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SALINITY MANAGEMENT ALTERNATIVES FOR THE RECHNA DOAB, PUNJAB, PAKISTAN

Volume Three

Development of Procedural and Analytical Links

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FOREWORD

This report is one of eight volumes under the umbrella title "Salinity Management Alternatives for the Rechna Doab, Punjab, Pakistan." The funding for this effort has been provided by the Government of The Netherlands through the Royal Netherlands Embassy in Islamabad under the Phase II project, "Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan." Between 1989-93, IIMI operated three field stations in Rechna Doab using Dutch phase I funding; much of this field data has been incorporated into this study.

Rechna Doab, the ancient floodplain between the Ravi and Chenab rivers covering a gross area of 2.9 Mha, is one of the most intensively developed irrigated area within the country. With over a century of modern irrigation development, primarily by diversions from the Chenab River, agricultural productivity was continually bolstered. Then, some localities were beset with the threats of higher subsurface water levels and soil salinization. The public sector responded by implementing Salinity Control and Reclamation Projects (SCARPs) beginning in 1960. These projects, plus a huge increase in private tubewell development since 1980, have lowered subsurface water levels; however, the use of poor quality tubewell water, particularly in the center of the Doab, has resulted in secondary salinization. This study is an integrated attempt across both space and time to address the systems responsiveness to the abovementioned concerns.

Vast amounts of data have been collected by public agencies in this study area since 1960. There are a number of agriculture census reports (1960, 1972, 1980 and 1990). Also, the Water and Power Development Authority (WAPDA) has done extensive investigations; their data were made available to IIMI through the General Management (Planning) and the SCARPs Monitoring Organization (SMO). In addition, WAPDA deputed an engineer half-time to participate in these studies who is knowledgeable on the Indus Basin Model Revised (see Volume Eight), which was used primarily to study the effect of groundwater balance constraints on cropping patterns.

The planning for this study was done during January-March 1995. Then, spatial database manipulations using GIS tools were employed to provide the base stratifications leading to the selection of sample sites for IIMI's field campaigns during 1995, which were meant to corroborate, and in many instances update, the information already gathered from public sources. This included, in addition to structured farmer interviews, physical observations on the useable pumped water quality, soil salinity, surface soil texture, and cropping patterns.

This integrated approach involves a synthesis of spatial modeling comprising drainage, salinity, and groundwater use constraints with a calibrated groundwater salinity model, a root zone surface and groundwater balance model, and production function models appropriate to the agroecology of the area. The output provides both suggestive and predictive links to the sustainability of irrigated agriculture in the Rechna Doab.

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I. INTRODUCTION

Much of IIMI's understanding of the irrigated agriculture within the LCC system of the Rechna Doab has come about as a result of research supported by the Government of The Netherlands under the project Managing Irrigation Systems to Minimize Waterlogging and Salinity Problems. Starting in 1989 with a phased program spread over 5 years, the initial effort was directed at field research involving studies of the distribution system, cropping patterns, land degradation, and conjunctive use. This was followed by the second phase of management interventions field tested in an action research mode. Through the sharing and wider use of generic irrigation system data, IIMI has been able to coordinate its action program with the staff of the Irrigation Department for integrated assessment of system operations and performance data.

The initial set of technical objectives laid stress on the quantification of the causes of waterlogging but did not encumber the threats from secondary salinization. Perhaps, this simply was because the effects of waterlogging were assumed to be far more severe than the effects of salinity on productivity of irrigated agriculture. Moreover, there was inadequate recognition of the degree to which much of the salinity in Punjab is now dissociated from waterlogging. Hence, while IIMI's research prior to launching the above mentioned project had confirmed incipient salinity problems related to conjunctive use, the selection of the sample locales for the study of the same was not exclusive of other interactions like high water tables and choice of cropping patterns. The salient conclusions derived from this generic understanding of the LCC system have been reported in Volume Two of this study.

Under an additional 5 year extension to the scope of waterlogging and salinity research spanning the 1989-93 period, the Government of The Netherlands approved IIMI's proposal towards a reconnaissance-level understanding of the system itself. This assessment, as part of the overall proposal on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan, encompasses the use of IIMI's past data sets and the results of public sector investigations within the Rechna Doab. The effort was deemed to be a major extrapolation of available data regarding environmental and agricultural productivity impacts due to waterlogging and salinity. To develop an understanding of the long term salinity trends, the increased utilization of groundwater supplies for supplemental irrigation was considered crucial to the analysis.

Defined as a subcomponent under the Salinity Management Component (part III of the main document), the workplan for the Salinity Management Alternatives for the Rechna Doab details the synthesis of spatial modeling comprising drainage, salinity, and groundwater use constraints with a calibrated groundwater salinity model, a root zone surface and groundwater balance model, and production function models appropriate to the agroecology of the area. The output anticipated both suggestive and predictive links to the sustainability of irrigated agriculture given the highly diverse and complex interactions peculiar to the physical regime of the Rechna Doab.

The study entails a major departure from the conventional approach to system-wide undertakings in that:

- the integration of the resource base is being accomplished for a very large irrigated domain with a multiplicity of agroecology zones;
- a spatial digital database is being used for coordinated referencing of physical data across time and scale;
- multithematic modeling pertaining to the soils, groundwater, and the surface topography is being used as a consolidated reference for the modeled appropriations for resource productivity;
- a sampling scheme, cognizant of the physical constraints, is being deployed through multivariate spatial interactions towards an updated assessment of the physical and farming regime;
- the predictive realizations on *groundwater quality, crop productivity, and available irrigation supplies* are being meshed into a host of integrated scenarios that explore the sustainability of the system to the year 2010; and
- the modeled portrayals on sustainability scenarios are being cycled back into the topological map referencing that is consistent for resource aggregation and flexible in terms of geographical upscaling.

The study is not meant to be all encompassing. Rather, its targeted accomplishments are directed towards a simplified understanding of the evolutionary constraints typical of irrigated agriculture. For the Rechna Doab, the rationality of this exercise is underscored by the intensity of the past land reclamation efforts combating the gradual decay of the environment due to a combination of physical constraints, not least of which is soil salinization.

Since the geographical diversity of the locale is overwhelming, no single public endeavor could circumvent the entire gamut of the environmental degradation. Hence, in the absence of a precedent set in the backdrop of the uniqueness defined above, a procedural framework had to be put into place whereby the interplay of the multivariate data, already available for the physical system and likely areas of updates, could be facilitated. The following sections describe the contributing blocks of information that were deemed critical for launching of the project activities. In doing so, both procedural and analytical links are explained leading up to the finalization of the results.

II. SPATIAL STRATIFICATIONS AND SAMPLING METHODOLOGY

The application of geographic information system (GIS) tools for resource productivity assessment is not new. The digital automation has borrowed from the techniques employed by the early planners that applied the spatial combinatorial approach through tracings on plastic overlays that permitted demarcation of desired information to the peering eyes. Spatial database manipulation through GIS tools have furthered these manual capabilities to the extent whereby inequalities in space and time have been integrated across a common reference. Additionally, the inherent complexities of the interacting elements, regardless of their convoluted response mechanisms, have been simplified greatly. Hence, for coordinated policy appraisals, such as the alternatives to salinity management within the Rechna Doab, the utilitarian value of a GIS could not be overemphasized in the wake of diverse data sets scattered in space and time.

The analysis leading up to the ascertainment of the choices in salinity management is structured to the use of mathematical and statistical models with specific data assimilation and processing requirements. For example, the results from the 3-dimensional groundwater salinity forecasting model do not overlap with the farm interview data critical for agricultural economic analysis which, in turn, is alien to the canal command level calculations for root zone water balance. In fact, it would be difficult to postulate a programmatic sequence that availed the input-output response characteristics of each of the modelings pursued in this study to arrive at a uniform set of deliverables. Such an attempt would be a failure from the start in the absence of a go-between medium. Not unlikely, the spatial capitulations from a GIS provide the transacting medium for the exchange of critical information that is hand-in-glove to the requirements of the individual.

A. The Integrating Link

On their own, the GIS models are not just limited to logical interrelationships in space, but also provide the higher medium of interaction through linkages with predictive capabilities of other models towards a spatial view of the future with simultaneous examination of alternative scenarios. For example, in the context of the exercise intended for the Rechna Doab, the cartographic deliverable from the GIS serve as the reference in space for the location of tubewells that have been identified for a degrading pattern in groundwater quality. For the same area, economic projections for yield affectation could be shown to overlap with the change in surface water supplies in the aftermath of canal remodeling. In fact, the simulations constitute a multiplier effect across the number of models with different results, with the spatial stratifications being the net against which the optimum selections are retained.

For ease of understanding, a process flow chart has been shown under Figure 1 for linkages across the models envisaged for the Rechna Doab study. The five basic *components* of information within this chart share their respective pools of knowledge in two distinct places, described as Inference I & II. For Inference I, the synthesis of information is primarily limited to the inputs provided by the GIS models (*Spatial Component*) and IIMI's field observations (*Survey Component*). The process leading up to the first of the two inferences starts with the collection of the mapped details from the public sector archives on the occurrence of soil salinity and accompanying texture, sources of pumped groundwater and its quality, the rise of the water tables, the public sector reclamation programs and canal administrative units. Each of these inputs comprised additional levels of qualitative and quantitative details that increased the spatial assimilations manifold. Since all of this information could not be had from a single source of uniform spatial reference, or one that could encompass continuity in time, the *Spatial Data Collection* included all the formalities of registration, sorting, and formatting that are a prerequisite for an integrated GIS database.

B. The Spatial Database and Subsampling

1) Spatial Models and Contextual Reference

The spatial database nurtures two independent but supportive sets of activities geared towards modeling and contextual support. The *Spatial Data Models* are combinations of thematic extractions, prepared during the collection and formatting stage, to observe the interaction of one or more variables in space. A host of multithematic models were prepared for the entire Rechna Doab with the *Overlay Operations* providing the point, linear, and delimited referencing in space for locational and information subsampling purposes. Examples could include canal/scheme administrative bounds, cities and towns, and the traverses of roads and streams/drains. This information does not have calculative connotations like the GIS models, but instead constitutes the positional referencing for interpretations scattered in space.

2) Selection of Sampling Sites

The modeled appropriations in the Spatial Component of the Process Flow Chart lend themselves to two separate subsampling procedures with different objectives; field sampling and the subdivisional stratifications. For *Field Sampling*, geographically delimited selections

