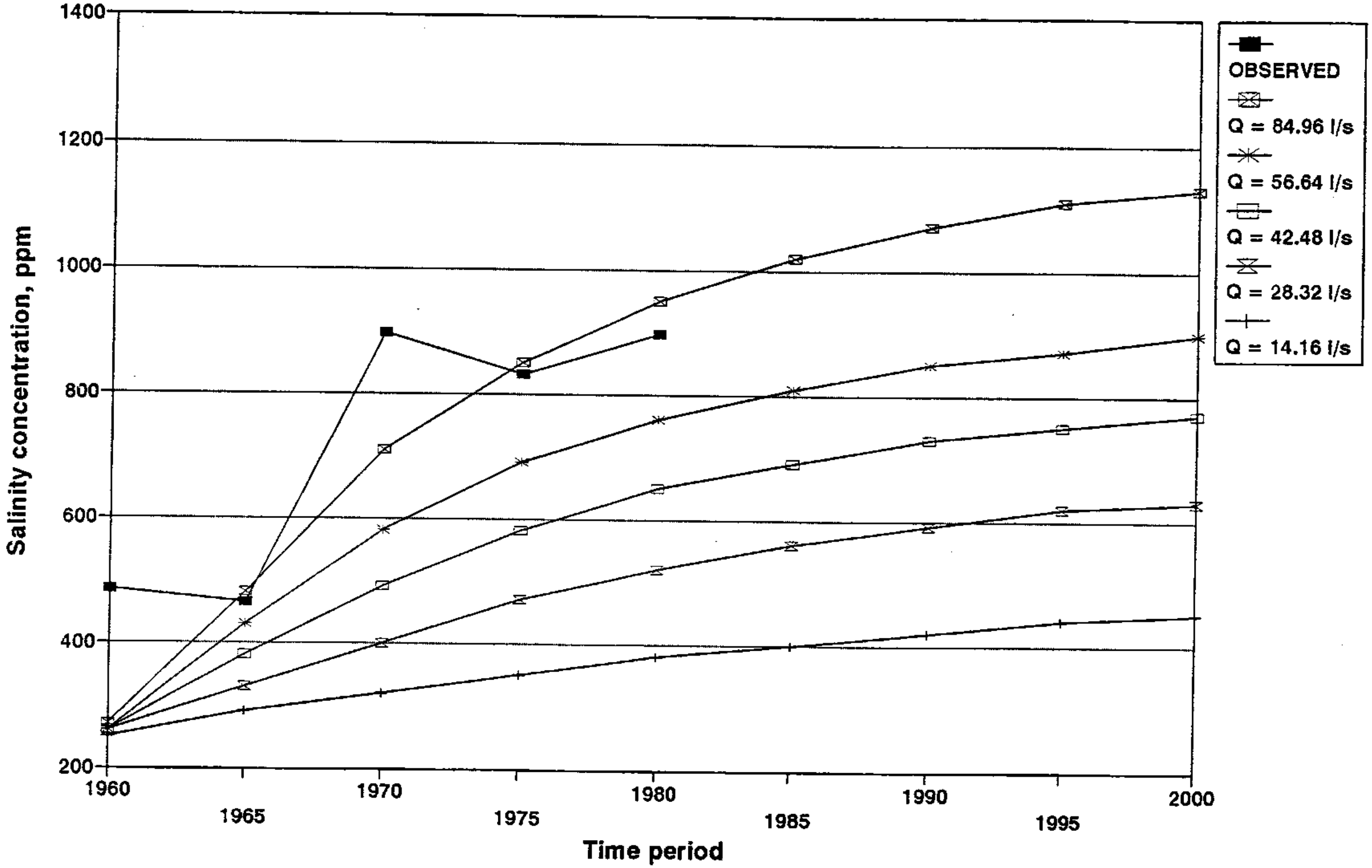

Figure 10. Salinity of groundwater vs. time period for Tubewell CK23 (discharge range of 84.96 l/s to 14.16 l/s, Case 1).

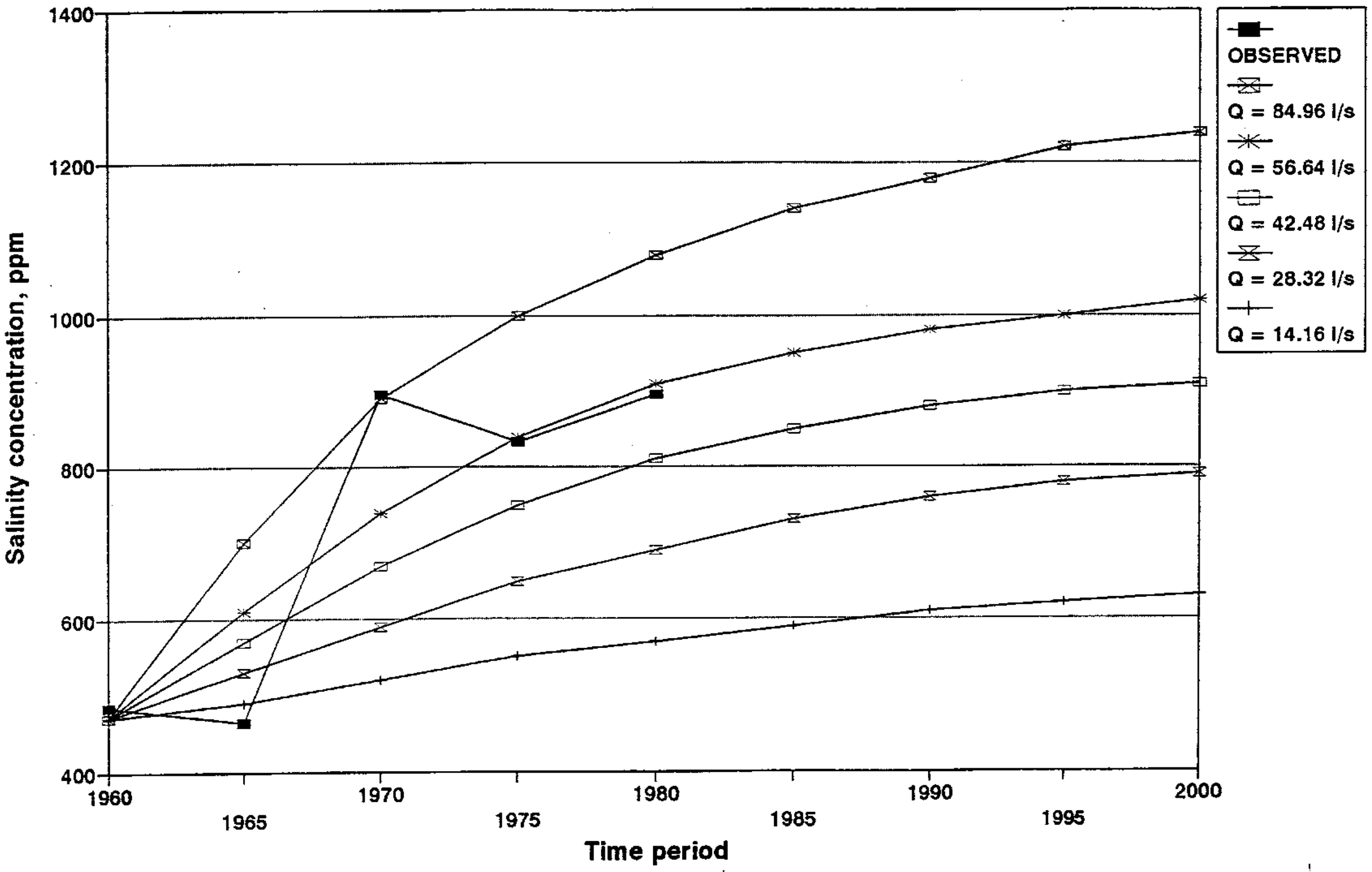

Figure 11. Salinity of groundwater vs. time period for Tubewell CK23 (discharge range of 84.96 l/s to 14.16 l/s, Case 2).

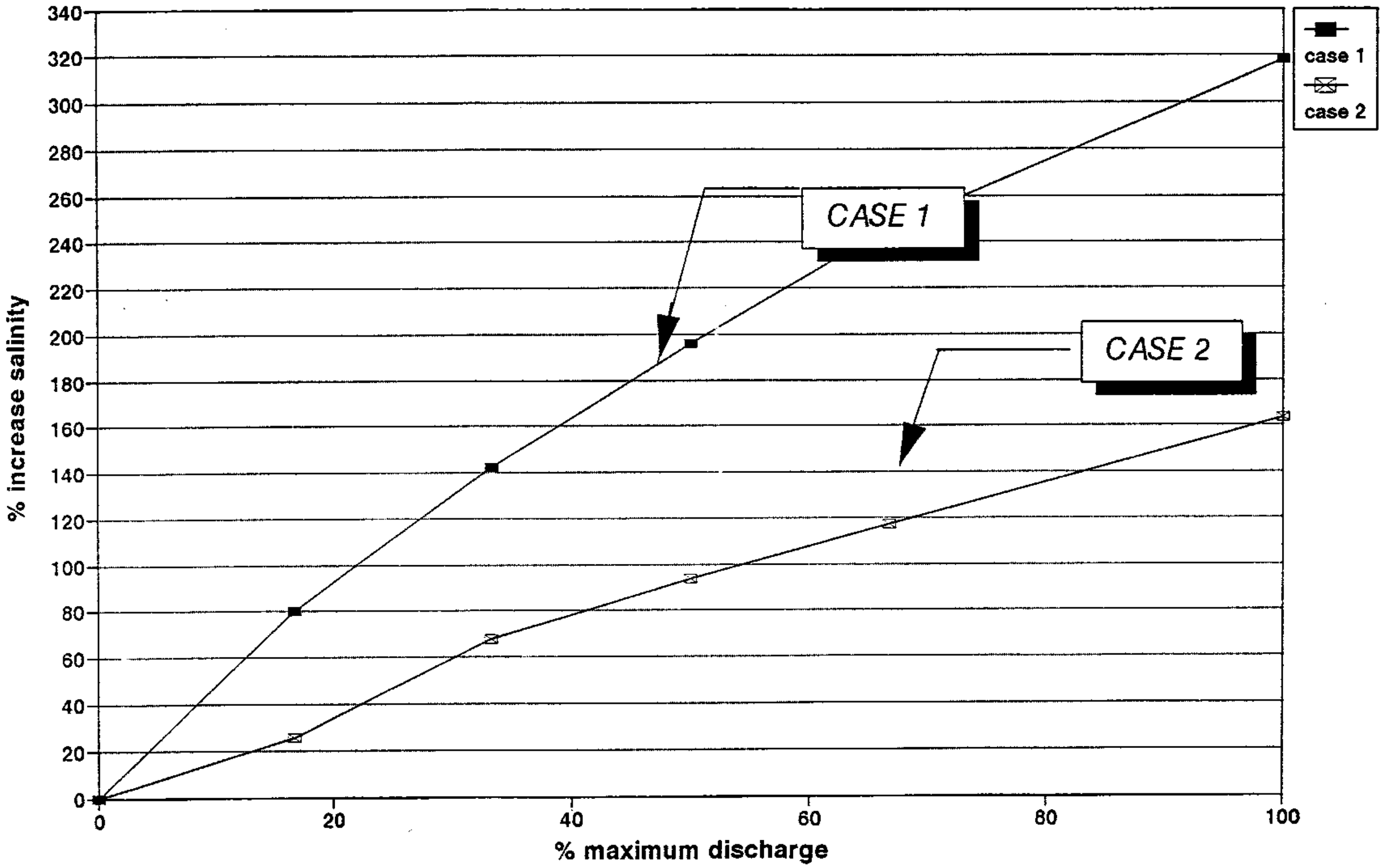

Figure 12. Percent increase in salinity of groundwater vs. percent of maximum discharge for Tubewell CK23 over the time period 1960-2000.

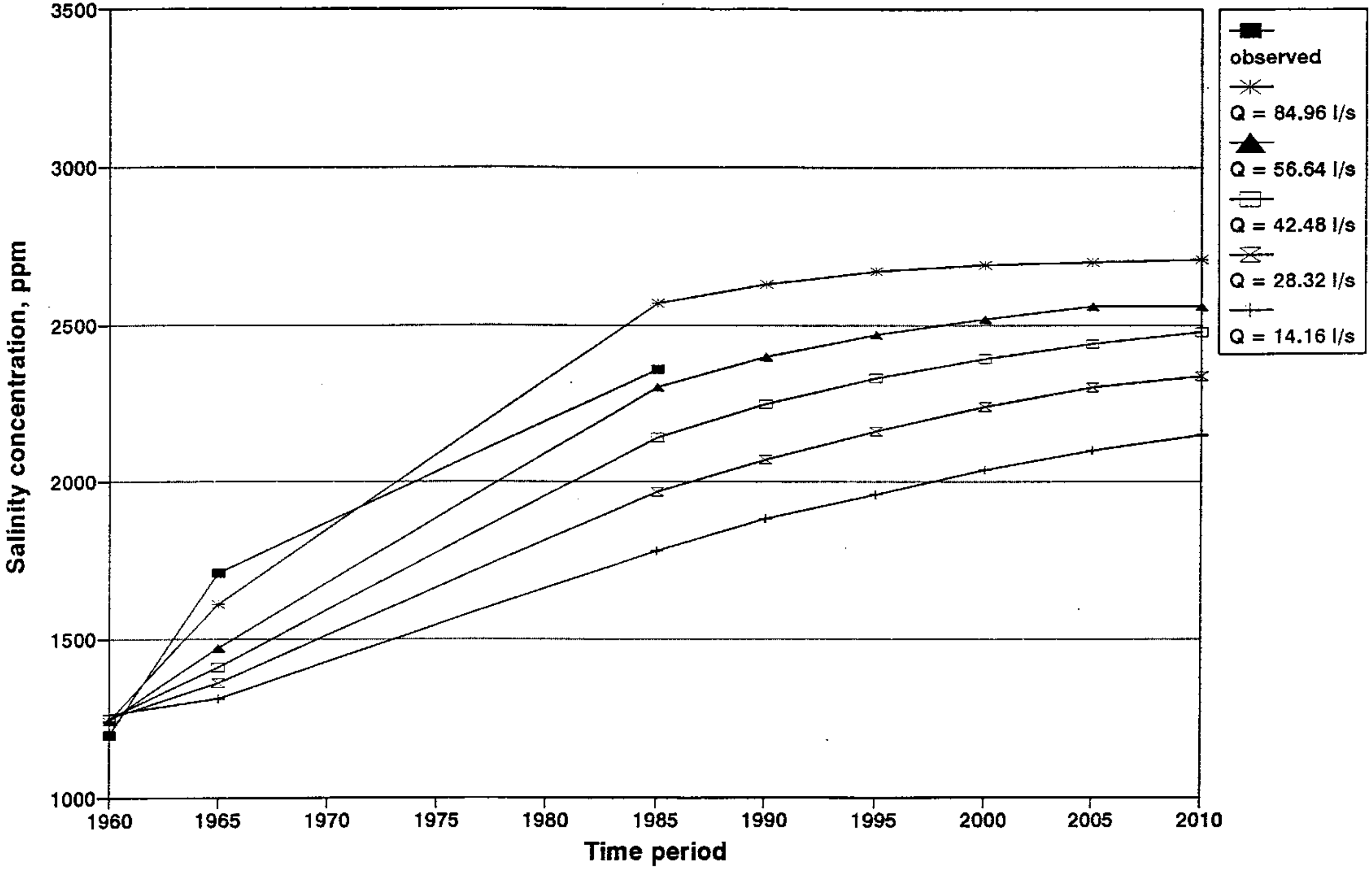

Figure 13. Salinity of groundwater vs. time period for Tubewell ZW217.

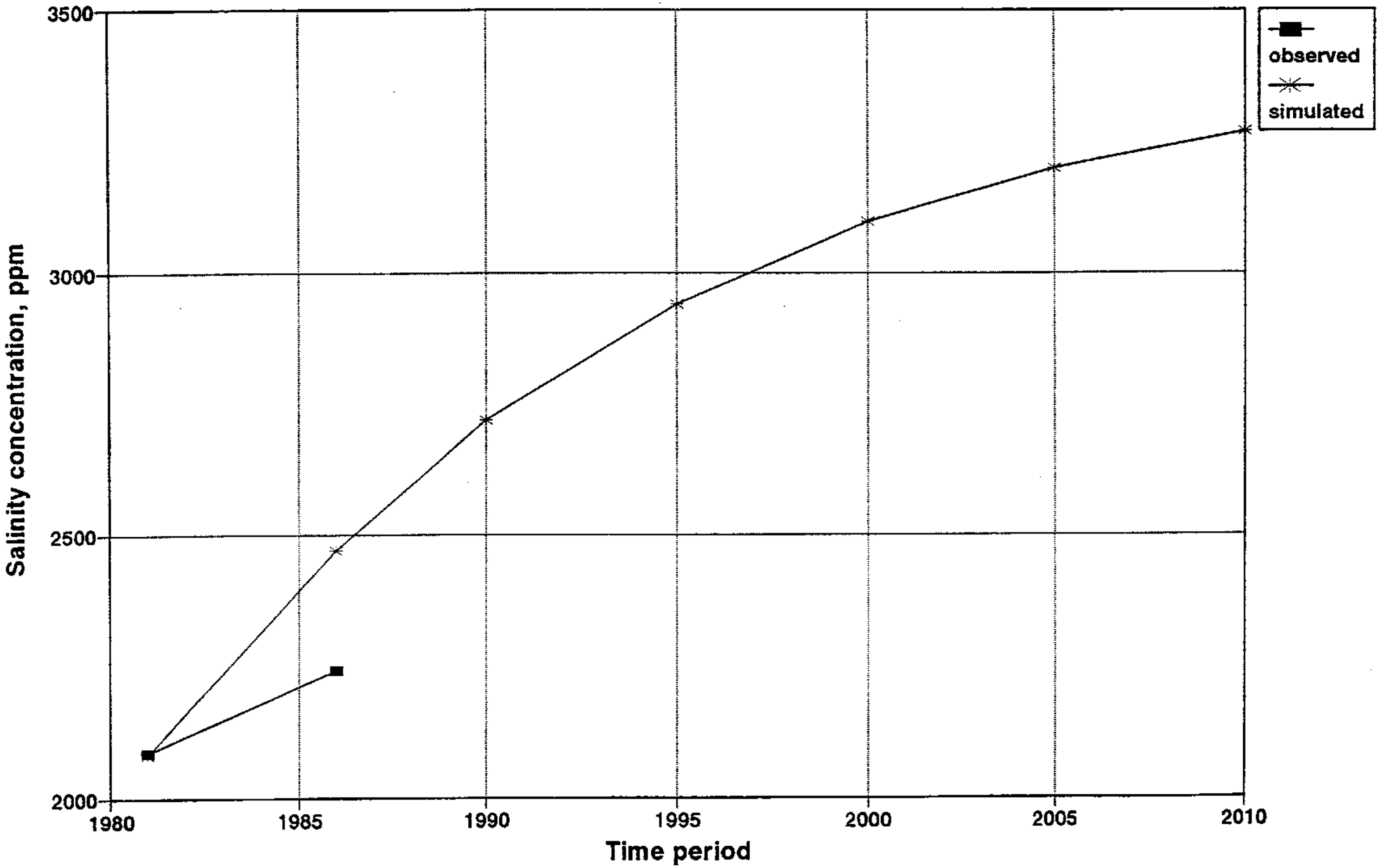

Figure 14. Salinity of groundwater vs. time period for Tubewell STN9.

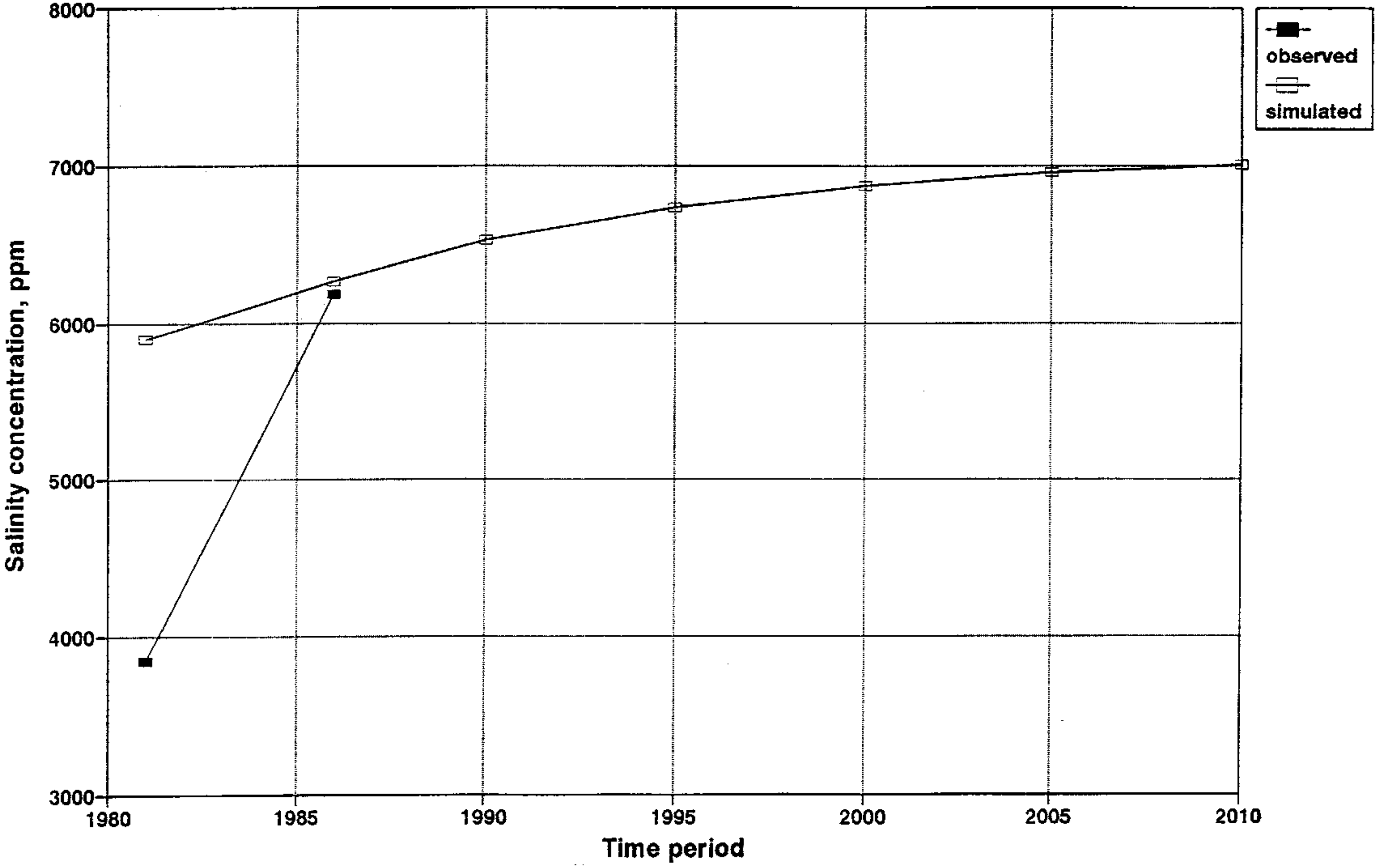

Figure 15. Salinity of groundwater vs. time period for Tubewell STN12.

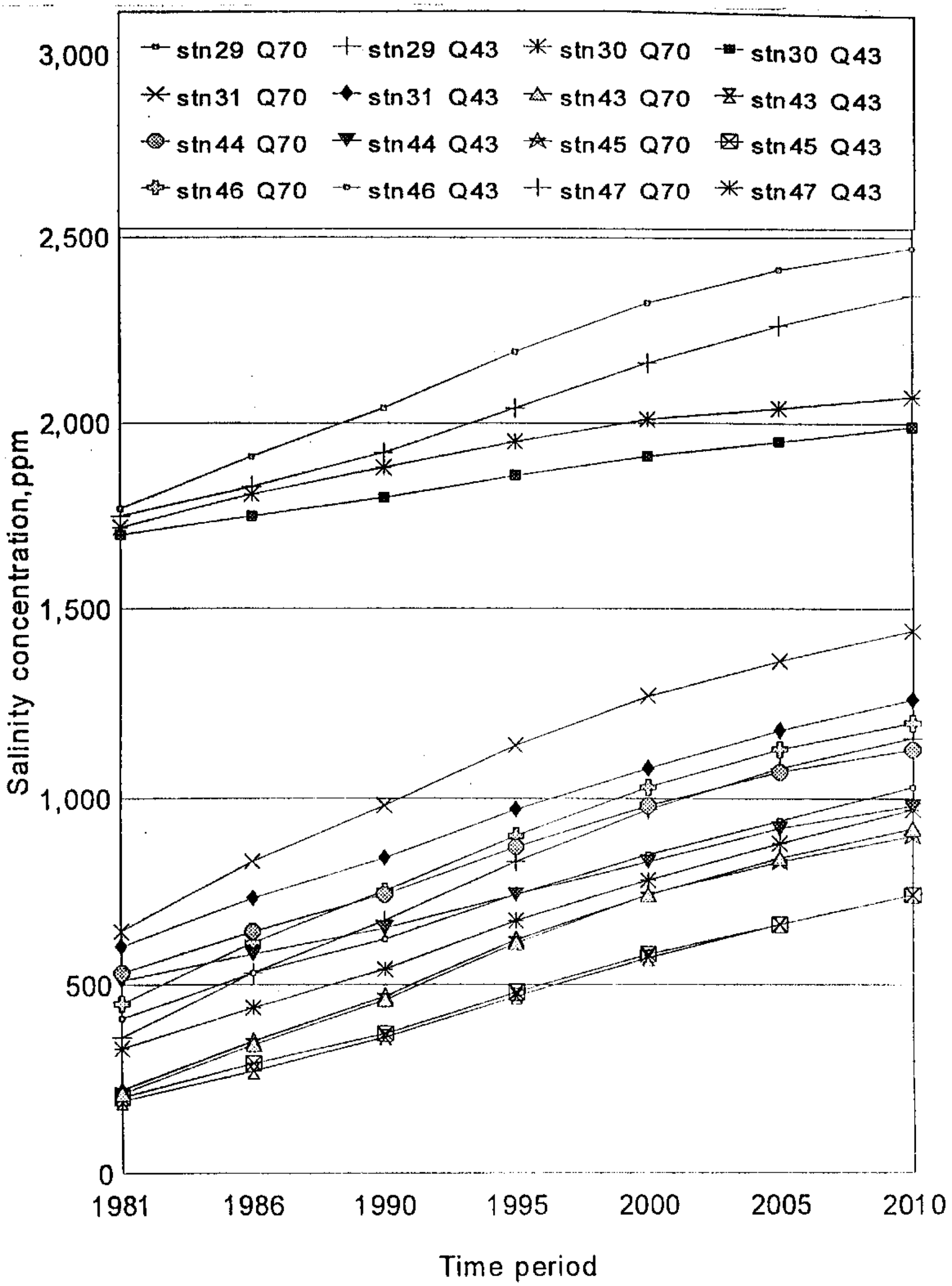

Figure 16. Salinity of groundwater vs. time period for Q = 70 & 43 l/s (density of 8 tubewells in Satiana Project).

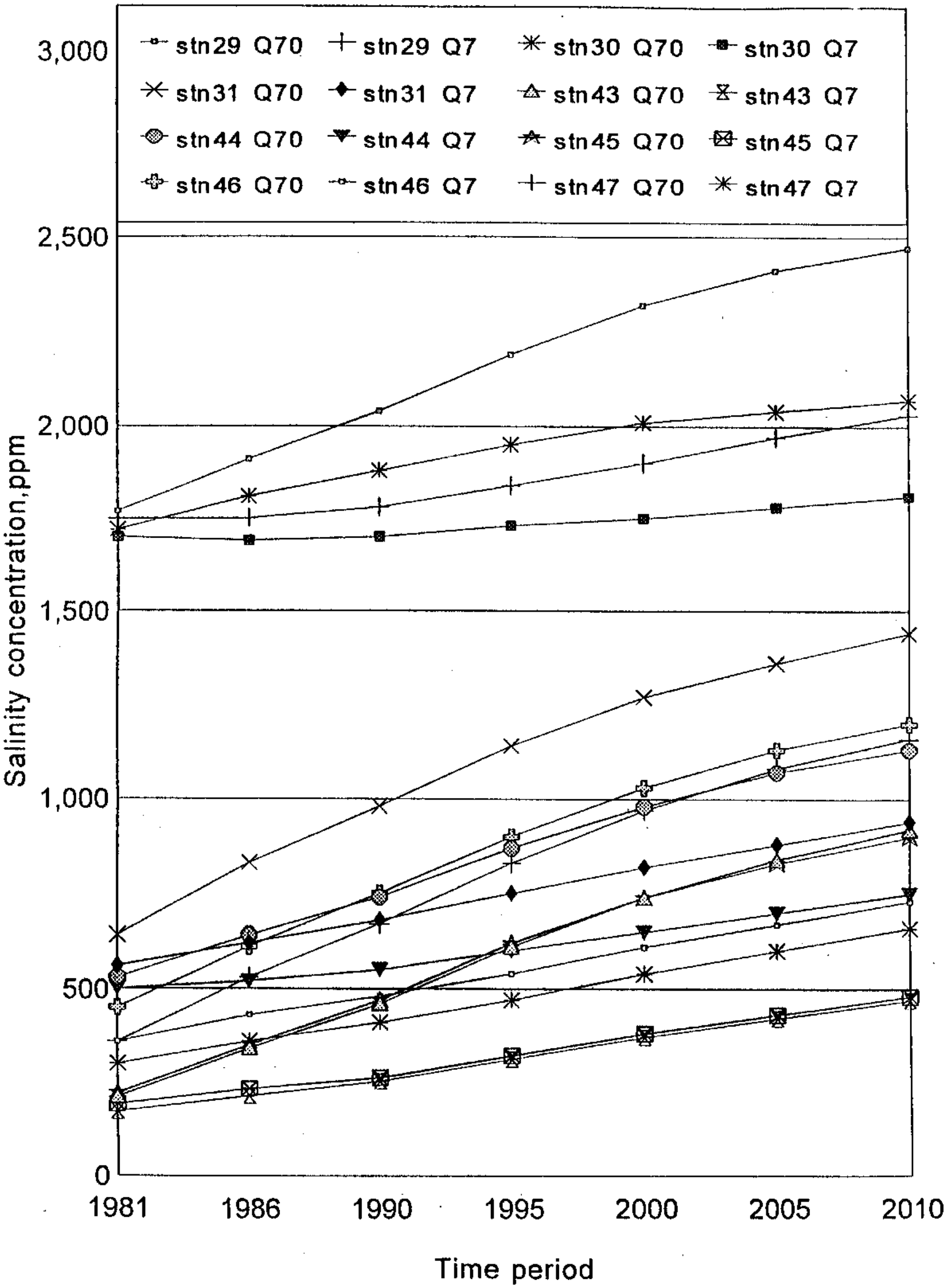

Figure 17. Salinity of groundwater vs. time period for Q = 70 & 7 l/s (density of 8 tubewells in Satiana Project).

Figure 13 shows the results of model simulations for Tubewell ZW217 having a discharge range of 84.96 to 14.16 l/s. The curves in this figure reveal that the salinity concentration of pumped water varied from 1240 to 2710 ppm, 1240 to 2560 ppm, 1250 to 2480 ppm, 1250 to 2340 ppm, 1260 to 2150 ppm for discharges of 84.96, 56.84, 42.48, 28.32 and 14.16 l/s respectively. Clearly, for the lowest value of discharge (14.16 l/s), the model showed a much smaller change in salinity concentration over the time period of 1960 to 2010.

The results of model simulations for Tubewells STN9 and STN12 are shown in Figures 14 and 15. In the case of STN9, the salinity concentration varied from 2080 to 3270 ppm during the 1981 to 2010 period and for STN12, the salinity increased from 5900 to 7010 ppm over the same time period of 1981 to 2010. Figures 16 and 17 reveal the impact of reduction in pumping discharge on salinity concentration of pumped water for a density of 8 tubewells in Satiana Project. For example, for STN29 pumping at 70, 43, and 7 l/s, the salinity concentration of pumped water increased from 1770 to 2470 ppm, 1750 to 2340 ppm and 1750 to 2030 ppm. Similarly, for STN30, at discharges of 70, 43, and 7 l/s, the salinity variation ranged from 1720 to 2070 ppm, 1700 to 1990 and 1700 to 1810 ppm, respectively. Figures 16 and 17 clearly show that at reduced discharge rates, the model predicted a much smaller change in salinity concentration of pumped water over the time period of 1981 to 2010. The modeling exercise has shown that the groundwater model predicted the temporal variations in salinity concentration of pumped groundwater fairly well.

ISSUES AND OPTIONS

The main ***issues*** related to groundwater irrigation are: (1) inequitable and unreliable canal water distribution; (2) groundwater quality; (3) salt balance; and (4) cropping pattern shift. The *options* being suggested for environmentally sustainable irrigated agriculture are: (1) equitable and reliable water distribution; (2) skimming well technology; (3) revision of water allocations; (4) low-delta crops; (5) on-farm water management; (6) conjunctive use; (7) farmer's awareness of land reclamation; and (8) monitoring of salt balance.

Issues

Inequitable and Unreliable Canal Water Distribution

Inequitable and unreliable canal water distribution caused by water shortage, poor operation and maintenance of the irrigation system, weak institutions, and illegal cuts and breaches by the farmers having large land holdings, is creating a heavy dependence on groundwater irrigation for agricultural production. In some cases, groundwater accounts for 50 to 70 percent, even 100 percent, of the total irrigation supplies. The majority of the tubewells are pumping marginal to poor quality groundwater use of which is causing a gradual increase in salinity and sodicity in the soil profile, which is a serious concern for sustainable irrigated agriculture in the Indus Plain.

Groundwater Quality

In Pakistan, in most of the cases, soil salinity is caused by shallow saline groundwater, but intensive use of poor quality groundwater without improving its quality is also converting good agricultural lands into salt-affected lands. Approximately 70 to 80 percent of tubewells of the Indus Plain pump sodic water because of which 2 to 3 million hectares of land have become sodic/saline (Rafiq, 1990).

Upper Rechna contains fresh water of 500 ppm, but in central and lower portion of the Rechna Doab, groundwater salinity concentrations varies from 3,000 to 18,000 ppm. IIMI's research on tubewells operation and quality of pumped water in LCC system of Rechna Doab has shown that all of the tubewells in watercourse commands of Lagar Distributary are pumping poor quality groundwater which is unfit for irrigation. If the present trend of pumping of groundwater and its use continues, it will pose the following problems:

- over exploitation of groundwater resource will occur due to excessive growth of tubewells in the irrigated areas;
- the use of poor quality groundwater for irrigation will cause a gradual build-up of salinity/sodicity in the soil profile due to which acreage of unproductive land will increase with time;
- farmers would need to bear extra expenditures for improving the quality of groundwater by using chemical amendments like gypsum and acids and also for reclaiming the salinized soils, otherwise farmers will get low crop yields from the affected lands or they will have to abandon those lands from cultivation permanently; and
- in the long-run, the presently good quality groundwater will be depleted from the fresh water layer and subsequently saline water will be pumped from the lower layers of the aquifers, thereby aggravating the problem of salinity and sodicity in the soils of irrigated areas.

In the light of above discussion it becomes clear that groundwater quality is a major issue to be considered for sustainability of irrigated agriculture.

Salt Balance

The tubewell irrigation causes an increase in salt addition to the soils, making the salt balance issue important for sustaining the productivity of the irrigated lands. The questions related to salt balance are how much salts are being added to irrigated lands by canal and tubewell water, how much salts are being removed from the irrigated area, where the remaining salts are accumulating, how the quality of groundwater will vary through continued recycling of pumped water, and at what level salt balance should be monitored, answers to these questions may be partially obtained from salt balance of an area. The issue of salt balance needs to be considered in order to identify the areas of imbalance salt flows.

Cropping Pattern Shift

The change in cropping pattern has replaced the low delta crops to high delta crops like rice, sugarcane, etc., resulting in over-exploitation of groundwater resource that is causing aquifer mining and salinity/sodicity build-up in soil profiles of irrigated lands.

Options

Keeping in view the abovementioned issues related to groundwater quality and tubewell irrigation, following ***options*** are suggested for environmentally sustainable irrigated agriculture:

Equitable and Reliable Water Distribution

Equitable and reliable water distribution should be enhanced by Irrigation Department especially for areas having shortage of or no canal water as well as for areas having groundwater unfit for irrigation. Institutional and management capabilities of the PID need to be strengthened in order to improve the hydraulic performance of the irrigation systems, which currently causes inequity in surface canal water supplies and increased dependence of especially tail end farmers on pumped groundwater of poor quality, thereby causing the occurrence of more soil salinity problems. The improved irrigation system management would increase equity, reliability, and reduce the variability in canal water distribution in the irrigation system.

Skimming Well Technology

The installation of skimming wells (fractional wells) should be encouraged in order to skim good quality groundwater overlying poor quality water. The farmers should be provided with technical assistance on improved well design and better operating strategies so that they may operate their wells in such a way that the fresh water layer is neither mined nor degraded significantly in quality.

Revision of Water Allocations

Keeping in view the change in cropping pattern, water allocations should be revised in order to meet the current crop water requirements in the irrigated areas. For this purpose new storage structures and remodeling of irrigation system will be required. There may be two other possibilities for managing soil salinization caused by tubewell irrigation: (1) redistribution of canal water along a secondary canal to ensure more equitable distribution of good quality water and (2) change in water allocations between commands, mainly from good quality groundwater areas to poor quality groundwater areas, but it may increase salinization in the good quality areas without effectively improving conditions in other areas.

Low-Delta Crops

The growth of low delta (low water consuming) crops in place of high delta crops should be encouraged in order to decrease the use of poor quality groundwater for irrigation and consequently to control groundwater contribution to soil salinity and sodicity problem.

On-Farm Water Management

Past research has indicated that the farmers have tendency of overirrigation. Poorly leveled fields are considered to be a major factor causing overirrigation. Availability of tubewell water is another factor related to overwatering in irrigated lands. Research in Mona indicated that 13 to 18 centimeters (cm) depth of each irrigation rather than 8 cm is very common in irrigated lands. Provision of more or less than the desired quantity of water to the fields results in inefficient irrigation practices and also gives rise to waterlogging and salinity problems.

The technology for using available water supplies most efficiently should be adapted for improving on-farm irrigation water management practices. Irrigation scheduling techniques that answer the questions that when to irrigate and how much irrigation water to apply are very important to assist management in efficient use of irrigation water on the farm especially in the areas of limited water supply. By managing other production inputs too, the maximum crop yields could be achieved. The improved irrigation scheduling and irrigation practices like land levelling by laser technology and appropriate combination of irrigation methods (sprinkler and surface irrigation methods), could result in reduced seasonal irrigation water requirements and consequently help in controlling waterlogging and salinity conditions in irrigated areas.

Conjunctive Use

In order to use poor quality groundwater in conjunction with canal water for irrigation, farmers should follow the recommendations given by the scientists working on conjunctive use of canal water and groundwater. The sodic groundwater can be used by mixing required quantity of chemical amendments like gypsum or acids and saline groundwater can be used by ensuring adequate leaching of salts using additional canal water. Currently, use of poor quality groundwater without giving any consideration to its quality, is creating soil salinity and sodicity problems in irrigated lands.

Farmer's Awareness of Land Reclamation

In general, farmers are aware of the adverse effects of salinity on agricultural productivity and many farmers have the capacity of managing successfully field-level salinity by modifying their farming and irrigation management practices, keeping in view the inequity in canal water distribution and the resulting effects on soil salinity. Though farmers seem to have an idea about soil sodicity (which needs chemical amendments and leaching for reclamation) caused by using sodic groundwater, they are not able to mitigate this problem because farmers are not aware of chemical amendments and leaching requirements which reflects a strong relationship between the percentage of increasingly poor quality groundwater used and levels of irrigation-induced soil salinity/sodicity. Farmers should be made aware of using chemical amendments and leaching for improving tubewell water quality and reclaiming salt-affected lands.

Monitoring of Salt Balance

There should be monitoring and evaluation on regular basis of salt balance in the root zone and groundwater reservoir on canal command level(where values of hydrologic parameters are generally available) in order to have an idea about salt accumulation in the soil profile and groundwater aquifer. Areas showing salinity/sodicity increase in soil profile should be monitored more frequently in order to determine the causes and to adopt management measures for control of soil salinity/sodicity problem.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusions that could be derived from the results of this study are:

- the groundwater model predicted gradual long-term increase in groundwater salinity fairly well;
- the predictive accuracy of the model is dependent on extensive and reliable field data;
- the gradual increase in salinity of pumped groundwater could be attributed to upconing of deep saline water;
- though the results of the model study are more general due to the lack of specific data for input and calibration, the results fulfill the study objective of prediction of temporal variation in salinity of pumped water; and
- The increased use of tubewell water of sodic nature for irrigation is posing a soil sodification hazard, which is a tremendous problem for environment and long-term sustainability of irrigated agriculture.

The main recommendations on the issues that need further research are provided in the following section.

- HST3D is applicable to situations involving the movement of conservative solutes like TDS, chlorides and sulfates. For any comprehensive study of groundwater salinity would need modification to HST3D or some other model in order to predict the behavior of non-conservative solutes;
- an extensive groundwater field data exploration program should be undertaken, primarily to determine the variation of hydraulic properties and salinity concentrations in the aquifer;
- private tubewell data on operation and quality should be collected by some government organization in order to have an idea about the long-term sustainability of groundwater development; and
- detailed research on management of conjunctive use of canal and groundwater should be undertaken in order to establish conjunctive use management requirements for safe use of groundwater for irrigation.

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ISSUES IN SPATIAL ANALYSIS FOR SALINITY MANAGEMENT: A SYNTHESIS ACROSS IRRIGATION UNITS OF LOWER CHENAB CANAL SYSTEM, PUNJAB, PAKISTAN

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ABSTRACT

Continuing advancements in digital spatial processing have stimulated and unfolded insights across disciplinary concerns regarding maps and allied sources of information. While the technological innovations have been robust in data processing and analysis, the peculiarities of coping with adaptive variance in space take sprecedence over all other considerations. When considered in the context of a century old irrigation system like the Lower Chenab Canal (LCC) in central Punjab, the irrigated expanse of 1.226 Mha poses monumental problems in reconciling complex and acutely divergent pieces of information. One also has to take cognizance of the unique character of this regime that has had the highest share of public sector land reclamation programs across the larger interfluvial setting of the Rechna Doab.

From irrigation an salinity management perspective, it is tempting to integrate the many incongruent sets of public and private sector investigations in a manner consistent with the capabilities of a digital geographic database. However, latent considerations in the assimilation and synthesis of all such information necessitate choices in data abstraction that are not unrealistic in space and time. For the LCC system, there is no dearth of information sources, but the shortcomings in data collection and portrayal preclude the digital integration so desirable for this purpose.

This paper addresses the ranking issues in spatial analysis realized as part of a separate interdisciplinary study on the salinity management alternatives across the larger setting of the Rechna Doab. The LCC constitutes the principal canal irrigation system within the area, hence choices in data collection, aggregation, analysis, and portrayal sustain nearly the same characteristics as observed for the entire doab. The discussion focuses on the principal considerations in analog to digital conversion of thematic and attribute data, and is inclusive of the issues relating to information duplication, update, coordination, integration, analysis, and sampling. The conclusions favor pragmatic choices in the spatial modeling of soil, water, and crop themes leading up to resource optimization and decision support.

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I. INTRODUCTION

In many ways, given the diversity of the cropping patterns, potential rainfall, and soil types, Rechna Doab (Fig. 1) could be considered to be the bread basket of the country. It has also been the forerunner to much of the intensive surface and groundwater irrigation development and land reclamation schemes within the country. Much of this development had been punctuated, both before and after independence, with intensive studies of the changes occuring across the landscape due to shifting patterns of land use and resource utilization. Against this backdrop of massive public and private sector investments towards boosting agricultural productivity, too often on a grandiose scale by current levels of undertaking, the solutions have met with mixed success in ensuring sustainable development into the future.

In many ways, the irrigated agriculture of the Rechna Doab represents a chronic malaise that is not unlike the management problems of Pakistan's irrigation systems typically characterized by a general shortage of good quality water, poor physical condition of the conveyance system, over centralization of control and recurrent recourse to short-sighted capital intensive solutions. These problems have been compounded by the environmental constraints inalienable to general system-wide deterioration across land and water resources. However, the past decade or so has seen a refocussing of the public sector priorities that directly address food security issues leading into the 21st century. It appears that somewhere within the growing milieu of advances in gene mutation, genetic engineering, disinvestment and decentralization, pesticide and fertilizer applications, infrastructural and varietal payoffs, lies the key to sustainability of the irrigated agricultural system. Perhaps, the key word here is ***integration*** which nonetheless devolves around the physical scale and scope of interventions envisaged for sustainability.

Accordingly, set in the backdrop of a host of focused land reclamation attempts, the lessons from Rechna Doab's geographical size do not favor piecemeal approaches to resource optimization. In fact, given the pressures of land fragmentation necessitating higher productivity, the resource worthiness of the farming community has been stretched to the thresholds of gains from the investments of yester years. Now, the past project-wise distinctions of returns to scale have blurred to represent a new balance in irrigated agriculture. And since water is the primary input and constraint to any furthering of the gains thereof, consideration of the strategic options must take into account the current ranking of the land use and the most likely scenario for its sustained growth.

This paper attempts to highlight issues (underlined, for reader attention) in resource inventory and operational gains for one of Rechna Doab's most important canal commanded regimes, the Lower Chenab Canal (LCC) system. Antecedent to the choice of strategic options would be the need to establish the framework whereby the vast information pool on land use and constraints to irrigated agriculture provides the essential backdrop for management interventions hitherto remiss from the capital

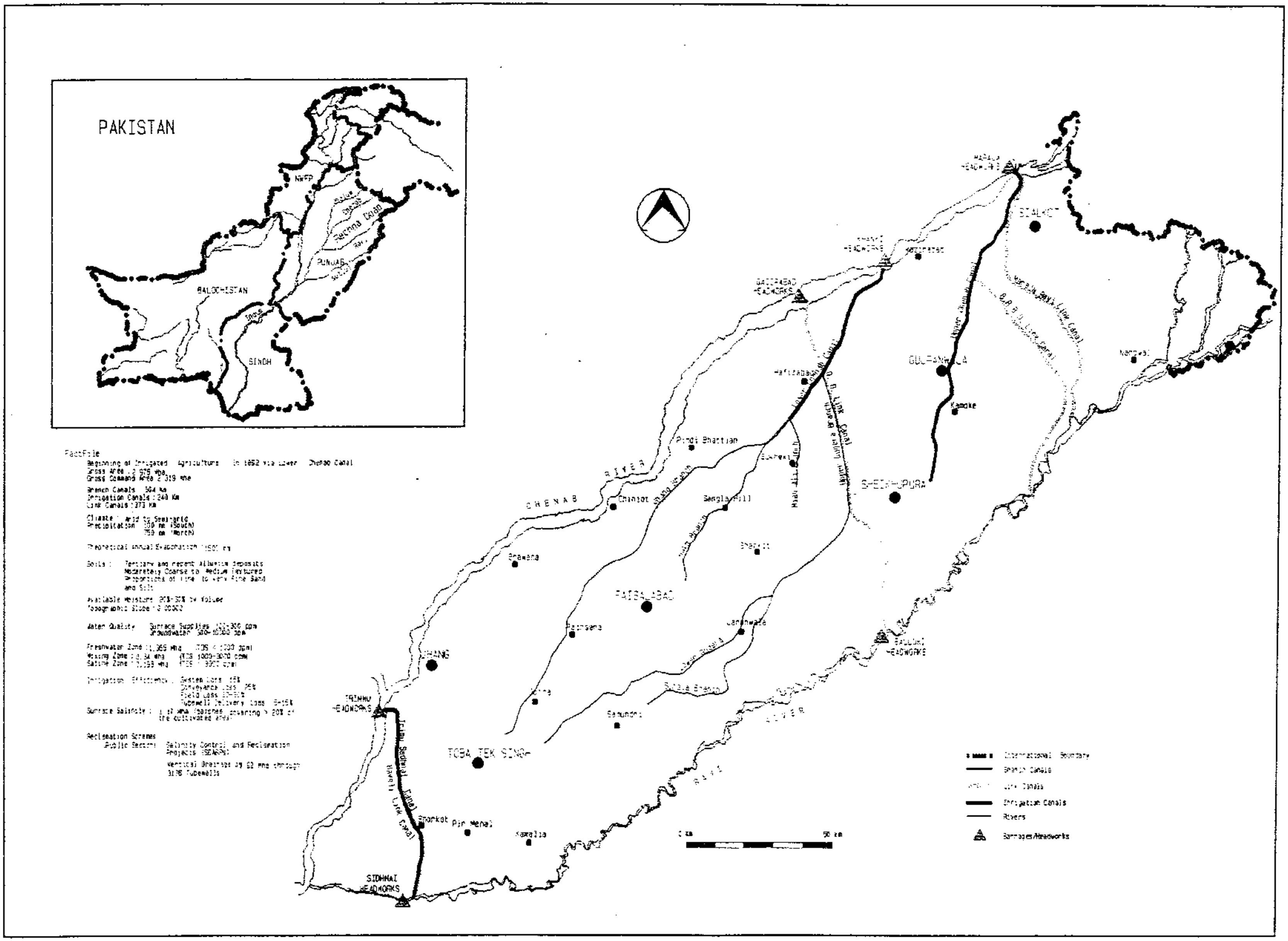


Figure 1. Location of Rechna Doab, Punjab.

intensive investments made in the past. In a less than exhaustive assemblage of the physical characteristics of the entire Doab, such an exercise was made part of a 2-year effort by IIMI, now coming to a close, to collate the most rational alternatives for salinity management in the area. The complex interweave of extent- and quality-wise differentiations rendered by past investigations into this huge area necessitated aggregation in space and time for comparative and modeling purposes. The choice of spatial information systems, thus, was quite natural to such a setting, whereby not only the information discontinuities were resolved in thematic renditions, but the analysis laid bare, in lieu of past trends, the most likely scenarios for system-wide sustainabilty.

While the principal findings from the above study are meant to be part of a voluminous report, the following dwells exclusively on the pragmatism needed to overcome the information mass typical to irrigation regimes such as the Rechna Doab. In this discourse of the ***issues***, the most important consideration is not to get mired in the plethora of information that characterizes the physical and quantitative description of the regime. Perhaps, there is no upper bound to information collection, and the utility of the spatial or geographic information systems in such circumstances becomes much more apparent in sifting for the most appropriate combinatorial mix of information needed to arrive at establishing the past trends in land degradation and predicting the sustainability into the future. Accordingly, the discussion identifies data sets constraining the physical regime, the missing pieces of information, lack of integration, and the technological considerations pertinent to spatial processing for selective addressal of salinity related issues.

II. DUPLICITY IN INFORMATION COLLECTION AND MISMATCH IN REPORTING

A. Salinity Surveys

Rechna Doab's irrigation system has had over 100 years of history, and has also been the starting point for the public sector land reclamation schemes within the country (SCARPs). As of now, following three decades of large land reclamation projects since 1960, there are still small pilot projects operating across its landscape. These projects continually add to one of the most exhaustive public sector archives on soil and crop investigations specific to the Rechna Doab.

In terms of extent and quantum of salinity incidence, the reporting across the Rechna Doab is coincident in time to the campaigns at the national level that have been far in between, and, depending upon the agency involved, difficult to correlate. The Indus Basin salinity survey by WAPDA during 1977-79 provides comparative figures with the earliest investigations dating back to the mid-fifties. Aside from the considerations pertaining to the intervening changes in salinity across more than two decades of reference and adequacy of sampling therein, the indications are that soil salinity is dissipating across all levels of classification. For example, in comparison to soil salinity assessments made by the Water and Soils Investigation Division (WASID) during 1953-65, WAPDA's Master Planning and review (MPR) survey data for the entire Doab indicates a total reduction in salinized extent by 11% (Fig. 2), much of it across the slightly salinized regimes which usually constitutes the first priority for reclamation gains.

Since no integrated assessments on soil salinization have been made beyond the 1977-79 Revised Action Program (RAP) survey by WAPDA, it is possible that these figures are no longer a potent reference of changes to soil salinization. In fact, in the period since then there has been an increase of nearly 55% in groundwater pumpage with salt loads anywhere between 0.89-2.35 tons/ha/year (Table 1).

Table 1. Estimated Salt Load in the Groundwater Irrigation Supplies, Punjab.

Area	Pumpage (Mhm)	Applied Quality (ppm)	Salts	
			(Mt)	(t/ha)
Public	0.8261	750	6.8	0.89
Private	2.7002	600	17.9	2.35

Source: Planning Division, Nov. 1988

This is in addition to the salts already being added via surface irrigation. While the estimates on the quantum of salts retained in the root zone may most likely take to conjecture, the broader reliance on soil chemistry would indicate a situation that would threaten the gains made through soil reclamation in the past.

Historically, there have been three major public sector agencies that have collected information pertinent to extent-wise reporting of soil salinity. The Directorate of Land Reclamation (DLR), a subsidiary organization within the Irrigation and Power Department of Punjab, maintains records going back to the pre-independence period. However, its mandate does not extend to the national level where WAPDA and the Soil Survey of Pakistan (SSoP) have conducted periodic campaigns since 1959. Since the manner of information collection, compilation, and reporting is dissimilar across all of the three agencies, it is impossible to independently verify and correlate the magnitude of salinity, much less the impact assessment needed as a consequence of this information. In such situations, the best correlations may probably result for the extents not affected by salinity; across salinity categorizations, the interpretation would be open to disconformities. The foregoing is better explained for the Upper Rechna regime where the integrated assessment of salinity indicates the following position:

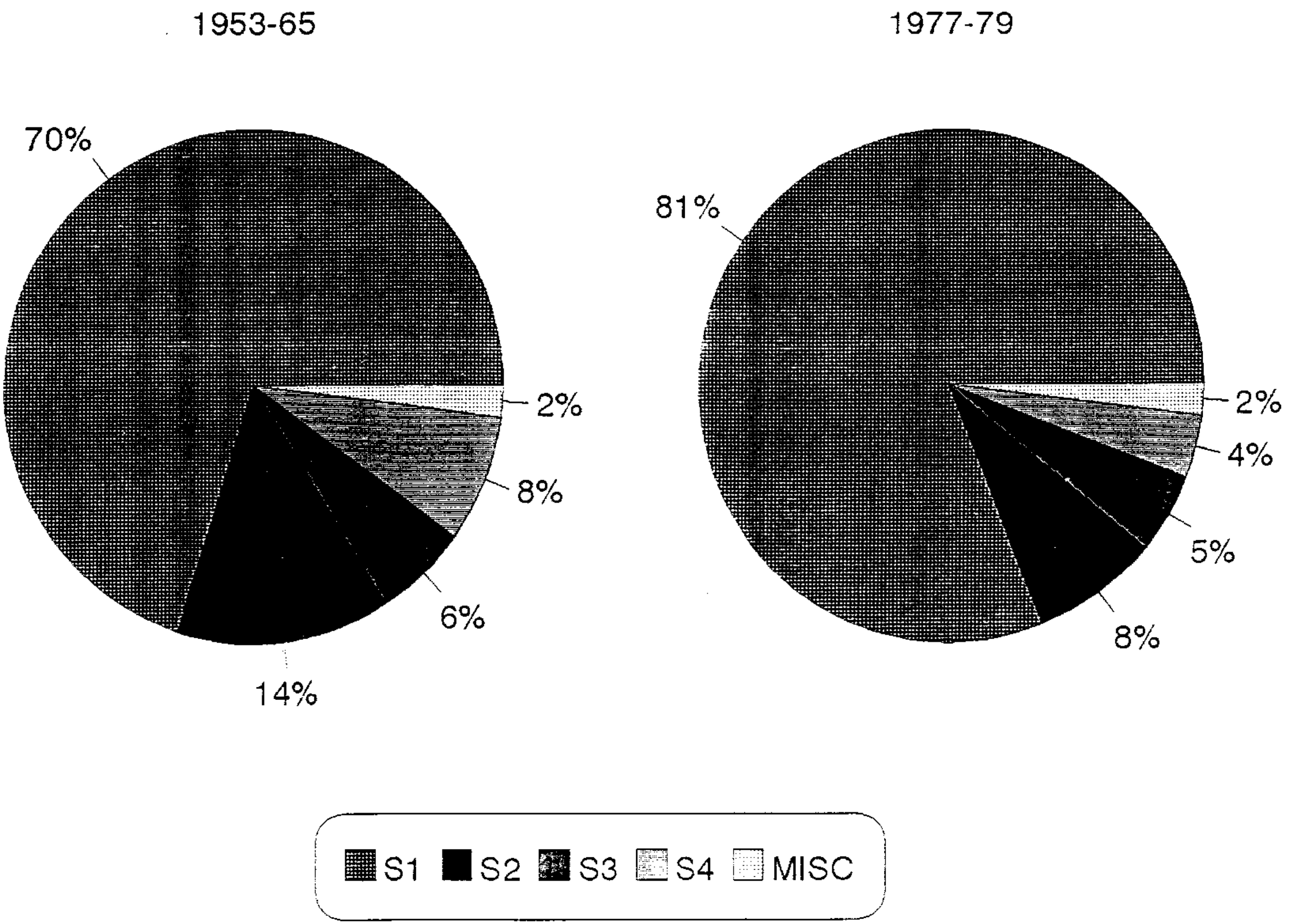


Figure 2. Comparison of the Soil Salinity Investigations by WASID (1958-65) and WAPDA MPR Survey (1977-79) in Rechna Doab, Punjab.

	SSoP (1965-68)	Irrigation Deptt.(1974-75)	WAPDA MPR (1977)
Salt free	81.0%	84.0%	84.5%
Saline Soils	18.4%	14.6%	13.9%

For the 2140 bore hole locations, a comparison of the WASID and MPR survey indicates that the top soil (0-6 in) non-saline land increased from 75% to 88% with a corresponding decrease in the incidence of saline-alkali and non-saline alkali soils.

The SSoP differentiates the saline-sodic soils into 2 categories; dense saline-sodic (15%) and porous saline sodic (3.4%). The dense saline-sodic soils with a 60-130 cm thick B horizon are non-calcareous to strongly calcareous. The porous saline-sodic soils are moderately calcareous and comprise silty clay, silty clay loam, silt loam and loam. The hydraulic conductivity of these soils is very slow, having median values of 0.18 cm/day for silty clay loam and 0.3 cm/day for silt loam.

In comparison to SSoP's categorizations, WAPDA's classification maintains a separation between the surface and profile salinity, regardless of the textural appreciation. For surface salinity, the inter-class differentiation is based on a range of electrical conductivity values for the saturation extract that take into account the general condition of the cropland. For profile salinity, the thresholds are based on a combination of electrical conductivity and SAR values for the determination of the salinity/sodicity status of the soil. It becomes difficult to comprehend how a veritable assessment of sodicity could be realized given the wide scatter of points (1 mile grid) for profile sampling without cognizance of the irrigation status and stratum-wise differentiation of the soil. This sampling strategy becomes further suspect in the context of local changes in relief and cropping pattern.

Unlike the analytical approach to salinity reporting by the institutions mentioned above, the DLR assessments are based on temporal and observational separations in canal commanded land suffering from loss of production. It addresses the salinity issue indirectly through the institutional mandate to make available extra irrigation supplies to those areas that have been surveyed to have a strong incidence of salinity. The internal classification ranks 'Thur Kohna' to have the most lasting impact on land productivity. Thur Girdawari, or visual salinity surveys, are conducted every year by the canal patwaris (surveyors) during the months of winter to account for this ranking in a proforma known as Khasra Sadmazada that has abstracted entries for the type of Thur and its location in terms of outlet and canal unit. It is the abstract of this information that gets reported to the Directorate's central office.

Although, procedure-wise, the exercise is sufficient for preliminary reporting purposes, its historical reckoning as the sole criteria for distribution of additional water 'shoots' for leaching purposes was questionable. Instead, there is need for a qualitative reckoning also in order to establish the severity of the problem in addition to the extent-wise survey already being carried out. A scientific approach in selecting blocks of land for additional supplies would have the edge over the conventional subjective selection procedure that is vulnerable to pressures from influential sources.

IIMI's independent *field observations* in the LCC point to a structural decline of soils resulting from irrigation with sodic groundwaters, a complication which poses an important obstacle to reclamation of saline soils by leaching. A rapid appraisal survey was conducted by IIMI in the command areas of 7 watercourses of the Mananwala Distributary in 1989, to record the presence of salinity---either as surface salting of obviously salt affected crops and of dense, hard subsurface layers. Results hint strongly at a general deterioration in soil conditions towards the tail of distributary canal commands due to secondary salinization.

Another rapid appraisal survey in 1993, this time of the entire Mananwala Distributary command (31,200 ha) gathered *evidence* of surface salting or obviously salt effected crops and came to the conclusion that there was a general deterioration in soil conditions towards the tail of distributary canal commands due to secondary salinization (Fig. 3).

B. Crop Surveys

Changes in cropping pattern, due to rampant inequity in the delivery system, are difficult to determine. The matter is not simply confined to the farmers choice for planting in lieu of available resources, but also difficult to corroborate in the absence of a rigorous cross checking approach of the Khasra (crop detail) information regularly collected towards assessment of water taxes. Determining actual cropping patterns therein is a laborious process of data extraction since these records do not relate to the hydrological units but are compiled at the village level. Moreover, no entry is made for any fallow field, and entries are made for non-irrigated crop fields only if they are within the CCA. Thus any calculations of irrigation intensity are bound to be error prone.

The Khasra records are supposed to be destroyed after 5 years, which in actual practice is not systematically followed. On occasions, even 10 year old records are still available, whereas the record of just the previous year may be missing. In general, because a Khasra is a revenue record, its availability is subject to restrictions.

A new Khasra is compiled for every crop season based upon two field inspections carried out by the revenue staff. The first of these is completed by mid-season followed by the second in the month or so before the end of the season (officially Oct. 14 for Kharif and April 14 for Rabi). Although all khasras are supposed to be inspected at the officer-cadre level, time constraints dictate otherwise. Accordingly, there are concerns about the accuracy of information that is also known to be misreported and distorted across space and time.

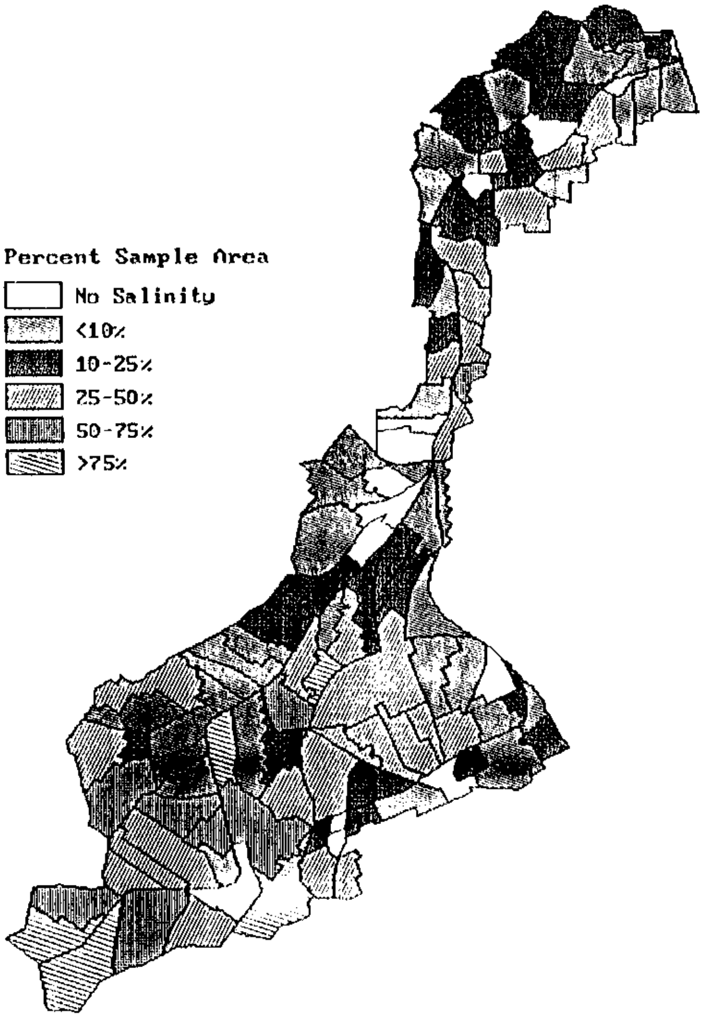


Figure 3. Distribution of Visual Salinty in the Mananwala Distributary Command, Upper Gugera Division of the LCC System, Rechna Doab, Punjab.

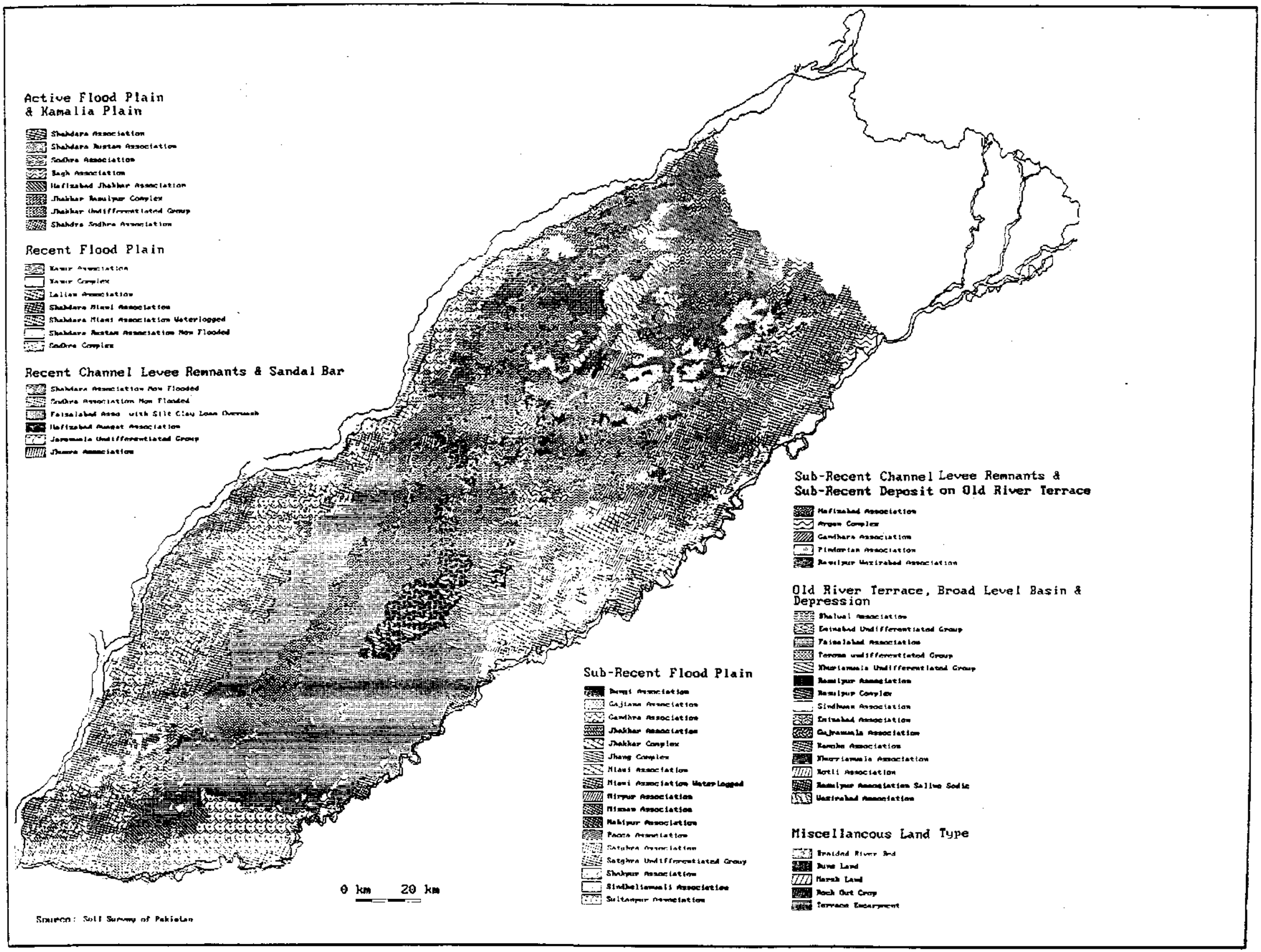
The Irrigation Register is a more readily available and easily used record of irrigated area maintained by the Irrigation Department. This record is organized hydrologically, i.e. data is compiled for each distributary command on an outlet by outlet basis. However, there are also problems in this compilation. First, all entries relate to irrigated cropped area only; it is not possible to disaggregate this data into different crop categories. Second, the information on CCA and GCA is not available for all outlets due to sanctioned alterations in the past. Finally, and perhaps most seriously, there are also doubts about the reliability of the data since it draws upon the same data base as the Khasra. Notwithstanding the subsequent derivation of information from a common data source, IIMI has observed significant differences in the total irrigated cropped area in the Irrigation Register and the Khasra. While the Irrigation Register provides ease of comparison between supplies and irrigated agriculture, it is important to realize that it is, for better or worse, the primary record available to all the irrigation officers.

Given the elaborate system of data collection and revenue reporting, the fundamental issues relate primarily to the utility of this information. The management issue herein relates to the transition from maintaining records for the sake of bureaucratic procedures to a process where information is utilized in a more interactive and purposeful manner. This transition would bring in its wake reliable and timely data collection procedures that would benefit from a sampling approach rather than the unnecessarily exhaustive details that are made a part of the conventional reporting.

C. Soil Surveys

The Soil Survey of Pakistan is the premier agency within the country responsible for the collection and reporting of soils related information. Besides striving to meet its mandate of country-wide soils mapping, it also undertakes large scale investigations to satisfy private sector requirements. For public dissemination, the results are available at or near reconnaissance scale in terms of soil associations and series-wise variants delimited at the district level. Most of the data belongs to the survey period between 1965-70, and updates are not common. Where updates have been made, drastic changes in interpretations are quite evident.

The primary source of data for soil survey interpretations has been the aerial photographic coverage of the Colombo Plan period (1956) whereby prints were marked for sample sites subsequently visited in the field. The sampling procedure consisted of undisturbed sampling for textural and color identification of A, B, and C horizons, besides the calcareousness of the profile. Interpetations group the different soil series and its variant compositions into soil associations that are distinguished by the occurrence pattern of the landform (e.g active flood plains, old channel infills, levees etc.). The interpretations are also revealing regarding the suitability of these soil types with respect to drainage, cropping, and the salinity status (porous and saline sodic soils). Figure 4 shows the distribution of the 64 composite classes of soil associations contained within



Source: Soil Survey of Pakistan

Figure 4. Soil Associations within the Rechna Doab, Punjab.

the district level reports covering the Rechna Doab. Since the original layouts at the district level have not been photogrammetrically corrected for interpretation purposes, it is impossible to achieve an acceptable merger of these 'maps' without digital georectification. Figure 5 shows these errors in space in the uncorrected form wherein the blank areas at the boundaries of the two adjacent maps indicate where the information pieces have failed to come together towards a perfect merge.

Contrary to the Soil Survey interpretations for scientific and detailed reporting purposes, the WAPDA soil classifications are meant to cater to engineering aspects of their water resources development and land reclamation projects. Accordingly, the 1959-62 WASID-related investigations have been interpreted on the basis of a gridded point sampling marked off of the Colombo Plan aerial photo coverage. The mapped reproductions are non-standard with respect to scale and differentiated in the horizon in terms of the surface cover (0-6 inches) and the stratum (6-72 inches). As an example, the strata-wise differentiation for the Rechna Doab are shown separately for surface and profile conditions in Figure 6. Again, the transfer of information from the aerial photographs does not entail photogrammetric corections but is the result of tracings effected in a manner similar to the procedure adopted by the Soil Survey of Pakistan.

While one would expect differences in the interpretation details from the two institutions mentioned above, there should be enough concordance with respect to the textural separations to permit a general inference on the coarseness of the soils. This, unfortunately, does not happen convincingly enough due to differences in the reporting scales adopted by the two agencies and the masking inherent in SSoP's associative groups that do not explicitly confirm the phase variations in the locale-specific setting.

D. Monitoring of Surface Inflows

Large scale irrigation systems in Pakistan, such as the LCC, are characterized by a low density of control structures for water management. In situations with less than optimum control, the repercussions in discharge variations and inequity of distribution are exacerbated throughout the design constrained system and there is little opportunity for downstream compensation of adverse upstream effects. The management concerns are partitioned at the level of geographic control that varies substantially between the main system flows and the farmer outlets. Quite expectedly, the farther the system distributes, the greater the diversity and variation in the utilization of the flows. It is this peculiarity of the space across which this resource utilization occurs that essentially determines the performance of the system.