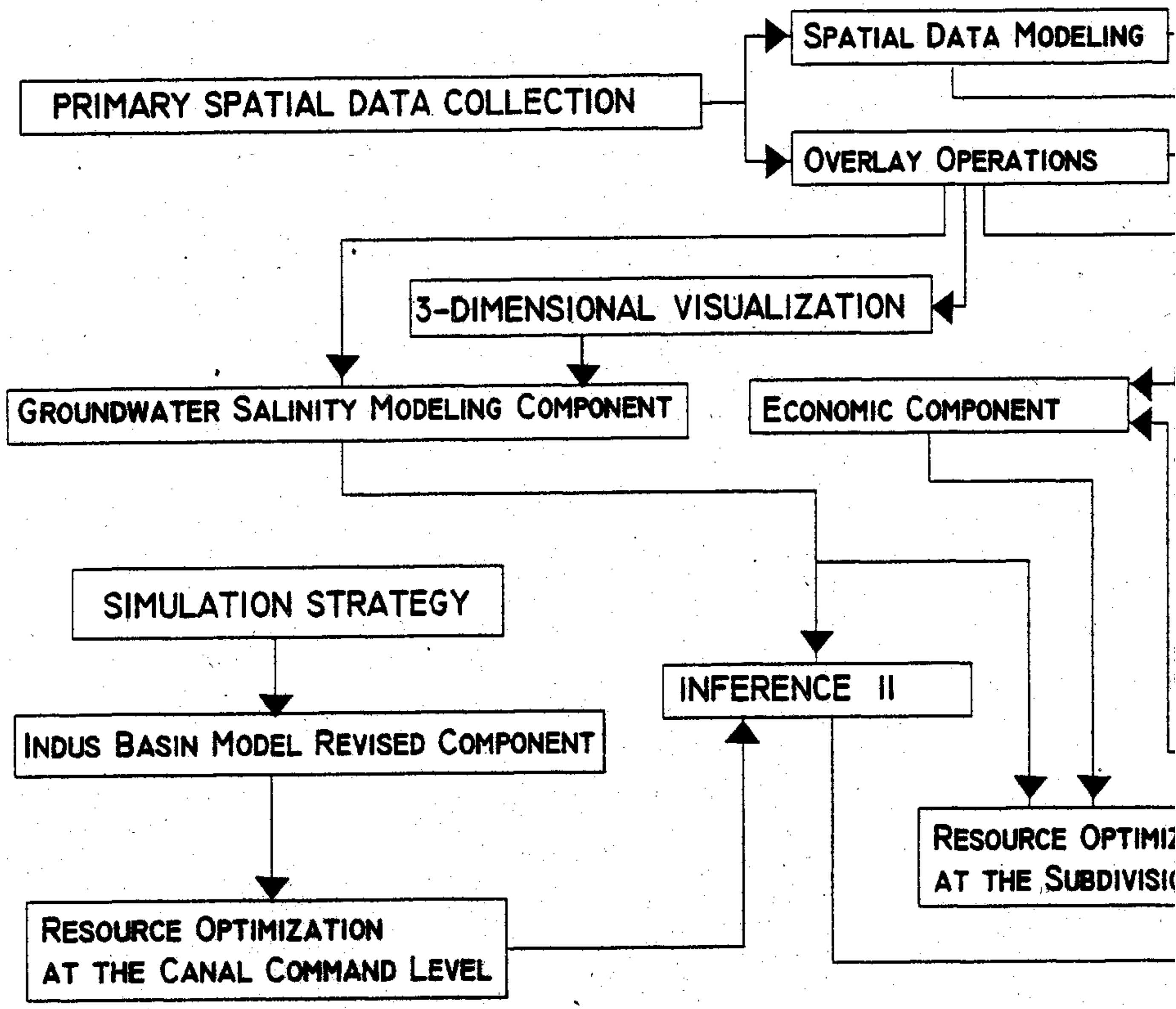
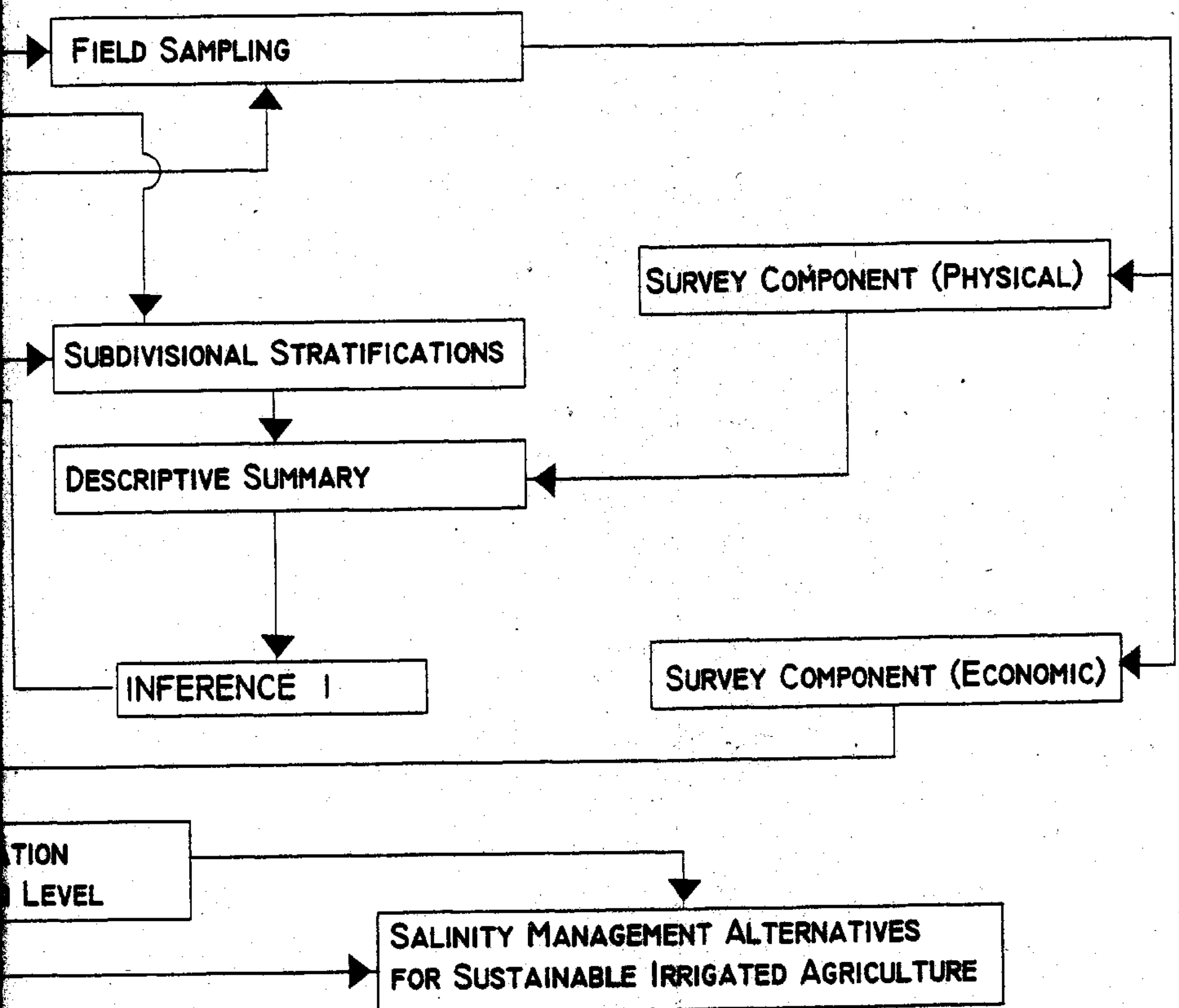


Figure 1. Process Flow Chart for the Study of Salinity Ma



nagement Alternatives in the Rechna Doab, Punjab, Pakistan.

from the models covering the entire space of the Rechna Doab are made in consonance with Overlay operations. Homogeneous in extent and limited in size (8-12 km^2), these selections correspond to the legend separations across the parent GIS models to be observed for soil salinity, soil texture, prevailing quality of groundwater, and combinations thereof (Figure 2). The purpose behind GIS-assisted field sampling is to substantiate and update, across a less than 5% spatial extent of the Doab, the mass of information integrated at the collection and modeling stages of the Spatial Component.

3) The Hydrological Divide

However, since the field information is limited to the spatial distribution of legend information of each GIS model used for this purpose, the geographical context of the sample delimitations amongst the models requires a common locational bound. In other words, for the legend-specific details of one spatial theme to be related to other themes with different legend informations, the locational bound provides a common geographical space where consideration could be given to the depiction of information from all of the models selected for representation. This bound has to be provided antecedent of the merger of the processed information from the Survey Component, or for that matter from other components, with the GIS models. The part on *Subdivisional Stratifications* facilitates this organization of spatial data across what essentially are the administrative separations at the lowest rung of the officer-cadre responsibility in the irrigation department. For the Rechna Doab, the 18 subdivisions of the LCC and Haveli command system lend vertical integration and provide standard locational reference to the encapsulation of GIS generated spatial themes (Figure 3).

C. The Descriptive Approach

Given the tremendous diversity in the data and the task of its coordinated interpretation with respect to the subdivisional bounds referred above, it would be less than pragmatic to continue using the combinatorial strengths of the GIS the way they were used previously for generating the GIS models. A plausible solution across this mayhem of interpretation is to *describe*, rather than *analytically differentiate*, the locational concurrence of all modeled and survey data within each of the subdivisions for noteworthy realizations. This descriptive process, appearing under *Descriptive Summary* in the flow chart, not only facilitates handling of the missing data but also relates well with the *Overlay Operations* support available to the *Subdivisional Stratifications* stage.

An example of subdivisional subsampling of GIS generated spatial models at the Rechna Doab level is presented in Figures 4-12 for the Chuharkana Subdivision of the LCC East Circle. Due to the limited extent of the groundwater quality data, the representation of the GIS model appropriate to the situation has been omitted from the subdivisional representation. Some additional physical themes on soil texture, drainability, and crop

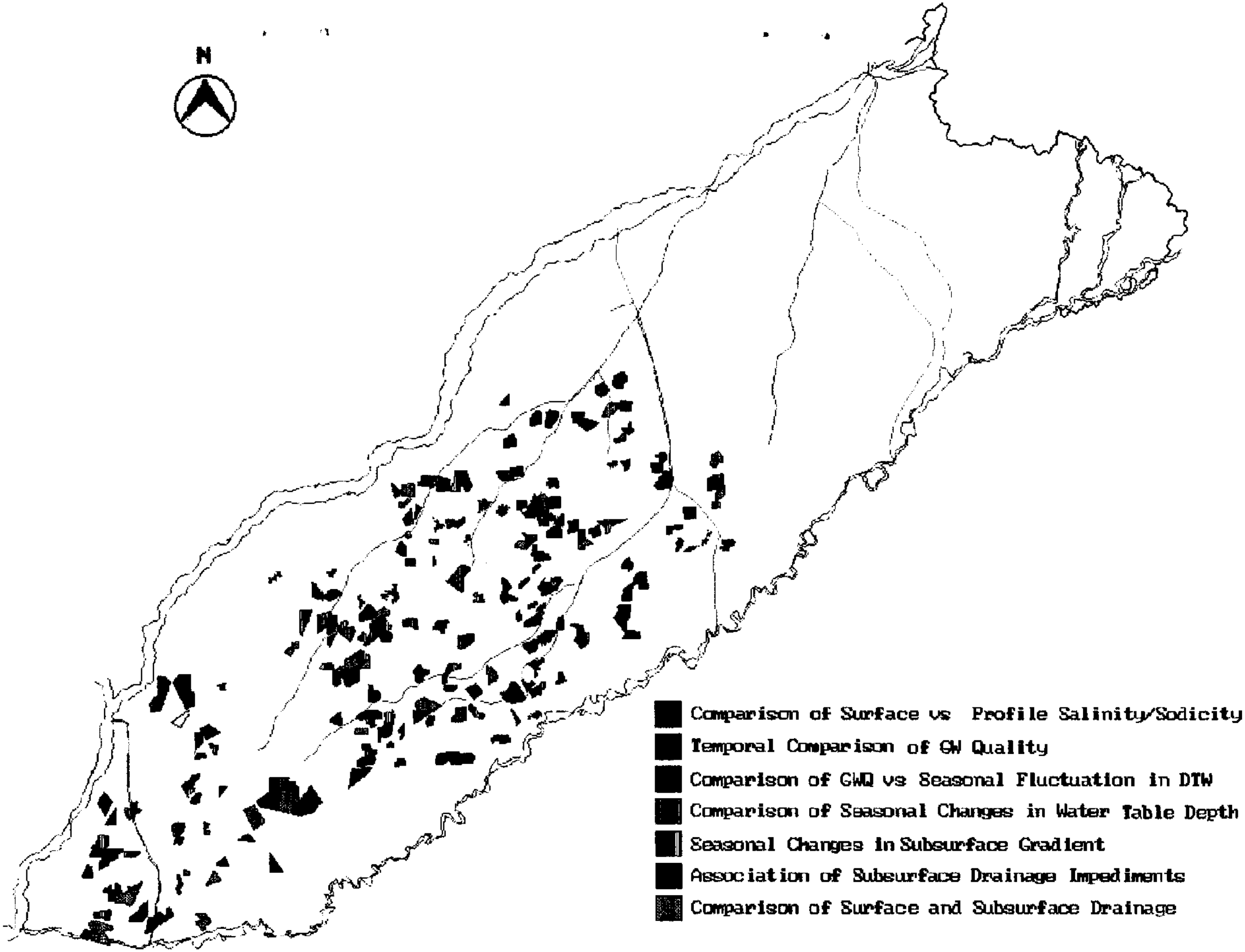


Figure 2 Location of IIMI Sample Sites in the Rechna Doab Punjab, Pakistan.

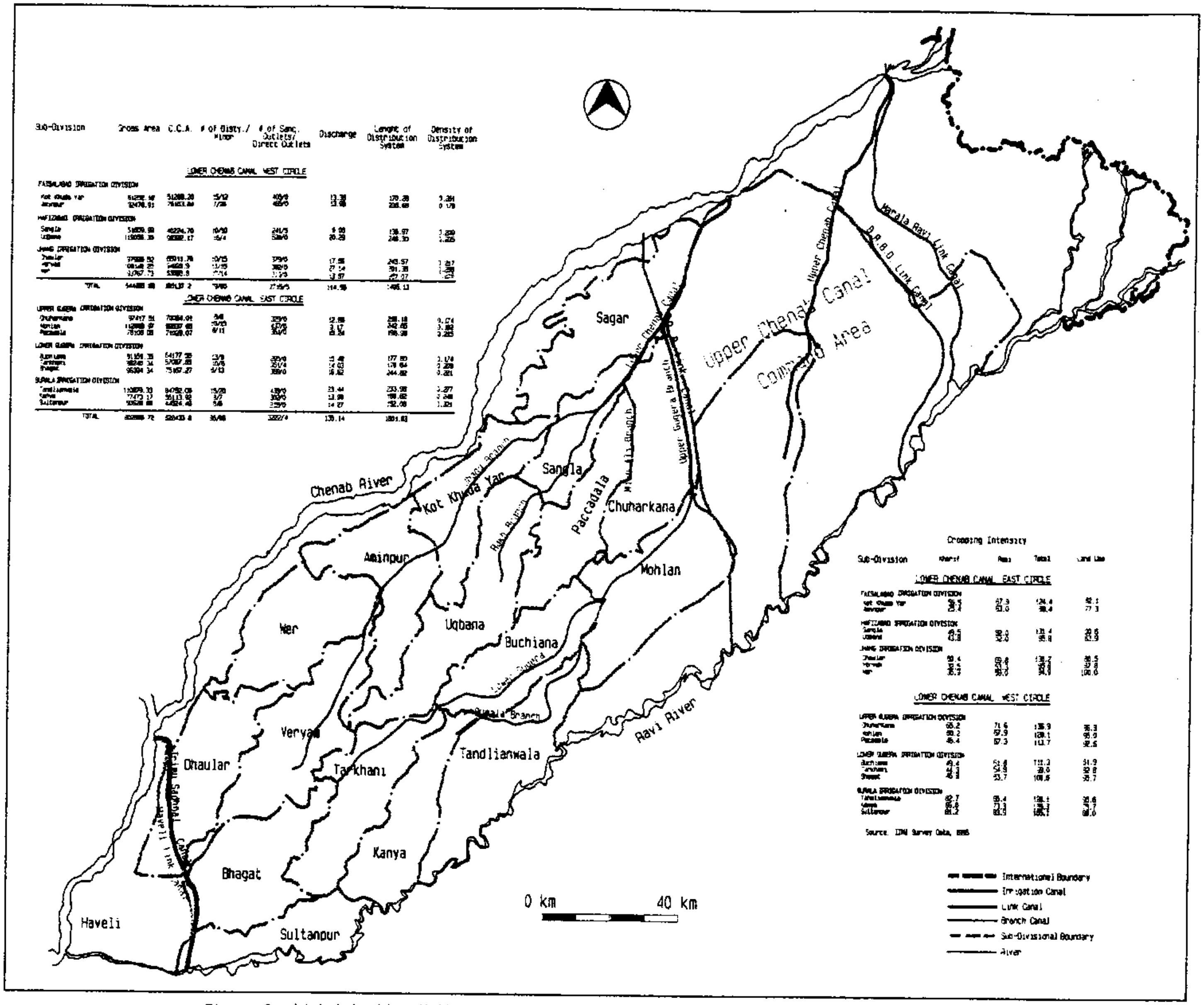


Figure 3 Administrative Units in the Lower Chenab Canal System, Rechna Doab, Punjab, Pakistan