While monitoring of the system inflows is the key parameter in quantifying benefits per unit volume of water across irrigated landscapes, the potent utilization of this information lends itself to several variants in the definition of the performance parameters. These parameters may be either exclusive to the hydrologic performance

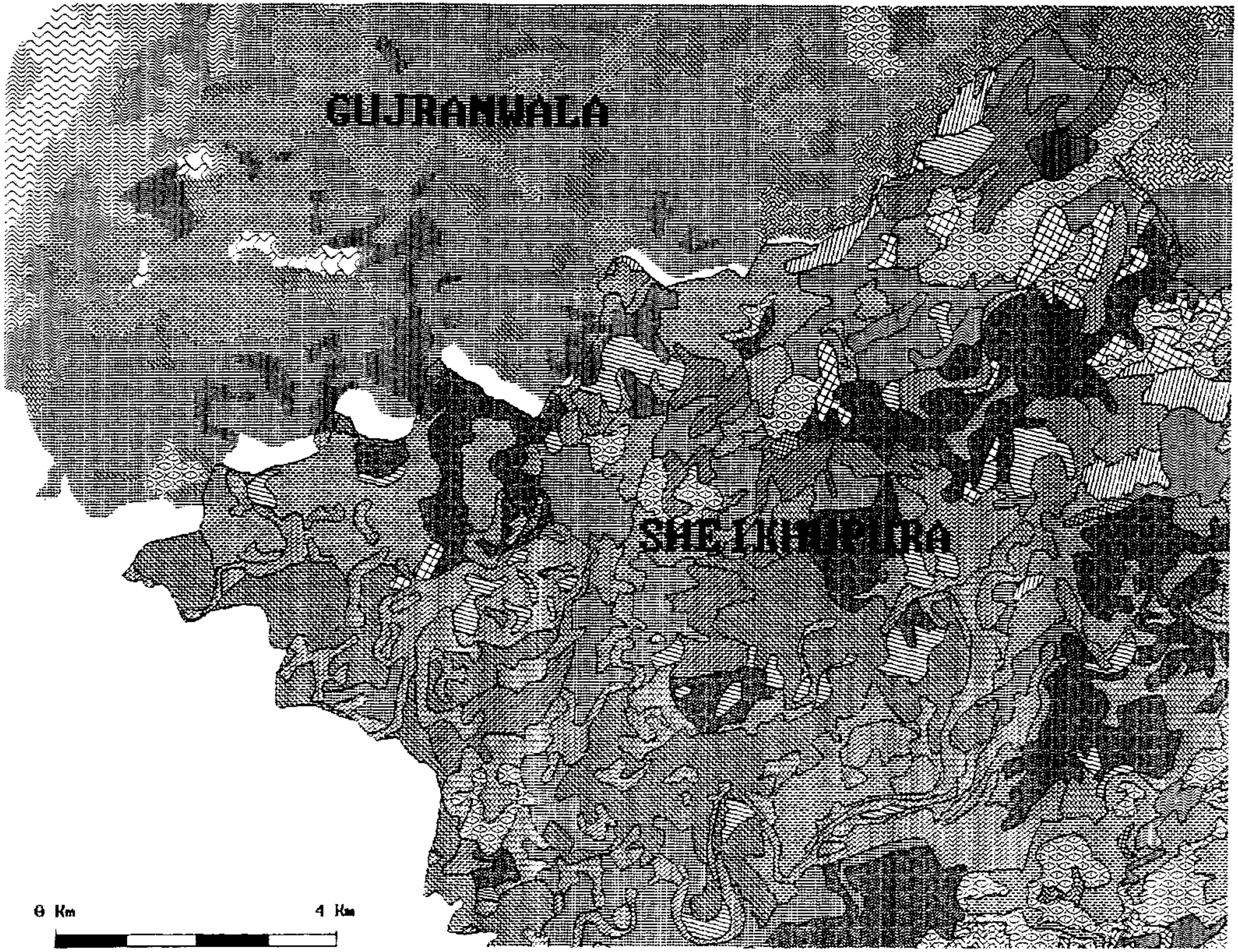
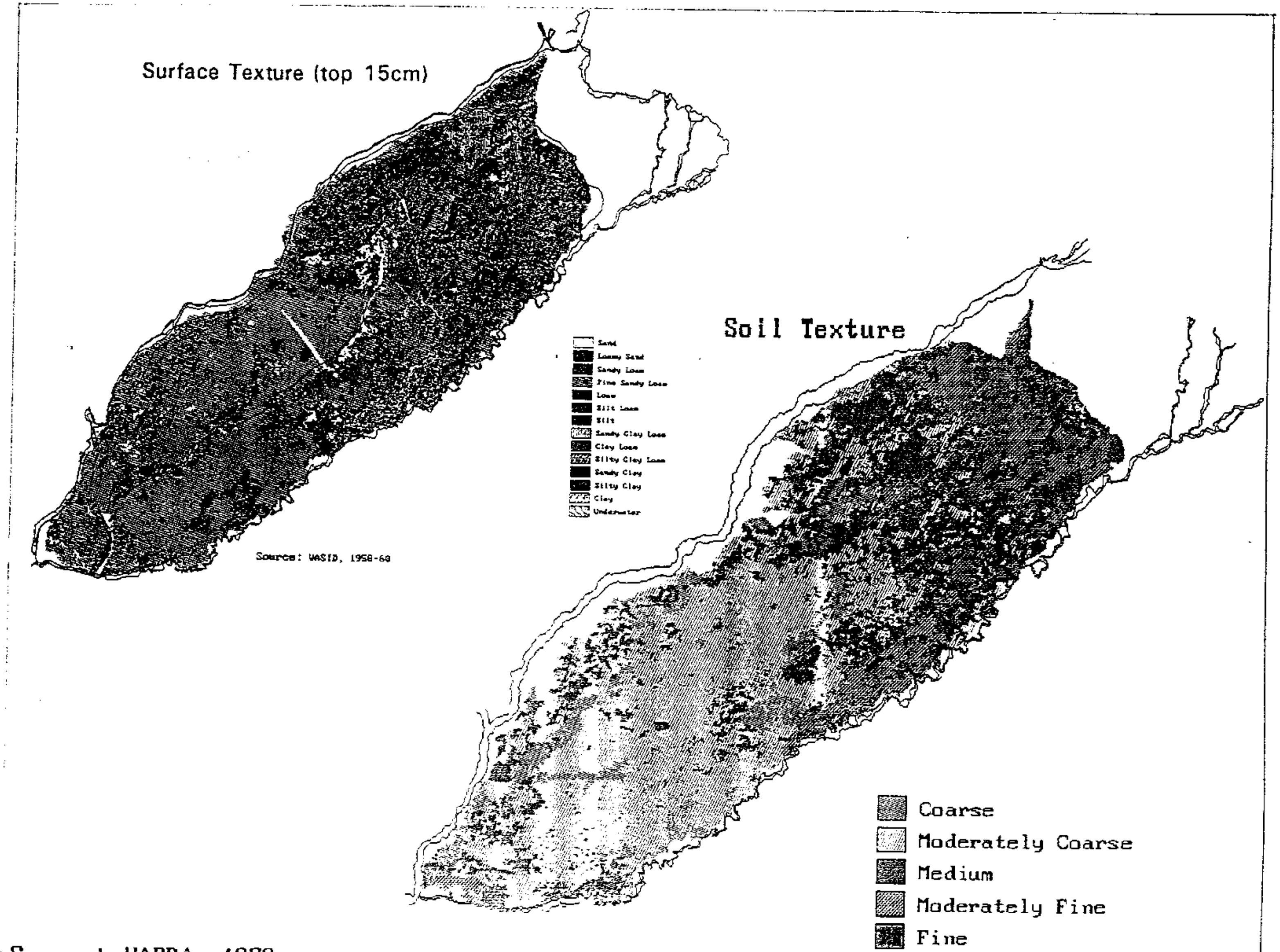


Figure 5. Uncorrected Map Definitions of Soil Survey Reports for Gujranwala and Sheikhupura.



Source: WASID, 1958-60

Source: WAPDA, 1978

Figure 6. Soil Surface and Profile Textures within the Rechna Doab.

of the channel in terms of equity, reliability, and variability concerns, or dependent on the regime therein. The latter includes the spatially pertinent attributes of cropping patternsand intensity, and overall utilization of the farming locale. In the absence of reciprocal figures on irrigation contributions, the contextual assessment of returns from the farming system are at best incomplete and sometimes even misleading. For example, research completed on Lagar Distributary of the Upper Gugera system in 1987 identified watercourse improvement as an additional cause of inequity in surface water distribution. This resulted from the tendency to concentrate watercourse improvement at the head reach outlets that led to establishment of the modular discharges where non-modular flows previously existed. The resultant increase in discharge was at the expense of the outlets located further downstream.

Elsewhere, results from the LCC East confirm that careful management of head gate structures is necessary if distributary discharge variability is to be reduced to, and maintained at, the lowest practical levels. In the absence of reliable rating curves for the gauge reader, in many instances the near absence of such gauges, the regulation of head discharge becomes a matter of guesswork. Here, notwithstanding the gatekeepers experience, IIMI's observation data suggests that this variability could be better controlled than it is now.

Aside from the necessity of qualitative improvements to the flow data being currently acquired, primarily at the secondary offtakes, it is important to consider the magnitude and extension of this exercise to encompass the broader scope of realizations at the system level. At the main canal level, it would include an estimation of the water balance and returns to scale from regime-specific productivity; the secondary system would lend itself to critical considerations in channel maintenance and reach-specific hydraulic performance, and finally at the farmgate the appreciation of this resource could be the control for agricultural performance and salinity management. Consequently, the emphasis is not on linking the successive levels of flow information, as is done in the statement of irrigation system prepared at the Division level, but on the emancipation of benefits at varying levels of scale.

E. Groundwater Utilization

The large-scale public sector emancipation of the groundwater resource, initially by the Ground Water Development Organization (GWDO) and subsequently by WAPDA, heralded the decade of the green revolution from the mid-sixties onwards that resulted in irrigation supplies over and above the surface allocations. Public sector groundwater development also served as the stimulus for the rapid increase in the number of private wells that significantly alleviated the uncertainty associated with the surface supplies. In fact, the cumulative pumpage from these smaller capacity wells has dwarfed the supplies from the public wells, which are invariably suffering from reduced specific capacities and poor maintenance. For instance, in one of IIMI's sample distributaries offtaking from the Upper Gugera Branch Canal, the total installed capacity of just the private wells exceeded the design surface allocations by a factor of 10. The actual amounts pumped are dependent on the cropping season, power source, and ownership of the well. The overall contribution from groundwater accounts for between 70-90% of all irrigation water during Kharif and declines to < 50% of total water use during Rabi.

There is emerging concern about the mushrooming growth of private wells reversing the annual recharge to aquifers in certain localized areas where the reliance on groundwater is quite siginificant as a secondary source if irrigation water supply. While there is documented evidence for reductions in groundwater levels across SCARPs (Table 2), there is no systematic research into linking such reductions exclusively to private wells. IIMI's piezometer- and bore depth-based observations in the Mananwala and Lagar distributary commands of the LCC system indicate substantial reductions in water levels in areas of higher tubewell densities.

Table 2. Scheme-wise Decline in Water Tables in the SCARP-I Reclamation Area of Rechna Doab (Malmberg, 1968).

Scheme	Average decline of the water table in 1960-61 to June 1968, in meters
Harse Sheikh	0.7
Hafizabad and Pindi Bhattian	1.61
Khangah Dogran	2.28
Beranwala	0.91
Sangla	1.65
Shah Kot and Chuharkana	1.65
Shadman and Chichoki Millian	0.67
Zafarwal	2.68
Jaranwala	0.67
Average for SCARP-1	1.43

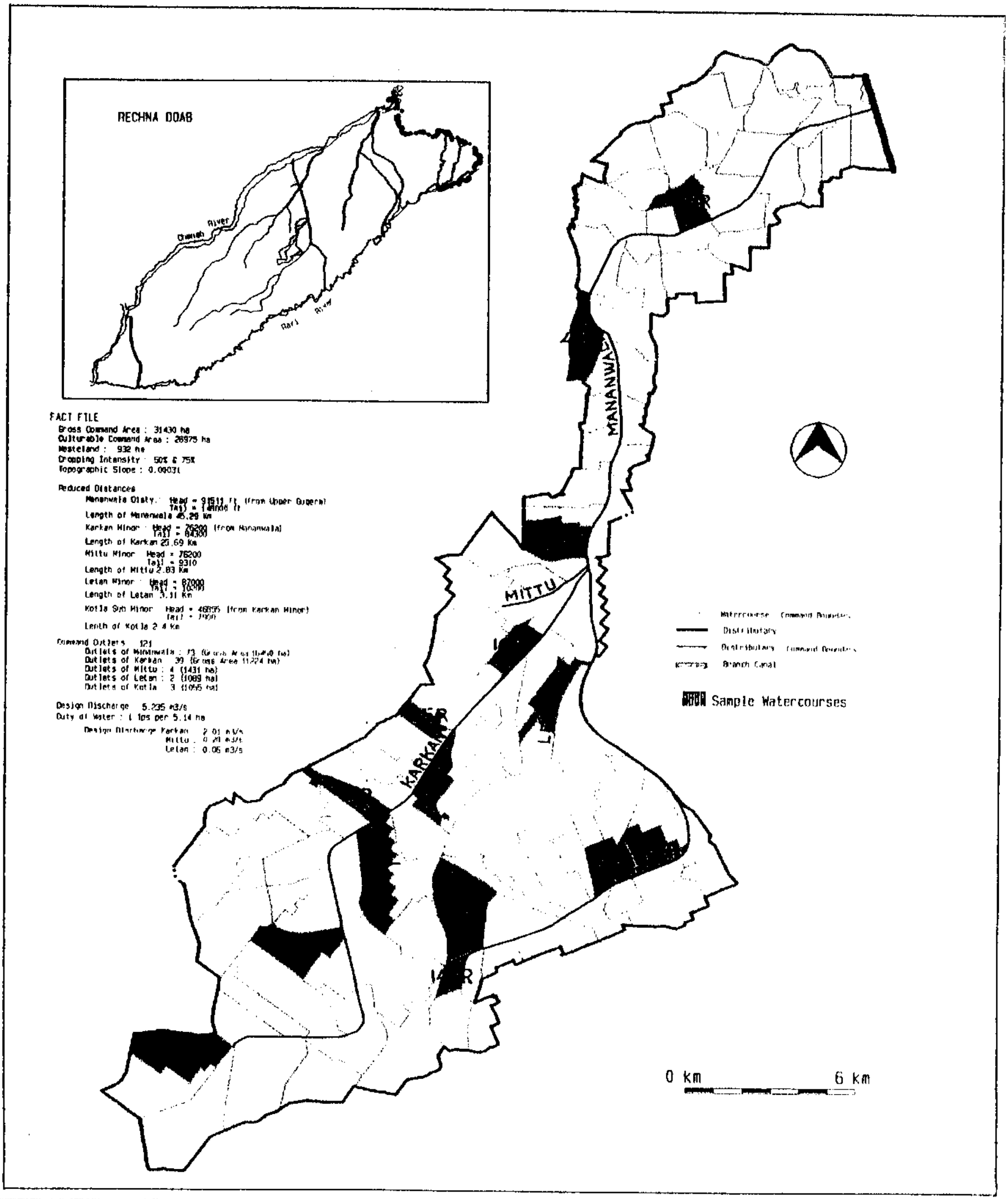
Accordingly, against this latent reliance on supplemental irrigation sources, it would be necessary to determine 'safe yield' extractions both in terms of quantity and quality of pumpage given the actual installed capacity and the utilization rates. Once again, IIMI's observations in the rice-wheat cropping rotation area of Sheikhupura District indicate that groundwater related extractions totalled some 90 cm of water per acre per year, that was much higher than the 35 cm/acre/year threshold limit recommended by WAPDA.

Besides monitoring of the tubewell discharges and recurrent impact on the groundwater tables, water quality was also determined as a latent consideration towards emerging utilization strategies. In one of IIMI's sample distributaries in the Upper Gugera Branch Canal system, the upstream watercourses receiving less surface flows during Kharif season compensated through higher tubewell contribution to total supplies. This was largely due to the useable groundwater quality in the area. The downstream watercourses were less fortunate in terms of useable groundwater quality, and despite somewhat higher surface supplies in a few instances, the farmers opted to pump less towards meeting the total irrigation water supply requirements. Clearly, the upstream watercourses represent a high consumptive use regime during Kharif that is fully exploited by higher tubewell densities.

In areas of useable groundwater quality, the contribution from private tubewells may exceed 60% in the rabi season and 80% in the kharif. This is especially true for the reaches along the Gugera channel where the installed capacities of the private tubewells is anywhere between 7-18 times the designed canal supplies and 5-8 times the present discharges of public tubewells. Also, there are distinct differences between the way various types of tubewells are used; according to a sample study in the Lagar distributary command (Bhatti, 1992), the utilization rate for electric tubewells is almost 5 times that of diesel pumps and 4 times the rate for tractor-powered wells. The differences are mainly due to lower operational costs for the electric wells that encourages farmers to buy water from a nearby electric well rather than run their own diesel pumps. As a consequence, owners of electric wells sell more water than do other tubewell owners.

Based on the utilization strategies mentioned above, the estimation of groundwater balance through differentiation in tubewell densities across irrigated commands is largely independent of the location along the command reach. Here, IIMI's past research into Mananwala Distributary may be cited as an example where not only detailed observations on surface flows and interseasonal cropping changes were made, but the conjunctive use regime was also studied over an extended period in the sample watercourses (Fig. 7). Based on a census of the tubewell population across the entire distributary, a mix of low to medium tubewell densities is encountered in the head reaches, which is not too different from the lower 1/3rd reach of the distributary. The exceptions are in the middle reach where the densities are significantly higher across a large cluster of watercourses (Fig. 8).

More realistically, there are variations to the pattern explained above, whereby farmers experiencing a severe deficit of surface supplies would adopt exploitation strategies that are both quantatively and qualitatively at odds with the prevailing use across a somewhat more balanced regime elsewhere. In such a situation, given the generally poor groundwater quality around the tail portions of the distributary, the repercussions of this singular reliance, brought about by the sheer need to sustain agriculture, would be alarming indeed.



FACT FILE
Gross Command Area : 31430 ha
Culturable Command Area : 28975 ha
Wasteland : 932 ha
Cropping Intensity : 50% & 75%
Topographic Slope : 0.00031

Reduced Distances
Mananwala Disty. : Head = 91511 ft (from Upper Gugera) Tail = 148000 ft
Length of Mananwala 45.29 Km
Karkan Minor : Head = 76200 (from Mananwala) Tail = 84300
Length of Karkan 25.69 Km
Mittu Minor Head = 76200 Tail = 9310
Length of Mittu 2.83 Km
Letan Minor : Head = 87000 Tail = 10300
Length of Letan 3.11 Km
Kotla Sub Minor Head = 46895 (from Karkan Minor) Tail = 7900
Lenth of Kotla 2.4 Km

Command Outlets 121
Outlets of Mananwala : 73 (Gross Area 16440 ha)
Outlets of Karkan 39 (Gross Area 11224 ha)
Outlets of Mittu : 4 (1431 ha)
Outlets of Letan : 2 (1089 ha)
Outlets of Kotla 3 (1055 ha)

Design Discharge 5.235 m3/s
Duty of Water : 1 lps per 5.14 ha
Design Discharge Karkan 2.01 m3/s
Mittu : 0.20 m3/s
Letan : 0.06 m3/s

Figure 7. Location of IIMI Sample Watercourses in the Mananwala Distributary Command, Upper Gugera Irrigation Division of the LCC System, Rechna Doab, Punjab.

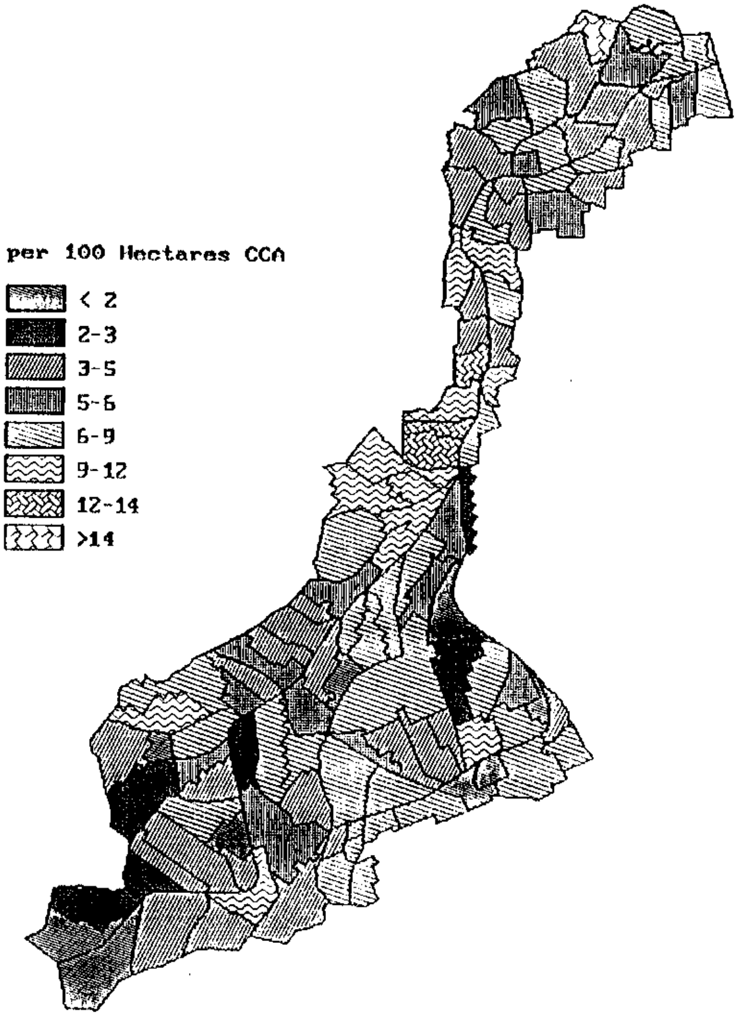


Figure 8. Tubewell Density in the Mananwala Distributary Command, Upper Gugera Irrigation Division of the LCC System, Rechna Doab, Punjab.

Government agencies must recognize that their policies can inflict great harm on agricultural systems. In regimes like the Rechna Doab, with probably the highest tubewell concentrations in the country, the goverment should begin systematic efforts to accurately track groundwater table levels and the quality of groundwater over time. In addition, the government can help moderate excessive groundwater demand by reallocating canal water and restructuring pricing of the energy used for pumping wells.

III. LACK OF INFORMATION UPDATE AND REMISSIONS IN COORDINATED REFERENCING

A. Infrastructural Updates

Information on land use and structural updates constitute the most neglected aspect of irrigation system inventory in Pakistan. In fact, notwithstanding the organizational mechanisms and procedural definitions to this effect, there are very few instances whereby alterations to the hydraulic and hydrologic regime, such as channel improvements and relocation of outlets, is reflected in the updated records. While the Drawing Branch within each irrigation division is the repository of maintenance updates like bank improvements, x-section modifications, reworked bed levels through desiltation, etc., the graphic reproductions/alterations are not fully representative of the physical state of the channel. The record would be indicative of the selective reach-wise O&M activities, but not reflective on the gaps in disrepair and overall state of the channel. This has important consequences on the conveyance capacity and coverage area of the channel for which there is already no monitoring of outlet withdrawals.

Similarly, other than the topographic relief information available since the earliest surveys for command delimitation, there is no coordinated effort to update changes in relief at all levels of the system. In fact, the benchmark referencing for such purposes has either become outdated or simply does not exist. Accordingly, issues relating to extension of the commanded regimes (through enhancement of existing discharges or provision of additional outlets) remain unsettled even after supplies have been officially 'sanctioned.' The same argument may be extended to include situations whereby commands benefitting directly from the On Farm Water Management and Command Water Management Programs activities are shown at the distributary or subdivision level alongwith improvements to watercourses and the supply regime.

Interestingly, while land reclamation activities have been fairly intense on the capital investment side, the resultant changes in communication and drainage infrastructure are at best referencible at the level of Patwar maps. Hence, efforts at sampling of the physical and socio-economic regime, whether project or impact oriented, are handicapped in lieu of poor accessibility to information, thereby precluding optimum site selection. The Design Branch, normally the first stop for such updates, continue to make do with tracings and ammonia prints of the maps dating back to the pre-partition days. Resultantly, while the calculations do exist for the changes in the commanded regime, they are not location specific within the watercourse.

For the LCC system, the impact of the abovementioned changes is most apparent in the wake of reclamation activities under SCARP-I. In 1970, SCARP-I was declared completed and handed to the Punjab Irrigation and Power Department for maintenance.

By then, nearly 0.5 Mha were being utilized for winter and summer crops versus a target figure of 0.55 Mha. A comparison of the aerial photographs taken twenty-three years apart (1953-54 vs 1976) showed:

- Surface waterlogged areas either disappeared altogether or were reduced in extent;
- A few salinized tracts were brought under cultivation. This extension occurred generally on the margins of saline land, and where the salinity occurred as small patches in a complex pattern.
- Large tracts of salt-affected lands remained out of cultivation.

Incidentaly, the comparison above was made possible in large measure to the only two coordinated efforts in the aerial photo coverage undertaken nation-wide. For changes not captured by such means, e.g. the tubewells no longer operational under SCARP-I, even the implementing agency did not have the required information on the commanded regime so affected. More glaringly, the locations of all the tubewells installed under SCARP-I were devoid of coordinate-wise referencing and relied exclusively on positional displacement from known land features. The same situation holds true for the network of piezometers installed across the Rechna Doab, many of which no longer exist. For the ones still contributing to bi-annual measurements, the readings are not coincident in time.

B. Impact Assessment

Coincident with the gains from irrigation system rehabilitation activities is the increase in the cropping intensity and agricultural productivity. However, these gains have to be translated into issues of long term sustainability for the projects to be truly efficacious beyond their operational life. From Figure 9, where temporal reference to changes in the cropping intensity has been made after substantial operational experience in SCARPs, the incremental trends are somewhat sharper for the newer SCARPs in comparison to SCARP-I, but not in magnitude of the parameter, which is primarily due to the very high density of private tubewells in areas comprising SCARP-I. It would suffice to say that while the farmers in SCARP-I have had a head start in tubewell development, the actual use of the resource is limited to meeting the high consumptive use on existing CCA rather than extensions elsewhere within the GCA. This can be grasped from the fact that in reference to the time period for the reporting on changes to cropping intensity above, SCARP-I had 90% of the land under non-saline to slightly saline category, which was much more than the corresponding figures of 78% and 83% for SCARPs IV & V, respectively (Fig. 10).

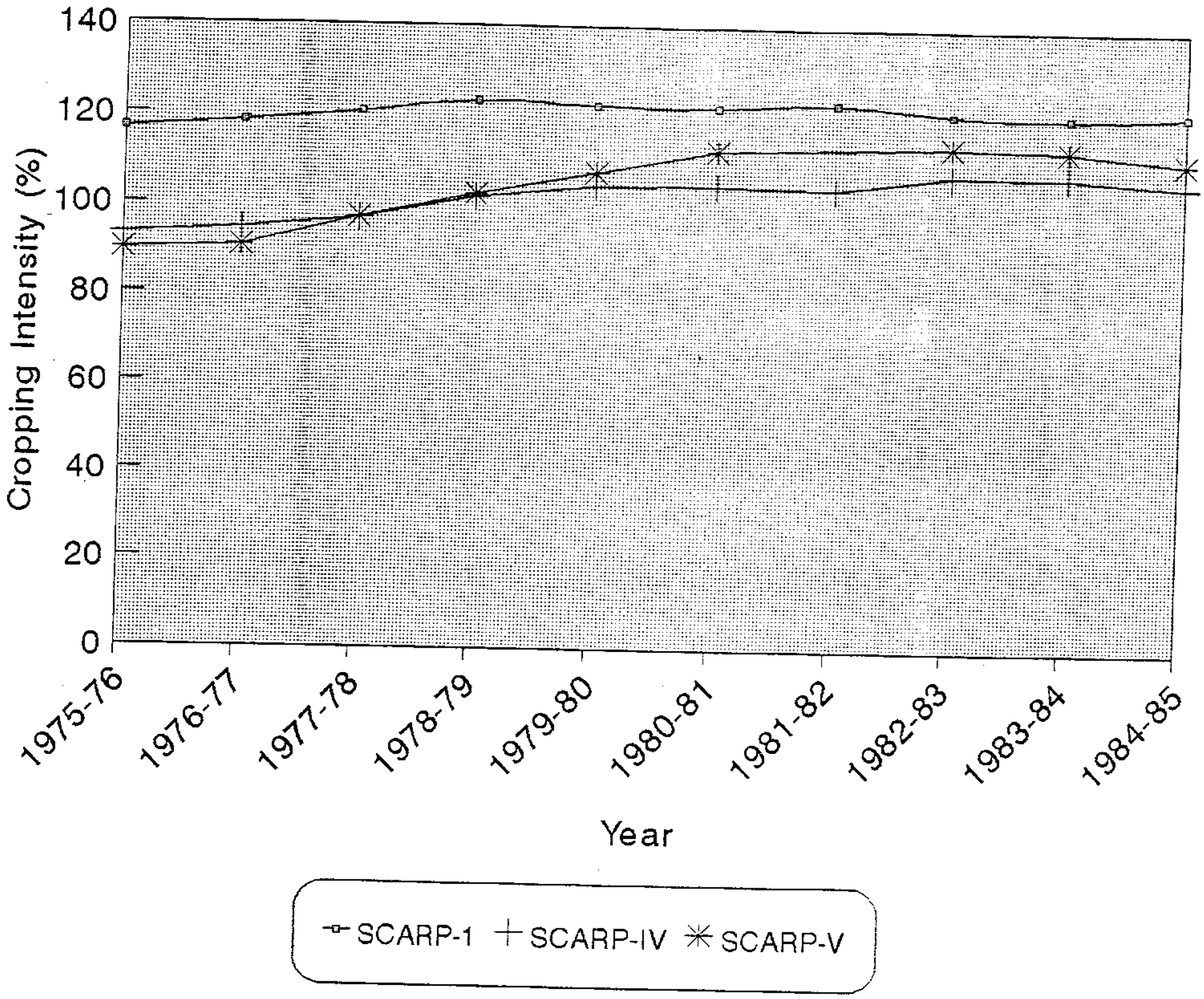
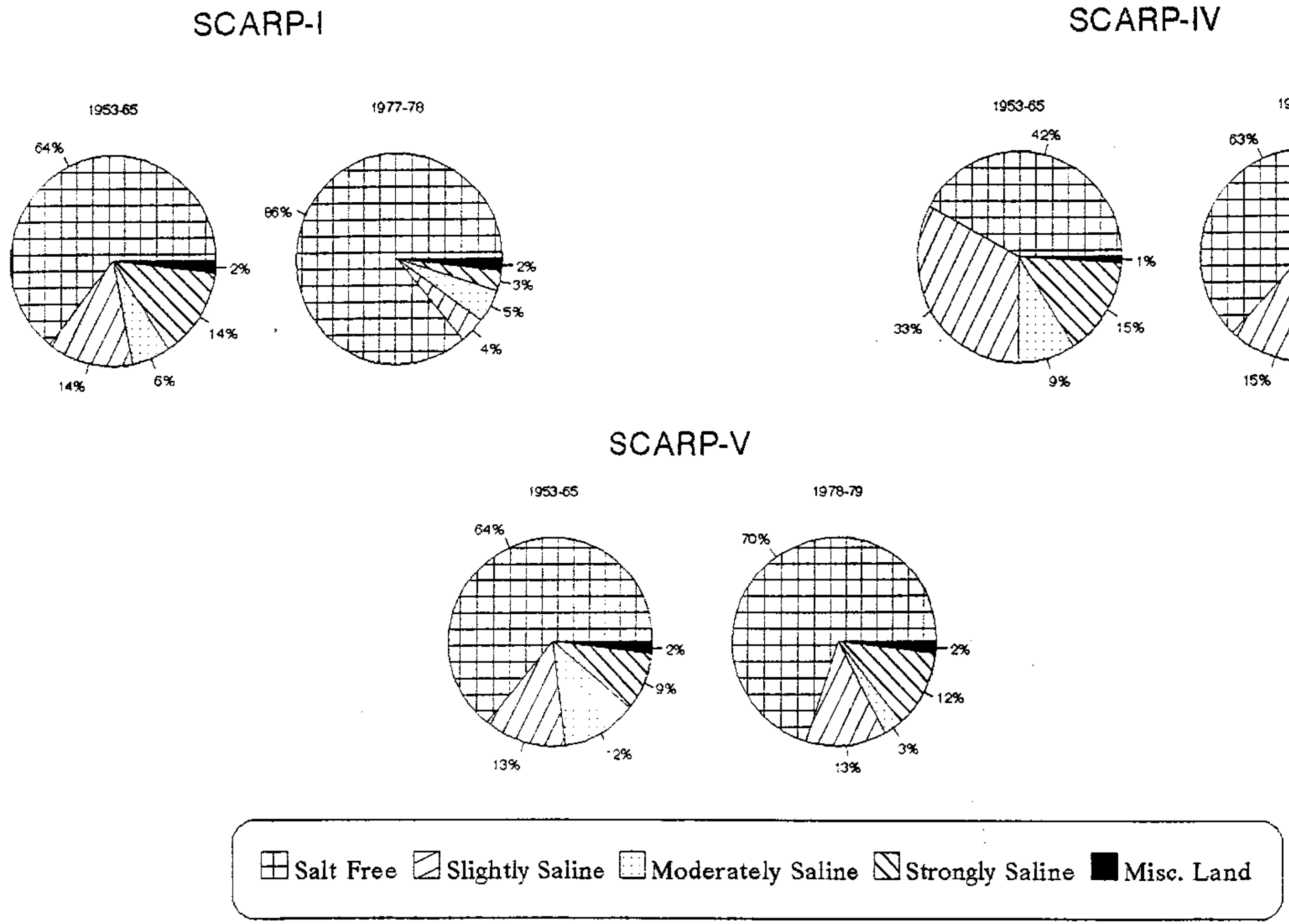


Figure 9. Cropping Intensity in the SCARP areas of the Rechna Doab, Punjab.



Source: Salinity and Reclamation Planning Division, WAPDA

Figure 10. Surface Salinity in the SCARP areas of the Rechna Doab, Punjab.

In contrast to the intensity gains above, the yields of major crops within the SCARPs have not shown sustained patterns of growth. Notwithstanding assumptions of incremental returns to yield at the time of project planning, a necessary pre-requisite to benefit/cost projections, judgements anchored solely to land reclamation as the panacea for all deficiencies are likely to suffer from misconceptions. For all practical purposes, reclamation is only an exercise to make additional land available for crop growth and not an instrument to effect gains in yield. From Figure 11, the most dominant inference casts a shadow of doubt on the potential of agricultural growth in areas that are reaching the limits of extensive growth aided by public sector reclamation schemes. The most recent of the three reclamation schemes, SCARP-V, with higher flexibility for extensive gains through the yet to be completed Shorkot Kamalia (Saline) project, shows a considerable jump in the yields of cotton, rice, and wheat crops after a sag interval in 1983-84; elsewhere, there have been no improvements in these crops since the start of the 1980s decade.

There would be an interest in knowing the impact of changes in cropping intensity and yield within SCARPs in relation to the macro-level agricultural growth figures like area and production across the LCC system. Outside WAPDA, the agricultural reporting in Punjab is done by the Provincial Agriculture Department (PAD). The data aggregation is accomplished across districts which are the middle order civil administrative and revenue units. Since the boundaries of these districts overlap with the WAPDA reclamation projects, the following comparisons are partially valid in space:

District of Sheikhupura	SCARP-I & IV
District of Toba Tek Singh	SCARP-V

For the Sheikhupura District, comprising much of the northern part of SCARP-I and SCARP-IV, cotton is steadily disappearing in what is increasingly becoming a high consumptive use environment for crops like rice and sugarcane. For rice especially, after steady increases in both area and production, there are indications that production levels are slackening despite continued growth in area under its cultivation. In the absence of genuine reasons to link this gap to an increase in salinity or waterlogging, a likely reason may be an over-reactive reliance on private tubewell pumpage in areas hitherto not covered by surface supplies and comprising soils not entirely suitable for its cultivation.

In Toba Tek Singh, somewhat erratic but steeper increases have been observed in production for all of the crops, especially cotton. These increases, in a transitional agroclimatic zone that also includes Jhang district, have been on the upswing in a manner not consistent with proportional increase in area. This intensification reflects a direct benefit of the improvements in land and water table conditions effected by SCARP V. If this intensification was borne out by significant increases in yield, then based on Fig. 9, where they overtake comparative figures for SCARP-I & IV by 1984-85, the corresponding increases in production at the district level are noticeable for rice and cotton, and to a much lesser extent for wheat.

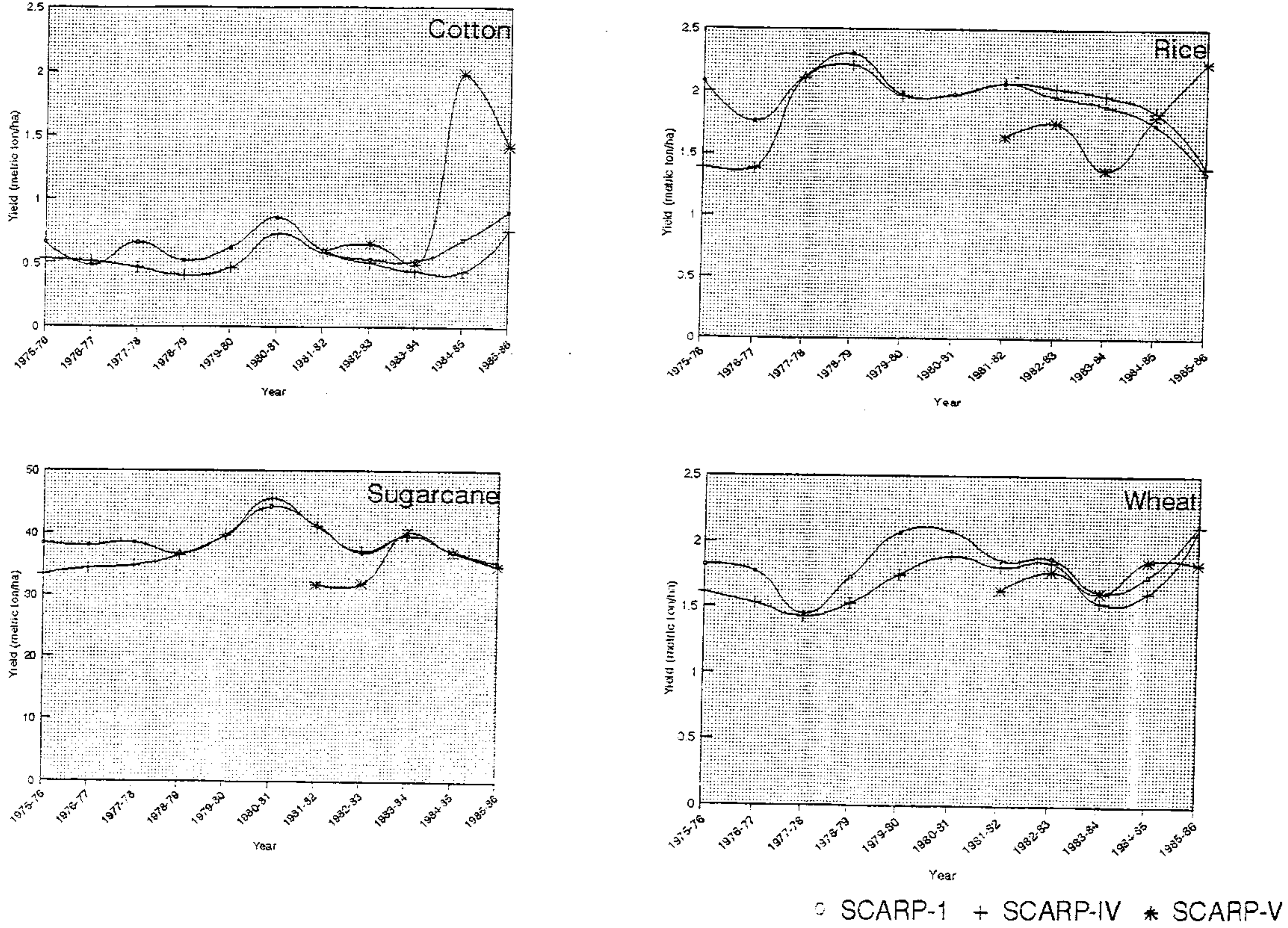


Figure 11. Yield of Crops in the SCARP areas of the Rechna Doab, Punjab.

When drawing conclusions, such as above, caution needs to be exercised in terms of the actual overlap of the project with the civil administrative boundaries. Crop information for areas outside the project bounds, but within the limits of the district, will undoubtedly affect the comparisons for intensity, yield, acreage, and production depending upon the significance of the exclusion zone. Unless independent project-specific surveys are conducted for impact assessment, the figures supplied by outside agencies will need to be disaggregated for enhancing accuracy.

C. Water Allocations

1. Irrigation Purposes

Punjab irrigation systems were designed to provide almost uniformity in equity: duties for all channels were essentially the same and, because the supplies were less than potential demand, the channels were expected to run at design discharges throughout the year. Almost doubling of the cropping intensities in many parts of the system has resulted in the distortion of the equity concept based on the design of the system, and resultant procedures for performance evaluation. For example, IIMI's sample research in parts of the LCC East Circle has shown stark variabilities in irrigation flows at the outlets during peak demand periods when considered in the context of applied *equity* set forth by the Irrigation Department (Table 3).

The operating policy necessitates at least 70% of channel design availability for equity to prevail. This policy is not uniformly coordinated in space and a clear distinction is maintained against the head and tail reaches of the system. While the < 70% supply availability enforces a rotation on the tail channels of the Lower Gugera, the same fluctuations occurring across the Upper Gugera outlets continue to aggravate distribution along the respective irrigation channels.

Data obtained by IIMI for several months in 1990 revealed significant inconsistencies in equitable distribution even when scheduled rotations are implemented, such as in the distributaries below Bhagat head regulator of Lower Gugera. Pir Mahal Distributary operated about 40% of the period below 70% of channel capacity when receiving its share of supplies through rotation; this contrasts sharply with the near continuous operations of neighboring Khikhi and Dabbanwala distributaries at 90% or more of authorised full supply.

The gap in original design criteria and present levels of system performance may be only partly caused by management deficiencies, whereas, partly it may be due to "un-manageability" of all or some of the original criteria within the present policy environment. Attempts at refining the data base on physical aspects is likely to be less productive as some conclusions on the degree of inequity and variability have already been reached, and appear to be sufficiently convincing, as demonstrated by IIMI research in the LCC system and elsewhere.

Table 3. Variation in Outlet Discharge During Peak Demand Period in the Lower Chenab Canal (East) Circle, Rechna Doab, Punjab.

Distributary/ Watercourse*	CCA (ha)	Design Discharge (lps)	Water Allowance (l/hr/ha)	Percentage of Design Discharge					
				May	June	July	August	Sept.	Oct.
UPPER GUGERA COMMAND									
Mananwala 24873-R	171	24.4	8.53	135	141	157	195	212	176
Mananwala 43506-R	225	29.7	7.94	88	89	77	92	92	91
Mananwala 71683-R	289	38.2	7.94	113	113	99	116	116	116
Mananwala 87670-R	240	47.9	11.96	185	189	176	207	214	212
Mananwala 121735-R	255	33.7	7.94	129	128	0	133	129	129
Mananwala 141542-R	514	68.0	7.94	38	24	0	25	0	0
Karkan 10435-R	158	31.4	11.94	103	107	87	101	122	107
Karkan 54892-R	231	46.2	11.96	78	82	0	96	98	102
LOWER GUGERA COMMAND									
Pir Mehal 70076-R	187	37.1	11.87	72	69	79	68	60	67
Pir Mehal 89250-L	174	46.2	15.87	58	56	64	52	45	48
Pir Mehal 133970-L	223	44.2	11.88	83	85	93	84	82	84
Junejwala 6619-R	118	31.1	15.86	100	114	99	103	119	109
Junejwala 27290-R	141	31.1	13.30	145	151	134	169	165	173
Junejwala 41234-L	159	31.7	11.93	86	94	68	96	93	90

* IIMI Sample Outlets of the LCC East Circle

An undue emphasis on performance ratings in the absence of mechanisms to translate irrigation and agriculture data into management information would be institutionally irrelevant and technically infeasible (Bandaragoda, personal communication).

Thus, attempts at matching existing management activities with design criteria are only of academic interest. In such situations, the focus of irrigation management research should be towards comprehensive "system renewal" whereby emphasis is placed on resource mobilization rather than impact assessments based on original system objectives.

2. Reclamation Purposes

IIMI investigations in the LCC system reveal that some 40% of the tail end areas do not receive any canal water at all, so that a gradual buildup of sodicity is inevitable. Surveys among farmers confirm this, as is apparent from the hardening of top soils, the decrease in the rate of infiltration and inadequate seed germination, all signs of the gradually worsening situation.

The DLR data on LCC East Circle indicates that its reclamation coverage in recent years has dropped (Table 4). In Kharif 1992, the saline area selected for reclamation supplies was only about 0.5% of the total CCA, and out of this only 59% was under rice, which is one of the recommended reclamation crops for Kharif season (Bandaragoda, 1994). The low percentage of area under rice confirms the farmers' comments (during field interviews by IIMI) that DLR's reclamation operations are not planned and initiated in time for them to start the rice cultivation. The data also indicates a decrease in the planned allocations for reclamation supplies which can partly be attributed to the lack of canal maintenance and the rest to the increase in the demand itself. However, from the sanctioned amounts, the provision of extra supplies for leaching purposes is operationally adequate, especially for rice.

The notion that reclamation shoots are based on additional water supplies, over and above the channel regulations, has not been substantiated by IIMI observations for the six distributaries in the LCC East Circle during Kharif 1992 (Table 5) (Bandaragoda, 1994). In fact, these extra provisions resulted in a further decline in the irrigation supplies at the tails of all the channels studied; not surprisingly, none of the reclamation shoots was sanctioned for the tail reaches of the distributaries where the incidence of salinity is usually the most.

Table 4. Reclamation Activities in the LCC (East) Circle (1985-86 to 1991-92).

Year	Total *Thur* area (acres)	Reclamation discharge demanded (cfs)	Reclamation discharge sanctioned (cfs)	Reclamation discharge actually utilized (cfs)	Area operated (acres)	Area declared reclaimed during the year (acres)
1985-86	261,614	319.24	117.55	114.16	5,282	2,595
1986-87	255,102	300.50	162.55	159.34	7,187	1,637
1987-88	263,680	317.04	184.44	174.00	8,118	889
1988-89	263,638	332.17	174.19	159.36	7,213	1,525
1989-90	264,836	319.53	128.04	106.17	4,810	1,397
1990-91	263,638	386.62	124.96	106.14	5,022	580
1991-92	-	373.93	172.77	163.22	5,434	-

Note: 1 acre = 0.4047 hectare; 1 cusec (cfs) = 28.32 l/s.
Source: LRO Office, LCC East Circle, Faisalabad.

Table 5. Design Head Gauge versus Observed Head Gauge of Sample Channels in the LCC (East) Circle.

Distributary/ minor	Design head gauge (feet)	Average, observed head gauge, kharif 1992 (feet)							
		March	April	May	June	July	August	September	October
Lagar	1.89	1.45	1.58	1.66	1.65	1.63	1.50	1.41	1.62
Mananwala	5.20	4.34	5.01	5.07	5.08	5.14	5.10	4.81	4.68
Karkan	3.31	2.51	2.96	3.06	3.09	3.04	3.04	2.58	2.51
Yakkar	1.25	1.18	1.03	1.07	1.21	1.22	1.26	0.99	1.05
Bhun	1.10	1.01	1.08	1.14	1.31	0.94	1.04	1.07	1.08
Rajana	1.20	1.13	1.24	1.19	1.05	1.12	1.05	1.07	1.09

D. Soil Suitability

As part of the country-wide soil investigations, mapping of the drainage-related constraints is accomplished by both WAPDA and the SSoP, though for completely different reasons. WAPDA's information has a clear slant towards engineering aspects, whereas the SSoP differentiates towards land use, particularly for irrigation purposes. Moreover, in lieu of its mandate, WAPDA's activities are confined to project areas for which a host of considerations specific to the physical and stratigraphic details are taken into account. These exhaustive considerations were not part of the earlier mapped investigations conducted by WASID; however, amendments have been made towards mapping descriptions similar to the ones used by the United States Bureau of Reclamation. The indexing makes use of an array of physical factors like soil permeability, slope, texture, water table depth, field capacity, etc.. Clearly, such levels of detail are not available across the entire expanse of the LCC system, however it is possible that some of the more recent reclamation projects might have benefitted from such intensive investigations.

The SSoP adopts a simplified approach towards the definition of soil drainability, whereby the emphasis is on the moisture holding capacity. For its reconnaissance level mapping, it provides a four-class definition of drainability that has a direct bearing on the suitability of the consumptive use. For example, for the Chuharkana irrigation subdivision of the LCC system, the association-specific characteristics of drainage in Figure 12(a) are corresponded to the crop suitability regimes in Fig 12(b). As part of the rice-wheat agroclimatic zone, this subdivision has an extensive cultivation of rice during kharif season even though the imperfect drainage conditions favoring puddling for its growth have a scarce spatial distribution.

E. Boundary Delimitation of Irrigation and Project Units

Under Section II A above, an allusion was made to the lack of relief information specific to the changes in the commanded regimes at the tertiary level. In fact, there has been no updates to this information since the earliest surveys; even the irrigation patwar maps for cropped areas cannot show the commanded differentiation *as a matter of fact* since many of the tail-ends in these watercourses seldom have access to water. In the absence of mechanisms for the update of distributary and subdivisional command maps, there is no concordance in the CCA figures aggregated through patwar surveys and the maps retained by the divisional Drawing Branch. This situation is compounded further due to the difference in reporting between the revenue and the irrigation patwaris effected by lack of agreement on 'kharaba' or land lost to productivity by waterlogging and salinity.

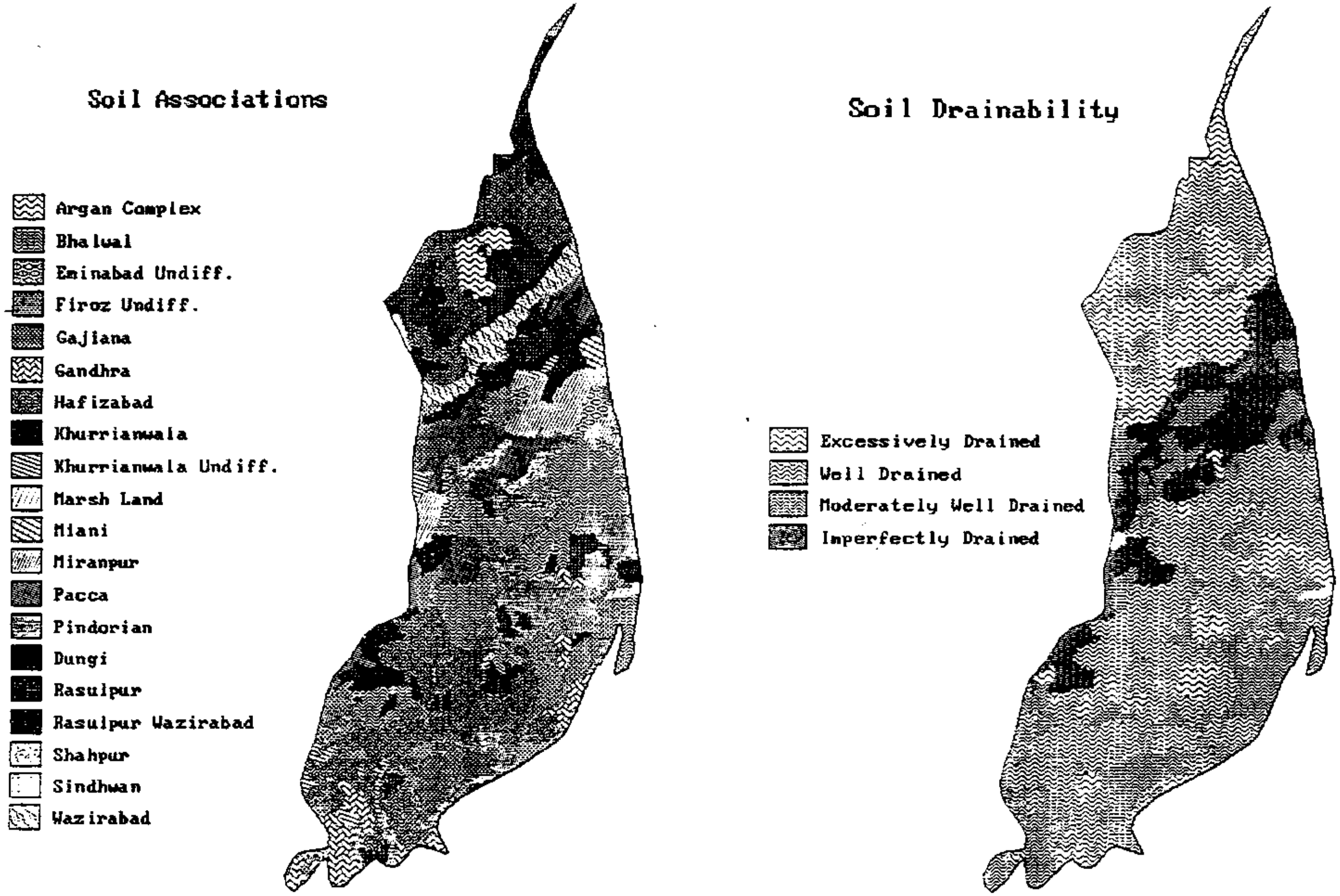
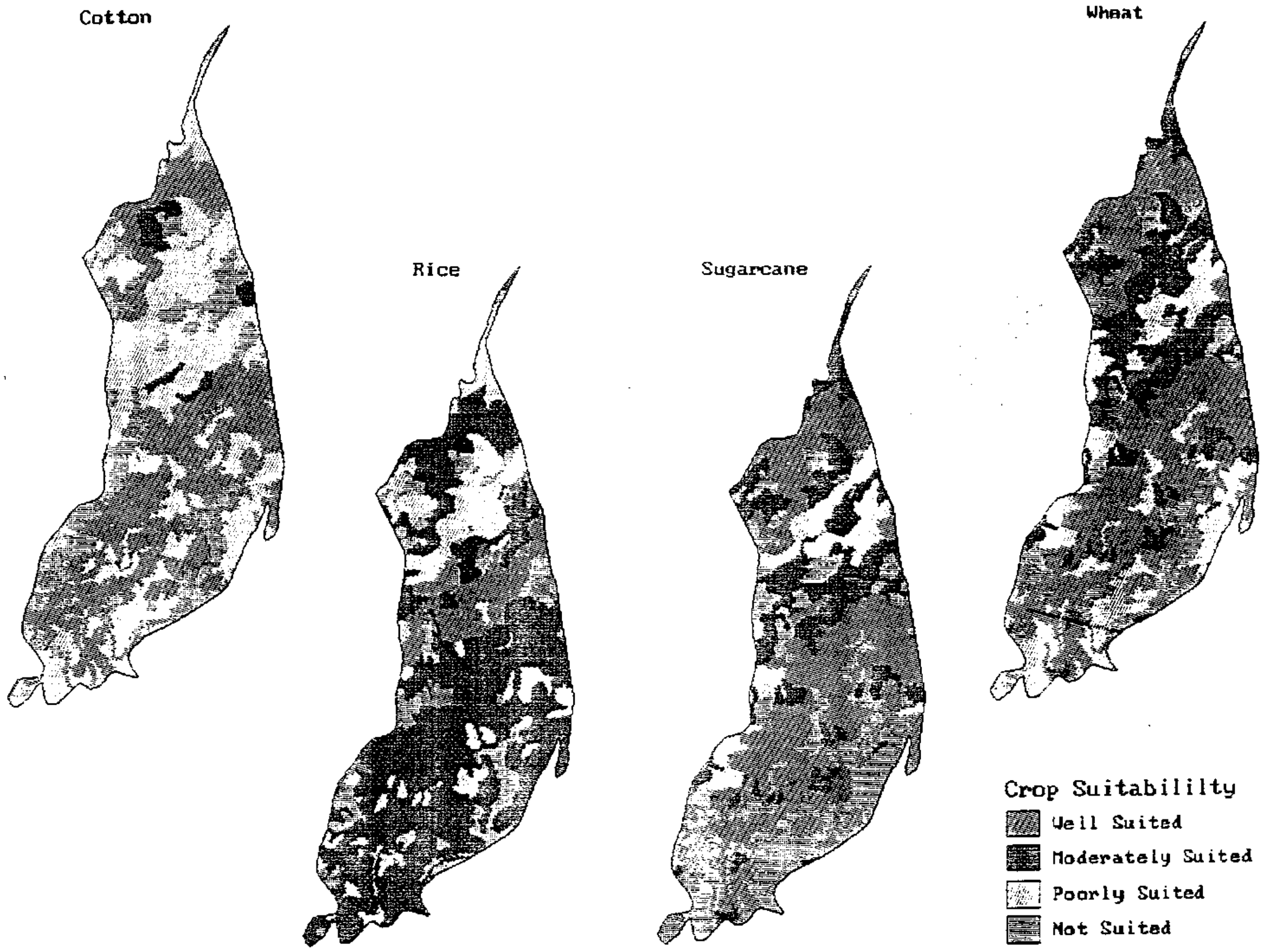


Figure 12(a). Soil Associations and their respective Drainabilities in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab.



Source: Soil Survey of Pakistan

Figure 12(b). Suitability of Soils for Major Crops in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab.

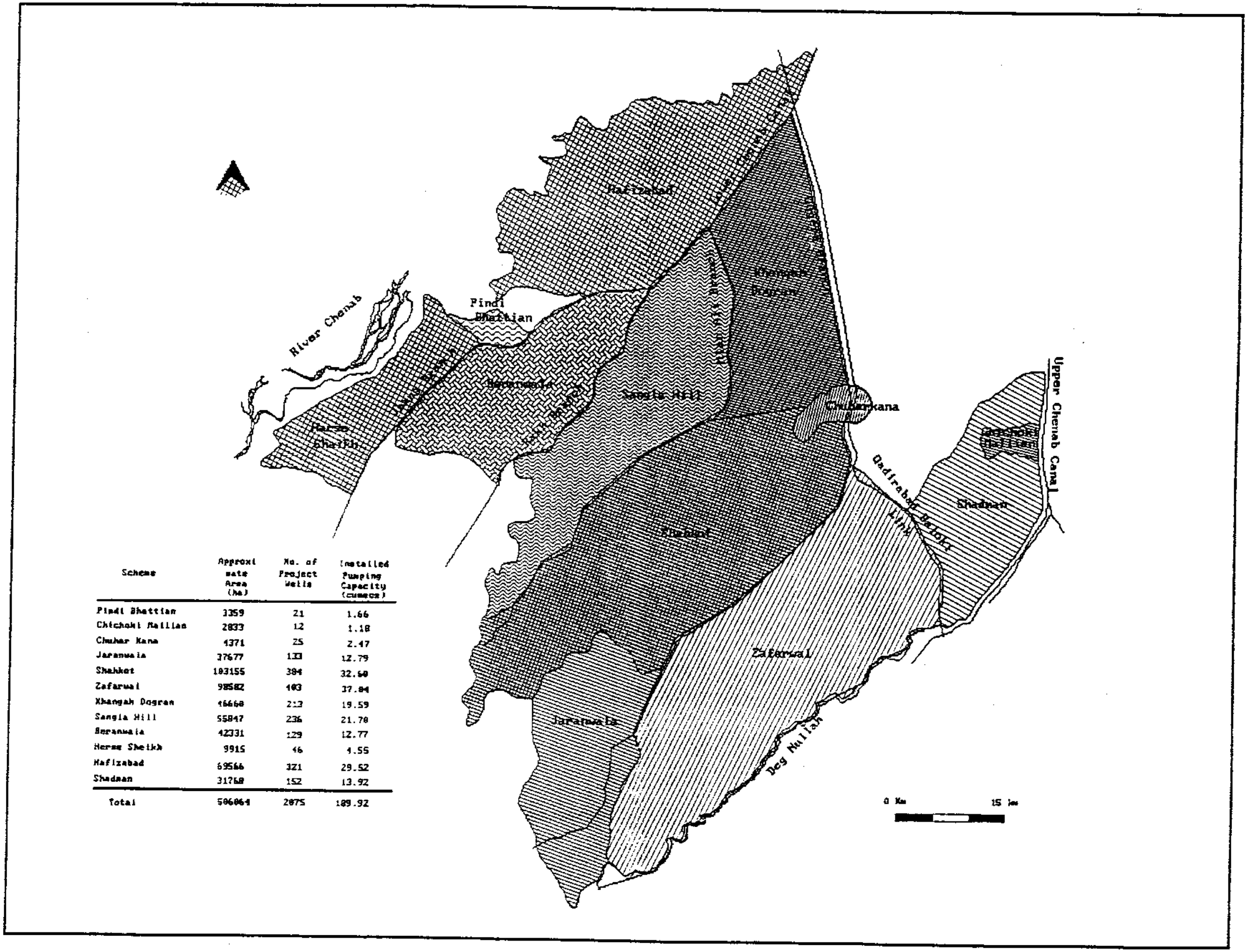
Project boundaries are subject to even less rigorous delineation, especially when political boundaries, such as tehsil and district level separations, are adopted instead of the more easily discernable hydrologic or communication bounds. Sometimes, the boundaries are a complex mix of political, irrigation, communication, and natural features that are difficult to identify on maps with remissions on any one of the bounding features. Such a situation occurs for the SCARP-I (Fig. 13) where the western boundary is a continuing mix of Chenab River and District Hafizabad; to the south is the District of Faisalabad; to the southeast is the Deg Nala; to the east is the Upper Chenab Canal and District Gujranwala; and finally, to the northeast is the Upper Gugera Branch Canal. Such boundary definitions are not cognizant of the concerns for determination of the hydrologic balance that is so vital to the success of the irrigation projects.

Given the lack of spatial control in data collection and sampling, the coordination in research and monitoring activities, specific to the projects, are usually the worst sufferers. The resultant gaps in spatial and temporal analysis preclude effective feedback mechanisms for project control. Again, for SCARP-I, the installed base of over two thousand tubewells suffered from intermittent monitoring of the performance and water quality data that had undesirable gaps in time and space. For example, an integrated picture of pumped groundwater quality for any one year is not possible since the sampled wells were not distributed in space to allow for uniform interpolation (Fig. 14).

F. Tubewell Performance

Areas comprising SCARP-I were not only the first to benefit from the continuing series of land reclamation programs across the country, but also derived succor through comprehensive monitoring of the tubewell performance and the resultant impact on the physical regime. Annual reports issued by WAPDA contain measured data on the decline in specific capacity, drawdown, volume of pumpage, and the reduction in water tables (static measurements through the bore). This wealth of information has had periods of remissions since the completion of the original installations in 1963, however at least till 1968 the data collections had been regular. Regardless of the discontinuities, it is possible to quantify the long term impacts of pumpage across nearly three decades of operation.

For example, comparing the spatial and temporal differentiation in pumpage, the SCARP-I schemes occupying the center of the Project area (Shahkot, Harse Shaikh, Sangla Hill, Khanqah Dogran, and Beranwala) have experienced a steady decline in pumpage across both rabi and kharif seasons. The abstractions during Kharif have been higher than Rabi most of the time. Since the installed pumpage capacity (as well as the number of tubewells) of these schemes was 48% of the total and across more than 50% of the project area, these reductions (more than 50% of the original by mid 1980s) have significant implications towards estimation of groundwater balance within the area. Contrastingly, the smaller schemes like Pindi Bhattian, Chichoki Mallian, and Chuharkana have stable Rabi contributions and the fluctuations in pumpage are unlike



Scheme	Approximate Area (ha)	No. of Project Wells	Installed Pumping Capacity (cumecs)
Pindi Bhattian	3359	21	1.66
Chichoki Mallian	2833	12	1.18
Chuhar Kana	4371	25	2.47
Jaranwala	37677	133	12.79
Shahkot	103155	384	32.60
Zafarwal	98582	403	37.84
Khangah Dogran	46660	213	19.59
Sangla Hill	55847	236	21.78
Beranwala	42331	129	12.77
Harse Sheikh	9915	46	4.55
Hafizabad	69566	321	29.52
Shadman	31760	152	13.92
Total	506064	2075	189.92

Figure 13. Location Map of SCARP-I, Punjab.

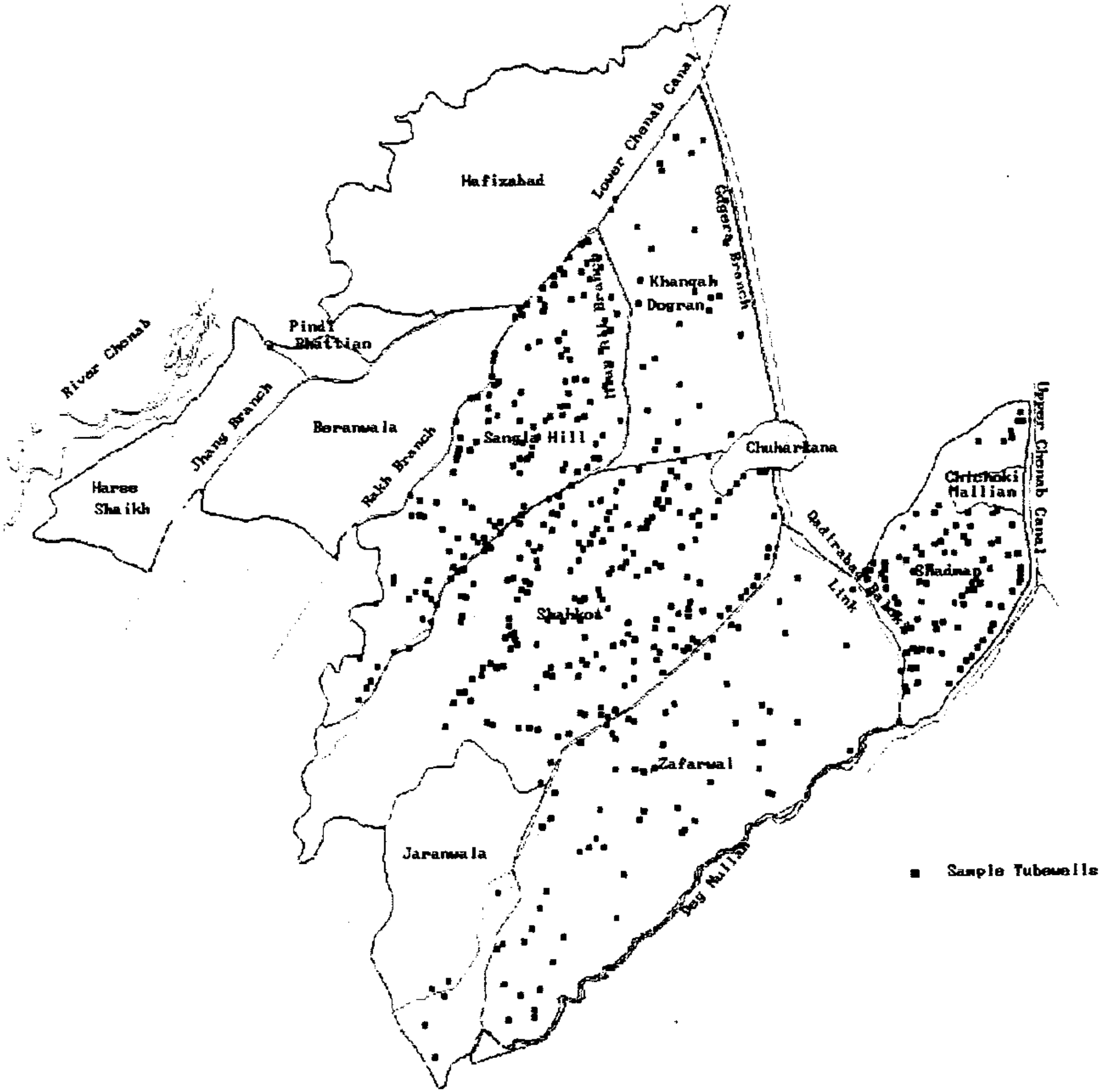


Figure 14. Distribution of Tubewells Sampled for Groundwater Quality in SCARP-I in 1989.

the steady trend in deterioration for the schemes in the center of the Project area. One logical explanation could be the geographical proximity of these schemes to zones of recharge like the Upper Chenab Canal, Upper Gugera/QB Link, and Chenab River that sustain subterranean inflows to the pump sites on a permanent basis. Also, pumpage close to these fresh groundwater zones was less likely to corrode the impellers as much as the tubewells in saline groundwater zones.

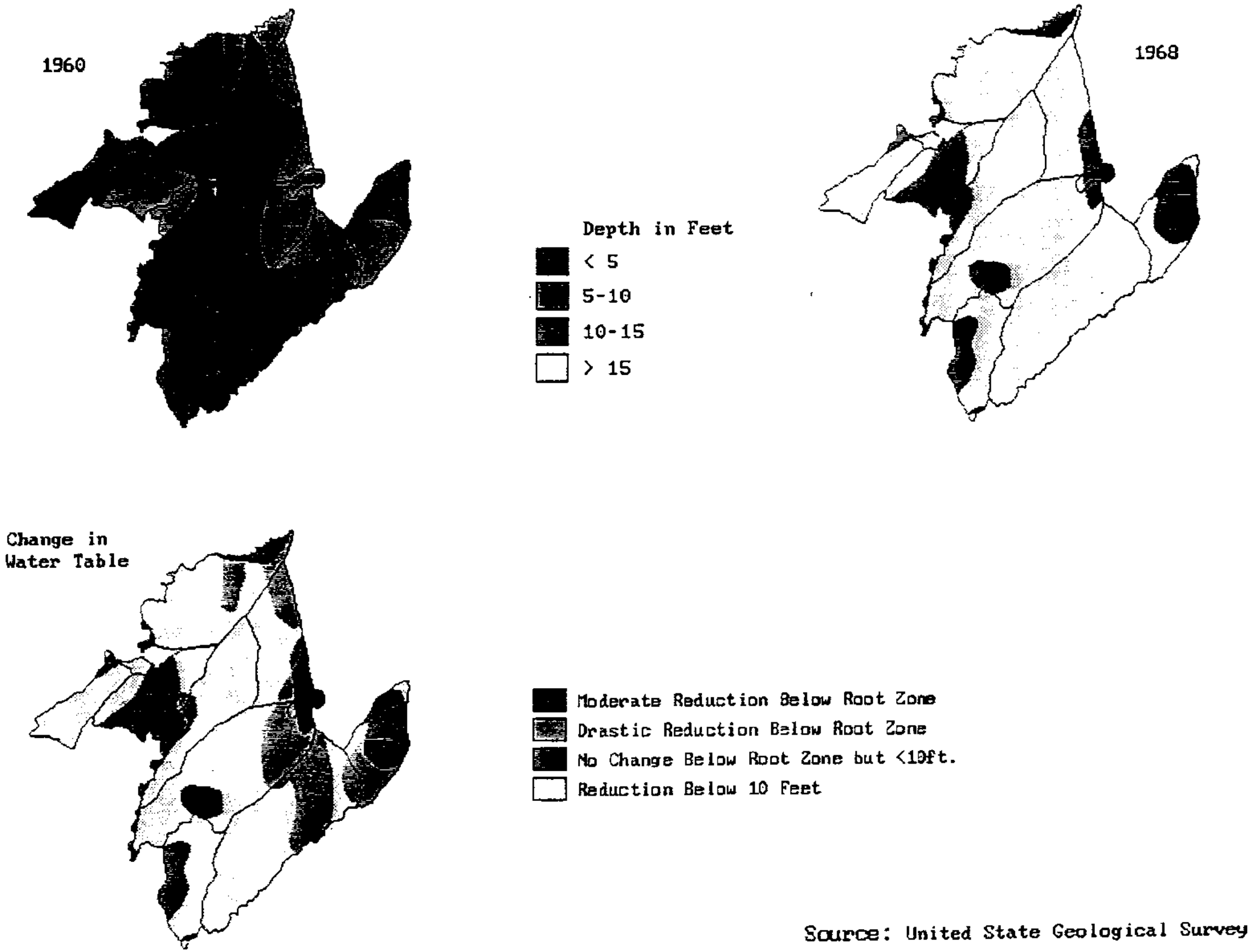
The impact of tubewell-specific pumpage on seasonal lowering of the water tables suffers from a lack of coordination in data collection and reporting. Data analysis upto 1968 indicates that for an annual average of about 284,000 hm of pumping in the SCARP-I since the start of operations, the lowering of the water table has been scheme-specific; maximum being for the Zafarwal and minimum for the Jaranwala and Shadman. By June 1968, in response to a net depletion of 0.2 Mhm from the reservoir (despite a net recharge of 1.267 Mhm), three distinct cones of depression, separated by seepage divides, had developed in Zafarwal, Khanqah Dogran, and Hafizabad schemes towards locale-specific lowering of the water tables (Fig. 15). This lowering has been unrelated to the gross pumpage occurring in the individual schemes based on tubewell capacity and density.

In terms of the spatial distribution of public wells, there is little understanding of the patterns of decrease in the specific capacities in relation to acceptance values. This has important connotations towards localized reductions in pumpage, especially in the fresh groundwater regimes. The SCARP wells in the Rechna Doab operated in the capacity range between 2-5 cusecs (57-142 lps). This design discharge could not be sustained due to decreases in the specific capacities at an average rate of 3 to 7% per year causing reductions in pumpage. Not only is this decrease not uniform, but the maximum affectation below 80% of acceptance specific capacity occured within the first 12 years of operation. Results of analysis to correlate acceptance specific capacity with tubewell pumpage deterioration (SCARPs I & IV) indicates greater longevity for tubewells with a lower value of acceptance (80-100 gpm/ft).

G. Water Quality Monitoring

In the context of Pakistan's Punjab, the deleterious effects of saline pumpage affecting the root zone are well documented. In fact, the threat is more from the presence of sodium salts that are non-uniformly distributed in space and somewhat predictable in time. This is especially true across the LCC system where the head reaches of the system benefit disproportionately from useable groundwaters, whereas unconfined aquifer transition to the south has predominantly sodium-rich ions.

For the LCC system, the early experience with vertical drainage was spurred by the installation of high capacity wells that, over an extended period of time, disturbed the inflow nets to the aquifer. Since these high capacity wells were not uniformly distributed



Source: United State Geological Survey

Figure 15. Temporal Changes in depth to Water Table within SCARP-I.