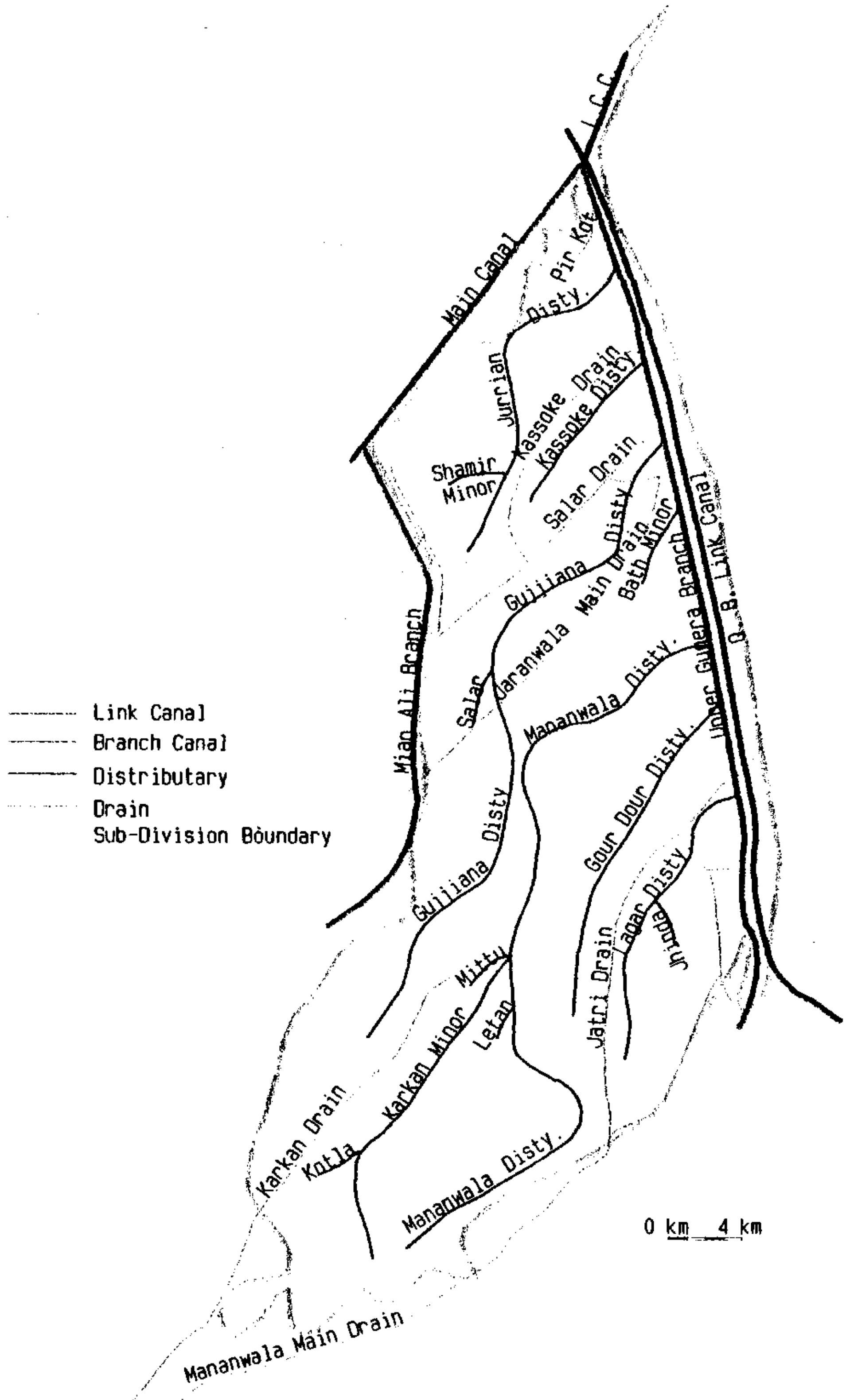
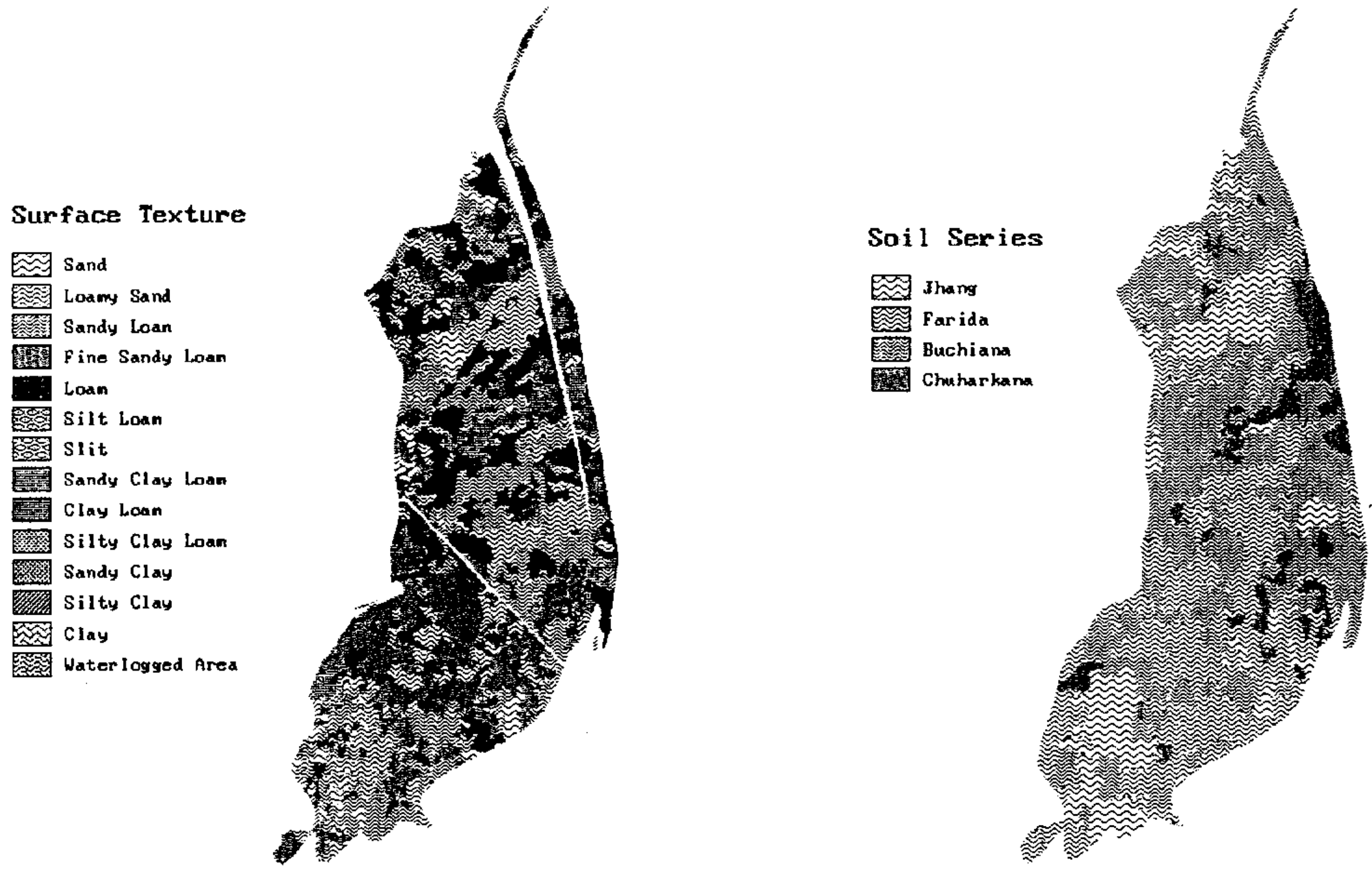


Figure 4 Chuharkana Irrigation Subdivision, Rechna Doab, Punjab, Pakistan.



Source: Scarp Monitoring Organization (WAPDA)

Figure 5 Surface and Profile Texture of the Soils within the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.

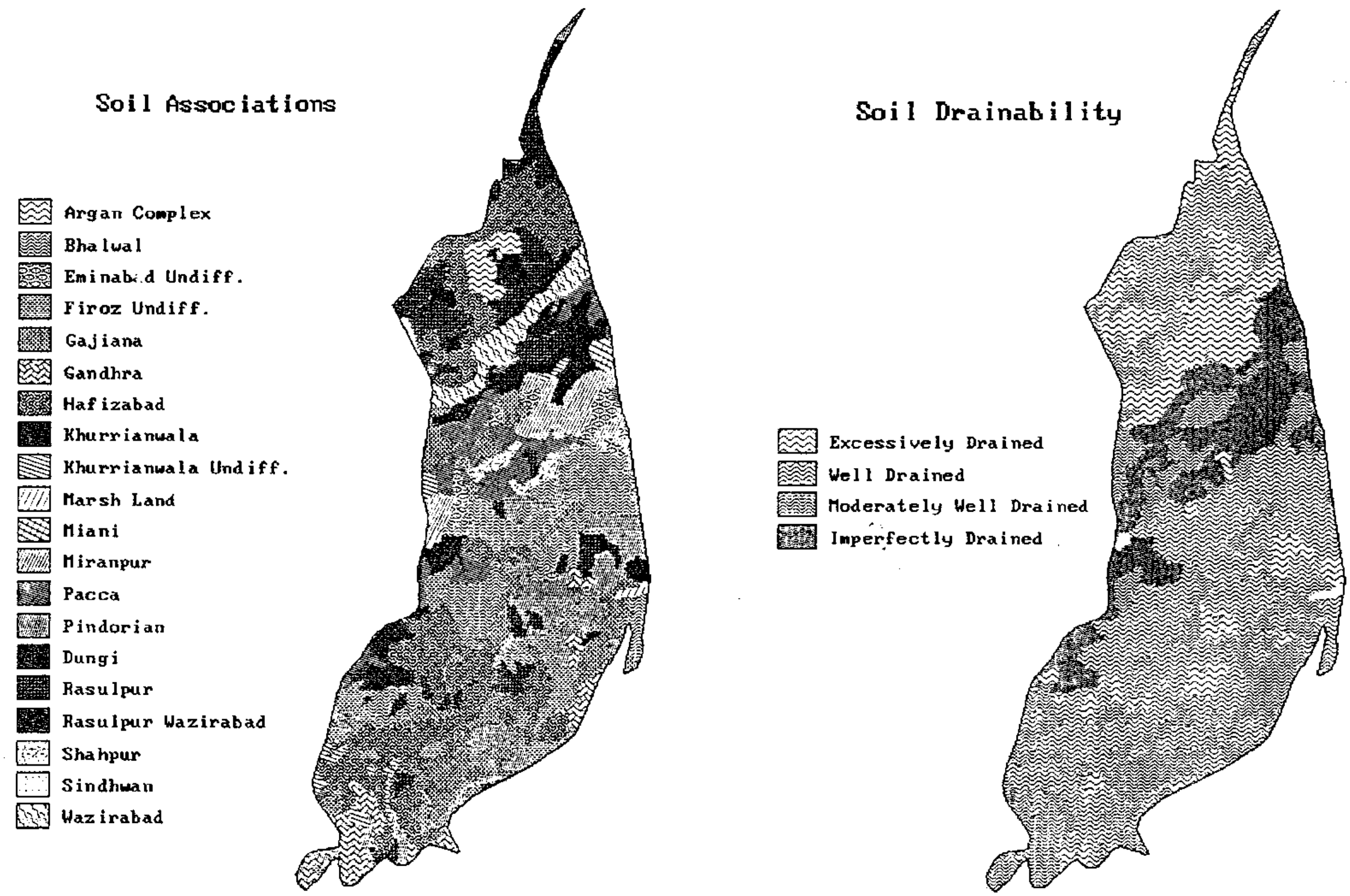
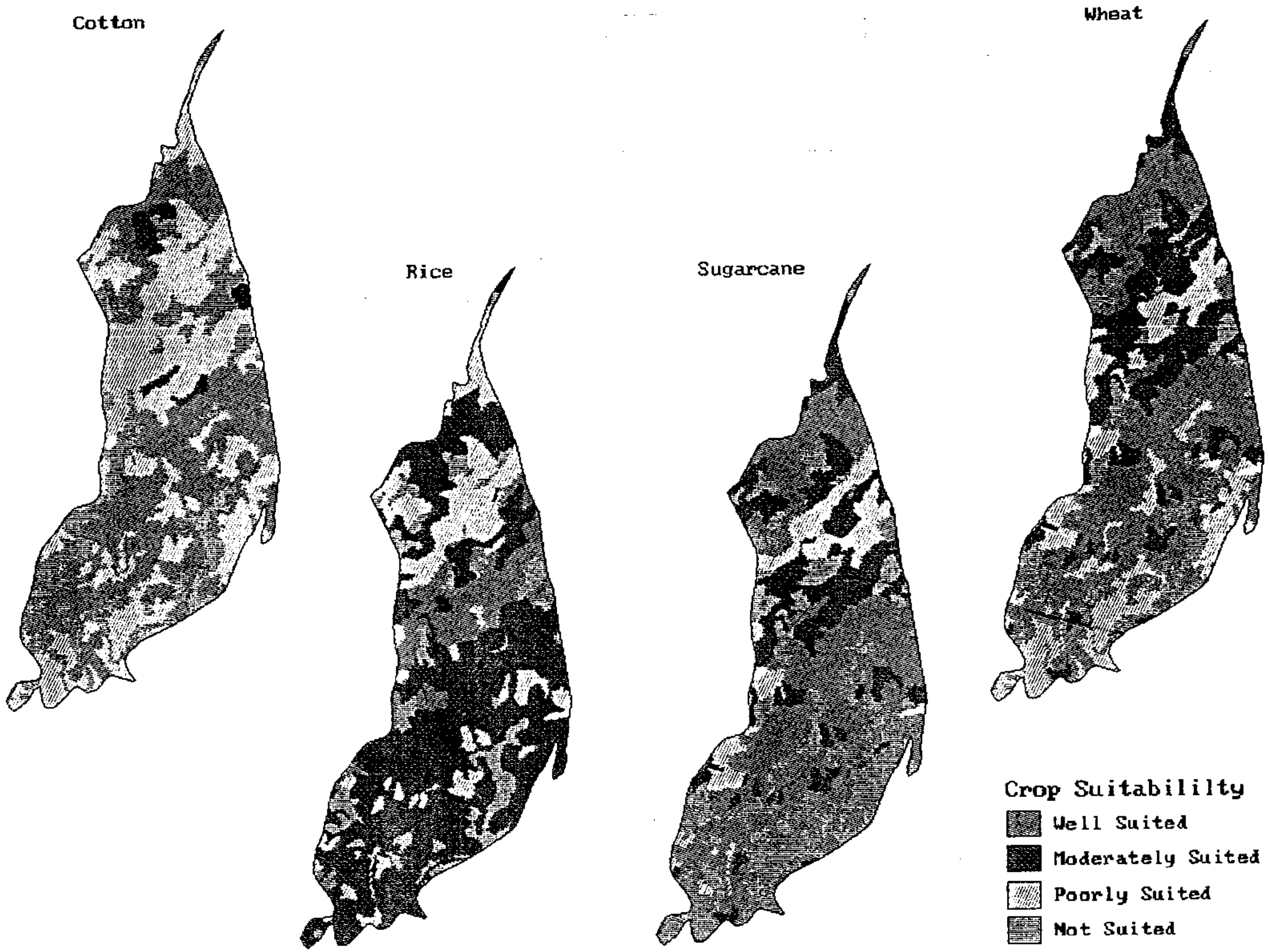


Figure 6 Soil Associations and their respective Drainabilities in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.



Source: Soil Survey of Pakistan

Figure 7 Suitability of Soils for Major Crops in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.

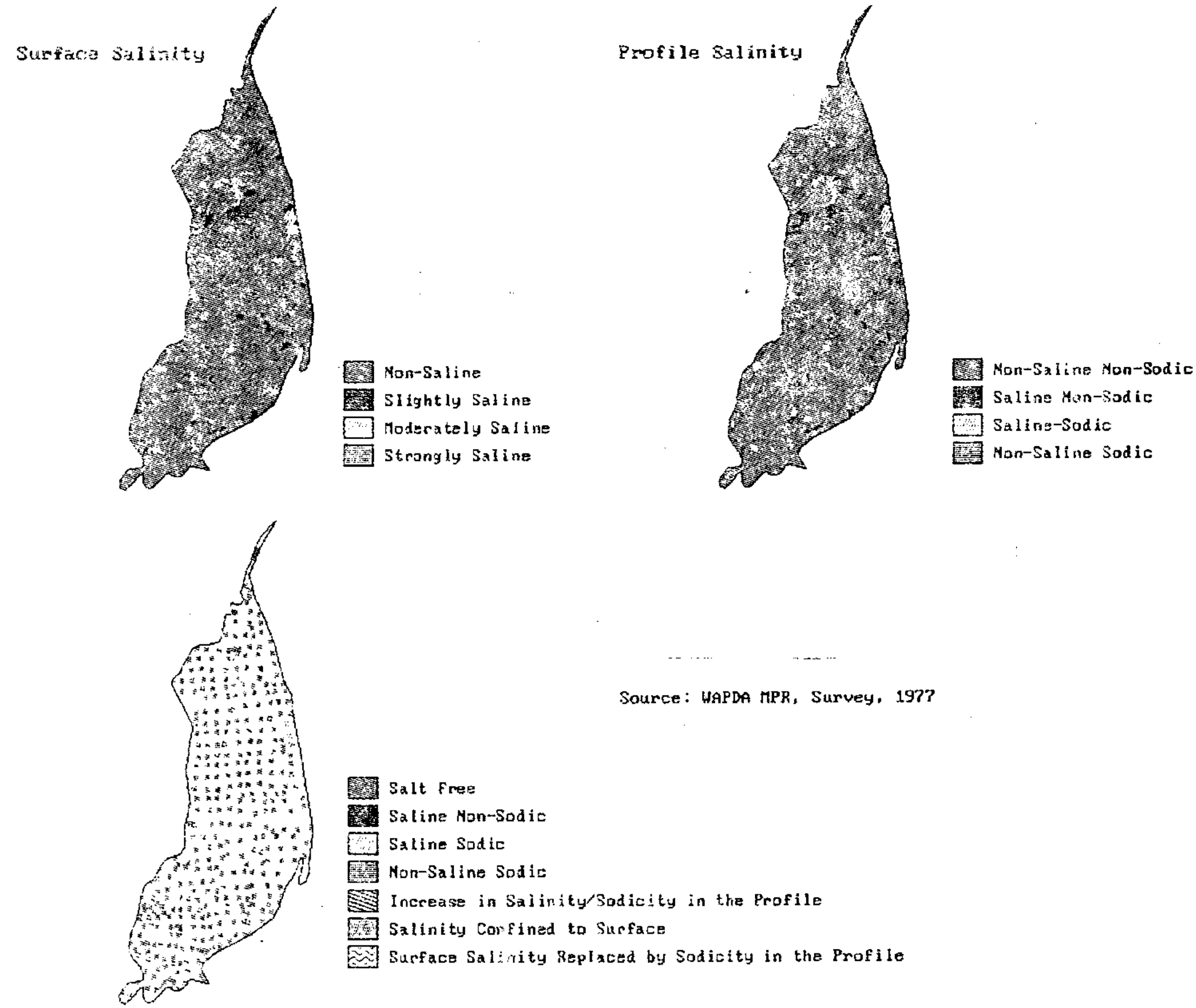


Figure 8 Comparison of Surface vs Profile Salinity in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.

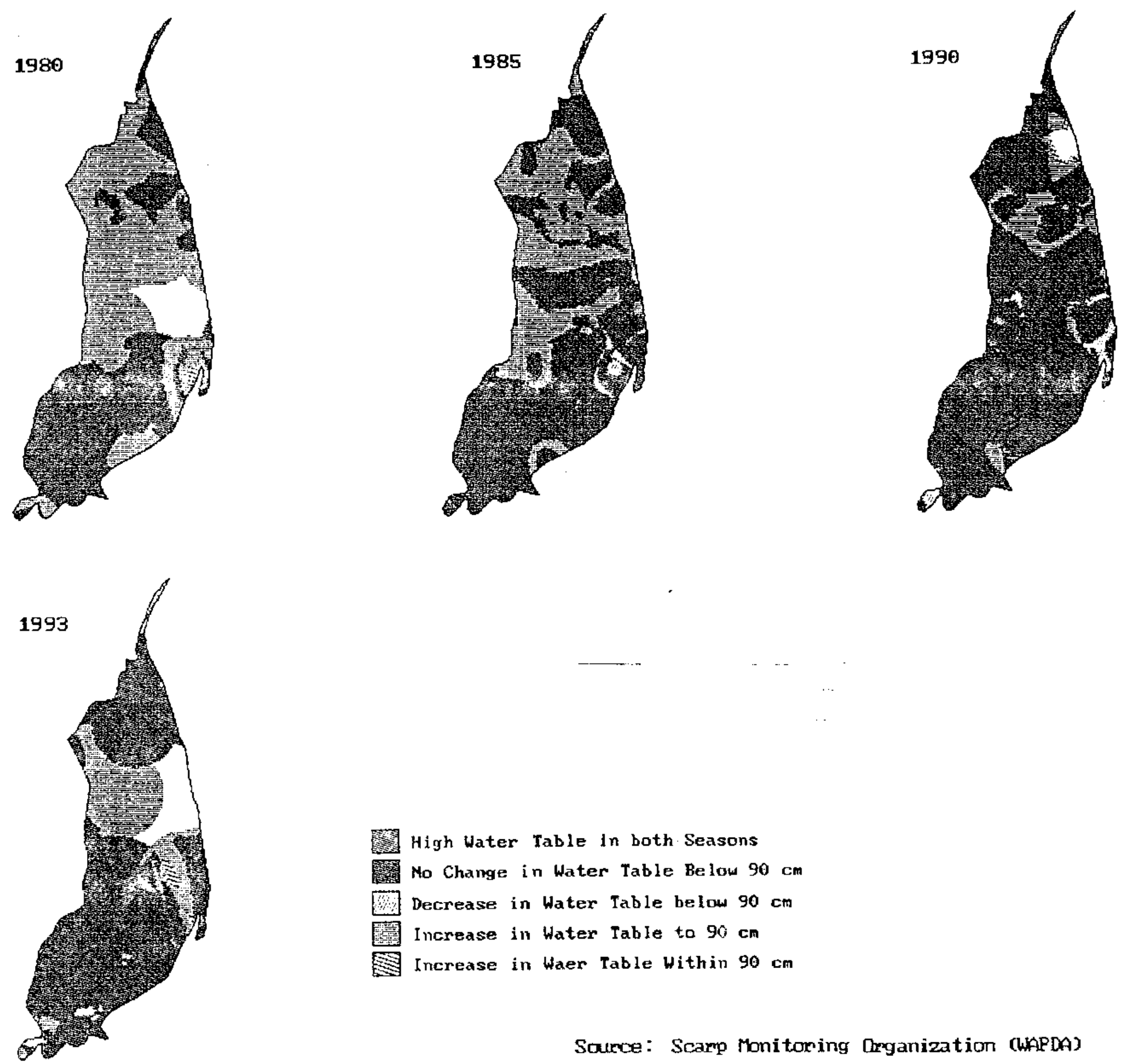


Figure 9 Comparison of Seasonal Changes in Water Table Depth in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.