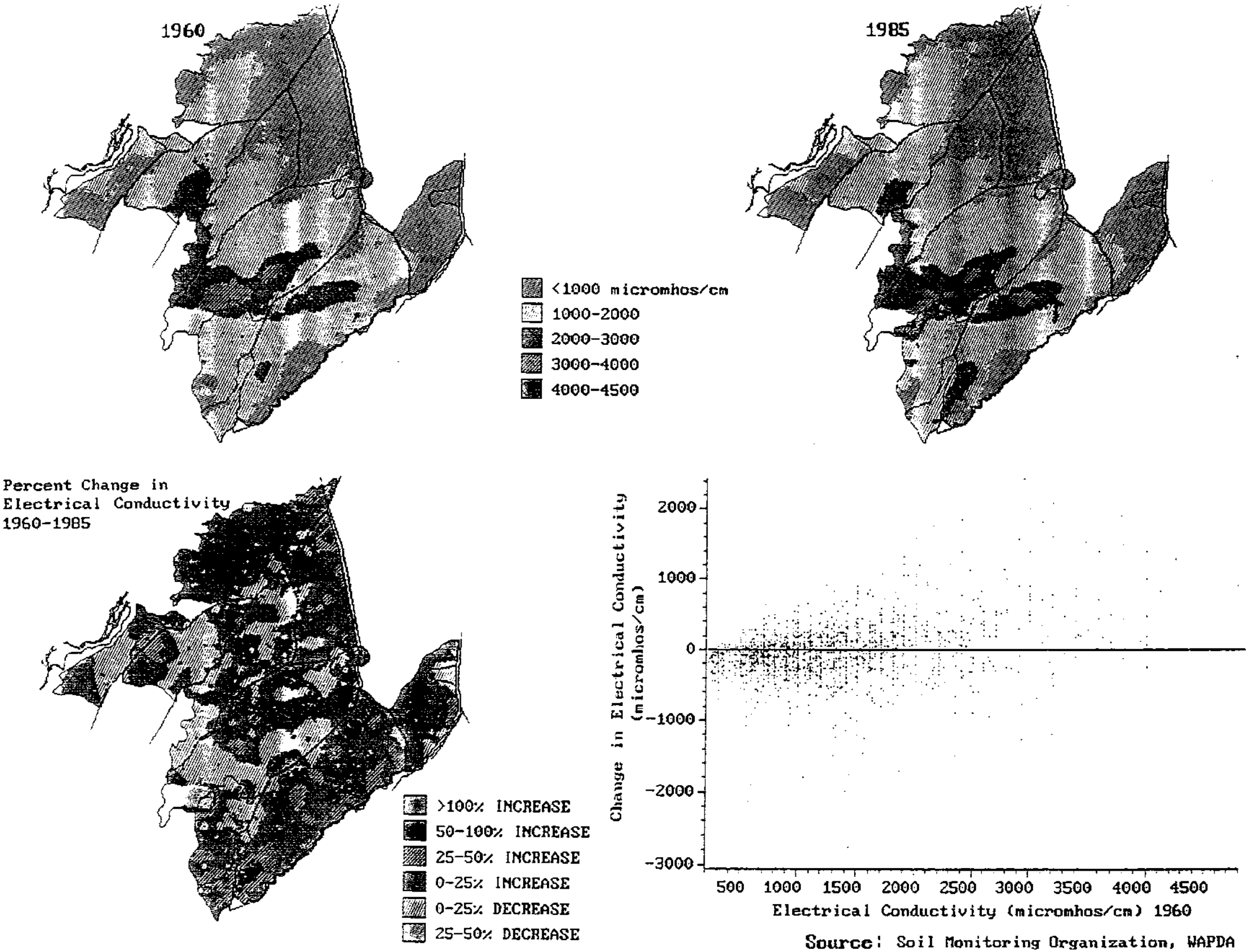
in space, the upconing of the hazardous/saline margins in the deeper strata were haphazard. In the time that these tubewells began to suffer a loss in specific capacity, the private tubewell development had picked up significantly. Resultantly, the negative flow nets of saline intrusion were sustained across aquifer locales previously reckoned to be of fresh water quality.

Scarp-I may be cited as an example of saline water intrusions into the FGW areas where the results of qualitative investigations across 25 years of tubewell operation are presented in Figure 16. The comparison of salient features in geographic space draws forth the following conclusions:

- the low values of EC in either time periods are concentrated along zones of high recharge, i.e. large irrigation canals;
- areas in the immediate vicinity of the Chenab River have been minimally affected;
- a majority of the pumpage regime has experienced upto a 25% increase in electrical conductivity with respect to 1960 benchmark levels;
- higher percentage increases in salinity have a large spatial scattering but mostly restricted to the south;
- improvements in water quality have occurred, rather surprisingly, even across the saline belt to the south;
- the fresh water regime in the head reach of the system has suffered drastic increases in EC values, but still remains under the 1000 micromhos/cm limit; and
- reductions in the quality of water have been more pronounced in the lower EC ranges, whereas the converse is true for highly saline waters.

An important qualifier for the determination of the abovementioned temporal and spatial trends is the use of the critical limits or standards adopted for the differentiation of the fresh and saline groundwater areas. It is not possible to set precise standards for irrigation water quality of wide applicability since the usage is largely dependent on the local conditions. For practical use, the groundwater quality may be classed as follows:

	Electrical Conductivity dS/m	SAR
Useable	< 1.5	< 10
Marginal	1.5-3.0	10-18
Hazardous	> 3.0	> 18



Source: Soil Monitoring Organization, WAPDA

Figure 16. Periodic Changes in Pumped Groundwater Quality within SCARP-I.

The FAO standards would revise the EC for fresh groundwater to be < 0.7 dS/m with a general upper limit of SAR at < 6. For sodic waters, the adjusted SAR is now generally recognized as a better index that results in around a 25% increase over the unadjusted SAR. In addition to the foregoing, the following standards have been adopted by Tipton and Kalmbach consultants for the project design of SCARP-V (Shorkot Kamalia);

	EC dS/m	SAR
Useable	< 1500	< 5
Marginal	1500-2000	5-12
Hazardous	> 2500	> 12

Based on its own experience in the processing of SCARPs related data, IIMI has made use of the following criteria for qualitative separations:

Fresh/Slightly Saline	------	EC < 1500 micromhos, SAR < 6
Moderately Saline Sodic	------	EC 1500-3000, SAR 6-10
Strongly Saline	------	EC > 3000, SAR < 6
Strongly Saline Sodic	------	EC > 3000, SAR > 10

Without bias to any of the foregoing qualitative criteria, the resultant impact of tubewell pumpage on the spatial distribution of aquifer water quality for SCARP-I is shown in Fig. 17.

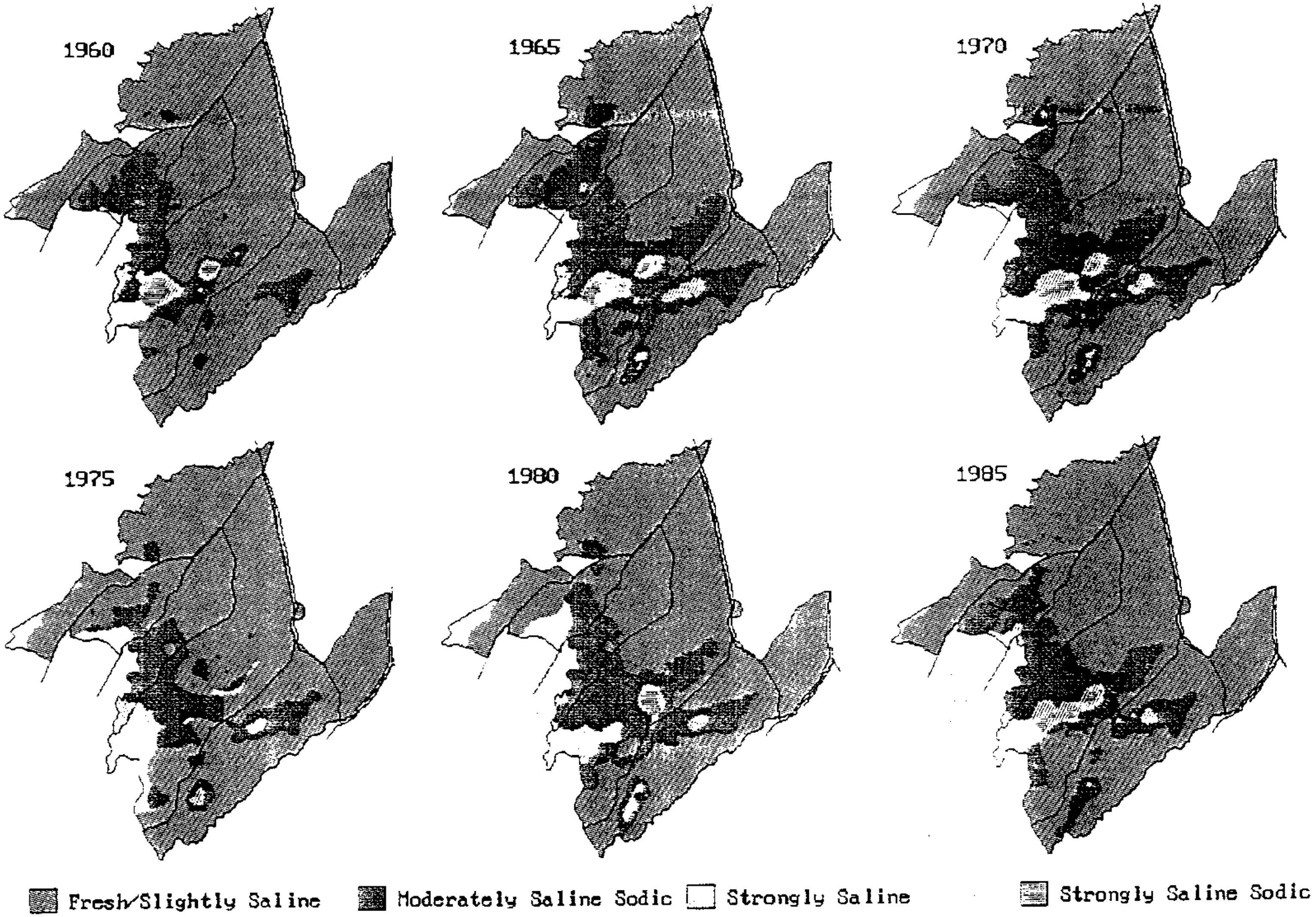


Figure 17. Changes in Pumped Groundwater Quality within SCARP-I between 1960 and

IV. ABSENCE OF MECHANISMS FOR VERTICAL INTEGRATION OF INFORMATION AND REPORTING

A. Deficiencies in Basemap Referencing

Reference to a lack of photogrammetric correction of aerial photography used for visual interpretation has already been made in Section II (C) above. Other than the standard map compilation work by the Survey of Pakistan this tendency persists in all other public agencies. Resultantly, the interpreted 'maps' so produced through tracings on the mosaicked photographs are topologically incorrect and not referencible in terms of the metric coordinate system provided by the Survey of Pakistan. Maps otherwise available from the Irrigation Department also have no metric coordinates on them, and this phenomenon is persistent from the smallest of the layouts (i.e. the patwar maps) up to the Circle level reproductions. The coordinate reference on the Division or Circle level maps, if provided, is the geographic easting or northing which in effect is not a reference with respect to the datum.

The likely consequence of this absence of coordinate control is the inflexibility in combining system-specific details across scales and the calculation of true distances. This problem was most glaringly observed when IIMI, in support of its field activities, attempted to combine together the village or mauza maps of two distributary commands in the Upper Gugera Branch command of the LCC system. Since these maps were the original reference to the system layout, it was thought prudent that the integration would be similar to putting together pieces of a block puzzle. Unfortunately, not only the village boundaries were inconsistent in mosaicking together, but the gridded reference of land parcelling was also misleading. To overcome these difficulties, the maps and their gridded reference were redrafted on standard engineering graph paper to construct the larger picture. A system of cut and paste was adopted where the grids changed alignment in between mauzas. Clearly, such a recourse at the Division or Circle level would be infeasible even if just the village divides are accounted for. This is not to say that villages are not marked at the Circle level, however, the reproduction of this information is suspect.

Probably the only consistently produced piece of thematic information related to irrigated agriculture is by the SCARPs Monitoring Organization of WAPDA for the interseasonal variations of water table depth. This is despite the doubts about the location accuracy of piezometers used for this purpose. Other than this annual exercise, there is hardly any agency that tackles thematic reproductions as part of its data evaluation or dissemination procedures.

B. Information Tabulation and Data Distortion

In the Irrigation Department, besides O&M assessments, the collection of cropped information is fairly regular on a seasonal basis. Details relating to the collection and compilation of this data appear under Section II (B) above. Regardless of the veracity of this information, absence of procedural drafts towards its assimilation in space necessitates recourse to tabulations that result in repeated aggregations until final reporting at the district level. During this process, the data loses its sensitivity with respect to the physical/hydrologic regime and the farm level characteristics therein. The 'Khatouni' or tax record so collected is an aggregation across ownership, howsoever the distribution of land holding in space. Therefore, at the time of compilation of agricultural statistics, the information appears bracketed under larger aggregates of farm size, production, gross cropped areas, average yields, etc..

The DLR also compiles aggregate figures on its reclamation operations facilitated by the once-a-year visual salinity observations made by the patwars. In such aggregations, there are differences in the extent-wise separations of the total figure on Thur in comparison to the class differentiations (Table 6). In extreme cases, such as for the LCC East Circle, the total Thur area remained unchanged for several years in a row (Table 7); this is despite the statements on reclaimed land made possible because of sanctioned reclamation discharges (Table 8).

C. Appropriateness of Scale and Reproduction Inaccuracies

The information contents in mapped reproductions are particularly sensitive to scale, especially when details at smaller scales are exploded to fit large scale geographic delimitations. An example of such a mismatch is the transfer of the canal alignments from the Divisional or Circle map to the distributary or watercourse level. Conversely, there are instances when information at the level of village or watercourse needs to be transferred to smaller scales for data integration purposes. Such transfers are inappropriate for point or symbol related informations like tubewells or location of structures and outlets. In this respect, reference may be made to the topological associations in the vicinity of the point for directions and distance.

WASID data for profile salinity in selected areas of the LCC shows symbological references that have little correspondence to the mapped details. This has largely to do with the oversized symbology chosen for this purpose. Elsewhere, the use of ammonia prints is the most common means of reproduction that often renders information unintelligible. A more time consuming alternative is the pentagraph but it also involves retracing of archived information and hence compounding of the errors.

Table 6. Differences in the Extent-wise separations of the total figure on Thur (Punjab) in comparison to the Class Differentiations, as reported by the DLR.

Yeay	Total Thur (acres)	Thur Kohna		Thur Punjsala		Thur Nau		Thur Juzvi		Thur Tirk	
		Area	%	Area	%	Area	%	Area	%	Area	%
1982-83	2739978	556928	20.33	240346	8.77	153221	5.59	1723301	62.89	3677	0.13
1983-84	2676607	533389	19.93	238970	8.93	151214	5.65	1695436	63.34	3599	0.13
1984-85	2669314	533513	19.99	239111	8.96	152667	5.72	1695482	63.52	3587	0.13
1985-86	2076616	533083	19.92	239095	8.93	152563	5.70	1695914	63.36	3632	0.14
1986-87	2816888	538398	19.11	253093	8.98	152962	5.43	1819417	64.59	3824	0.14
1987-88	2880540	538178	18.68	269086	9.34	150379	5.22	1865529	64.76	4092	0.14
1988-89	2904080	538576	18.55	270562	9.32	152524	5.25	1881139	64.78	4095	0.14
1989-90	2886776	533250	18.47	270817	9.38	152578	5.29	1877424	65.04	4209	0.15
1990-91	2879021	533203	18.52	270801	9.41	152721	5.30	1857921	64.53	13868	0.48
1991-92	2852149	537488	18.85	270336	9.48	154109	5.40	1836270	64.38	3923	0.14
Overall	27981969	5376006	19.00	2562217	9.86	1524938	6	17947833	65	48503	0.14

Source: LRO (Thur & Sem Division),
Directorate of Land Reclamation, Lahore.

Table 7. Total Thur area remaining unchanged for several years in a row in the LCC (East) Reclamation Division.

YEAR	AREA SURVEYED	THUR KOHNA	THUR PUNJSALA	THUR NAU	THUR JUZVI	THUR TIRK	THUR RECL.	TOTAL THUR	%AGE THUR
1982-83	1854568	28313	36452	18859	171795	719	7430	263568	14.21
1983-84	1854568	28313	36452	18859	171795	719	7430	263568	14.21
1984-85	1854568	28313	36452	18859	171795	719	7430	263568	14.21
1985-86	1854568	28313	36452	18859	171795	710	7430	263568	14.21
1986-87	1854568	28313	36452	18859	171795	719	7430	263568	14.21
1987-88	1854568	28313	36452	18859	171795	719	7430	263568	14.21
1988-89	1854568	28313	36452	18859	171795	719	7430	263568	14.21
1989-90	1854568	22254	36416	18803	171915	719	7401	257508	13.89
1990-91	1854568	22254	36416	18803	171915	719	7401	257508	13.89
1991-92	1856568	28332	36452	21460	181578	718	7380	275920	14.86

Source : Annual Data Statements by LRO (Thur & Sem)
Directorate of Land Reclamation Punjab, Lahore.

Table 8. DLR Statements on Reclaimed Land made possible because of Sanctioned Reclamation Discharges.

Year	Reclamation supply actually utilized (cusecs)	Area operated in acres	Area reclaimed during the year (acres)	Area reclaimed upto date in acres
Area Reclaimed upto 1947-48				143046
1948-49	2254.48	102347	25164	168210
1949-50	2345.79	107921	19437	187647
1950-51	2107.55	96897	20195	207842
1951-52	2161.35	103113	17644	225486
1952-53	2624.14	128979	14798	240284
1953-54	4142.97	179172	26827	267111
1954-55	4004.77	169066	27841	294952
1955-56	3498.92	153148	34383	329335
1956-57	3156.44	150766	23901	353236
1957-58	3040.59	140903	27843	381079
1958-59	3090.25	152807	37067	418146
1959-60	2547.90	127355	27251	445397
1960-61	2407.84	121258	38507	483904
1961-62	2106.88	99872	21912	505816
1962-63	2019.38	96788	21801	527617
1963-64	2239.84	106143	31468	559085
1964-65	2350.05	113018	27621	586706
1965-66	2704.22	128840	29230	615936
1966-67	2561.00	125592	34596	650532
1967-68	2679.81	130399	36144	686676
1968-69	2825.05	133636	28206	714882
1969-70	2329.93	116794	37738	752620
1970-71	1979.75	97319	36087	788707
1971-72	1862.29	91090	21387	810094
1972-73	1853.51	90838	30249	840343
1973-74	2040.41	96313	33689	874032
1974-75	2088.13	100418	20247	894279
1975-76	2082.20	97689	34563	928842
1976-77	2159.45	101529	38132	966974
1977-78	2161.74	101618	20931	987905
1978-79	2320.05	109828	38515	1026420
1979-80	1902.08	88552	42739	1069159
1980-81	1465.89	69806	22575	1091734
1981-82	1216.36	62383	15465	1107199
1982-83	1037.62	55682	25284	1132483
1983-84	823.40	39505	18451	1150934
1984-85	805.80	37944	10092	1161026
1985-86	860.12	42738	8514	1169540
1986-87	1015.16	48866	16362	1185902
1987-88	1118.62	51992	14007	1199409
1988-89	984.96	47170	17219	1217128
1989-90	1074.63	46270	16426	1233552
1990-91	973.96	45774	12998	1246550

Source : Directorate of Land Reclamation,
Punjab Irrigation and Power Department, Lahore.

D. Choice of Mapping Units

Information worthiness in maps is largely determined by the scale (affecting linear features) and the choice of the minimum mapping units (MMUs) (enclosed features). For example, at the national level, crop production could be shown by the aggregations at the district level which would be the minimum mapping unit for this purpose; however, the same would not unfold the spatial variations at the provincial level due to the comparatively large geographical bounds of the districts. Similarly, the cropping pattern changes at the watercourse level are much more revealing in comparison to the village level aggregations typically performed by the patwaris.

For irrigation managers, it is most desirable that the choice of the MMU should correspond not only to the scale variations but also sustain the successive hydrological delimitations in going from watercourse level to the circle level. Accordingly, a standardization of the most representative formats would be the prerequisite across different scales. Here, a rule of thumb may be used for general guidance in that the choice of the MMU should not extend beyond two orders of magnitude in successive irrigation unit delimitations. This would imply that watercourses, as an MMU, would be inappropriate for information portrayal in space beyond the higher order distributary or subdivisional scale.

For information that is spatially less discretized as compared to crop data aggregations, such as water table depths or contours of water quality, the MMUs should constitute larger spatial bounds that may subsequently be 'condensed' across the smaller fractions in space, if needed. With current deficiencies in reliable and consistent monitoring of the physical regime, it is difficult to evaluate trends across the larger domains, much less the contextual inference required at the local level.

V. ISSUES IN DIGITAL SPATIAL ARCHIVING AND ANALYSIS

A. Consistency in Data Organization and Retrieval

Spatial information systems are most prolific when handling large sets of data. Because of the flexibility to relate information across different scales, it is essential that the thematic combinations derived from overlay analyses have consistency in space and time. For example, if the constructs of the topological reference at the watercourse level have remissions in terms of square/acre lines, access/drainage ways, delineating of settlements and wastelands, etc. then comparisons across time for changes in land use or cropping pattern would be less than obvious. This adherence to the capture of cartographic details is thus a standardization of information portrayal that is uniform in space and selective across scales.

The above would also imply a common reference (indexing or coding) to geographical entities that avoids multiplicity in database and facilitates ease of feature extraction. This becomes most demanding when collecting information from diverse sources, especially when relating to information with unconfirmed boundaries in the physical world or corresponding to a different classification criteria. In such situations, it is prudent to proceed with data organization that first resolves large scale (small area) discrepancies ahead of the spatial integration at smaller scales. The converse is not advisable as it imposes an accumulated set of systematic and non-systematic errors on the final integration.

B. Thematic Derivatives and Modeling Rationale

Spatial analysis not only links disparate pieces of information in time and space but also allows derivation of new themes from parent sources. For irrigated regimes, such renditions would include examples of the slope maps and digital elevation models from known topographic relief, water table elevations and subsurface slopes from piezometer data, and changes in pumped groundwater quality from interpolations across the tubewell locations. Such derivations are not limited to point locations, as in examples above, but include the entire spectrum of mathematical operators that facilitate such analysis for all geographic entities. However, it must be realized that the generated maps are an extension of the logic inherent in the original data and the transformation method and assumptions play a key role in the utility of the final product. For example, in deriving water quality maps from point samples in space, the choice of the interpolation technique should account for, in addition to other factors, the zone of influence exercised by the tubewell. An unreasonable estimation with respect to geographical proximity to other wells would yield an incorrect determination of the water quality in the area.

The LCC system characterizes complex interactions in the physical and farming systems for which the irrigation network acts like a tie-in amongst the heterogeneities in space, and to some extent in time. While it would be impossible to fathom the girth of system-wide interactions latent to, and having evolved out of, the century old system, the manipulations through a GIS could lay bare the dominant trends and interactions fundamental to our perception of the area. In this respect, the choice of mapping units and classifications native to the respective themes would dictate the results of these interactions in two-dimensional space (much like the potential combinations in a two-dimensional matrix). Thus, the higher the number of classifications in the interacting space of two or more themes, the larger the diversity of the resultant GIS model. Since all of these interactions may not be significant on their own, it would be logical to frame the resultant model into more simplified stratifications. This, in fact, is the key to the modeling rationale within the GIS.

C. Resolution and Storage

One of the fundamental considerations in digital spatial databases is the integrity of the information being used for the analysis. In this respect, the investment in preserving the original contents is largely dependent on the analysis and outputs; higher resolutions promise greater accuracy but are difficult to sustain in cost and storage. While the emergent trends in data storage and computing have overcome the output and analysis constraints associated with vector data, there remain gaps in efficient handling of the storage-intensive raster or cell data. Much of the raster data is synonymous with the remotely sensed coverage that has varying degrees of spatial resolution; the higher the resolution in space, the greater the requirement for storage. In the context of the LCC system, an unreasonable emphasis on higher spatial accuracy would necessitate a trade-off to the extent whereby undue strain on the conventional personal computing technology is avoided.

D. Non-spatial Attributes

The manipulative capabilities inherent in any spatial information system rely on two principal sources of information---the cartographic entities for spatial reference and alpha-numeric attributes for descriptive or coded ranking of the former. Hence, only those pieces of information could be processed through a GIS that have a spatial counterpart in the real world. However, the real world defies reliance on the discretized modeling offered by the GIS and hence there is a need to also encumber information that is essentially scalar and not bound by coordinate references in space. For irrigation systems, it would include information on farmer perceptions and opinions, financial base, quality of education, water related disputes, social interactions and so on. Towards a meaningful interaction with the GIS database, the above information would need to be accessed as a hypertext or context-sensitive supplement to the spatial portrayals.

The fusion of non-spatial attributes of information to the spatial knowledgebase is meant primarily to offset tendencies at oversimplification of the physical world. The infrastructural investments are only the stimulant to the development of the agrarian culture that is locale-specific and constantly evolving through human interactions. While mathematical and statistical models can interface with GIS to predict likely outcomes of resource utilization, the ultimate determinant of human response to potential gains remains in the value of the social life it spawns and nurtures.

E. Visualization and Decision Support

Within the GIS, thematic interactions are achieved across a two-dimensional space wherein information is resampled or subsampled to represent a higher and more complex portrayal of the physical space. Situations necessitating modeling of the depth' of the thematic interactions are achieved through a discretization of the three-dimensional space at specified intervals. However, these stratifications across depth may not be justifiable in certain situations, as would be the case for aquifers with sharp gradients in water quality. The same would apply for soil profiles where detailed bore information is available explaining variations in texture. A visualization of the above is beyond the conventional capabilities of a GIS and, therefore, would require outside tools that not only preserve the coordinate referencing native to a GIS, but sustain it in the 3D without resort to stratifications.

For this continuity in space, the qualitative details specific to a thresholding criteria, like saline water divide, can be searched for decisions pertaining to site selection for useable groundwater quality. Further advancements to this technology also yield volumetric estimates of the phenomenon in 3D; however, at present, interactions as such, like 2-D interactions within a GIS, are not encumbered by these visualization techniques due to computational limitations.

VI. CONCLUSIONS

This paper has addressed issues deemed critical to the establishment of a digital spatial information system or GIS for salinity management across an irrigated landscape. The experience owes exclusively to the consideration of the salinity management alternatives for the Rechna Doab with particular emphasis on the the Lower Chenab Canal system. With over a hundred years of history, the LCC offers useful insights into the protracted and doggedly resilient efforts aimed at sustaining the productivity of the area that continues to be threatened by land salinization. The huge coverage of the LCC irrigation network is not in itself the only challenge to its geographical emancipation, rather it is the sheer volume of historic investigations into the physical regime that poses monumental problems. From a salinity management perspective, it is the understanding of the crop, water, and soil related themes that would constitute the plausible basis for rationality in spatial analysis.

Somewhat ironically, the affluence of available information on land and water resources is offset by the lack of coherence and abundance of discontinuities in space and time that are writ large over the public sector data collection campaigns within the area. Examples from WAPDA, the SSoP, DLR and PID have been cited for duplication and mismatch in reporting of field data, infrequent updates to system-wide land and water resource utilization, remissions in inter-agency coordination in data sharing, and the absence of mechanisms that retain data integrity in reporting. Reliance on the spatial information processing and analysis mechanisms will not be the sinecure to the above travails, as commonly perceived. Indeed, the requirements for digital conversion and adaptability have their own connotations in terms of consistency in data organization, storage requirements, rationality in spatial modeling, and decision support mechanisms.

In a nutshell, the foregoing establishes the shortcomings in public sector information collection and reporting that has seen very few improvements towards comprehension of the factors that affect the productivity of the irrigated regimes. The study of the LCC system has been useful, given the flexibility of the information collation tools utilized for this purpose. However, without a fundamental understanding of the issues preceding spatial analysis, the current levels of sub-optimum sharing of information and manipulation are unlikely to be improved upon. The negative repercussions of this mismanagement, especially in the context of land degradation, would be a major threat to sustainable reliance on irrigated agriculture.

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RESOURCE USE AND PRODUCTIVITY OF IRRIGATED AGRICULTURE IN THE RECHNA DOAB, PUNJAB, PAKISTAN

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ABSTRACT

The knowledge of factors responsible for variations in productivity differences across different regions would be of immense help for planned improvement of the agricultural sector on a sustainable basis. With this end in view, this study has attempted to determine the efficiency of land use on farms in the Rechna Doab (land between Ravi river and Chenab river; consisting of 2.45 million hectare (Mha) of total farm area, out of which the cultivated area is about 2.3 Mha). Estimates are made regarding the operational distribution of land holdings in the Rechna Doab across different farm-size groups and their relationship with unused cultivable lands. The spatial and temporal relationship between cropping intensity and the size of holding, as well as the influence of the level of irrigation on the cropping intensity, are also explained. After examining the level of efficiency in land utilization at the district level, as well as at the Rechna Doab level, it estimates the additional potential productivity of the major crops. This study made use of both the primary data collected from 432 farms in the Rechna Doab, along with forty years secondary data, which were taken from four Agricultural Census reports of Pakistan for the years 1960, 1972, 1980 and 1990. The regression results, of log-linear functional form, revealed that farm size is related positively to culturable waste lands, while it is related negatively to cropping intensity. Conclusions indicate that if a full level of land utilization could take place in the Rechna Doab, the total additional crop area could be increased by about 2.3 million acres and there is potential that the production of four major crops (i.e. wheat, rice, cotton and sugarcane) could be increased, by 0.95, 0.28, 0.10 and 4.6 million tons, respectively.

Importance

Land and irrigation are the basic resources in agriculture. The role and importance of these resources and their contribution towards productivity, in the context of the country's increasing population, can hardly be exaggerated. Pakistani agriculture is set in a very distinctive situation of increasing population on the one hand and diminishing resources on the other. The population of Pakistan was reported to be 131.63 million in 1996 and is projected to be 207 million in 2013 (GOP, 1996 and WSIP, 1990). The agriculture sector has to face the difficult task of doubling existing food production by the turn of this century. The situation demands for the horizontal and vertical growth in the productivity, either by bringing more land under cultivation, or by increasing the cropping intensity of the existing land resources, or by bringing more land under cultivation from the cultivable uncultivated area (a large proportion of which is existing on medium and large farms under water-logged or saline conditions). In this context, it becomes important to identify the nature of the relationship which exists between farm

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size and unculturable wastelands and what kind of changes the green revolution/SCARPS projects has brought into this relationship.

Objectives

The objective of the present study are the following:

- To estimate the operational distribution of land holdings in the Rechna Doab across different farm size groups in terms of percentage distribution of holdings;
- To determine the total unused cultivable land in the Rechna Doab and to study the relationship between the size of holding and the level of unused cultivable land;
- To study the relationship between cropping intensity and the size of holding as well as the influence of the level of irrigation on the cropping intensity;
- To determine the level of efficiency in land utilization for the Rechna Doab, as well as at the district level; and
- To assess the additional potential productivity of four major crops in the Rechna Doab.

Physiography of the Rechna Doab

The cultivated area in the Rechna Doab is regarded as the grainary of the Punjab. It consists of two distinct agro-climatic zones i.e. Punjab Rice-Wheat (PRW) Zone and Punjab Sugarcane-Wheat (PSW) Zone (WAPDA, 1979). Irrigated agriculture started in Rechna Doab in 1892 via the Lower Chenab Canal. The irrigation system in Rechna Doab consists of 504 km of branch canals, 240 km of Main Canals and 373 km of Link canals. Rechna Doab has a gross area of 7.35 MAc, from which 5.73 MAc is the Gross Command Area. The Major canal systems are M.R.Link Canal, which started in 1956 and has 0.155 MAc of Canal Command Area (CCA); Upper Chenab Canal started in 1912 and has 1.02 Mac of CCA; Lower Chenab Canal started in 1892 and has 3.03 Mac of CCA; and Haveli Canal started in 1939 and has 0.178 MAc of CCA. The physiography of the Rechna Doab consists of: (a) active flood plains; (b) abandoned flood plains; (c) bar uplands; and (d) Kirana Hills (longitudinal across the doab). Regarding the ground water quality Rechna Doab is divided into three distinct zones: (i) Fresh Water Zone (FNZ, TDS < 1000 ppm) 1.36 Mha; (ii) Mixing Zone (MZ, TDS 1000-3000 ppm); and (iii) Saline WaterZone (SWZ, TDS > 3000 ppm) 0.198 Mha (IWASRI, 1988). The soils are tertiary in nature and have recent alluvial deposits which are having proportions of fine to very fine sand and silt. Soils are southwesterly sloped and the slope is 0.38 m/km and 0.29 m/km in the upper part and the lower part, respectively. Surface salinity is found in patches covering more than 20 % of the cultivated area in Rechna Doab (1.17 MAc).

Data Source

The primary and secondary data sets have been used to carry out the present study. The primary data set was comprised of the survey data of 432 sample farms. IIMI conducted this survey during 1995 and the sample areas were identified through the use of spatial models. These sample sites were located in six districts (Sheikupura, Hafizabad, Faisalabad, T.T. Singh, Jhang and part of the Kabirwala Sub-district of Khanewal District). The primary data were collected on a well designed pre-tested questionnaire from farms located in 144 different sampling sites (Figure 1).

The district-wise temporal data and cross-section data used in the study are taken from the Agricultural Census reports of Pakistan for the years 1960, 1972, 1980 and 1990 [Pakistan Agricultural Census Organization (1963, 1975, 1983 and 1994]. One advantage of this data set is that it not only covers the Pre-green revolution/pre-SCARPS period (1960), but also takes into account the Green Revolution/SCARPS period (1972), Post Green Revolution/Post SCARPS period (1980) and Matured Green Revolution/ SCARPS transition period (1990).

Land Use Intensity

Since 1960, agriculture in Rechna Doab has undergone major structural changes due to the introduction of new technologies and large investments in water development. Part of the enhanced water availability contributed to the increase in both cropping intensity and crop yields, while part of it was used to bring more land under cultivation. The 1990 census data reveals that despite all efforts to increase the cultivated area in the Rechna Doab, the total cultivated area amounted to 5.69 million acres out of 6.03 million acres, while still there were 0.13 million acres of land on agricultural farms which are cultivable but have not been brought into cultivation and are classified as cultureable waste lands. Since the cultivated areas are approaching their limits in cropping intensity, there lies the chance to increase agricultural production in the country by bringing the cultivable uncultivated areas under agriculture. Tables 1 and 2 provide figures pertaining to total number of farm holdings, farm size and culturable waste land, which provide insights regarding the pattern of agricultural land use and its distribution in Rechna Doab. Out of 6.06 million acres of total farm area in the Rechna Doab, 15.26 percent is in Faisalabad District and the rest is distributed as 8.88 percent in Toba Tek Singh, 25.08 percent in Jhang, 17.46 percent in Gujranwala, 16.69 percent in Sialkot District and 16.63 percent in Sheikhupura District. Regarding the size-wise distribution at the Rechna Doab level, these tables show that small and medium farms, which have a larger number of farm holdings, have a smaller percentage of total farm area, while a smaller percentage of large farms have more than 27 percent of the farm area. A similar trend exits in the distribution of land among farm categories at the district level (Table 1).