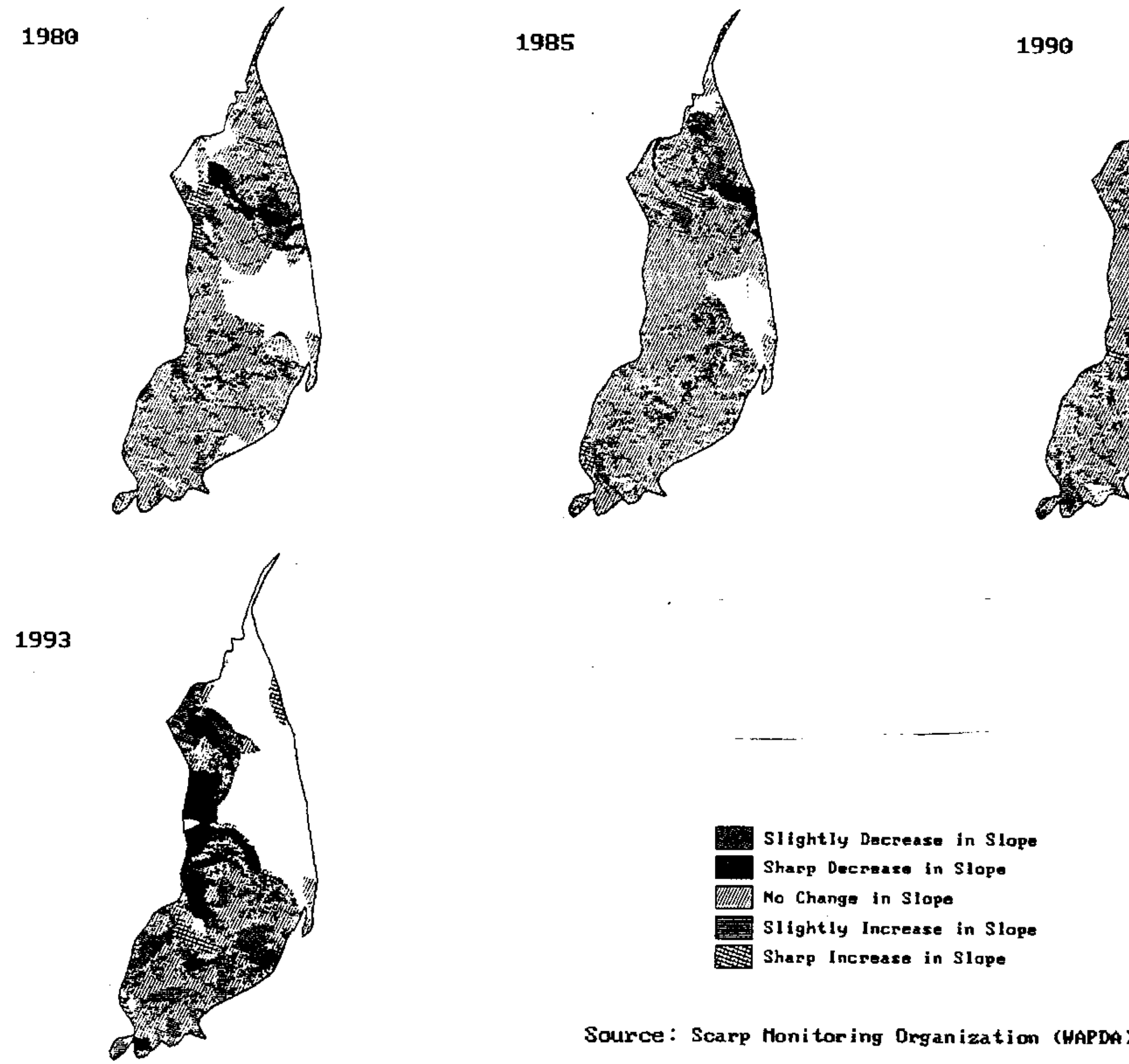
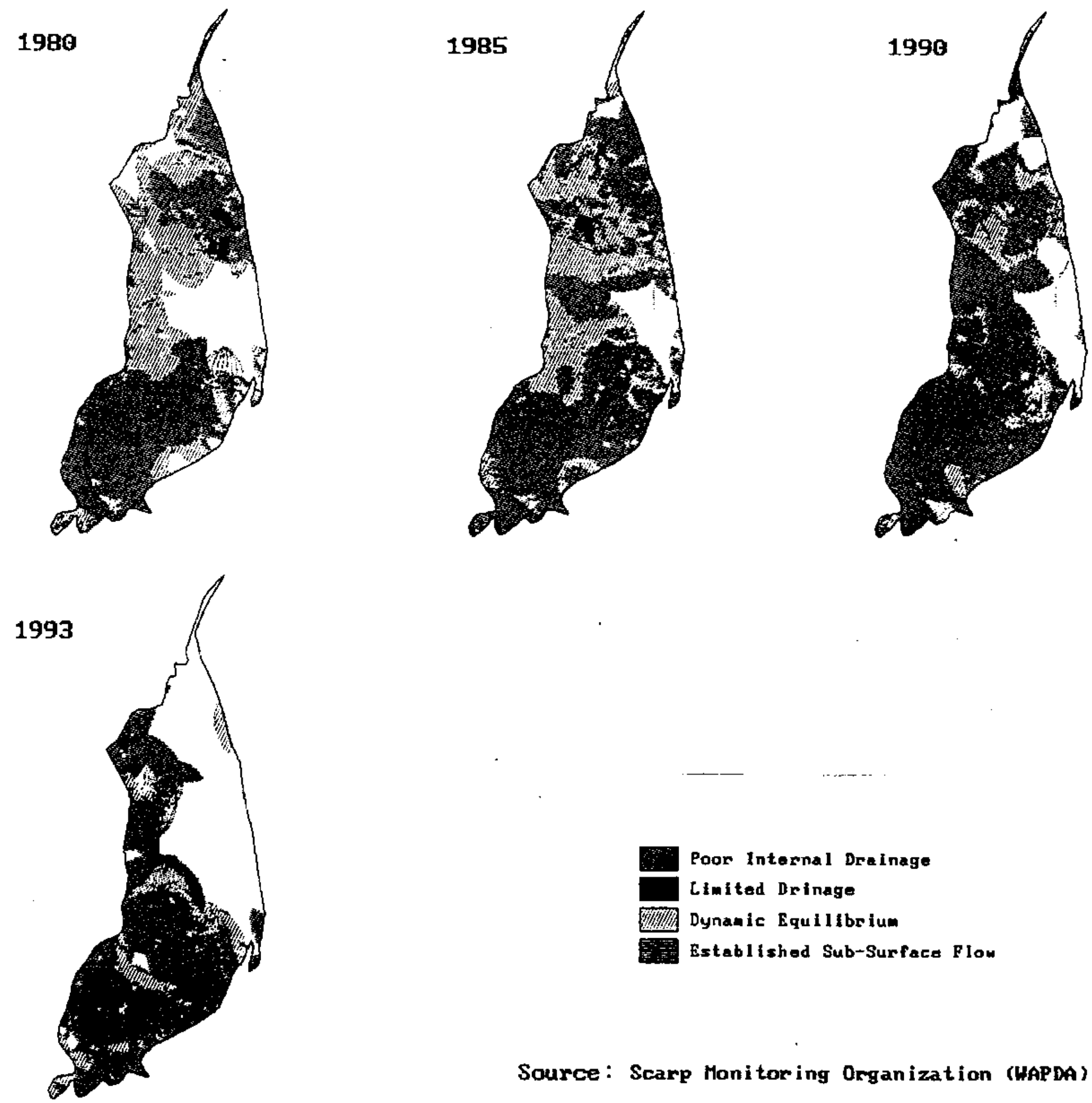
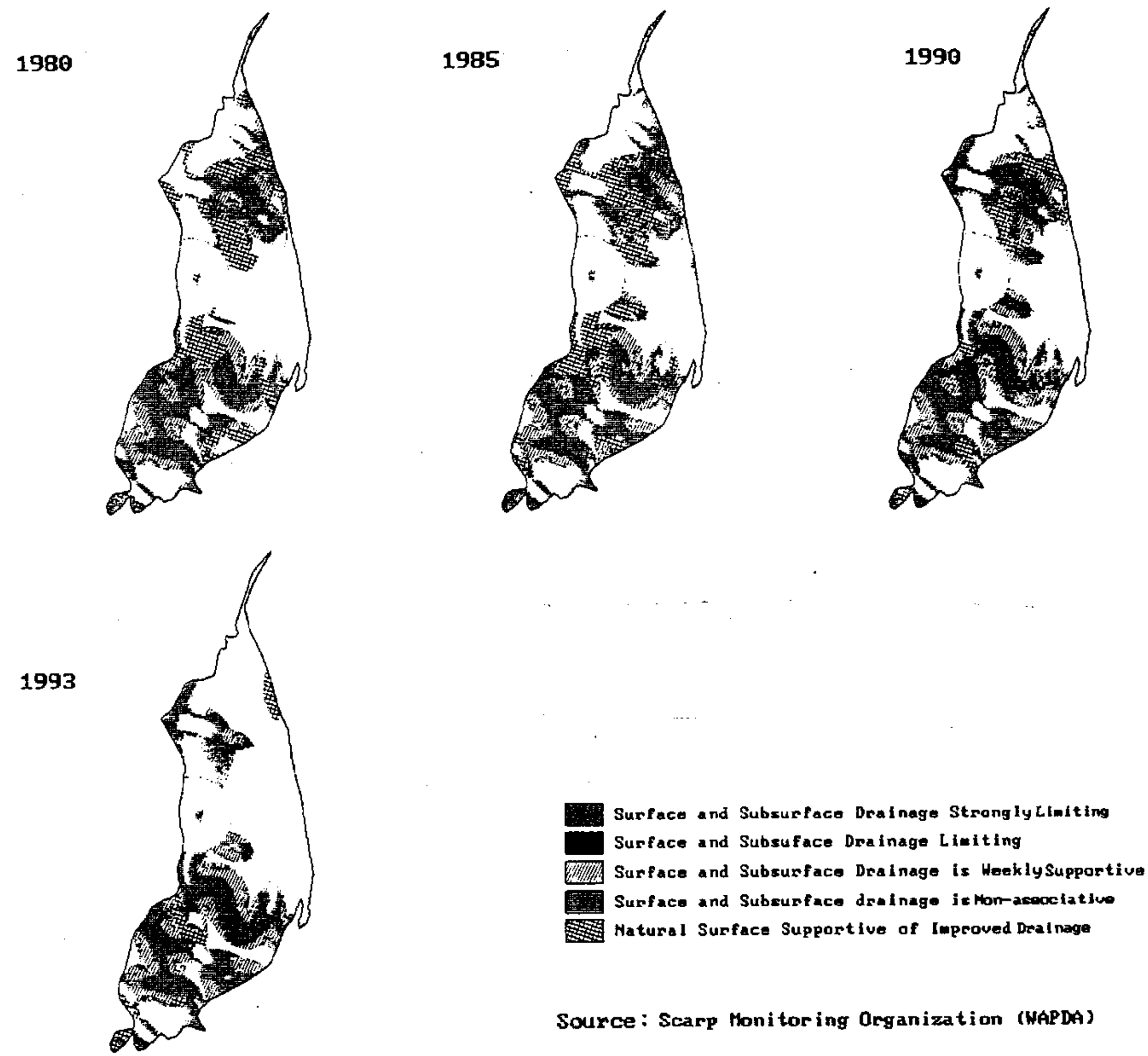


Figure 10 Seasonal Changes in the Gradient of Water Table in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.



Source: Scarp Monitoring Organization (WAPDA)

Figure 11 Association of Subsurface Drainage Impediments in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.



Source: Scarp Monitoring Organization (WAPDA)

Figure 12 Comparison of the Surface and Subsurface Drainage in the Chuharkana Subdivision of the LCC System, Rechna Doab, Punjab, Pakistan.

suitability have been included to facilitate the descriptive process. Similar separations have also been achieved across all the remaining subdivisions of the LCC system as a summarised account of the physical regime.

The *Economic Component*, in comparison to the *Groundwater Salinity Modeling Component*, benefits directly from the above sequence of events in the estimation of resource productivity and contingent returns to scale. The physical description of the regime is abetted by inputs from IIMI's farm-level questionnaire information critical to production function modeling. For the combination of information sustained at the subdivision level, the resource optimization scenarios could be expanded to include the larger geographical divide at the canal command level where simulations on surface flows, and the corresponding water balance at the root zone, are available for management and capital intensive scenarios. The *Inference II* box weighs the surface and groundwater balance constraints, so developed at the canal command level, against the economic viability of the cropping pattern predicted up to the year 2010. It is qualitatively abetted by the predictions on the quantum of reliance on continued groundwater extractions that threaten aquifer depletion and degradation of the quality of pumpage.

D. Spatial Feedbacks

The inputs from the groundwater salinity modeling and economic inputs, rendered at the *subdivisional level*, provide the base reference to the resource optimization that would be expected at this scale. Although this information is without the simulations on the quantum of surface and groundwater flows available within each of these administrative units, the remissions could be compensated in lieu of the data on surface design flows and the anticipated density and utilization of tubewells expected for the area. Moreover, the diversity in production function models and the resultant strategic choices for resource optimization are retained in comparison to the aggregations at the canal command level. The finality of information on potential productivity at subdivision level is thus the outer most reach of a feedback mechanism whose deliverables return to the same spatial reference from where the initial portrayals had evolved.

E. Planning Framework and the Analytical Links

The foregoing description of information flow has dwelled on the linkages amongst the process flow chart components. Details to this effect are retained in another similar depiction where the choice of data sets, sources, and utilization across intervals of time are shown towards the generation of the single and multi-layer thematic models through GIS. Many of the spatial themes referred to in Fig. 13 have already been shown in Vol. II's introduction to Rechna Doab, the exceptions being where thematic maps have been combined, such as depiction of pre- and post-monsoonal changes in water tables and their further comparison with changes in the subsurface water table slopes (Figs. 9-12 above).

The component-wise breakdown of analytical links in Figure 13 is not meant to be exhaustive, and neither is the itemized reference to the inputs for the spatial and non-spatial models therein.

For ease of reference, the information flow in Figure 13 has been numbered to highlight the sequence of activities under each component of the study before concluding at the stage wherein the salinity management alternatives are recommended from this study.

1) The Spatial Component

Items 1-15 comprise the building blocks of this component whereby much of the data needed for spatial modeling is extracted through multiple combinations of these basic spatial themes. Items 1-11 constitute the core data set for which locational reference is provided via items 12-15. Beginning with item 1, all of the data pertaining to subsurface water levels is interpolated to primary GIS themes under items 20, 21 & 22. These primary themes, through selective secondary and tertiary level combinations, produce four of the seven final GIS models encompassed for the *Survey Component* defined under Section II. A above. Item 23 is another theme that is interpolated from the piezometer locations with respect to mean sea levels, and provides additional input to the visualization of the groundwater quality encumbered under a separate package (item 25).

Items 2, 3 & 4 collectively define the pumped groundwater quality for the several SCARP tubewells operating in the Rechna Doab. Together, they directly contribute to item 37 (a secondary-level GIS model), and more significantly to another two main GIS models under items 48 & 50. The reason item 37 is not one of the main GIS models is because its utility is limited to a particular time period, much like the pre- and post-monsoonal processing for water table depth under item 22. However, when multiples of information in item 37 are combined together for multi-temporal differentiation, the result (item 48) is revealing on the changes brought about due to mining of the aquifer for irrigation purposes. Somewhat lesser duration temporal variation is taken into account when the water table fluctuations for a given year are combined with the once-a-year observation of pumped groundwater quality interpolated to map form under item 37.

Information on soil salinity under items 7 & 8 collectively contributes to the last remaining GIS model (item 38) that is an integrated version of both surface and profile salinity as observed by WAPDA during the Master Planning and Review surveys of 1975-79. This representation contains over 9000 point locations within the Rechna Doab that have been summarised to seven distinct legend differentiations under one map.

Items 9, 10 & 11 are the single-theme constructs of the soils information that are needed for the subdivisional stratifications mentioned under Section II.B.(3) above. Much of this information is meant to assist towards extrapolation of the results of the *Survey Component* (items 31 and 60) and development of the production function models (item 54).

Finally, items 12-15 cater to the essentials of the locational reference that is critical to the systematic evaluation of the results at the subdivision level. There are two key areas where this support is provided, i.e at item 42 for orientation to the sample domain, and at item 55 where contextual reference to the discretized output of the three-dimensional groundwater is needed. Hence, by virtue of its utility, this information is essential to four out of the five *components* established for the study (the exception being the *Indus Basin Model Component*).

2) The Economic Component

Item 16 lists the information collected from the public archives under the Economic Component. Item 31 shows two key levels of processing accomplished on this data; first, an integrated reference is established at the district level for trends in area and production of principal crops and the utilization of agricultural land within the Rechna Doab. Second, as a supplement to the scope of this district level information, a farm-level questionnaire is prepared (and pre-tested) to satisfy the economic aspects of the information to be collected through the *Survey Component* under item 32.

As part of the processing leading to the application of the production functions under item 54, a host of research issues are defined at item 46 towards a critical understanding of the first level of inferences achieved via item 45. This intermediate step constitutes the most important realization of the results achieved through the *Spatial*, *Survey*, and *Economic* components at the irrigation subdivision level. Its repercussions are felt at two distinct places in the flow chart; first, in the feedbacks to information tie-ins in space (item 65), and second when resource productivity is assessed at the canal command level (item 66).

Following application of the production function models to the respective irrigation subdivisions (item 54), the sequence of steps under items 61, 62 & 63 explores the resource potential at this level. The integrity of this information is maintained for feedback to the GIS-assisted portrayals (item 65), however, in support of the Indus Basin Model simulations, the subdivisional stratifications are combined at the respective canal command level.

3) The Survey Component

The physical and economic aspects of the *Survey Component* rely on a common sampling regime that is defined under item 42. The selection of these sample sites is based exclusively on the selective combination of the spatial themes derived above. The physical data collection in these sites evolves from the concerns under items 51, 52 & 53 towards concurrent assessments on the status of soil salinity and quality of available groundwater. Upon processing, these become part of the *Descriptive Summary* of spatial information envisaged for each of the irrigation subdivisions. The economic part, under item 32, is meant to facilitate the implementation of the farm-level questionnaire conceived under item

31. This questionnaire includes aspects of both quantitative and qualitative information for which details are provided under Appendix-D of Volume Four.

4) The Groundwater Salinity Modeling Component

Predictive assessment of the changes in the aquifer water quality, due to continuing pumpage for irrigation purposes, is one of the fundamental considerations of the study undertaken within the Rechna Doab. Accordingly, items 17 & 18 represent the basic data inputs needed to calibrate the groundwater salinity model implemented under item 33. The four critical considerations benefitting directly from the model predictions are listed under item 39. These considerations represent the core issues towards the sustainability of the ever increasing reliance on groundwater to supplement, and quite often totally replace, the available surface water supplies. For qualitative discrimination of the predictive potential, the simulations account for changes in the quality of the groundwater across two decades of pumpage. The results are absorbed at two different levels of geographic scale; first, as part of the spatial feedback comprising the irrigation subdivisions, and secondly to interface with the final inference at the canal command level (item 66) wherein the results from the other components of the study are also amalgamated prior to the relegation of options for salinity management.

5) The Indus Basin Model Revised Component

Somewhat isolated in data processing and generation of simulation strategies from the the rest of the activities, the *Indus Basin Model Component* targets its contributions to the penultimate level of assessments under item 66. This is primarily because of the inflexibility of the model to interact with any of the key components of the study below the canal command level. Item 19 defines the three key elements of data that collectively relate to the Model's constraint definitions within the Rechna Doab. Although there are six canal commands covering the areas within the Rechna Doab, greater importance is attached to the simulation inputs for the Jhang and Gugera branches of the LCC system where IIMI had concentrated most of its sampling effort. The targeted realizations from the Model are given under items 40 & 41, which in effect define the synthesis framework needed for the simulations. The simulations, leading up to the year 2010, are broadly split up into management and capital investment scenarios. The Model's output, under item 64, is compared with the information on inefficiency in resource productivity derived by the *Economic Component*. This information, originally at the irrigation subdivision level, is encumbered for aggregation at the canal command level for comparison with the IBMR's determinaiton of the potential water requirements at the root zone. The negative impact of surface irrigation water shortages is further reinforced at item 66 wherein information on sustainable use of groundwater is already available based on the predictions of the groundwater salinity model.

The steps leading to the calibration of the groundwater salinity model, the statistical aggregation of the economic models, and the sensitization of the Indus Basin Model Revised to the post-Water Apportionment Accord realities for the Rechna Doab canals are some of the additional exercises not suitably covered by the flow of information in Figure 13 and, accordingly, will be covered in the following sections.

III. THREE-DIMENSIONAL GROUNDWATER SALINITY MODELING

A. Background

To properly solve 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 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 tube wells. 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. 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). This design includes the determination of the optimum location, penetration depth, number, spacing, pumping rate, and pumping sequence to maximize the production of fresh groundwater while minimizing the mixing of fresh and saline waters. 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 as shown in Figure 14. Reilly and Goodman (1987) presented a good description of the salt water upconing phenomenon under a production well.

> *Generally, if the pumping rate is less than a certain critical value, the equilibrium position of the cone is a stable saltwater interface, with the apex of the cone some distance below the bottom of the well. Freshwater will flow toward the well along the interface, and no significant flow will occur in the saltwater once the steady-state stable interface position has been attained. Increases in the pumping rate will produce higher equilibrium, stable, cone positions until the critical pumping rate is reached. At this pumping rate, the apex of the cone (Fig. 1) is still below the bottom of the well, but the cone is in the highest position at which it can remain stable. If the well discharge is increased beyond the critical pumping rate the stable interface will be disrupted, flow will occur within the saline water and the discharge of the well will become partially saline (p. 171).*

In reality, a sharp interface between fresh and saline water does not exist because both waters are miscible liquids and dispersion causes mixing and spreading of solute, thereby forming a transition zone in which the salinity concentration changes gradually from saline water to fresh water. Clearly, it is important to understand miscible fluid displacement (groundwater flow and solute transport mechanisms, advection, dispersion, and molecular diffusion) in order to study the changes in groundwater salinity considering the recharge and pumping wells in an irrigated area.

B. Groundwater Quality in the Rechna Doab

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). Besides the surface irrigation supplies, the groundwater is being extracted on a large scale by means of tubewells due to the highly permeable and unconfined groundwater aquifer. The quality of this water deteriorates with distance from the rivers and with depth (Figure 15). 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).

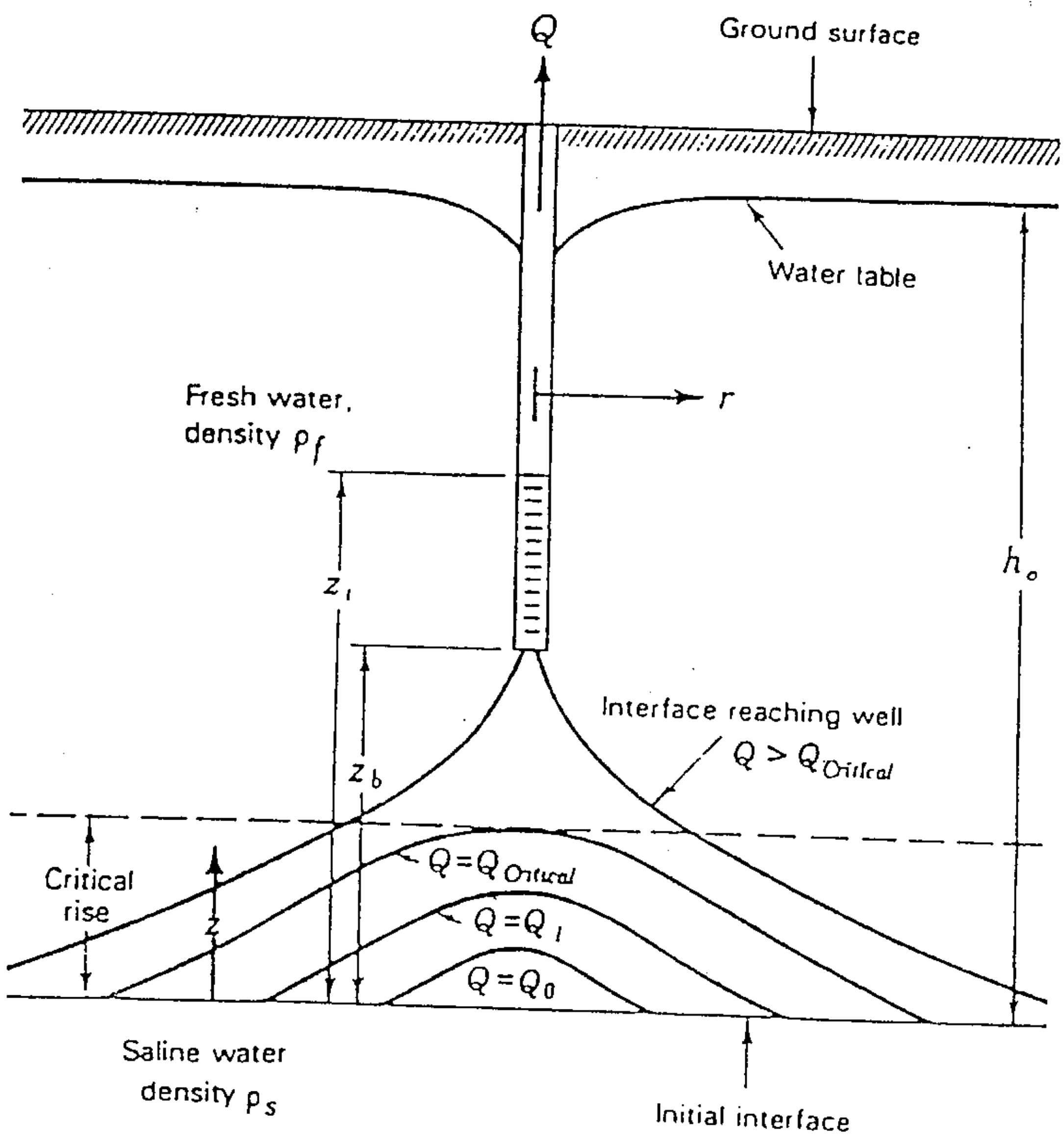


Figure 14 Salt Water Upconing Beneath a Pumping Well.

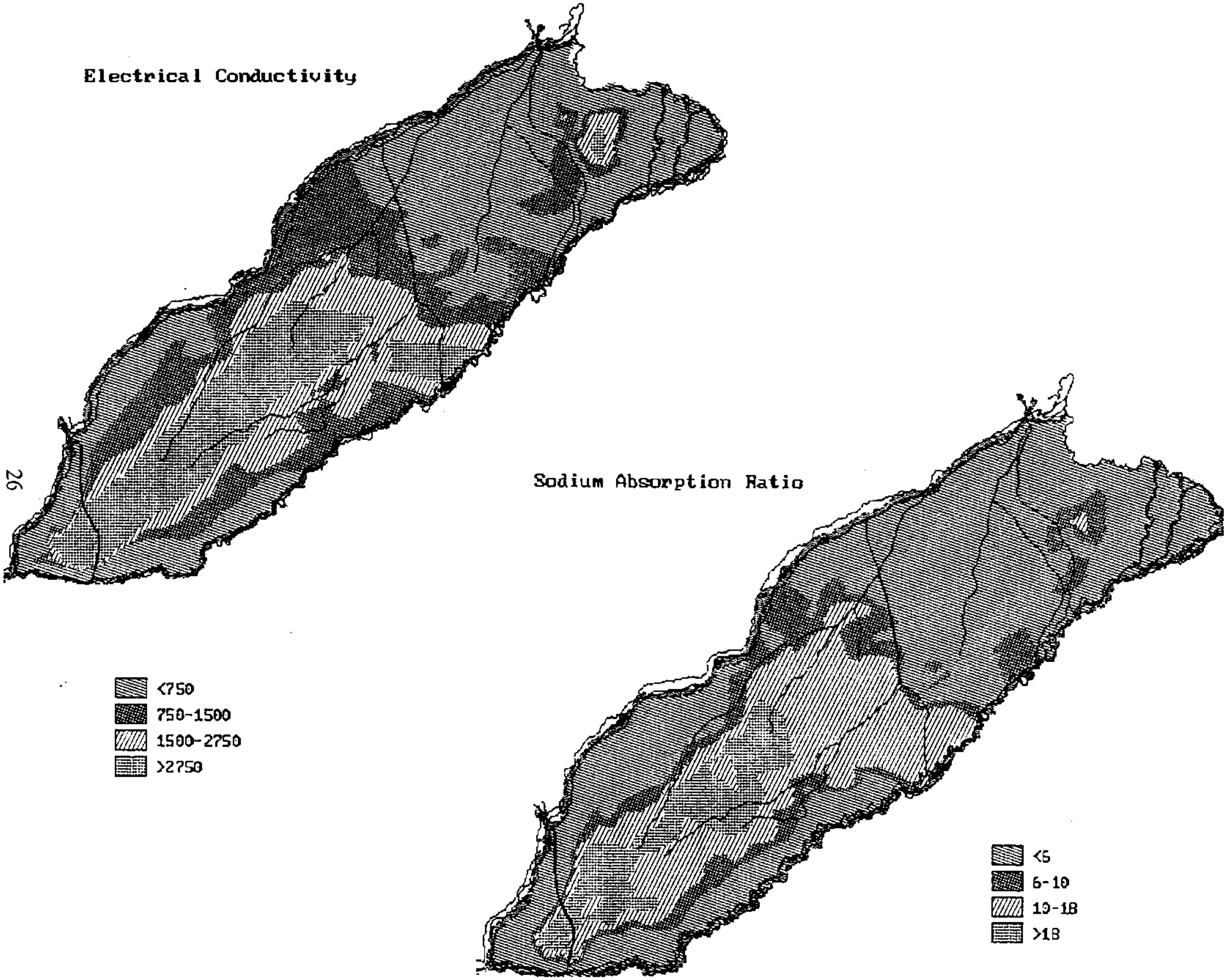


Figure 15 Groundwater Quality in the Rechna Doab.