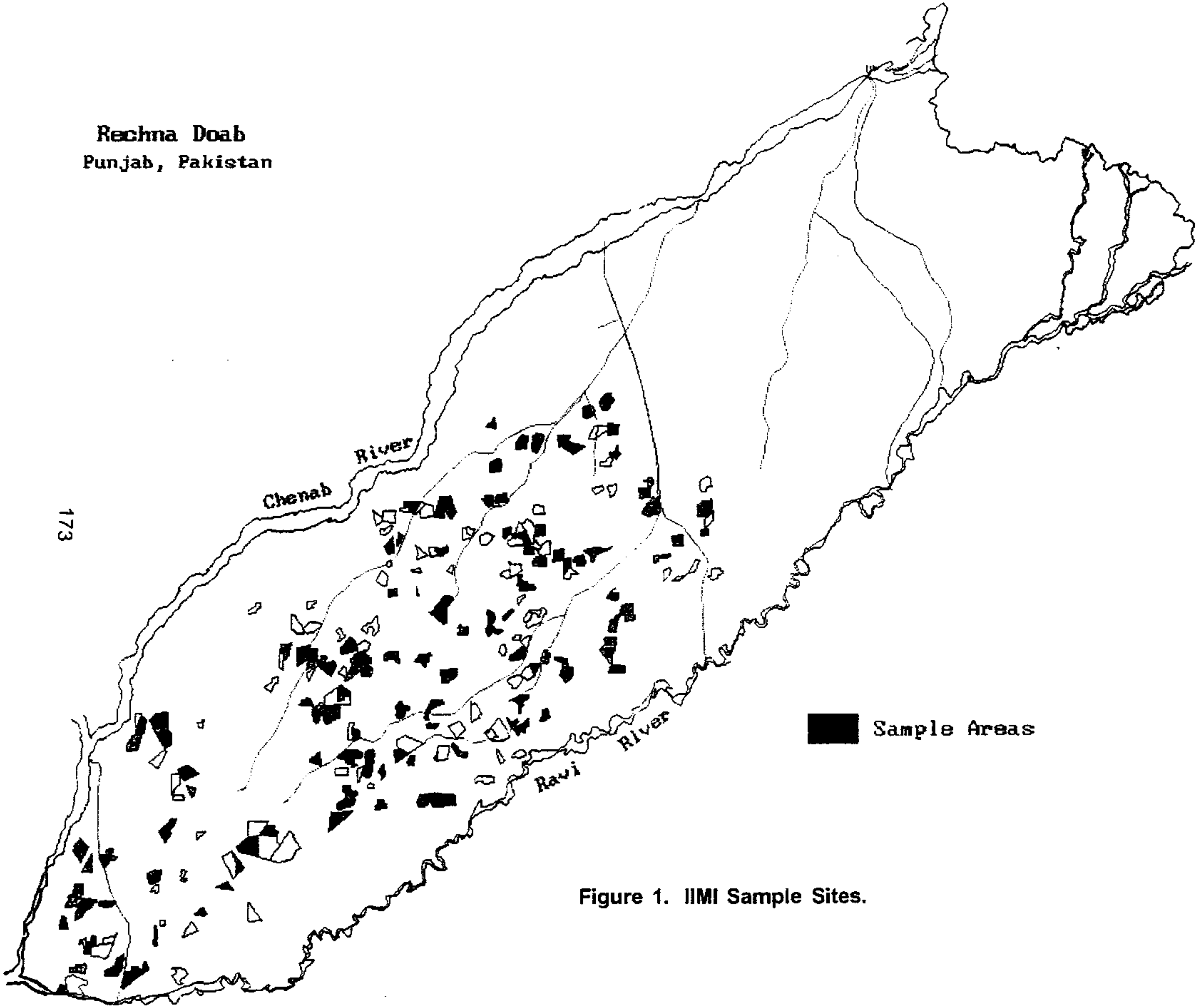

Figure 1. IIMI Sample Sites.

Examination of Tables 1 and 2 also reveals that during the census year 1990 about 4 percent of the total area on agricultural farms was not used at all and was kept as culturable wastelands. Regarding the distribution of cultivated lands and the cultivable uncultivated lands (culturable waste area), Table 2 shows a similar distribution trend, to that of total farm size, i.e. highest percentage of cultivated area lies in Jhang (24.51 percent), and then comes Gujranwala (17.28 percent), Sialkot District (17.13 percent), Sheikhupura (16.79 percent), Faisalabad (15.44 percent), and Toba Tek Singh (8.85 percent); whereas with regard to the distribution of culturable waste area, Table 2 shows that more than one-half (56.24 percent) of total culturable waste area lies in Faisalabad, Toba Tek Singh and Jhang Districts. In Faisalabad, Toba Tek Singh, Jhang, Gujranwala, Sialkot and Sheikhupura Districts, the proportionate share of

Table 1
Percentage Distribution of Total Farm Holdings and Total Farm Area Across Farm Size Groups and Districts in the Rechna Doab 1990

DISTRICTS	Class of Total Holding			All Groups Total (Acres)	Percentage Distribution Across Distt.
	Small (%)	Medium (%)	Large (%)		
Faisalabad	52.48 (19.26)	44.77 (63.18)	2.75 (17.56)	140331 (924883)	18.66 (15.26)
T.T.Singh	42.48 (13.43)	52.72 (63.79)	4.80 (22.78)	67661 (538083)	9.00 (8.88)
Jhang	34.45 (8.31)	58.12 (57.25)	7.43 (34.44)	143784 (1519836)	19.12 (25.08)
Gujranwala	38.14 (9.38)	53.98 (52.82)	7.88 (37.80)	102809 (1058215)	13.67 (17.46)
Sialkot	60.32 (23.07)	37.47 (60.06)	2.22 (16.87)	177342 (1011538)	23.58 (16.69)
Sheikhupura	43.74 (12.79)	50.53 (57.54)	5.73 (29.67)	120216 (1008079)	15.98 (16.63)
Rechna Doab	46.62 (13.83)	48.50 (58.48)	4.88 (27.69)	752143 (6060634)	100.00 (100.00)

Note: Figures without parenthesis give distribution of number of holding FNO and figures within parenthesis indicate the distribution of total farm area (FAT) culturable waste area is reported to be 17.11 percent, 14.20 percent, 24.93 percent, 17.85 percent 7.52 percent and 18.39 percent, respectively. Looking at the sizewise distribution at the Rechna Doab level; the smallest proportion of culturable waste area is on small farms, while the highest proportion of culturable waste lands is found on the large farms. This trend is the same at the Rechna Doab as well as the District level. The impression from examining these gross numbers is that, as the farm size increases, the area under cultivable uncultivated lands also increases. In order to test that statistical relationship which exists between farm size and culturable waste area, this study investigates the distribution of total unused cultivable land in Rechna Doab and its relationship between the size of holding and the level of unused cultivable land by using the disaggregated District data.

Table 2
Percentage Distribution of Operational Farm Area and Culturable Waste Area across Farm Size Groups and Districts in Rechna Doab 1990

Districts	Size Class of total holding			All groups total (Acres)	Percentage Distribution Across Rechna
	Small (%)	Medium (%)	Large (%)		
Faisalabad	19.67 (12.18)	63.47 (60.26)	16.87 (27.55)	879654 (36229)	15.44 (17.11)
T.T.Singh	13.99 (5.05)	64.20 (57.02)	21.80 (37.93)	504256 (30067)	8.85 (14.20)
Jhang	8.66 (3.88)	59.05 (36.33)	32.28 (59.79)	1396678 (52785)	24.51 (24.93)
Gujranwala	9.95 (2.20)	54.89 (32.26)	35.16 (65.54)	984855 (37800)	17.28 (17.85)
Sialkot	23.61 (8.41)	58.49 (45.96)	15.23 (45.63)	976182 (15930)	17.13 (7.52)
Sheikhupura	13.04 (7.35)	58.08 (48.20)	28.87 (44.45)	956998 (38941)	16.79 (18.39)
Rechna Doab	14.35 (6.15)	59.58 (45.54)	26.07 (48.31)	5698623 (211752)	100.00 (100.00)

Note : Figures in parenthesis give distribution of Culturable Waste Area (CWA) and figures without parenthesis indicate the distribution of operational farm area CAT.

Specification of the Model

There are two aspects of the problem of underutilization of lands as mentioned earlier, viz., the proportion of cultivable area actually cultivated and how intensively the cultivated area is cropped in a year. Assuming a multiplicative relationship and using the econometric criteria suggested by Fuss, Mcfadden and Mundlak (1978); Madala (1988) and Ramaramunathan (1992), the log-linear models were found to be the best fit for testing the relationship between farm size, proportion of irrigation and their effects after the green revolution/SCARPS on culturable waste areas and cropping intensity. The dependent and independent variables, which are included in the models, are defined in the following:

$$\ln CWA = \ln a + \ln D_{72} + \ln D_{80} + \ln D_{90} + B_1 \ln FAT + B_2 \ln FAT_{72} + B_3 \ln FAT_{80} + B_4 \ln FAT_{90} + e. \tag{1}$$

$$\begin{aligned}\ln CWA = {} & \ln a + \ln D_{72} + \ln D_{80} + \ln D_{90} + B_1 \ln FAT + B_2 \ln FAT_{72} + B_3 \ln FAT_{80} + B_4 \ln FAT_{90} \\ & + B_5 \ln (CAI/FAT) + B_6 \ln (CAI/FAT)_{72} + B_7 \ln (CAI/FAT)_{80} + B_8 \ln (CAI/FAT)_{90} + e.\end{aligned} \tag{2}$$

$$\ln CI = \ln a + \ln D_{72} + \ln D_{80} + \ln D_{90} + B_1 \ln FAT + B_2 \ln FAT_{72} + B_3 \ln FAT_{80} + B_4 \ln FAT_{90} + e. \tag{3}$$

$$\begin{aligned}\ln CI = {} & \ln a + \ln D_{72} + \ln D_{80} + \ln D_{90} + B_1 \ln FAT + B_2 \ln FAT_{72} + B_3 \ln FAT_{80} + B_4 \ln FAT_{90} \\ & + B_5 \ln (CAI/FAT) + B_6 \ln (CAI/FAT)_{72} + B_7 \ln (CAI/FAT)_{80} + B_8 \ln (CAI/FAT)_{90} + e.\end{aligned} \tag{4}$$

Where:

CWA = Culturable Waste Area in each farm category;
CI = Cropping intensity in each farm category;
a = Constant term;
B_{1-8} = Estimated Coefficients;
D_{72-90} = Intercept Dummies for year 1972, 1980 and 1990, respectively;
FAT = Average size of holding per farm in each farm category;
FAT_{72} = 1972 dummy for average size of holding per farm on each farm category;
FAT_{80} = 1980 dummy for average size of holding per farm on each farm category;
FAT_{90} = 1990 dummy for average size of holding per farm on each farm category;
(CAI/FAT) = Proportion of irrigated area per farm on each farm category;
$(CAI/FAT)_{72}$ = 1972 dummy for proportion of irrigated area per farm on each farm category;
$(CAI/FAT)_{80}$ = 1980 dummy for proportion of irrigated area per farm on each farm category;
$(CAI/FAT)_{90}$ = 1990 dummy for proportion of irrigated area per farm on each farm category; and
e = Random error term.

According to Equation 1, if the proportion of culturable wasteland increases with the size of holding, then the value of the beta coefficient (B_1) will be greater than one which means that, as the farm size increases, it will increase in the amount of culturable waste area (CWA) more than proportionately before the green revolution/SCARPS projects. In order to find how this relationship has been affected by the green revolution/SCARPS projects, the slope coefficients are summed up to see whether this relationship is strengthened or weakened, depending upon the sum of (B_1+B_2, B_1+B_3, B_1+B_4) (whether it is greater than or less than the B_1, respectively). To see how the increase in proportionate area under irrigation affects the CWA, Equation 2 was estimated . A negative relationship is anticipate between the increase in proportionate area under irrigation and the effect of irrigation on CWA. The intercept term will capture the impact of the technological development. A negative relationship is expected between technological development and CWA. The equations in Models 3 and 4 were estimated to study the relationship between cropping intensity (CI) and other variables, such as the farm size and level of irrigation, both before, during and after the green revolution/SCARPS projects. The results are reported in the following section. A negative relationship is expected between farm size and CI and a positive relationship between the proportionate area under irrigation and the CI. The technological development should lead to an increase in the CI and a positive sign is expected for the intercept term. The intercept dummies will provide information about the temporal changes in the impact of technological development on the CWA and CI.

Cultivable Uncultivated Land and its Relation to Farm Size and Irrigation

The regression results derived through Models 1 and 2, specified in the earlier section, are summarized in Table 3. Model 1 captures the effect of farm size on the CWA. In order to study the effect of increase in proportionate irrigation supply along with the farm size on the culturable waste area, the parameters in Model 2 were estimated. The results shows both the regression equation for Rechna Doab has high explanatory power and the expected signs and magnitude for the estimated parameters. The explanatory power (R^2) is 0.7529 and 0.7543 for Model 1 and Model 2, respectively. Both of the equations in Models 1 and 2 are statistically significant at the 99 percent level of confidence. The examination of Table 3 confirms that the postulated relationship between farm size and culturable waste lands is empirically valid in all of the four time periods (before, during and after the Green Revolution/SCARPS). Surprisingly, ten years after the green revolution, during, the 1990s, the CWA has increased in the Rechna Doab as the coefficient for FAT_{90} is positive, higher than the FAT_{80} and statistically significant at the 99 percent level of confidence. One of the reasons might be that the secondary salinization (due to the exploitation of the poor quality ground water through SCARPS tubewells), led to this increase in the cultureable waste area during the 1990s. The intercept term and intercept dummies have negative signs and the coefficients are significant (at the 99 percent level of confidence) for 1972, 1980 and 1990, which confirms that the technological development led to a decrease in the CWA. In the case of Model 2 the relationship between farm size and CWA remains the same during the 1980s and 1990s, as that of 1972, because the coefficient for FAT_{80} and FAT_{90} is non-significant.

Table 3
Culturable Waste Area with Respect to Farm Area and Proportionate Irrigated Area in the Rechna Doab 1990

VARIABLES	CWA	CWA
CONSTANT	-0.4900*** (0.0159)	-3.3313*** (0.7024)
DV72	-6.229384*** (1.611136)	
DV80	-3.692016** (1.598577)	
DV90	-4.895129*** (1.622920)	-0.9014*** (0.2200)
FAT	0.825946*** (0.106572)	1.0439*** (0.0584)
FAT72	0.442947*** (0.142248)	0.2154* (0.1103)
FAT80	0.239886* (0.141403)	
FAT90	0.331482** (0.144055)	
CAIFAT		-0.7640*** (0.2539)
CAIFAT72		N.S
CAIFAT80		N.S.
CAIFAT90		N.S.
F-CALC	81.97616***	95.7013***
D.F.	179	179
ADJ-R^2	0.75293	0.7543

Note : Figures in parentheses are standard error
* Significant at 90 percent level of confidence
** Significant at 95 percent level of confidence
*** Significant at 99 percent level of confidence
N.S. = Not significant at 90 percent level of confidence

Table 4
Cropping Intensity with Respect to Farm Area and Proportionate Irrigated Area in the Rechna Doab 1990

VARIABLES	CI	CI
CONSTANT	4.6995***	4.6939***
	(0.0158)	(0.0155)
DV72	0.6699***	0.6755***
	(0.1088)	(0.1054)
DV80	0.7219***	0.7636***
	(0.1147)	(0.1121)
DV90	0.6315***	0.6247***
	(0.1134)	(0.1101)
FAT		
FAT72	-0.0447***	-0.0447***
	(0.0095)	(0.0092)
FAT80	-0.0412***	-0.0420***
	(0.0100)	(0.0097)
FAT90	-0.0256**	-0.02199**
	(0.0100)	(0.0099)
CAIFAT		N.S.
CAIFAT72		N.S.
CAIFAT80		0.1372**
		(0.0562)
CAIFAT90		0.2015
		(0.1116)
F-CALC	54.6251***	45.5198***
D.F.	182	179
ADJ-R^2	0.63119	0.6557

Note : Figures in parentheses are standard error
* Significant at 90 percent level of confidence
** Significant at 95 percent level of confidence
*** Significant at 99 percent level of confidence
N.S. = Not significant at 90 percent level of confidence

Regarding the partial effect of irrigation on CWA in Model 2, it has been found that irrigation played a significant role in reducing the CWA in the case of the 1960s (as the elasticity coefficient for irrigation is negative and significant at the 99 percent level of confidence). In the case of the period after the 1960s, there was no much improvement in the proportionate area under irrigation, which could play a significant role in decreasing CWA.

Cropping Intensity and its relation to Farm Size and Irrigation

The existence of a negative relationship between farm size was expected. In order to test this relationship, Model 3 with cropping intensity as the dependent variable and the farm size, and their post-1970s dummies as the explanatory variables were tested in the equations. The regression coefficient estimates of Model 3 are summarized in Table 4. All of the coefficients have the expected size and sign, proving the argument of an inverse relationship between farm size and cropping intensity as they are significant at the 99 percent level of confidence. The explanatory power of the Model (R^2) is 0.6312 and 0.6557 for Models 3 and 4, respectively. It is clear from the equation for Model 3 that, the greater the farm size, the lower will be the cropping intensity. This inverse relationship is significant at the 99 percent level of confidence during 1972, 1980 and 1990. This relationship persists during the Green Revolution as well as after the Green Revolution period.

After examining the relationships between farm size and cropping intensity, it was thought that the irrigation level could possibly be an important factor affecting cropping intensity. In order to test this relationship, Model 4, was estimated by incorporating the proportionate area under irrigation per farm along with the farm size and intercept dummies. The summary of results from Model 4 is also given in Table-4. It shows that the intercept is positive and all the FAT coefficients after the 1970s are significant at the 99 percent level of confidence and have a negative sign, showing the negative relation between farm size and cropping intensity. Regarding the effect of irrigation on cropping intensity, it is positive and significant at the 99 percent level of confidence during 1980s. This means that if sufficient irrigation was made available, then there are many areas which are culturable, but they need this irrigation to assure the returns to investment in those areas. If irrigation can be brought to these areas, they will have a tendency to bring more area under cultivation and thereby reduce the unculturable waste areas.

The above discussion confirms that small farmers crop their lands more intensively than the large farmers and this trend persists even after the green revolution. This does not mean that the actual cropping intensity has gone down, rather that in comparison to the large farms, the small farms are growing crops on their lands more efficiently.

Cropping Intensity and Levels of Inefficiency of Land Use

The results from Tables 1 and 2 showed that both intensive and extensive use of land is lower on large farms compared to small farms. In other words, as farm size increases, both intensive and extensive use of land decreases. So what happens if everybody uses the land the way the small farmers are using it? Or what if redistribution of land takes place? Whatever policy is implemented to fully utilize the land, at least the unirrigated area will be cultivated once and the irrigated area cultivated twice. If such a policy is followed, then how much inefficiency exists in extensive and intensive farming at the aggregate level and at the district level? On the basis of these assumptions some indices have been developed (indicated in Tables 5 - 9). These indices will help to establish how much land is underutilized and then how it is distributed among different farm categories in different regions. In order to estimate the index of inefficiency, certain assumptions had to be considered reasonable within the limitations of the available data. For measuring the inefficiency in cropping intensity, irrigated areas (CAI) are assumed to have potential for two crops and unirrigated areas (NSA) have potential for at least one crop. As such, the minimum potential number of times a unit area of land is croppable (GCA) is equal to twice the net-irrigated area added to the unirrigated area. There is a possibility that a negative number may occur in certain cases because the unirrigated area may be cropped more than once and/or the irrigated areas may be cropped more than two times a year, thereby making GCA greater than the sum of NSA and CAI. The lower is the index number, the lower is the inefficiency.

Table 5 shows that at the Rechna Doab level the measure of inefficiency varies from 12.66 percent for small farms, 19.64 for medium farms, and 22.58 percent for the large farms, implying that large and medium farms are less in their efficiency.

Table 5
Measures of inefficiency in Cropping Intensity of net Cultivated Area across Farm Size Groups and Districts in Rechna Doab 1990.

Districts	Size Class of total holding			All groups total (Acres)
	Small (%)	Medium (%)	Large (%)	
Faisalabad	22.44	29.13	29.69	27.90
T.T.Singh	20.23	24.87	27.30	24.74
Jhang	18.51	27.80	31.93	28.26
Gujranwala	7.17	10.84	14.10	11.61
Sialkot	-0.30	5.89	13.51	6.18
Sheikhupura	14.43	16.12	17.42	16.27
Rechna Doab	12.66	19.64	22.58	19.47

* $\frac{(NSA + CAI - GCA)}{NSA + CAI} * 100$

From the measures of inefficiency, it is observed that cropping intensities of net cultivated area can be improved. The additional area which can be cropped through intensification of cropping is given in Table 6. At the aggregate level, the additional croppable land through the improvement in cropping intensity was determined to be about 2.1 million acres. The District wise distribution of this land across farm-size groups is computed in Table 6. The major contribution is coming from the medium and large holdings of Faisalabad, Jhang, Sheikhupura, Toba Tek Singh, Sialkot and Gujranwala Districts.

Table 6

Percentage Distribution of Additional Croppable Land* Through Improvement in Cropping Intensity Across Farm Size Groups and Districts in Rechna Doab

Districts	Size Class of total holding Small (%)	Medium (%)	Large (%)	All Groups total (Acres)	All groups Percentage Distribution Across Distt.
Faisalabad	15.94	66.25	17.82	484138	22.97
T.T.Singh	11.59	64.42	23.98	244372	11.60
Jhang	5.92	58.64	35.44	748957	35.54
Gujranwala	6.19	51.34	42.48	223915	10.63
Sialkot	-1.17	56.30	35.10	102440	4.86
Sheikhupura	11.78	57.80	30.42	303481	14.40
Rechna Doab	9.41	60.05	30.07	2107303	100.00

* NSA + CAI - GCA

The indices to measure the inefficiency in total land use were computed by combining the inefficiency in cropping intensity with the lands which are currently lying as culturable waste area (CWA). These indices have been computed at the Rechna Doab and District level by incorporating the CWA into the above indices inefficiency in cropping intensity. The District level and the Rechna Doab level indices are reported in Table 7). These indices show similar trends in the distribution of inefficiency in total land use among different farm categories as are reported in Table 5 for the measures of inefficiency of in cropping intensity of net cultivated area. Table 8 shows the indices computed to see the percentage of distribution of additional croppable land through improvement in culturable waste areas at the Rechna Doab and District levels. On the Rechna Doab level, about 2.319 million acres of additional land can be brought under the croppable area through the improvement in the culturable waste areas. Again, the major contributors are the medium and large farms of Faisalabad, Toba Tek Singh and Jhang Districts.

Table 7
Measures of Inefficiency in Total Land Use Farm Size Wise for Rechna Doab and Districts 1990

Districts	Size Class of total holding			All Groups Total (%)
	Small (%)	Medium (%)	Large (%)	
Faisalabad	23.42	30.51	32.03	29.37
T.T.Singh	21.08	26.85	30.96	26.96
Jhang	19.20	28.67	34.42	29.66
Gujranwala	7.57	11.86	17.14	13.31
Sialkot	0.04	6.59	15.81	7.07
Sheikhupura	15.41	17.54	20.04	17.98
Rechna Doab	13.38	20.83	25.30	21.01

* $\frac{NSA + CAI + CWA - GCA}{NSA + CAI + CWA} * 100$

Table 8
Percentage Distribution of Additional Croppable Land* Through Improvement in Culturable Waste Area Across Farm Size Groups and Districts in Rechna Doab

Districts	Size Class of total holding			All Groups Total (Acres)	All groups Percentage Distribution Across Distt.
	Small (%)	Medium (%)	Large (%)		
Faisalabad	15.67	65.83	18.49	520367	22.44
T.T.Singh	10.88	63.61	25.51	274439	11.83
Jhang	5.79	57.17	37.04	801742	34.57
Gujranwala	5.61	48.58	45.81	261715	11.29
Sialkot	0.12	54.91	36.52	118370	5.10
Sheikhupura	11.27	56.71	32.02	342422	14.77
Rechna Doab	9.51	58.75	31.74	2319055	100.00

* NSA + CAI + CWA - GCA

Table 9
Districts Wise Increase in Cropped Area Through Improvement in Cropping Intensity and Use of Presently Culturable Uncultivated Area in Rechna Doab

Districts	Increase in cropped area by reclaiming and bringing under cultivation currently unused land*	Increase in cropped area by improving cropping intensity of currently cultivated land	Total Increase in cropped area (Col.2) + (Col.3)	Increase in CA by improving CI of CCA as %age of TICA (Col.3)*100 / (Col.4)	Col.4 as %age of Total croppable area**
(1)	(2)	(3)	(4)	(5)	(6)
Faisalabad	36229	484138	520367	93.04	29.37
T.T.Singh	30067	244372	274439	89.04	26.96
Jhang	52785	748957	801742	93.42	29.66
Gujranwala	37800	223915	261715	85.56	13.31
Sialkot	15930	102440	118370	86.54	7.07
Sheikhupura	38941	303481	342422	88.63	17.98
Rechna Doab	211752	2107303	2319055	90.87	21.01

* A cropping intensity of 1 is assumed

** $$\frac{(NSA + CAI + CWA - GCA)}{NSA + CAI + CWA} * 100$$

CA = Cropped Area
CI = Cropping Intensity
CCA = Currently Cultivated Area
TICA = Total increase in cropped area

By using the above measures of inefficiency, total land loss is computed at the Rechna Doab and District levels (Table 9). The total increase in cropped area at the Rechna Doab level, by making improvements in cropping intensity and by bringing in the additional area from culturable waste lands, amounts to 2.319 million acres, which is about 40.69 percent of the total croppable area. Regarding this total additional croppable land, 21.01 percent comes from improvements in cropping intensity and the remaining area comes from bringing unculturable waste lands into cultivation. By looking at Table 9, in Faisalabad, Toba Tek Singh and Jhang districts, the croppable areas can be developed significantly, simply through improvements in cropping intensity. The trend is similar for Gujranwala, Sheikhupura and Sialkot Districts.

Table 10

Share of Major Crops in Total Cropped Area In Districts of Rechna Doab (Percentage)

DISTRICTS	WHEAT	RICE	COTTON	SUGARCANE
Sialkot*	40.33	34.00	0.00	1.67
Gujranwala*	38.67	36.33	0.00	1.00
Sheikhupura	37.09	22.58	1.46	5.48
Faisalabad	38.46	3.06	5.74	17.07
T.T.Singh	37.47	7.37	12.20	13.32
Jhang	41.71	5.58	19.31	11.86
Rechna Doab	38.95	18.15	9.68	8.40

Source : Rechna Doab Survey 1995
* Census of Agriculture 1990

Table 10 provides estimates regarding the distribution of area under different crops with respect to the GCA in the Rechna Doab. It shows that on the average about 39 percent of the GCA falls under the wheat crop in the Rechna Doab. In case of the rice crop, the area ranges from 3.06 percent of the GCA in the Faisalabad District to about 36 percent in Gujranwala District. The estimates show that the area under the cotton crop ranges from 1.46 percent of the GCA in Sheikhupura District to about 19.31 percent in the Jhang District. The area under sugarcane ranges from 1 percent and 1.67 percent in Districts Sialkot and Gujranwala to about 17.07 percent of the GCA in the Faisalabad District. On the average, the distribution of the area under the rice, wheat and sugarcane crops comes to 18.15 percent, 9.68 percent and 8.4 percent, respectively.

Table 11

Potential Increment in Area Under Major Crops In Districts Of Rechna Doab (Acres)

DISTRICTS	WHEAT	RICE	COTTON	SUGARCANE
Sialkot	47742	40245	0	1973
Gujranwala	101196	95089	0	2616
Sheikhupura	127018	77326	4985	18772
Faisalabad	200108	15933	29860	88847
Toba Tek Singh	102831	20219	33488	36543
Jhang	334392	44762	154787	95106
Rechna Doab	913289	293576	223122	243859

Assuming that the farmers cropping pattern does not change and if the additional croppable area of 2.319 million acres is distributed under the four major crops, Table 11 shows that, on the average, about 0.91 million acres will be cultivated under the wheat crop, 0.29 million acres will be cultivated under the rice crop and the average area under the cotton and the sugarcane crop will be 0.22 and 0.24 million acres, respectively. The major contribution is in terms of the area under all of the four major crops is coming from the Jhang District. Next are the Districts Faisalabad, Sheikhupura and Gujranwala, which are the major contributors in the area under all four crops.

Taking into consideration the existing average yields of the four major crops on the farms in the Rechna Doab Table 12 estimates the potential productivity of the four major crops (wheat, rice, cotton and sugarcane) in the Rechna Doab. Table 12 shows that by increasing the cropping intensity of the existing cultivated areas and by bringing the cultureable uncultivated area under cultivation, the Rechna Doab has the potential to produce 0.947 million metric tons of wheat, 0.281 million metric tons of rice, 0.103 million metric tones of cotton and 4.671 million metric tons of sugarcane. once again, the major share of the production is coming from the Jhang and Faisalabad Districts.

Table 12
Potential Increment In Production of Major Crops in Rechna Doab (Metric Tones)

DISTRICTS	WHEAT	RICE	COTTON	SUGARCANE
Sialkot	39200	16700	0	36000
Gujranwala	93800	49900	0	43900
Sheikhupura	151000	84000	2300	439200
Faisalabad	228400	12800	12400	1772900
T.T.Singh	111400	14500	13700	701900
Jhang	344100	54400	93200	2073100
Rechna Doab	947200	281800	103100	4671900

CONCLUSIONS

The study attempted to estimate the operational distribution of land holdings in the Rechna Doab across different farm- size groups in terms of percentage distribution of holdings and to estimate the total unused cultivable land in the Rechna Doab. After estimating the relationship between the size of holding and the level of unused cultivable land, this study aimed at analyzing the relationship between cropping intensity and the size of holding and the influence of the level of irrigation on cropping intensity. Also estimates, of the additional productive potential of four major crops (wheat, rice, cotton and sugarcane) being grown in the Rechna Doab. The conclusions which emerged from this study are as follows:

- If a full level of land utilization (by making improvements in the cropping intensity and by bringing the CWA under cultivation) takes place, the total crop area can be increased by about 2.319 million acres.

- The possible share of the cropped area under four major crops (wheat, rice, cotton and sugarcane) could be increased by 0.91, 0.29, 0.22 and 0.24 million acres, respectively.

- There is a possibility that the production of four major crops (wheat, rice, cotton and sugarcane) could be increased, by 0.95, 0.28, 0.10 and 4.6 million tons, respectively.

- Of this total improvement in cropped area from improvement in cropping intensity and extensive use of land, 34.57 percent of the area will from the Jhang District, 22.44 percent from Faisalabad District, 14.77 percent from Sheikhupura District, 11.83 percent from Toba Tek Singh District, 11.29 percent from Gujranwala District and about 5.1 percent area will come from Sialkot District.

- Of the total additional croppable area which comes under cropping through better utilization of land, 58.75 percent will come from the medium farms, 31.74 percent from large farms and only 9.51 percent of the additional croppable area will come from the small farms.

- Within the Rechna Doab, there are wide interdistrict disparities. On the average there can be about 21 percent improvement in land utilization. In three Districts (Jhang, Faisalabad, Toba Tek Singh), the cropping intensity can be improved more than 75 percent, but there are Districts (Sialkot) where only 7.1 percent improvement is possible.

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PREDICTING SUSTAINABLE IRRIGATED AGRICULTURAL ADJUSTMENTS, ACROSS THE LOWER CHENAB CANAL SYSTEM

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ABSTRACT

The Lower Chenab Canal (LCC) system is the most productive, as well as problematic, area of the irrigation system of the Rechna Doab,Punjab, Pakistan. The area under the system this served from two major branch canals of Jhang and Gugera , with culturable commands of 1.168 Million acres (Ma) and 1.866 Ma, respectively. Out of 3.034 Ma of total CCA, 80% is underlain with fresh groundwater suitable for irrigation and the remaining 20 % is of saline groundwater (TDS > 3000 PPM) unsuitable for irrigation purposes, 64% of which is under the Gugera Branch canal command. The total crop area under the LCC command during 1989-90 was 4.109 Ma, which has increased to 4.342 Ma during 1994-95, showing an average increase of 1.13% per annum. This total area constitutes 39% and 61% for Jhang and Gugera canal commands, respectively.

Under the study, "Salinity Management Alternatives for Rechna Doab, Punjab", the LCC system has been selected to study the temporal changes in cropping pattern, crop water requirements, canal water supplies, usage of groundwater, etc. and their impact on water shortages in the system and crop yields. The Indus Basin Model Revised (IBMR), based on agricultural modelling techniques, has been adopted in order to analyze the irrigated agriculture system performance during the last five years (1990-91 to 1994-95) and to simulate the future scenarios by year to 2010. The results show that during the last five years, the area under wheat, basmatti rice and sugarcane has increased, but there is no change of area under IRRI rice whereas the area under cotton has decreased tremendously. Similarly, the average yield of wheat and sugarcane has increased, but the yields of rice and cotton have decreased. The variation in annual canal diversions range from 5 to 11 %. The annual water requirements of crops at the root zone has increased by 9%, whereas the water supplies have increased by only 8% and this gap has resulted in an increase of water shortages by 15% during the last five year period. The groundwater inflow-outflow analysis shows a positive net inflow to the aquifer system, which is an indicator of rising water tables.

The simulated results for year 2010 show a decrease of water shortages by 32%. The results show that the water stress to crops is occurring in saline areas and the increase in canal water supplies have resulted in reductions in crop stress. The yields of crops like cotton, wheat and sugarcane increased by 30%, 13%, and 9%, respectively. The results of groundwater inflow-outflow show that there is a potential for further groundwater development that can be used for irrigation purposes to supplement the canal water to overcome the shortages in the system.

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1. INTRODUCTION

The Lower Chenab Canal (LCC) system is the largest canal system in Punjab, offtaking from the Khanki Headworks on the Chenab River. The system was designed with a discharge capacity of 11,595 cusecs, 4097 cusecs for Jhang Branch Canal and 7498 cusecs for Gugera Branch Canal. The design CCA of the system is 3.034 Million Acres(Ma) (including 0.148 Ma designed as non-perennial on the Gugera Branch) with a cropping intensity of 46 % in kharif and 50 to 75 % in rabi.The design delta (depth of water) is 1.76 ft. (kharif) and 1.70 ft. (rabi) for the Jhang Branch Canal command and 8.51 ft. (kharif) and 3.17 ft. (rabi), for the Gugera Branch Canal command (WAPDA 1979). Assuming the canals run at design capacity for 180 days in kharif and 150 days in rabi (allowing for closure), the system was designed to divert 4.14 MAF in kharif and 3.45 MAF in rabi with the annual supply of 7.59 MAF at the canal head. It is not possible to ascertain the irrigation efficiency adopted in the design but the comparison between the water allowance at the diversion point and design delta indicates that the system efficiency was assumed as 0.29 for kharif and 0.69 for rabi (Abidi et al.1992).

The annual diversions during 1994-95 were 7.195 MAF, supplemented by 5.83 MAF provided by groundwater (4.25 MAF pumped from about 34,600 private tubewells and 1.58 MAF from public tubewells).

2. STUDY OBJECTIVES

The objective of the study is to examine the performance of the irrigation system and predict or define the measures in the context of different Management and Capital investment options , required for sustainable irrigated agriculture under the LCC system. The study is based on an analysis of the following parameters affecting the system performance:

- To predict the temporal changes in surface and groundwater supplies;
- To estimate and predict the crop consumptive use under temporal changes in cropping pattern;
- To estimate the water shortages or surpluses and define the measures to alleviate the shortages;
- To study the impact of water allocations and cropping pattern on groundwater inflow-outflow; and
- To estimate the groundwater potential for a safe aquifer yield.

3. METHODOLOGY FOR SYSTEM ANALYSIS

3.1 Adoption of Indus Basin Model Revised (IBMR)

The study was carried out through application of IBM-III, a revised version of the Indus Basin Model Revised (IBMR), developed by the World Bank for the evaluation of different water resources development projects under any Water Sector Investment Plan for the Indus Basin irrigated agriculture. The IBMR is an agro-economic and irrigation optimization model based on a linear programming algorithm which for any given set of inputs, constraints,parameters and objective function, will seek the "best" economic pattern of water use. To arrive at an optimal solution, the model delivers water to the canal commands in such a way as to maximize the economic value of the crop produced, taking a large number of physical, economic and institutional constraints into account. The model has been written in General Algebraic Modelling System (GAMS), a computer language developed by the World Bank.

The structure of the IBM-III is based on the twelve (12) Agro-climatic Zones and forty five (45) canal commands of the Indus Basin Irrigation System with a proper mapping corresponding to respective fresh and saline groundwater areas. Fourteen crops have been included in the model. The simulation is carried out starting from a base year for which the model is updated and the projections for future simulation periods are made according to the growth rates, management and capital investment options and resource availability.

The command area of LCC system falls under two separate Agro-climatic Zones (ACZ) i.e. the Punjab Sugarcane-Wheat (PSW) and Punjab Rice-Wheat (PRW) zones. Since the simulation by the model is carried out on an ACZ basis, necessary modifications were incorporated in the model program such that the zonal model could be run with the surface water network model (SWM) of the Indus Basin Irrigation System(IBIS) and the model results can be obtained on a canal command level according to areas of groundwater quality (fresh and saline). This was achieved through weighting factors provided in the model according to ACZ-Canal-Sub area (fresh or saline) mapping on the basis of CCA classification.

3.2 Updating and Validation of IBMR

The input to the model consists of multi-disciplinary data relating to agronomy, agri. economics, surface and groundwater hydrology, reservoir and canal system operation, project planning, available resources, etc. Therefore efforts were made to update the input data as much as possible according to the availability of data from primary or secondary sources, volume of data, and time schedule constraints of the study.

The model was validated according to the conditions of 1995 in respect of the actual crop area, crop yields, canal water allocations and tubewell pumpage.

4. SYSTEM PERFORMANCE ASSESSMENT DURING 1991-95

To examine the canal system operation in conjunction with usable groundwater and its impact on irrigated agriculture under the canal commands of the LCC system during the last five years period (1991-95), the IBMR was used taking 1989-90 as a base year, simulating up to year 1994-95 such that the simulated results of different variables match the actual data of 1994-95. The growth rates of crop area and yields were determined for the future projections. The simulated results, in the context of different variables, are discussed below.

4.1 Crop Area and Yields

The total crop area under the LCC command during 1989-90 was 4.109 Ma which has increased up to 4.342 Ma during 1994-95 , showing an average increase of 1.13 % per annum. This total area is constituted as 39% and 61% for Jhang and Gugera canal commands, respectively, of which 82% is fresh and 18% is of saline groundwater areas. The crop area and average yield of the major crops for the total LCC system is depicted in **Figure 1** and the details are given in **Table 1** for Jhang and Gugera Branch canals.

Figure 1 shows that the area under wheat, basmati and sugarcane increased by 5%, 19% and 36%, respectively, under the LCC system, but no change for IRRI rice, whereas the area under cotton decreased (30%), which may be due to a serious virus attack on this crop during this period. There is a decreasing trend of average yield of basmati and IRRI rice and cotton crops (11%,17% and 38%, respectively) but wheat and sugarcane crops show an increase of 12% and 1% ,respectively.

Table 1. Crop Area and Average Yield by Canal Command.

Jhang Branch Canal

	Crop Area (Million Acres)		Avg. Yield (Tons per Acre)	
	1990	1995	1990	1995
Basmatti Rice	0.256	0.304	1.302	1.161
IRRI Rice	0.024	0.024	2.105	1.743
Cotton	0.090	0.063	0.589	0.362
Sugarcane	0.107	0.145	15.891	16.090
Wheat	0.663	0.702	0.847	0.953

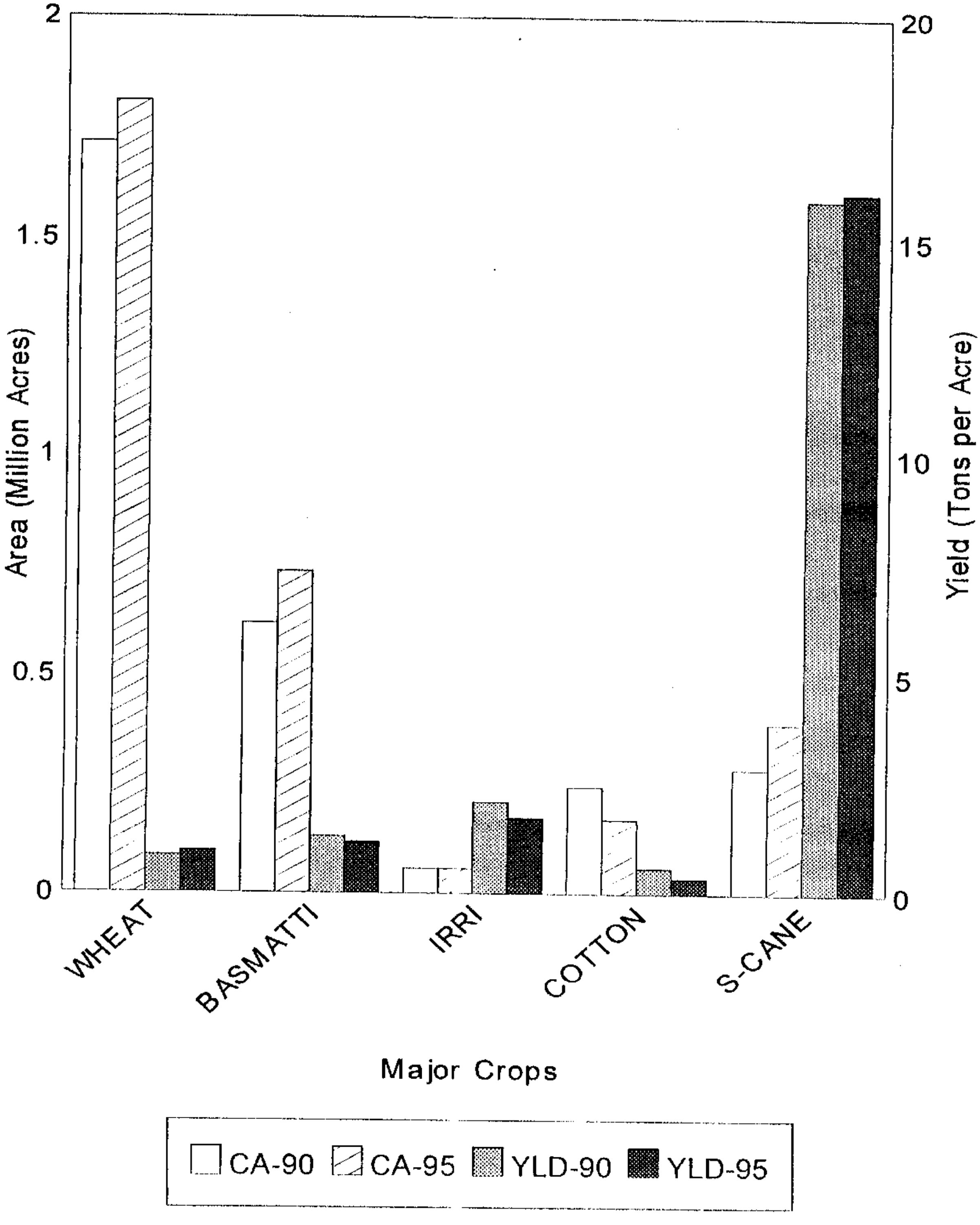


Figure 1. Crop Area and Yield during 1991-95.

Gugera Branch Canal

	Crop Area (Million Acres)		Avg. Yield (Tons per Acre)	
	1990	1995	1990	1995
Basmatti Rice	0.363	0.433	1.311	1.161
IRRI Rice	0.033	0.033	2.112	1.743
Cotton	0.156	0.109	0.590	0.362
Sugarcane	0.180	0.245	15.923	16.047
Wheat	1.053	1.107	0.850	0.948

4.2 Water Diversions at Canal Head

The Canal diversions are made against the indents placed by the provincial irrigation and power departments (PIDs) to the Indus River System Authority(IRSA), which are met subject to the availability of river flows or storage reserve. To examine the pattern of canal supplies to canals under the LCC system, a comparison has been shown in **Figure 2** about the seasonal canal diversions during the last five years, with the apportioned quantities under the Water Apportionment Accord of 1991. Details about these diversions to the main branch canals of the system are given in the following **Table 2**:

Table 2 A Comparison of Seasonal Canal Diversions (MAF)

	Jhang Branch Canal			Gugera Branch Canal			Total LCC System		
Year	Rabi	Kharif	Annual	Rabi	Kharif	Annual	Rabi	Kharif	Annual
1990-91	1.578	2.035	3.513	1.672	2.323	3.995	3.150	4.358	7.508
1991-92	1.297	1.838	3.134	1.472	2.098	3.571	2.769	3.936	6.705
1992-93	1.437	1.877	3.314	1.623	2.143	3.766	3.060	4.020	7.080
1993-94	1.452	1.898	3.350	1.644	2.167	3.811	3.096	4.065	7.191
1994-95	1.477	1.913	3.390	1.658	2.147	3.805	3.135	4.060	7.195
W-accord	1.238	1.946	3.184	1.389	2.184	3.573	2.627	4.130	6.757

Table 2 shows that the variations of annual canal diversions has been from 5 to 11 % during the last five years.

4.3 Crop Water Requirements and Supplies at Root Zone

The water shortages or surpluses are derived through water balance computations at the root zone, where the water requirements are met from supplies through surface (canal and rainfall) and groundwater sources (pumpage from tubewells and sub-irrigation through capillary action). The annual water balance for the total LCC system is illustrated in **Figure 3**, which shows that the annual water requirements of 9.17

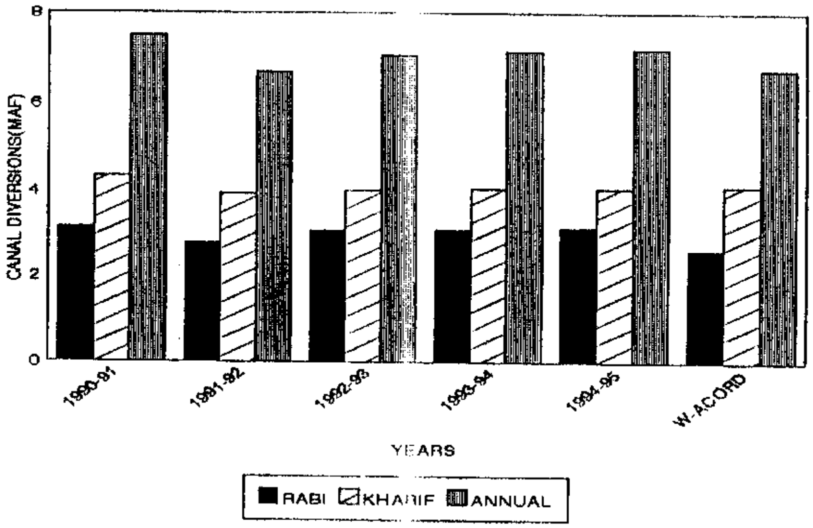


Figure 2. Canal Diversions at Canal Head (1991-95).

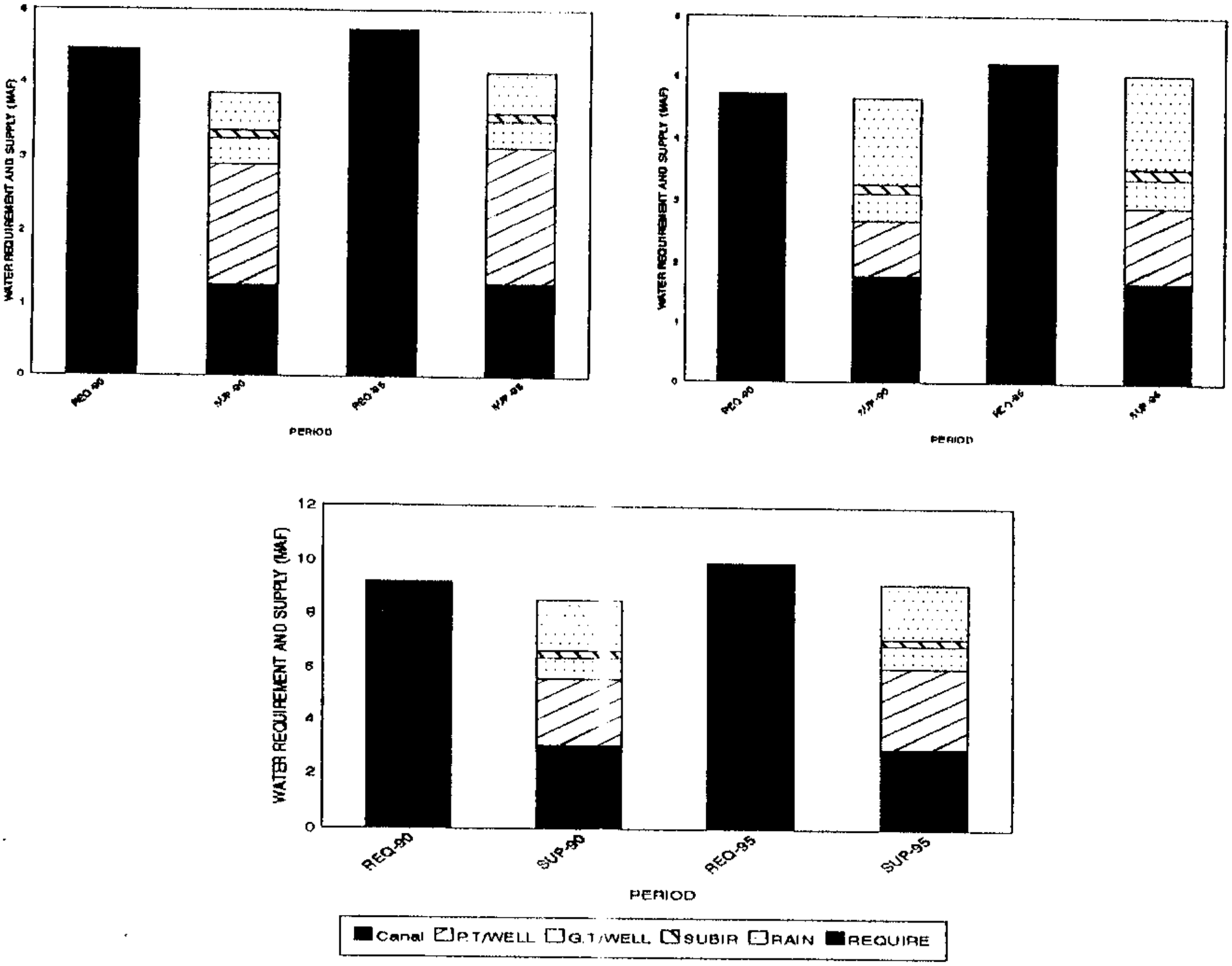


Figure 3. Water Balance at Root Zone during Rabi, Kharif and Annual (1990-95)

MAF have increased to 9.95 MAF , resulting in an increase of 9%. Similarly, the total supplies have increased from 8.50 MAF to 9.18 MAF, resulting in an increase of 8%, thereby, increasing the shortage by 15%, during this period. The water requirements are met from canal supplies (35 to 40 %), rainfall and sub-irrigation (15 to 20%) and pumpage from groundwater (40 to 50 %) and this contribution is more during rabi than in kharif seasons. The canal command comparison of water requirements and supplies at the root zone, for the years 1990 and 1995, are given in Table 3.

Table 3. Crop Water Requirements and Supplies at Root Zone by Canal Command.

Description	Rabi		Kharif		Annual	
Jhang Branch Canal	1990	1995	1990	1995	1990	1995
Crop water requirement	1.72	1.83	1.86	2.06	3.58	3.89
Water Supplies						
Canal	0.57	0.59	0.79	0.76	1.36	1.35
Eff. Rainfall	0.19	0.21	0.54	0.59	0.73	0.80
Sub-irrigation	0.04	0.04	0.05	0.06	0.09	0.10
Tubewell Pumpage						
Public	0.13	0.14	0.18	0.18	0.31	0.32
Private	0.66	0.74	0.38	0.52	1.04	1.26
Total	0.79	0.88	0.56	0.70	1.35	1.58
Total Supplies	1.59	1.72	1.94	2.11	3.53	3.83
Shortage(-) Surplus(+)	-0.13	-0.11	+0.08	+0.05	-0.05	-0.06
Gugera Branch Canal						
Crop water requirement	2.73	2.90	2.86	3.16	5.59	6.06
Water Supplies						
Canal	0.69	0.70	0.96	0.91	1.65	1.61
Eff. Rainfall	0.31	0.33	0.84	0.91	1.15	1.24
Sub-irrigation	0.07	0.08	0.10	0.10	0.17	0.18
Tubewell Pumpage						
Public	0.22	0.22	0.28	0.29	0.50	0.51
Private	0.98	1.10	0.52	0.71	1.50	1.81
Total	1.20	1.32	0.80	1.00	2.00	2.32
Total Supplies	2.27	2.43	2.70	2.92	4.97	5.35
Shortage(-) Surplus(+)	-0.46	-0.47	-0.16	-0.24	-0.62	-0.71

The Jhang Branch is showing a shortage of 0.17 MAF in saline areas and a surplus of 0.04 MAF in fresh areas during rabi (net shortage of 0.13 MAF), whereas for the kharif season, there is a surplus of 0.12 MAF in fresh areas and shortage of 0.04 MAF in saline areas, (net surplus of 0.08 MAF) during 1989-90, resulting in a net annual shortage of 0.05 MAF for the year 1991. Similarly, the annual net shortage during 1994-95 is 0.06 MAF (shortage of 0.11 MAF in rabi and surplus of 0.05 MAF in kharif). Also, under the Gugera Canal command, there is a shortage of 0.46 MAF in rabi (0.13 in fresh and 0.33 in saline areas) and during the kharif season, there is a shortage of 0.16 MAF (0.04 in fresh and 0.12 in saline areas) during 1989-90; this shortage has increased for both seasons during 1994-95, with an overall increase of the annual shortage of 15% from the base year 1990 (**Figure 4**), which is due to a decrease of canal supplies during 1994-95.

4.4 Ground Water Inflows and Outflows

The groundwater balance is the measure of imbalance between inflows through recharge to the aquifer from different seepage sources like canals, watercourses, farm fields, link canals, rivers etc. and outflows in the form of extractions from the subterranean aquifer through tubewells and evaporation from ground water. The positive numbers indicate net inflows (rising water table) and negatives are the indicator of net outflows due to pumping (falling water table). Based on the model results for the years 1990 and 1995, the total recharge to the Jhang Canal command was 2.50 MAF during 1989-90, which has decreased to 2.441 MAF during 1994-95 due to a decrease in canal supplies, of which 85% is occurring in fresh areas and only 15% in saline areas. The recharge during the kharif season is more (58%) than in rabi(42%). Similarly, in Gugera Canal command , the recharge decreased from 3.955 MAF (1990) to 3.868 MAF (1995) and the distribution in fresh and saline areas is the same as for Jhang Branch Canal. The annual groundwater balance for the command area under the LCC system is shown in **Figure 5** where "S" stands for seepage from various sources and "P" stands for pumpage from tubewells. The Figure 5 depicts that the entire system is showing an imbalance of + 0.851 MAF during 1989-90, which has decreased to 0.143 MAF during 1994-95, showing a trend of falling water table during this period.

4.4.1 Recharge and Pumpage

Based on previous studies conducted in the Indus Plains, it is assumed that 70 % of the water lost in the canal conveyance system contributes to the groundwater. Similarly, the contribution of recharge from watercourses, farm fields and rainfall are 80 % of the losses occurring through these sources. The seepage losses from public tubewell use are computed in a similar way as for canal water. The private tubewells are assumed to be closer to the fields where the water is used and the watercourse losses are therefore halved, but the same field losses are assumed. The seepage from link canals is estimated on the basis of link loss factors provided for each link canal,

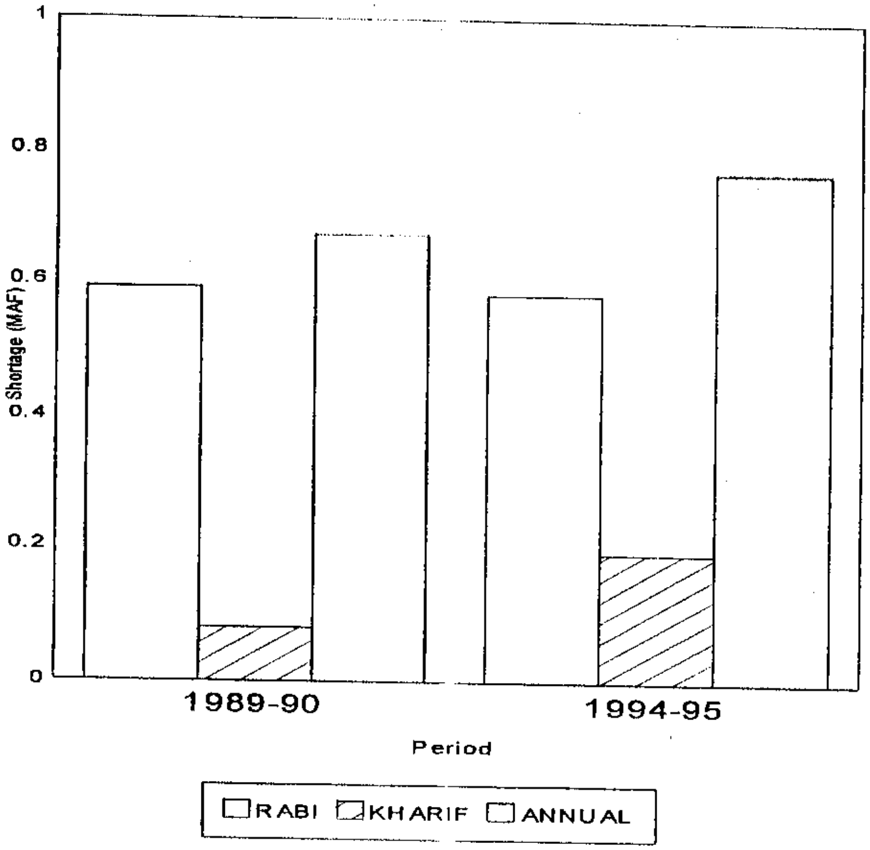
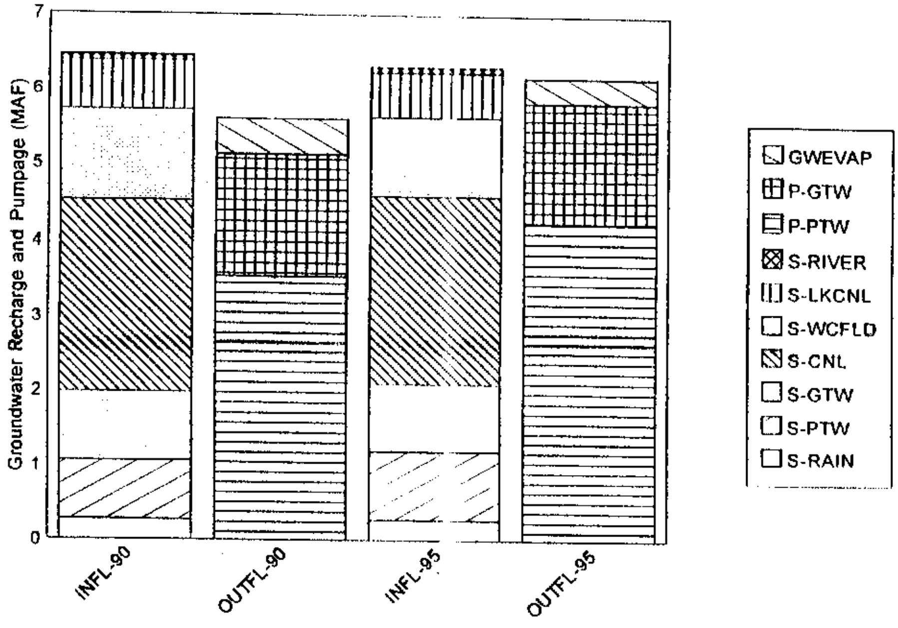


Figure 4. Net Water Shortages at Root Zone (1991-95).



Figue 5. Annual Groundwater Balance (1991-95).

which are based on previous studies. The main river that recharges the aquifer in Rechna Doab is the Chenab. The Chenab River does not recharge on its right bank and, therefore, the canal commands that receive recharge are the Upper and Lower Chenab and Haveli canals. The river losses are estimated from river loss and gain computations through river flow routing for each of the river reaches and the losses contributing to groundwater are computed from the proportionate factors provided in the model.

The total recharge to groundwater in the irrigated areas of the LCC Command area has been estimated to be 6.455 MAF in 1990 and decreased to 6.310 MAF in 1995 due to decrease in canal supplies, out of which 85% of the recharge occurs in fresh groundwater areas and the remaining 15% in saline groundwater areas as shown below.

Table 4. **Recharge to Groundwater in MAF.**

	Fresh Areas		Saline Areas		Total	
Areas of Pumpage	1990	1995	1990	1995	1990	1995
Jhang Branch Canal	2.135	2.083	0.364	0.358	2.499	2.441
Gugera Branch Canal	3.319	3.243	0.635	0.624	3.954	3.868
Total LCC Command	5.454	5.326	0.999	0.982	6.453	6.309

The total pumpage of groundwater in the irrigated areas of LCC command has been estimated to be 5.129 MAF, out of which 1.582 MAF (31%) occurs in public sector and 3.548 (69%) in private sector. The pumpage has increased to 5.833 MAF in 1995 out of which 4.251 MAF (73%) is from private sector and 1.582 (27%) is from public sector, as shown below.

Table 5. **Groundwater Pumpage in MAF.**

Areas of Pumpage	Public Sector		Private Sector		Total	
	1991	1995	1991	1995	1991	1995
Jhang Branch(LCC)	0.612	0.612	1.451	1.752	2.063	2.364
Gugera Branch(LCC)	0.970	0.970	2.096	2.499	3.066	3.469
Total LCC Command	1.582	1.582	3.547	4.251	5.129	5.833

Public projects for groundwater development are planned in such a way that the proposed pumpage equals the recharge, so that no long term depletion of the aquifer takes place. However, in case of private tubewells, there is no restriction on the number of tubewells that can be installed in a certain area and the quality of water that can be pumped by these tubewells. The results show that the pumpage from private tubewells has increased from 3.547 to 4.251 (MAF).

4.4.2 Groundwater Development Potential

Having determined the recharge and the pumpage occurring in the areas of the LCC command, it is now possible to estimate the remaining development potential as shown below. Net recharge is the actual usable recharge minus evaporation from groundwater and the net pumpage is the actual pumpage from public and private tubewells minus the recharge that occurs from the pumped groundwater when the same is used for irrigation(recycled water), which has been used as the measure of the net inflow-outflow of the groundwater. The difference of usable net recharge and the net pumpage gives an estimate of potential for development of groundwater that is available in the canal commands. The results show that the remaining development potential in the LCC Command in 1995 is 1.971 MAF, which is the net pumpage that can be effected without over development of groundwater.

Table 6 **Groundwater Development Potential in the LCC Command Area.**

Canal Commands	Usable Net Recharge(MAF)		Net Pumpage (MAF)		Groundwater Development Potential(MAF)	
	1990	1995	1991	1995	1990	1995
Jhang Branch	2.321	2.315	1.389	1.639	0.932	0.676
Gugera Branch	3.659	3.661	2.028	2.366	1.631	1.295
Total LCC Command	5.980	5.976	3.417	4.005	2.563	1.971

5. SIMULATION for YEARS 2000 AND 2010

5.1 Selection of Simulation Scenarios

To study the effects of resource allocation and capital investment under the existing irrigation constraints as well as identification of different management options for the improvement of irrigated agriculture, three simulation periods were selected (1989-90 to 2000, 1994-95 to 2000 and 1994-95 to 2010) to run the model according to a combination of 13 simulation scenarios(assumptions) as highlighted in **Table 7**, which are based on different capital investment and management options.

Table 7. Codes alongwith their Definition for the Simulation Scenarios.

Code	Defition of Simulation Scenarios
A	Base year 1990, the yield, production, and acreage figures as reported by the Agricultural Statistics of Pakistan and the actual surface water supplies for the year 1990-91. The cropped area and yields projection were taken according to the growth rates for the period 1991-95, for the year 2000.
A1	Same as under "A" except, the cropped area and yields projection were taken according to the reported figures as recommended by the National Commission on Agriculture for the year 2000.
B	No change in the crop production area, canal diversions for 1990 are assumed to be equal to the actual diversions reported for 1994-95, and maintained till the year 2000. Crop yields for 1990 as 90% of yields reported for 1995 by IIMI survey, with yields increasing @ 2.5% per annum upto the year 2000. Public tubewell contribution no more than 30% of the total groundwater contribution, and decreasing at the rate of 2% per annum upto the year 2000.
C	Ccrop area and yield, same as under 'B". Average canal diversions for 1991 are the ones reported for 1994-95, and for 1995-2000 it is 10% higher. Crop yields for 1990 are 90% of yields reported for 1995 by IIMI survey. Yields increase @ 2.5% per annum upto year 2000. Public tubewellcontribution for 1991-95 no more than 30% of the total groundwater contribution, and thereafter less than 10% upto the year 2000.
D	No change in crop . Canal diversions, same as under "C". Crop yields from IIMI data of 1995, and thereafter increasing by 3% per annum. Public tubewell contribution for 1990-95 no more than 30% of the total groundwater contribution, and thereafter less than 10% upto the year 2000.
E	No change in crop for 1991-95, and thereafter increasing by 0.5% per annum. Average canal diversions for 1991-95 are the ones reported for 1994-95, and for 1995-2000 is 10% higher. Crop yields from IIMI data of 1995, and thereafter increasing by 3% per annum. Public tubewell contribution for 1990-95 no more than 30% of the total groundwater contribution, and thereafter less than 10% upto the year 2000. Both field application efficiency and conveyance efficiency is improved by 5% each.
F	The crop area increases by 0.5% per annum from 1995. Canal diversions are 105% of the actual for 1994-95. Crop yields increase by 3% over the IIMI survey actuals for 1995. Public tubewell contribution is uniformly reduced to zero during 1995-2000. Field application efficiency is improved by 5%.

Code	Defition of Simulation Scenarios
G	Cropped area and yield same as under "F". Canal diversions are 110% of the actual for 1994-95. Crop yields increase by 3% over the IIMI survey actuals for 1995. Public tubewell contribution is uniformly reduced to zero during 1995-2000. Field application efficiency is improved by 5%.
H	No change in cropped area. Canal diversions are 110% of the actual for 1994-95. Crop yields increase by 3% over the IIMI survey actuals for 1995. Public tubewell contribution is uniformly reduced to zero during 1995-2000. Both field application efficiency and conveyance efficiency is improved by 5% each.
I	The cropped area increases by 0.5% per annum from 1995. Canal diversions and crop yields as of under "H". Public tubewell contribution is uniformly reduced to zero during 1995-2000. Both field application efficiency and conveyance efficiency is improved by 5% each.
J	The cropped area increases by 0.5% per annum from the base year. Canal diversions are 120% of the actual for 1994-95. Crop yields increase by 3% over the IIMI survey actuals for 1995. Public tubewell contribution is uniformly reduced to zero during 1995-2000. Field application efficiency is improved by 5% and conveyance efficiency is improved by 10%.
K	The cropped area increases by 0.5% per annum from the base year 1995 till 2000, and thereafter no increase to 2010. Canal Diversions are 105% of the actual for 1994-95 till 2000, and thereafter 110% to 2010. Yield data from the IIMI survey of 1995 and yields increase by 2.5% per annum during 1995-2000, and thereafter by 3% per annum till the year 2010. Public tubewell contribution is uniformly reduced to zero during 1995-2000. Both field application efficiency and conveyance efficiency is improved by 5% each during 1995-2000, and thereafter by another cumulative 10% till 2010.
K1	The cropped area increases by 0.5% per annum from the base year till 2010. Canal diversions are equal to proportional allocations of average post Tarbella to each canal by season. Yield data from the IIMI survey of 1995 and yields increase by 3% per annum from the base year till the year 2010. Public tubewell contribution is uniformly reduced to zero during 1995-2010. Both field application efficiency and conveyance efficiency is improved by 10% till 2010.

According to the assumptions (Table 7) based on the situations prevailing during the yearrs 1990 and 1995 (base cases), in order to identify the salinity management alternatives, the model results in the context of different variables are described in the following section.

5.2 Cropped Area and Average Yield

From a comparison of results for all scenarios (**Figure 6**), the maximum cropped area is obtained from the cropped area growth trend during 1991-95 period, except for cotton, which is based on the moving averages during this period, followed by the results based on the recommendation of the National Commission on Agriculture (NCA). Lastly on the 0.5% increase scenario By the years 2000 and 2010. The results for some major crops have been given in **Table 8**. The yield of rice is that of paddy rice and cotton is that of seed cotton. The results of future projections for crop area and average yield under the three scenarios , show a lower trend under the historical growth. The difference of results between the NCA and 3% growth scenarios, are due to the reasons, firstly, that the per annum growth rate for each crop under the NCA is different whereas a 3% growth rate for all major crops has been assumed under the last scenario ; secondly, the yields under the NCA recommended projection are for the whole of the irrigated area of the country.

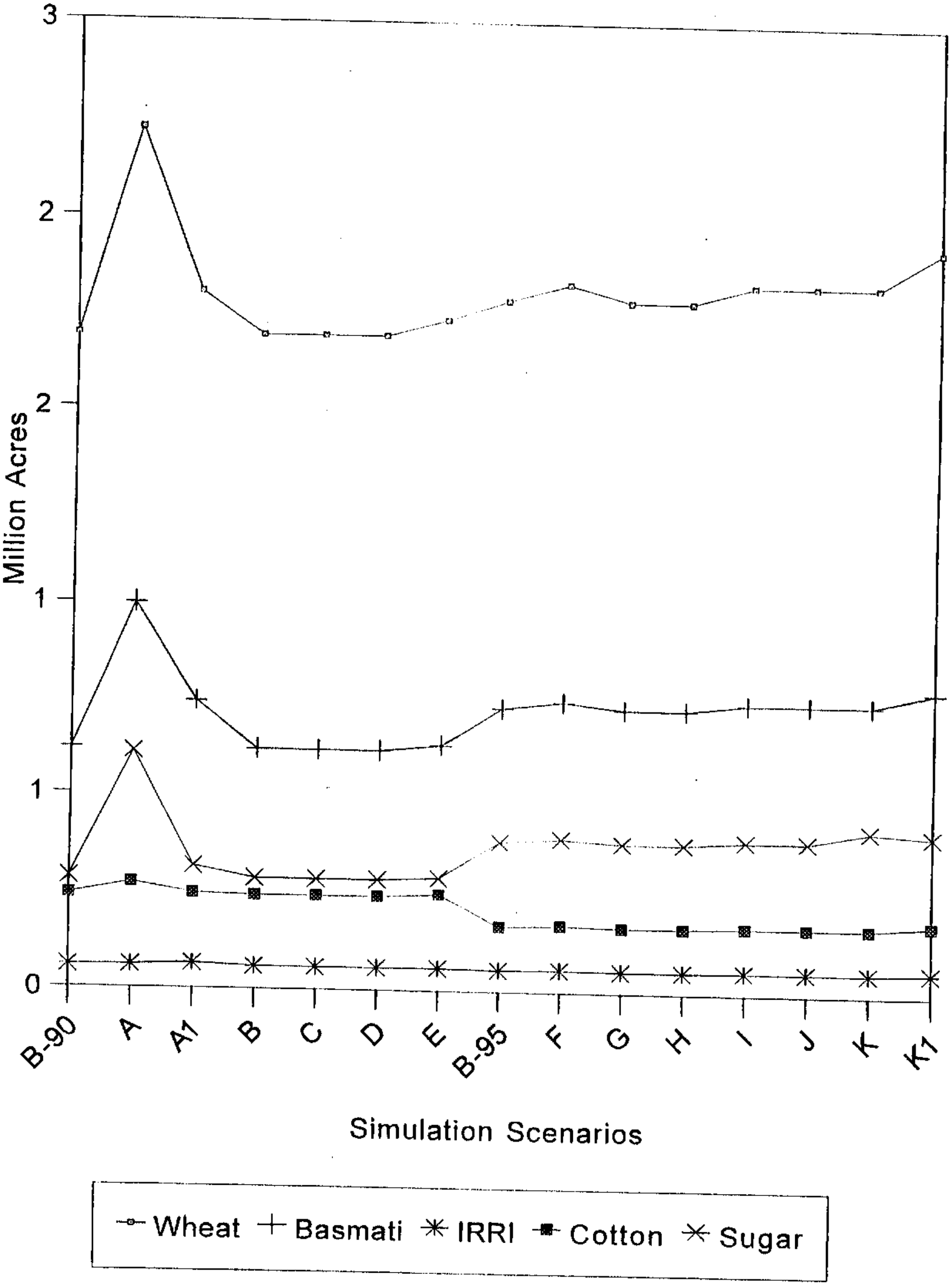


Figure 6. Comparison of Simulated Crop Area of Total LCC System.

Table 8. **Simulated Cropped area and Avg. Yield by the Year 2000 and 2010 (Million Acres and Tons per Acre).**

Major Crops	Growth during 1991-95 for year 2000		NCA growth rate for year 2000		0.5% increase in Area & 2.5 to 3% yield growth 2000		2010	
	Area	Yld.	Area	Yld.	Area	Yld.	Area	Yld.
Jhang Branch Canal Command								
Wheat	0.868	0.983	0.698	1.149	0.712	1.184	0.749	1.514
Basmatti Rice	0.414	1.427	0.308	2.078	0.310	1.348	0.326	1.810
IRRI Rice	0.025	3.440	0.027	2.593	0.024	2.292	0.025	2.760
Cotton	0.099	0.747	0.090	0.756	0.063	0.841	0.067	0.612
Sugarcane	0.225	16.770	0.117	20.100	0.147	18.600	0.154	25.770
Gugera Branch Canal Command								
Wheat	1.357	0.982	1.109	1.152	1.122	1.188	1.180	1.510
Basmati Rice	0.585	1.426	0.435	2.094	0.441	1.347	0.464	1.808
Irri Rice	0.034	3.412	0.037	2.622	0.033	2.364	0.035	2.714
Cotton	0.172	0.744	0.155	0.761	0.110	0.845	0.116	0.612
Sugarcane	0.383	1.650	0.196	20.160	0.248	18.580	0.261	25.650

The simulated area and average yield of major crops for the total LCC system are shown in **Figures 7 and 8,** which illustrate that an increase in crop area for the year 2000 for crops like wheat (1.38%), basmatti(1.9%), IRRI(3.6%), cotton(0.58% and sugarcane (1.31%), whereas the yield has increased from 15 to 100 % for different crops. Similarly, there is an increase of crop area between 6 and 9 % such as wheat(6.6%), basmati(7.2%), IRRI(9.1%), cotton(6.4%) and sugarcane(6.4%) while the yield is showing an increase between 50 and 70 %, up to year 2010.