1) The Deep Aquifer Quality

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 Jammu 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 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 the Rechna Doab (WAPDA, 1979).

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.

2) SCARP-Related Pumpage

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). Though, the occurrence of waterlogging has been significantly reduced by the operation of public and private tubewells, the salinity problem is still increasing due to inadequate amounts of irrigation water for leaching salts from the root zone and also due to using pumped groundwater of poor quality for irrigation (Aslam, 1994).

C. Groundwater Quality Modeling

The explosive increase in the exploitation of the shallow groundwater aquifer during the last two decades has already been discussed under Section X. B. of Volume Two. IIMI's research during 1989-1993 on groundwater utilization within sample distributary canal commands served by Gugera Branch Canal in the Lower Chenab Canal (LCC) system has only substantiated the belief in the poor management of this resource that is often used as an additive, rather than a substitute, for irrigation purposes. With the added complication of structural decline of soils due to application of sodic groundwaters, the need to contain this threat of incipient salinization due to poor groundwater quality pumpage is fundamental to any planning and reclamation strategy. Towards establishing 'safe' limits of this pumpage, and continued reliance on this resource into the future, a quantification of this phenomenon is essential. Computer-assisted groundwater quality prediction tools are invaluable for this purpose wherein not only the regimes for safe extration could be established across the three-dimensional aquifer, but also the most probable limits of our continued reliance on this resource into the distant future.

Groundwater flow and solute transport analysis under variable fluid density conditions is a complex phenomenon. This kind of analysis requires the solution of two simultaneous non-linear partial differential equations which 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 and the physics of salt water upconing phenomenon in a groundwater flow system. For the Rechna Doab Study, 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) was adapted in order to simulate the solute transport in the groundwater flow system with pumping wells, thereby simulating temporal salinity concentration changes in pumped groundwater under current as well as reduced pumping capacities of the tubewells in various locations in the Rechna Doab. Considerable emphasis was placed on using the three-dimensional groundwater model to predict the future trends in tubewell salinity discharges. A three-dimensional model was required because a vertical salinity gradient exists in the groundwater reservoir. The HST3D model as used for simulating groundwater flow and solute transport in the presence of pumping wells in an unconfined aquifer is being described in the next section.

IV. Description of Groundwater Flow and Solute Transport Model

Simulation of groundwater flow by the HST3D model is actually a calculation of the changes in the amount of fluid mass contained within the void spaces of the solid matrix with time. Considering a fully saturated solid matrix, the total fluid mass may change with time due to ambient groundwater inflows, recharge or discharge wells, and density changes due to changing temperature or concentration. In fact, HST3D keeps track of the fluid mass balance at every point in the simulated groundwater system by considering changes with time due to flows, wells, and density changes. The fluid mass balance equation (groundwater flow equation) is solved in the HST3D model by simulating the movement of groundwater through a porous medium as described below. The main components of the groundwater salinity model are given in Figure 16.

A. Groundwater Flow Equation

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:

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

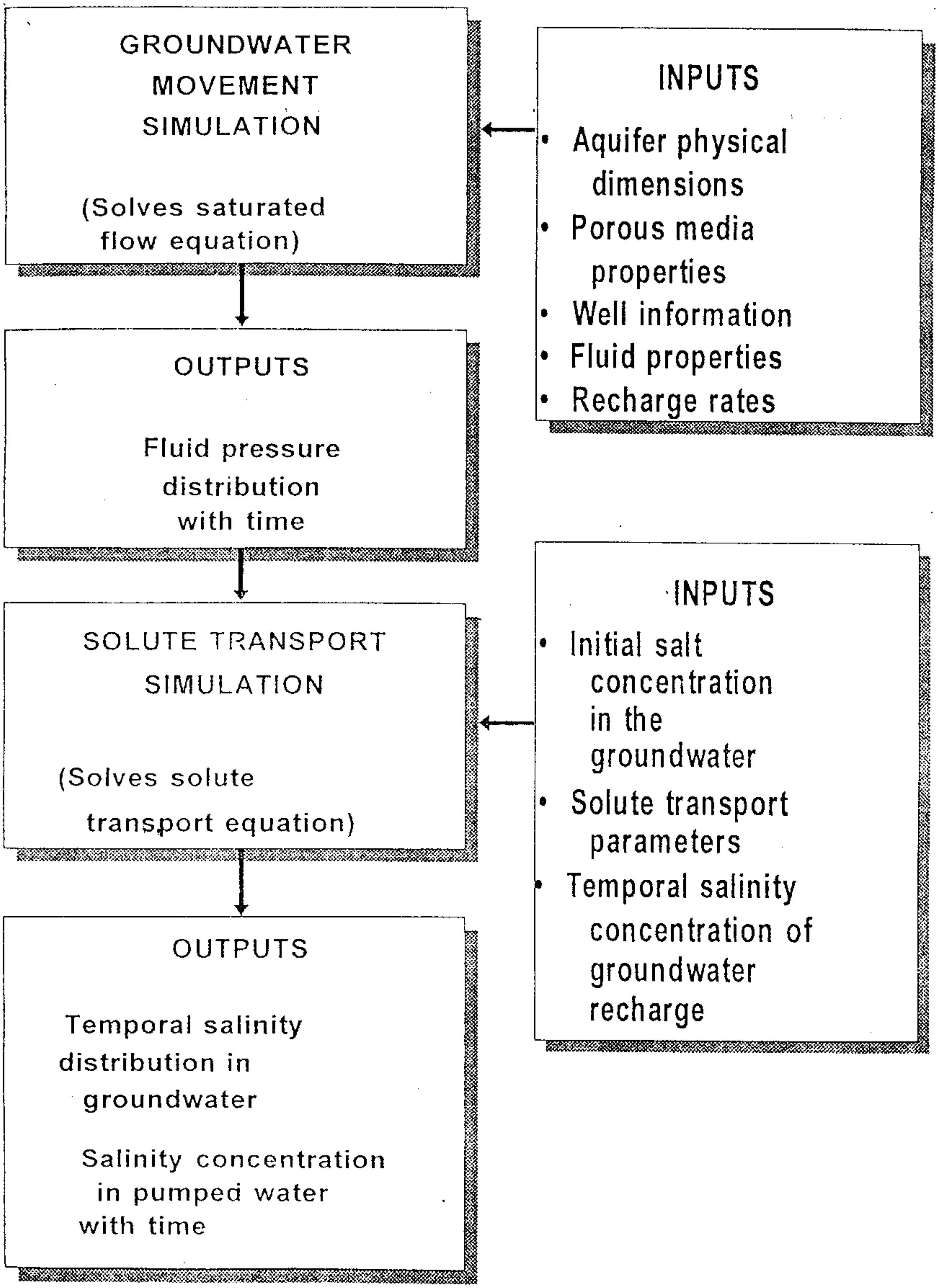


Figure 16 Component Diagram of the Groundwater Salinity Model.

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:

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

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

The groundwater flow equation in HST3D is based on the following assumptions:

1. Groundwater fully saturates the porous medium within the region of groundwater flow;
2. Groundwater flow is described by Darcy's Law;
3. The porous medium is compressible;
4. The fluid is compressible;
5. The porosity and permeability are space functions;
6. The fluid viscosity is a function of space and time through dependence on temperature and solute concentration;
7. Density-gradient diffusive fluxes of the bulk fluid are neglected relative to advective-mass fluxes;
8. Dispersive-mass fluxes of the bulk fluid from spatial-velocity fluctuations are not included; and
9. Contribution to the total fluid-mass balance from pure solute-mass source within the region are not included.

B. Solute Transport Equation

Solute mass transport in a porous medium caused by the movement of groundwater is termed as advective transport. Dispersion also causes movement of solutes in groundwater. Dispersion is mixing and spreading caused in part by molecular diffusion and in part by the variation in velocity within the porous medium (Wang and Anderson, 1982).

The HST3D solute transport simulation is based on advective-dispersive mechanisms of 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 due to 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 transport of solute in the porous medium is expressed as:

$$\frac{\partial(\varepsilon \rho w)}{\partial t} = \nabla \varepsilon \rho D_S \nabla w + \nabla \varepsilon \rho D_m I \nabla w$$

$$- \nabla \varepsilon \rho \underline{v} w - \lambda \varepsilon \rho w - \rho_b R_{fs} + q \rho^* w^* \tag{3}$$

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; and ρ_b is the porous medium bulk density. For the solute in the solid phase, the transport equation is:

$$\frac{\partial(\rho_b \overline{w})}{\partial t} = \rho_b R_{fs} - \lambda \rho_b \overline{w} \tag{4}$$

where $\overline{w}$ is the mass fraction of solute in the solid phase. The solute in the solid phase is immobile. Under the assumption of linear-equilibrium sorption, the fluid and solid phase concentrations can be related by an equilibrium distribution coefficient as follows:

$$\overline{w} = K_d \rho w \tag{5}$$

where K_d is the equilibrium distribution coefficient.

Combining Eq's. 3, 4 and 5, the final solute transport equation given by Kipp (1987) is written as:

$$\frac{\partial}{\partial t}(\varepsilon + \rho_b K_d) \rho w = \nabla \varepsilon \rho [D_S + D_m I] \nabla w$$

$$- \nabla \varepsilon \rho \underline{v} w - \lambda (\varepsilon + \rho_b K_d) \rho w + q \rho^* w^* \tag{6}$$

The solute transport equation given by Kipp (1987) is based on the following assumptions:

1. Thermal diffusion is neglected;
2. Pressure diffusion is neglected;,
3. Solute transport by local, interstitial, velocity-field fluctuations and mixing at pore junctions is described by a hydrodynamic dispersion coefficient;
4. Forced diffusion by gravitational, electrical, and other fields is neglected;
5. The only reaction mechanism is linear decay of solute;
6. The only solute, porous medium, interaction mechanism is linear equilibrium sorption; and
7. No pure solute sources occur in the fluid or solid phases.

In HST3D, fluid density is assumed to be a function of pressure, temperature, and solute concentration. The fluid density function used in the model is:

$$\rho(p,T,w') = \rho_0 + \rho_0\beta_p(p - p_0) - \rho_0\beta_T(T - T_0) + \rho_0\beta_w w' \quad (7)$$

where ρ_0 is the fluid density at a reference pressure, p_0, temperature, T_0 and mass fraction, w_0; β_p is the fluid compressibility; β_T is the fluid coefficient of thermal expansion; β_w is the slope of the fluid density as a function of the mass fraction divided by the reference fluid density; w' is the scaled solute mass fraction $= (w - w_{min})/(w_{max} - w_{min})$; $\rho_0\beta_w' = \rho(w_{max}) - \rho(w_{min})$; w_{min} is the minimum solute mass fraction; and w_{max} is the maximum solute mass fraction.

C. The Well Model

Though most of the groundwater flow and sources or sinks affect the simulations through the boundary conditions, a well is considered as a source or sink for the flow and solute transport equations in the HST3D simulator. A well which is a finite-radius cylinder for the well model, can be used for injection or production of fluid along with injection or production of solute. The well model for the HST3D is more sophisticated than well models used in most groundwater flow models (Kipp, 1987). In HST3D, there are various options available for specifying pressure or flow rate conditions for well operation.