5.3 Water Shortages and Surpluses

Due to variations in canal diversions , it is difficult to predict the water availability at the canal heads by the years 2000 and 2010. Therefore, the allocations for year 2000 are based on an increase of 1994-95 diversions from 10 to 20 % and a proportional allocation of historic average post Tarbella diversions are used for the year 2010. From the comparison of simulation results of water requirements and supplies from different sources according to scenarios (A to K1), a comparative statement about

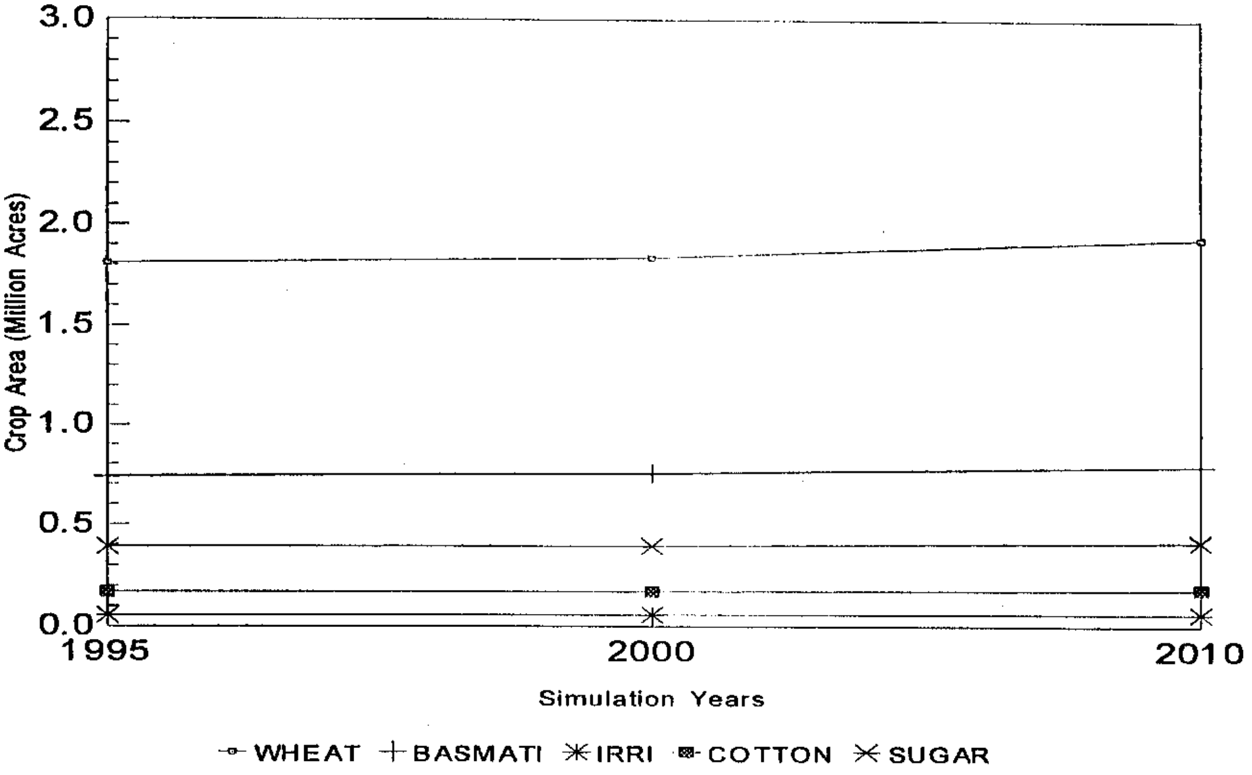


Figure 7. Simulated Crop Area for Years 2000 and 2010 of Total LCC System.

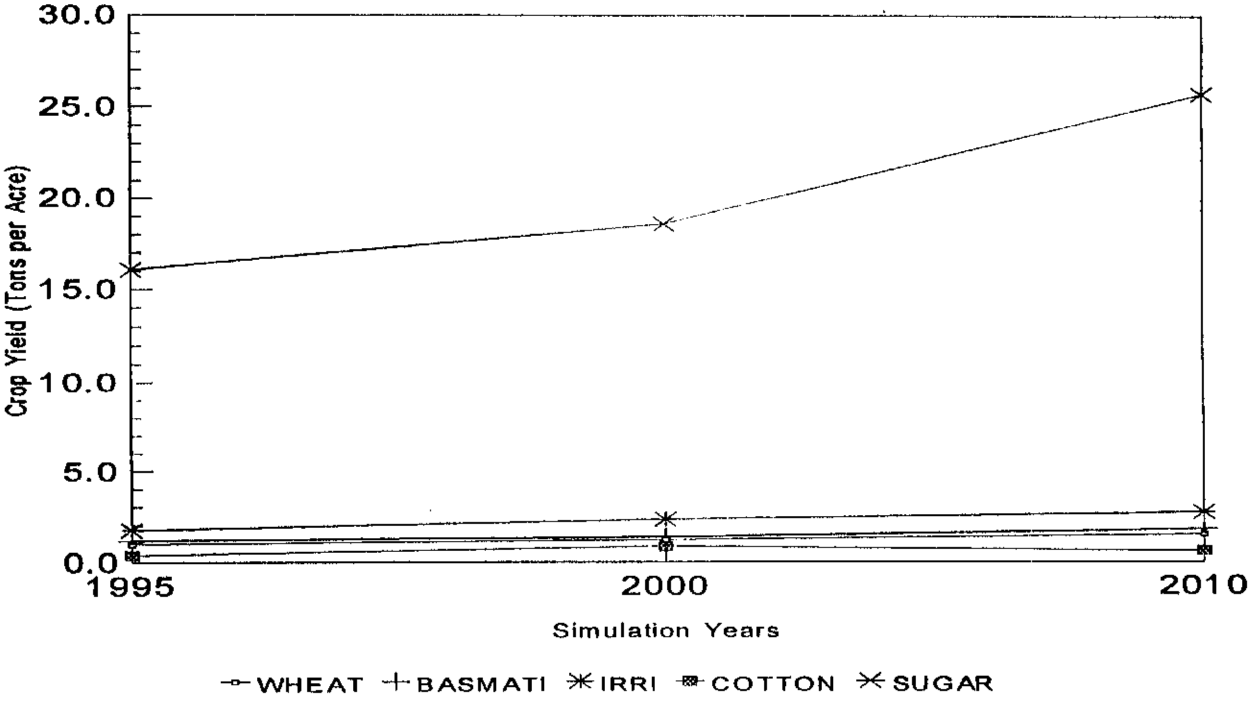


Figure 8. Simulated Crop Yield for Years 2000 and 2010 of Total LCC System.

the water shortages and surpluses in the LCC system is given in **Table 9** and shown in **Figures 9 and 10** ,from where it is apparent that the shortages have been minimized under Scenario D where the cropped area of 1994-95 has been maintained up to the year 2000 and canal supplies have been increased by 10%, which is practically unrealistic approach, followed by the results under Scenario J where the crop area has been increased by 0.5 % per annum and canal supplies have been increased by 20 % ; hence, the results of Scenario J have been used for future discussion for the simulation year 2000. Similarly, the results of Scenario K1 has been used for the year 2010. From the results presented in Table 9, it is apparent that both shortages as measured by crops grown under stress, and surpluses as measured by the excess of water available over net requirements, exist in the canal commands of LCC system.

Table 9. **Simulated Water Shortages and Surpluses of the LCC System.**

Description	Jhang Canal			Gugera Canal		
	1995	2000	2010	1995	2000	2010
Net Requirements	2.98	3.03	3.19	4.63	4.70	4.94
Water Supplies						
Canal	1.36	1.66	1.72	1.61	1.97	2.04
Tubewell Pumpage	1.60	1.50	1.59	2.33	2.16	2.30
Total Supplies	2.96	3.16	3.31	3.94	4.13	4.34
Shortage(-)	-0.02			-0.69	-0.57	-0.60
Surplus (+)		0.13	0.12			

The annual water requirements are net of effective rainfall and sub-irrigation, while annual water supplies are canal and groundwater pumpage . The groundwater pumpage by the years 2000 and 2010 are only from private tubewells because the contribution from public tubewells has been assumed to be zero because of the transition of SCARP tubewells to the private sector . The annual water shortages have been alleviated in the Jhang Canal command area and converted to a surplus of 0.13 MAF up to the year 2000 and 0.12 for the year 2010, whereas the shortages in Gugera Canal command have decreased by 17 % only, **Figure 11** shows the comparison of requirements and supplies at the root zone for the years 1995 (base year), 2000 and 2010. **Figure 12** shows that the total contribution of groundwater has been reduced from 57% to 50% (2000) and 51% (2010) due to an increase in canal supplies by the year 2010. The annual shortages have been reduced by 38% from 0.71 MAF (1995) to 0.44 MAF (2000) and 0.48 MAF (2010).

5.4 Crop Yield Water Stress Relationships

When the crop water requirements are not met from the available water supplies then instead of reducing the crop area, the crops are stressed in particular months to a certain limit with associated lower yields and the embedded economic costs of incurring stress. The stress is occurring in the saline areas only because in most of the fresh areas the tubewell capacity is sufficient so the crops do not need to be stressed

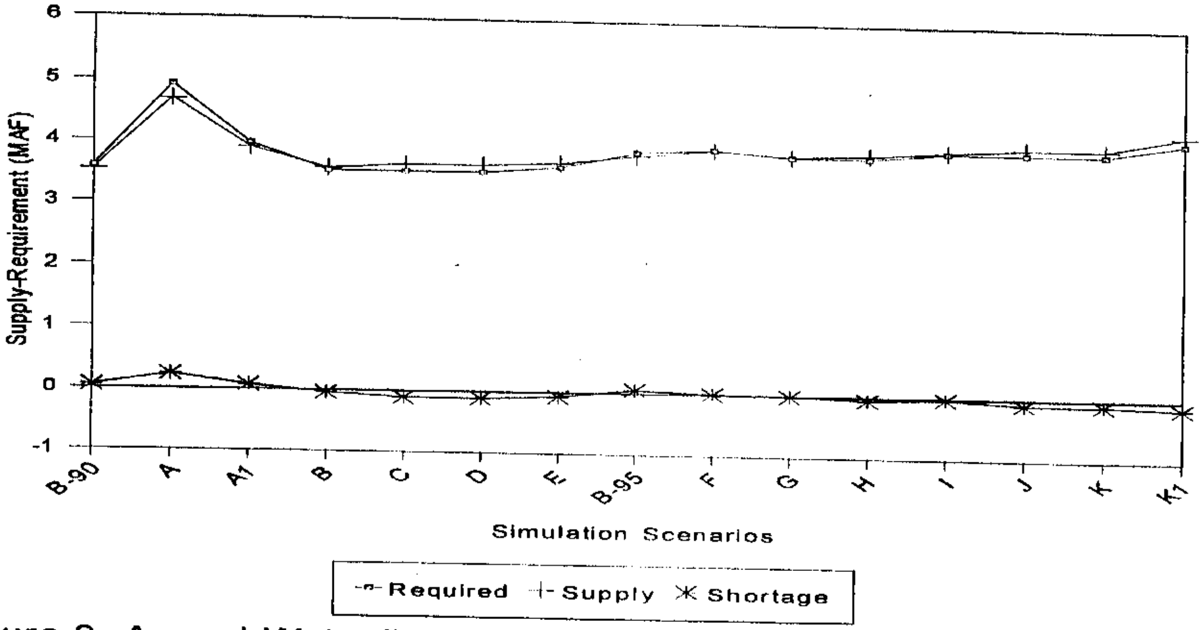


Figure 9. Annual Water Balance at Root Zone for Jhang Branch Canal.

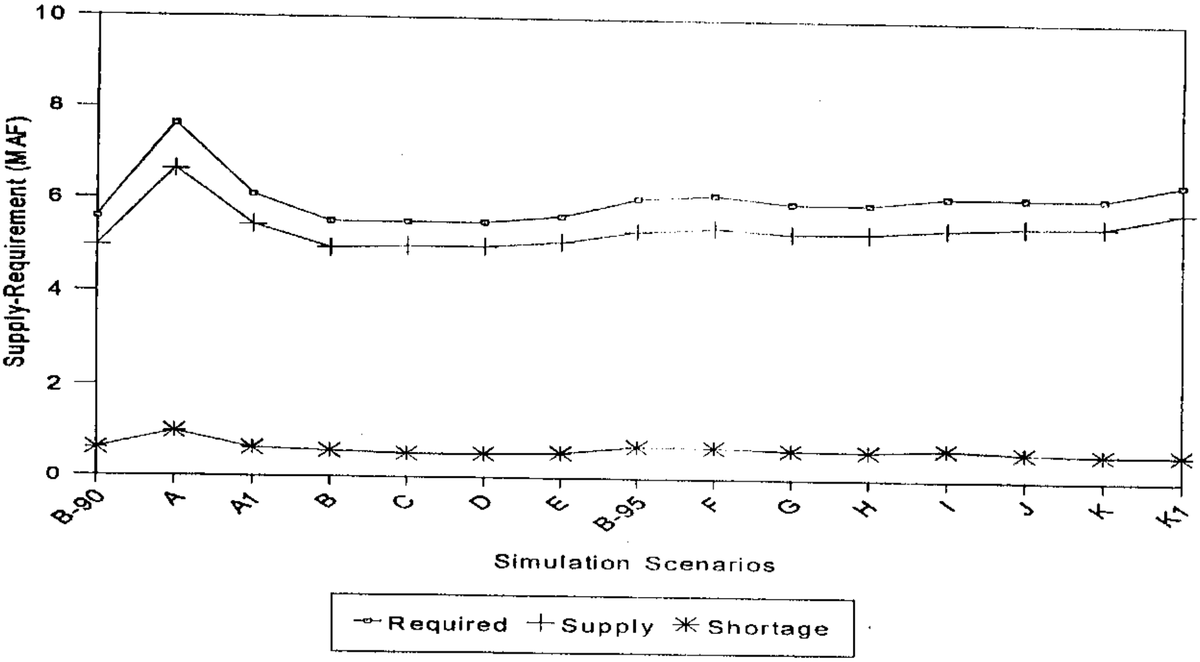


Figure 10. Annual Water Balance at Root Zone for Gugera Branch Canal.

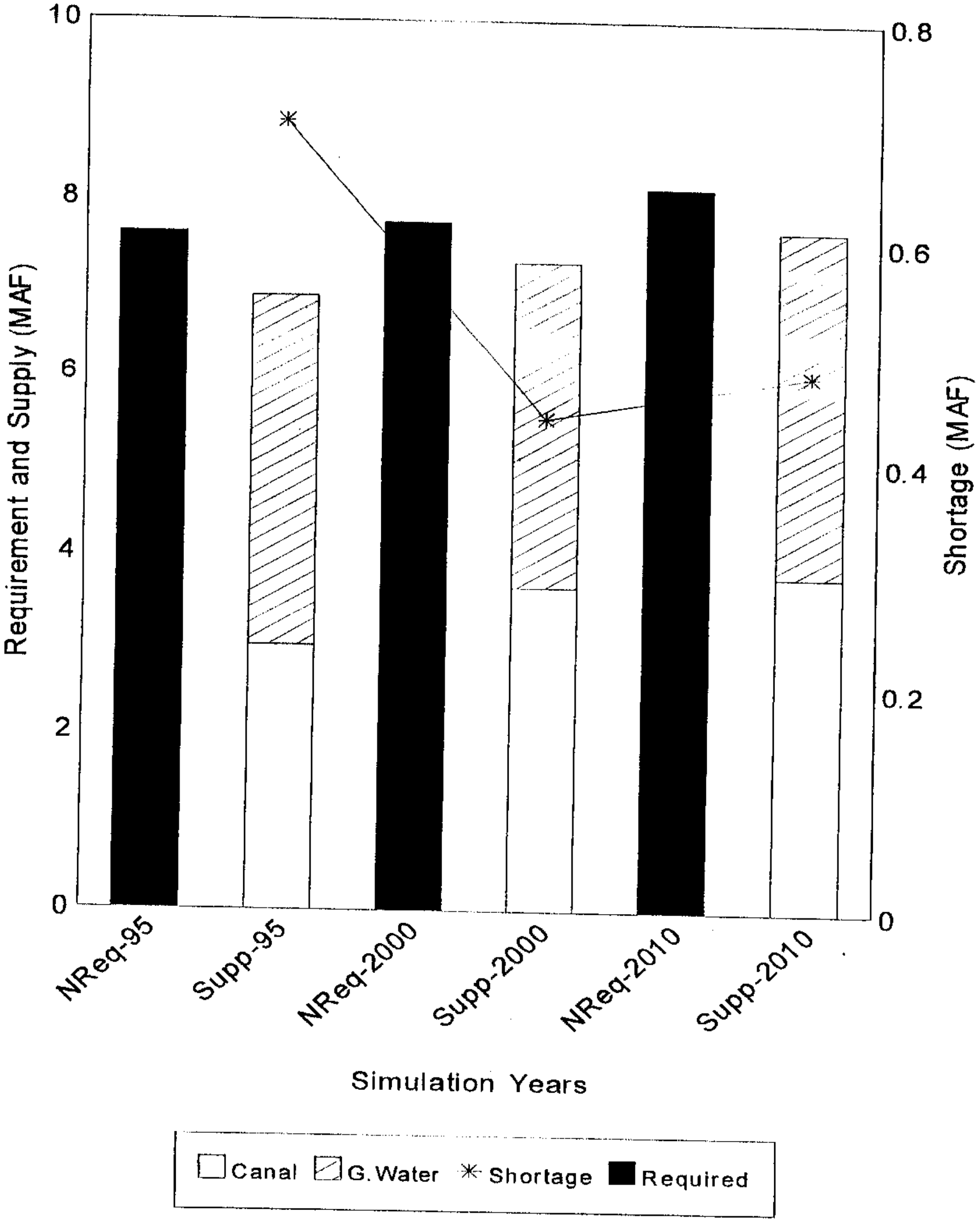


Figure 11. Simulated Annual Water Balance at Root Zone.

but in all saline areas, the net water requirements are met from canal supplies only, and the stress is often incurred particularly in rabi season. The **Table 10** shows how the improvement in crop yield is occurring for different crops in fresh and saline areas with increase in water supply and reduction in crop stress during 1995-2010 period. The increase in yields of major crops like cotton,wheat and sugarcane are 30%, 13% and 9% respectively in saline areas because the reduction of stress has occurred in saline areas only.

Table 10 Water Supply and Yield Relationships.

		Base Year-1995			Simulation Year 2010		
Area	Crop	Supply %	Yield (Kg/A)	Yield %	Supply %	Yield (Kg/A)	Yield %
Fresh	Cotton	100	396	100	100	616	100
Fresh	R-Fod.	100	10000	100	100	10000	100
Fresh	Maize	100	594	100	100	572	100
Fresh	K-Fod.	100	400	100	100	400	100
Fresh	Sugar	100	17614	100	100	27442	100
Fresh	Wheat	100	998	100	100	1555	100
Fresh	Fruit	100	3775	100	100	3799	100
Saline	Cotton	40	277	70	100	616	100
Saline	R-Fod.	30	6500	65	30	6500	65
Saline	Maize	40	416	70	40	401	70
Saline	K-Fod.	74	327	82	69	314	78
Saline	Sugar	60	11978	68	72	21195	77
Saline	Wheat	50	699	70	72	1291	83
Saline	Fruit	70	2926	78	70	2945	78

5.5 Water Reallocation

In approaching the question of water reallocation, either between canals or within canal commands, the value of water in its alternative uses(its opportunity costs) is paramount. The mathematical model, like IBM-III, generates these values as shadow prices in each solution and these values for canal water are measured at the root zone in rupees per-acre foot as shown in **Table 11** below:

Table 11. **Shadow Price of Water at Root Zone (Rupees per Acre-Foot).**

	Base Year 1995			Simulation Year 2010		
Months	PSW-Fresh	PSW-Saline	PRW-Fresh	PSW-Fresh	PSW-Saline	PRW-Fresh
January	312	53316	309	310	4527	307
February	312	53316	309	310	4527	307
March	312	53316	309	310	4527	307
April	312	53316	309	310	4527	307
May	312	1400	309	310	1400	307
June	312	1400	309	310	1400	307
July	EPS	EPS	309	310	1400	307
August	EPS	53316	309	310	4647	307
September	312	53316	309	310	4647	307
October	312	53316	309	310	4647	307
November	312	53316	309	310	4647	307
December	312	53316	309	310	4527	307

Note: EPS is the quantity not equal to zero but approaching the zero.

When the shadow price is zero, it means that water has no alternative use, which corresponds to finding that water is surplus. In fresh areas, the values range from 307 to 312, which reflects the opportunity costs of tubewell pumping. Tubewells are being used because the canal supplies have been exhausted. Additional supplies would allow a reduction in tubewell use and some cost savings. However, the higher values in saline areas reflect the fact that stress is occurring. Additional canal supplies would permit a reduction in stress levels and an increase in crop yields. The higher values during September-April imply that a high value crop is being stressed.

5.6 Ground Water Inflows and Outflows

The recharge to the groundwater reservoir from different sources of percolation cannot be measured directly, but can be calculated indirectly from the equation of hydrologic equilibrium, which is based on the theory that a balance must exist between the quantity of water entering any given area and the amount stored within or leaving the same area for any period of time. Measurement of various components considered in the equation of hydrologic equilibrium permits a quantitative evaluation that is necessary for the successful operation of any water resources development program. In its simplest form, the equation is as follows:

$$I=O\pm\Delta S$$

where I is equal to inflow, O is equal to outflow and S is the net change in storage. If there is a net increase in storage , it is added to the right side of the equation; if there is a net decrease , it is subtracted. This equation is suitable for the analysis of the total surface as well as groundwater budget. To study the effects of varying irrigation system parameters/ characteristics (Scenarios A to K1) under the existing system constraints and policy interventions, on behavior of changes in groundwater storage, a comparison is illustrated in **Figures 12 and 13** for the Jhang and Gugera canals for the simulation years 2000 and 2010. The results for the annual groundwater balance show that groundwater is more than the pumpage inflow under all scenarios except scenario A. A comparison of annual groundwater inflow-outflow for canals in the LCC System is given in **Table 12** and has been illustrated in **Figure 14** for the total command of the LCC system:

Table 12. **Annual Groundwater Balance for LCC System (MAF).**

	Jhang Branch			Gugera Branch			Total LCC Command		
	1995	2000	2010	1995	2000	2010	1995	2000	2010
Inflow	2.441	2.570	3.309	3.868	4.035	3.976	6.309	6.605	7.285
Outflow	2.364	2.795	2.276	3.468	4.045	3.384	5.832	6.840	5.660
Inflow-Outflow	0.077	-.225	1.033	0.400	-.010	0.592	0.477	-.235	1.625

The above results show that during 1994-95, due to decreases in canal diversions, the pumpage was more, resulting in a decrease in recharge to the aquifer compared with extractions. But for the year 2010, the system is showing an increase in recharge, which is an indicator of rising water tables.

5.7 Groundwater Development Potential

After having determined the incoming recharge to the aquifer system and outgoing extractions from the aquifer, it is now possible to estimate the remaining groundwater development potential in the LCC canal system for the years 2000 and 2010 on the basis of scenarios mentioned above, which is illustrated in **Table 13.**

Table 13. **Groundwater Development Potential in LCC System (MAF).**

Simulation Year	Usable Net Recharge	Net Pumpage	Groundwater Development Potential
1995	5.976	4.005	1.971
2000	6.295	5.105	1.190
2010	6.951	4.514	2.437

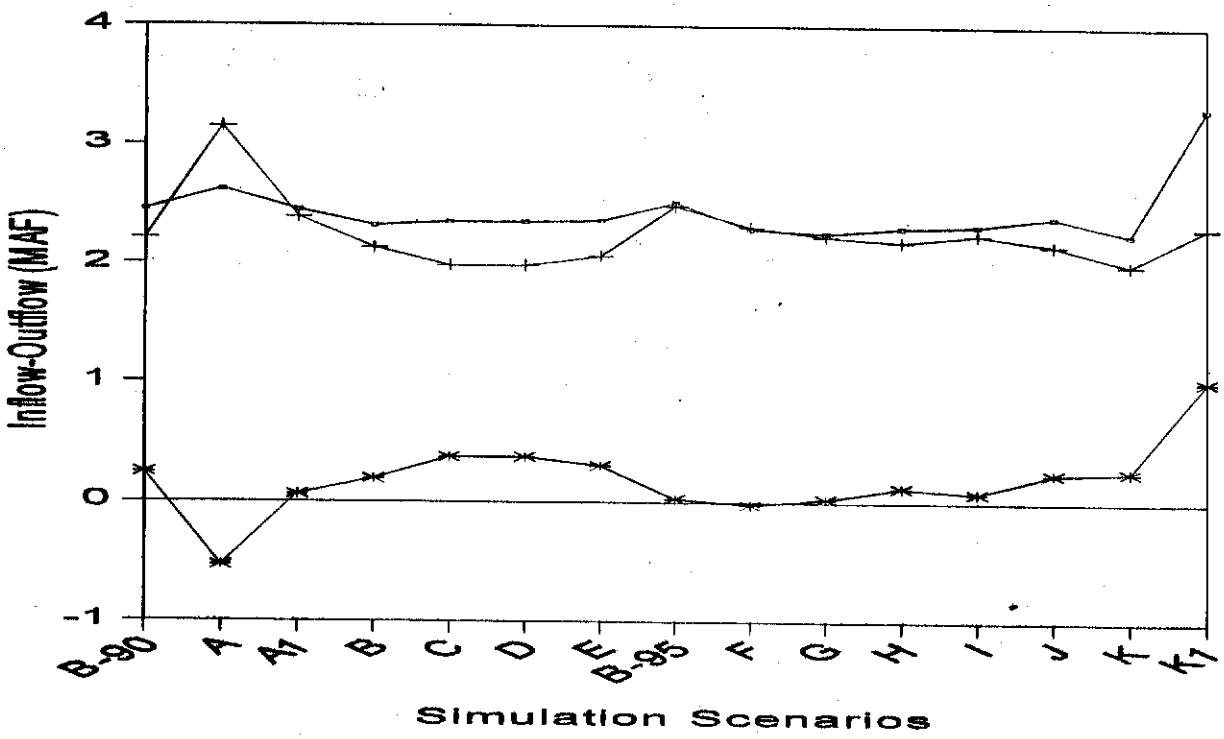


Figure 12. Simulated Annual Groundwater Balance for Jhang Branch.

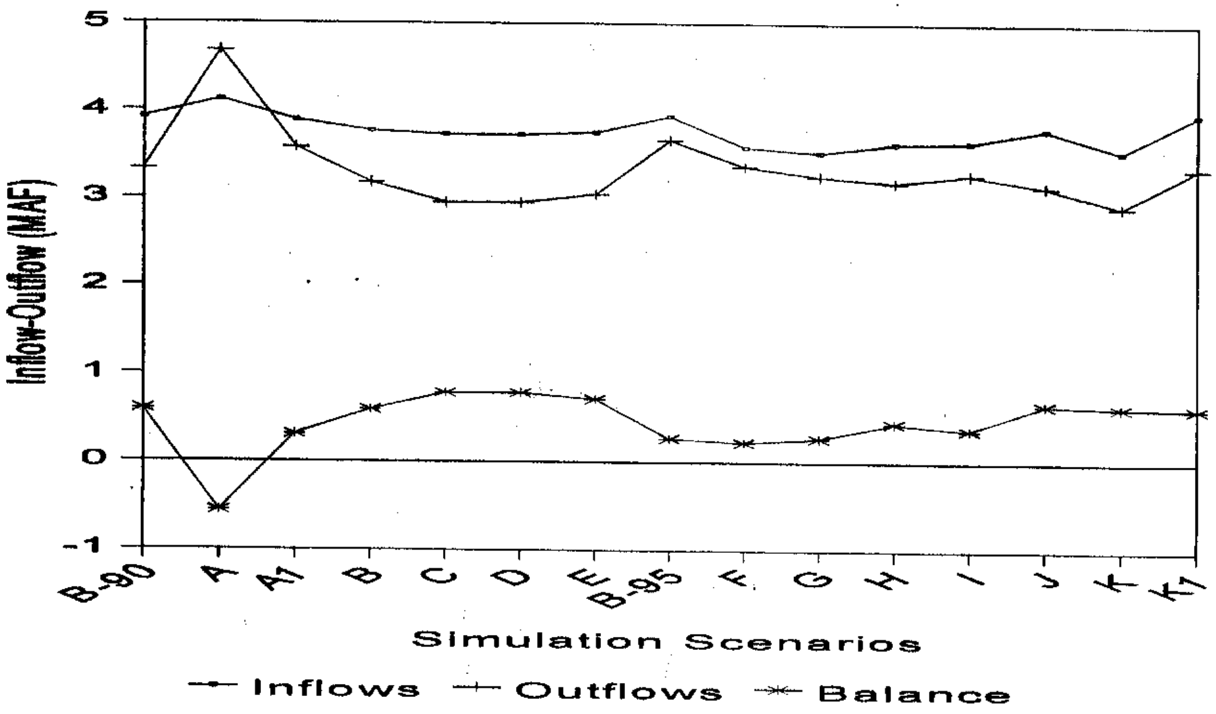


Figure 13. Simulated Annual Groundwater Balance for Gugera Branch.

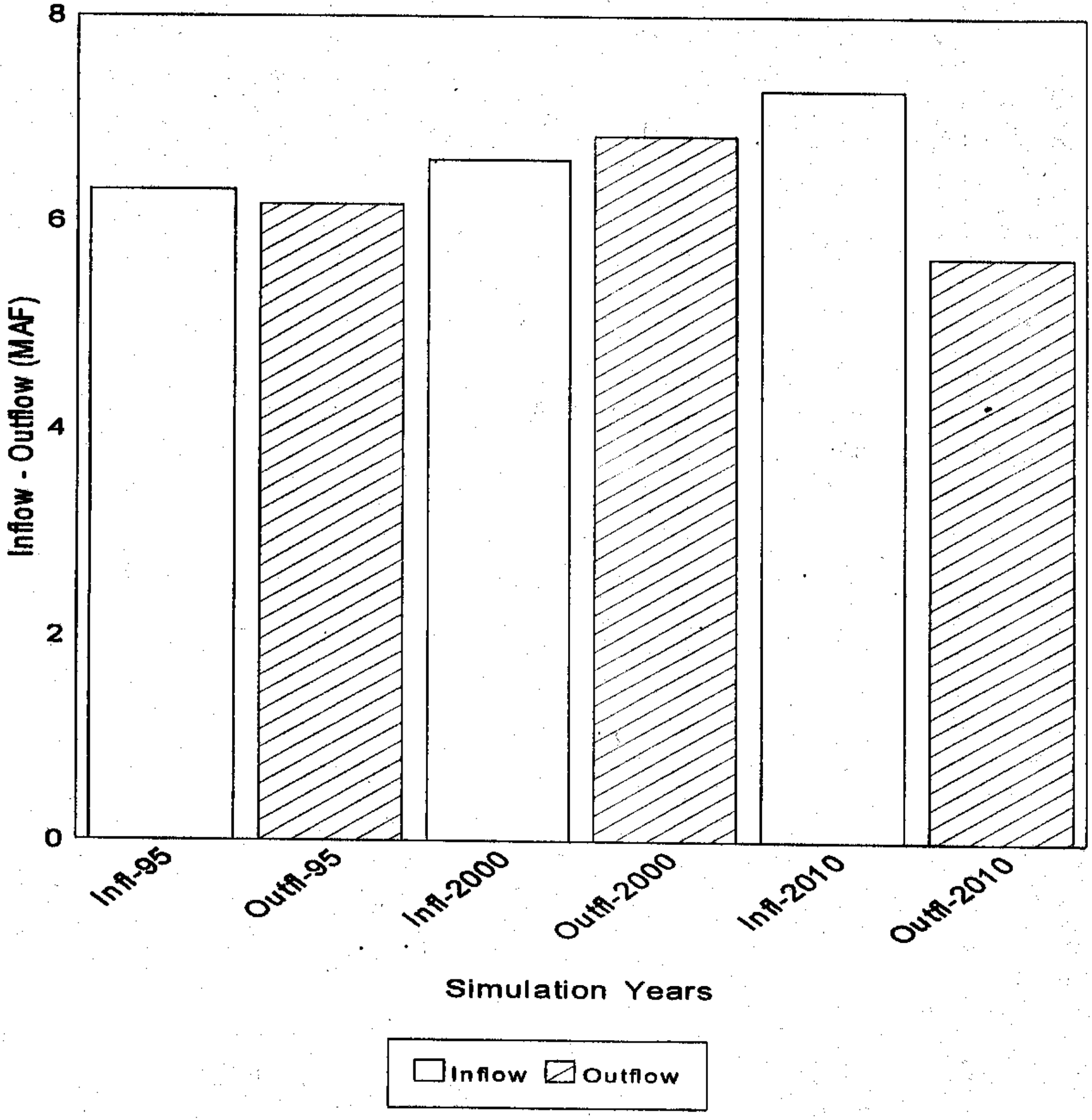


Figure 14. Simulated Annual Groundwater Balance of LCC Command.

The usable net recharge is the actual recharge less the evaporation from groundwater and the net pumpage is the total tubewell pumpage less the recharge contributed from the tubewell pumped water (recycled groundwater) when the same is used for irrigation purposes. The groundwater development potential is the difference between usable net recharge and net pumpage, with the positive values indicating the remaining groundwater potential that can be exploited for irrigation or other purposes.

6. CONCLUSIONS

From the above discussion, the following conclusions are made:

i The surplus water is only available in fresh groundwater areas of the Jhang Branch of LCC, but there is a shortage in saline areas and this shortage is more during the rabi season than kharif, resulting in a shortage during the rabi season, and a net surplus during the kharif season.

ii The Gugera Branch showed a net shortage of water during both the rabi and kharif seasons . Amongst the total annual shortage, 75% is occurring during rabi and 25% during kharif, while 70% occurs in saline areas .

iii The net surplus water under the Jhang Canal command during the kharif season can be reallocated to saline areas of the Gugera Branch canal to overcome the shortages to some extent, but due to net shortages during the rabi season, there is a need of allocating additional water to the system which can only be met from an addition of new water storage facilities to trap the short duration monsoon flood peaks during kharif.

iv As a consequence of interventions occurring in the canal command system of LCC under the proposed capital investment and management scenarios, the groundwater inflow-outflow balances have resulted in a net groundwater potential, for the aquifer system that can be extracted under safe limits and can be used to alleviate the water shortages in the fresh groundwater areas of the LCC system in conjunction with canal water.

v Proper legislation is required for regional groundwater management to control groundwater extraction, specially in the private sector, so that mining of the aquifer may not occur which would have serious consequences for contamination of the fresh aquifers by saline intrusions.

vi The practice of deficit irrigation is recommended, aimed at optimizing crop production under conditions of water deficit. The methodology allows the crops to be stressed to varying degrees during the crop season, while attempting to minimize the stress during the critical stages of crop development when moisture deficit can most adversely affect the crop yields. The use of a computer software is recommended as a practical tool for applying the principles of deficit irrigation.

vii Mostly, the shortages are occurring in saline areas where the canal water is the only source of irrigation. The practice of saline agriculture is recommended for reclaiming and placing salinized lands to productive use through cultivation of salt tolerant crops.

viii Improved water use would require that the canal system operation be redesigned based on clearly defined objectives. This would form part of an in-depth diagnostic analysis of the system to be undertaken through a multidisciplinary team. The Simulation Models for studying the performance of individual canal systems under different modes of operation and the Integrated Optimization Models for studying the interactions between the crop area, the canal system network, and the river/reservoir system are recommended as tools for achieving the defined objectives.

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Report No.	Title	Author	Year
R-1	Crop-Based Irrigation Operations Study in the North West Frontier Province of Pakistan (Volume I: Synthesis of Findings and Recommendations	Carlos Garces-R D.J. Bandaragoda Pierre Strosser	June 1994
	(Volume II: Research Approach and Interpretation)	Carlos Garces-R Ms. Zaigham Habib Pierre Strosser Tissa Bandaragoda Rana M. Afaq Saeed ur Rehman Abdul Hakim Khan	June 1994
	(Volume III: Data Collection Procedures and Data Sets)	Rana M. Afaq Pierre Strosser Saeed ur Rehman Abdul Hakim Khan Carlos Garces-R	June 1994
R-2	Salinity and Sodicity Research in Pakistan - Proceedings of a one-day Workshop	IIMI-Pakistan	Mar 1995
R-3	Farmers' Perceptions on Salinity and Sodicity: A case study into farmers' knowledge of salinity and sodicity, and their strategies and practices to deal with salinity and sodicity in their farming systems	Neeltje Kielen	May 1996
R-4	Modelling the Effects of Irrigation Management on Soil Salinity and Crop Transpiration at the Field Level (M.Sc Thesis - pulished as Research Report)	S.M.P. Smets	June 1996
R-5	Water Distribution at the Secondary Level in the Chishtian Sub-division	M. Amin K. Tareen Khalid Mahmood Anwar Iqbal Mushtaq Khan Marcel Kuper	July 1996
R-6	Farmers Ability to Cope with Salinity and Sodicity: Farmers' perceptions, strategies and practices for dealing with salinity and sodicity in their farming systems	Neeltje Kielen	Aug 1996
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Report No.	Title	Author	Year
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R-18	**Proceedings of National Conference on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan**	M. Badruddin Gaylord V. Skogerboe M.S. Shafique (Editors for all volumes)	Nov 1996
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