The well can be divided into two parts as shown in Figure 17. The lower part, from the bottom of the borehole to the top of the uppermost screened interval, is termed as the well bore, while the upper part, from the top of the screened interval to the land surface, is

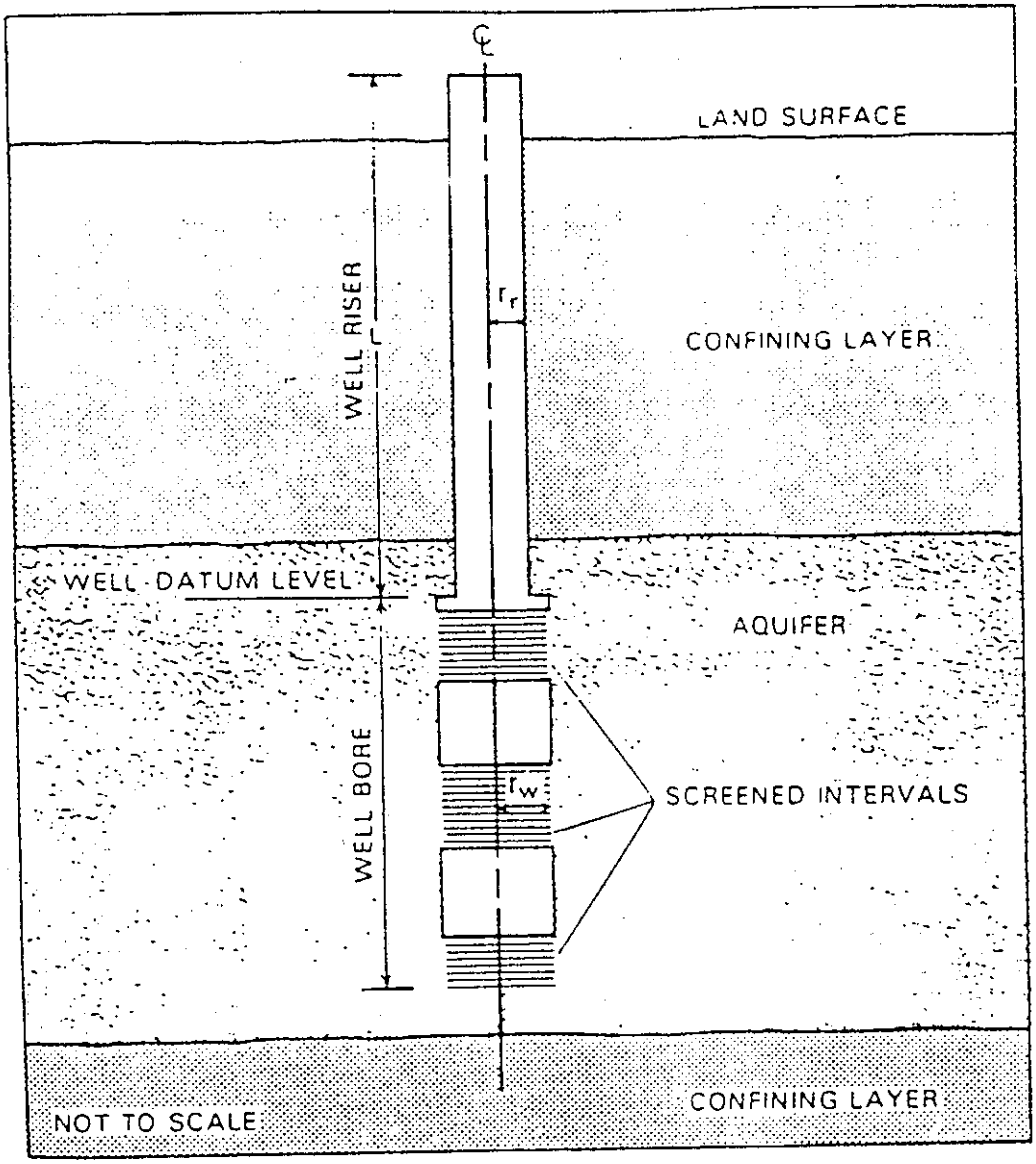


Figure 17 Well Model Geometry Sketch Showing the Well-Bore and Well-Riser Sections and the Well-Datum Level.

called the well riser. The location where the well riser and the well bore join each other is termed as the well-datum level, or the bottom hole. In the following sections, a brief description of the well-bore model is provided.

In HST3D, for a three-dimensional cartesian coordinate system, the well flow rate per unit length of well bore as a function of the pressure change between the well bore pressure and the aquifer average pressure is given by:

$$q_w = \frac{2\pi K_w \left(r_e^2 - r_w^2\right)\left(p_w - p_{av}\right)}{\mu\left[r_e^2 \ln\left(r_e/r_w\right) - 0.5\left(r_e^2 - r_w^2\right)\right]} \tag{8}$$

where q_w is the volumetric flow rate per unit well bore length (positive for flow into the aquifer and negative for flow from the aquifer into the well); K_w is the average permeability $= \sqrt{K_x K_y}$; K_x is the permeability in the x-direction; K_y is the permeability in the y-direction; r_e is the radius of influence of the well; r_w is the well bore radius; p_w is the pressure at the well bore; p_{av} is the average pressure between r_w and r_e ; and μ is the fluid viscosity. A well index, which represents the parameters that influence well bore flow rate and do not depend on time, is defined as:

$$W_I = \frac{2\pi K_w \left(r_e^2 - r_w^2\right)}{r_e^2 \ln\left(r_e/r_w\right) - 0.5\left(r_e^2 - r_w^2\right)} \tag{9}$$

where W_I is the well index per unit length of well bore. Now, Eq. 8 can be written as:

$$q_w = W_I \frac{\left(p_w - p_{av}\right)}{\mu} \tag{10}$$

The total well flow rate is expressed as follows:

$$Q_w = \int_{l_L}^{l_U} q_w \, dl \tag{11}$$

Substituting the q_w value from Eq. 10 into Eq. 11, a new form of Eq. 11 is obtained:

$$Q_w = \int_{l_L}^{l_U} (p_w - p_{av}) \frac{W_I(l)}{\mu(l)} dl \qquad (12)$$

where Q_w is the volumetric well flow rate (positive for flow from the well to the aquifer and negative for flow into the well from the aquifer); l is the distance along the well bore; l_L is the lower end of the screened interval; and l_U is the upper end of the screened interval. More information about the well bore model in the HST3D simulator can be found in Kipp (1987).

D. HST3D Numerical Algorithm

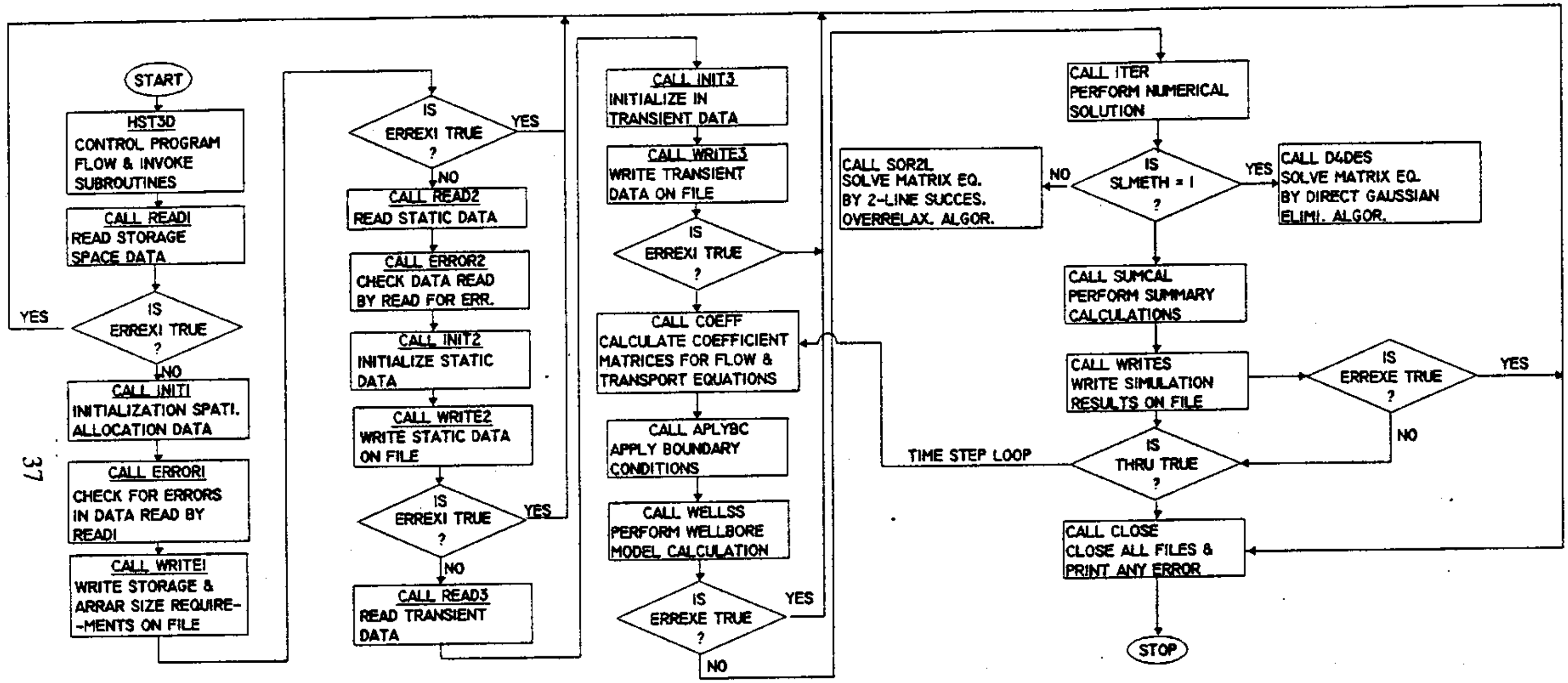
A simplified flow chart of HST3D is provided in Figure 18. In HST3D, partial differential equations which govern the groundwater flow and solute transport are discretized in space and time using a finite difference numerical technique. Then, for given initial and boundary conditions, the groundwater flow and solute transport equations in finite difference form are solved sequentially after modifying by a partial Gauss reduction method reported by Kipp (1987). Finally, these equations are solved repeatedly, as the simulation time progresses, employing either an alternating diagonal, direct-equation solver or a two-line, successive-overrelaxation solver. Actually, the HST3D methodology is complex, but is well documented by Kipp (1987).

1) Spatial Discretization

In the finite difference spatial approximation, first a grid of node points and their associated cells is developed in the simulation region. The grid is set by specifying the distribution of nodes in each of the three coordinate directions in the case of a cartesian coordinate system and two directions in the case of a cylindrical coordinate system. The volume associated with each node is called a cell which is formed by cell boundaries. The HST3D provides various options for grid setting in the simulation (flow) region (i.e., user-specified grid setting or automatic one).

For a cylindrical coordinate system, placing automatically the radial-grid system between the interior and exterior radii, the grid lines are spaced using the following expression:

$$\frac{r_{i+1}}{r_i} = \left[\frac{r_{N_r}}{r_1}\right]^{1/(N_r - 1)} \qquad (13)$$



NOTES:

IS ERREXI TRUE ? = TRUE IF PROGRAM ABORTS DUE TO INPUT ERRORS.
IS ERREXE TRUE ? = TRUE IF PROGRAM ABORTS DUE TO EXECUTION ERRORS.
IS THRU TRUE ? = WHETHER THE SIMULATION IS COMPLETE OR NOT.

FIGURE 18. FLOW CHART OF THE GROUNDWATER SALINITY COMPUTER MODEL

where N_r is the number of grid points in the radial direction; r_{N_r} is the exterior radius; and r_1 is the interior radius. Equation 13 provides a logarithmic node spacing in the radial direction. The cell boundaries for the cylindrical faces are determined by the following formula:

$$r_{i+\frac{1}{2}} = \frac{r_{i+1} - r_i}{\ln\left(r_{i+1}/r_i\right)} \qquad (14)$$

2) Temporal Discretization

In HST3D, the time derivative can be evaluated either by centered-in-time differencing (CT), known as the Crank-Nicholson technique, or by backward-in-time differencing (BT).

The time derivative is approximated by the finite difference as:

$$\frac{\partial}{\partial t}\left(a_m u_m\right) \cong \frac{\left(a_m u_m\right)^{n+1} - \left(a_m u_m\right)^n}{t^{n+1} - t^n} \qquad (15)$$

where t_n is the time at level n. Following the CT method, the right-hand-side, F, of the groundwater solute transport equation is approximated as follows:

$$F \cong \frac{1}{2}\left(F^{n+1} + F^n\right) \qquad (16)$$

where F^n is the spatial-difference function estimated at time n. The backward-in-time differencing has the following form:

$$F \cong F^{n+1} \qquad (17)$$

A general form for time discretization is obtained by combining Eqs. 15, 16, and 17 as follows:

$$\frac{\left(a_m u_m\right)^{n+1} - \left(a_m u_m\right)^n}{t^{n+1} - t^n} = \theta F^{n+1} + (1 - \theta) F^n \qquad (18)$$

Specifying the value of θ will specify the selection of a temporal discretization method. For example, $\theta = 1$ gives BT differencing and $\theta = 1/2$ gives CT differencing.

3) Time Step

The selection of the time step is an important factor in the solution of partial differential equations by numerical methods. In general, the more quickly the conditions change, the smaller the time steps that are needed for an accurate solution. The HST3D model provides an automatic time-step option that employs an algorithm developed by INTERCOMP Resource Development and Engineering, Inc. (1976).

After specifying the maximum values of change in pressure and mass fraction considered acceptable, and also the maximum and minimum time step allowed at the beginning of each time step, the following adjustments are made depending on the following conditions:

For the case $|\delta u_{max}| > \delta u^{s}_{max}$:

$$\delta t = \frac{1}{2}\delta t_{o}\left(1 + \frac{\delta u^{s}_{max}}{|\delta u_{max}|}\right) \qquad (19)$$

For the case $0 < |\delta u_{max}| < \delta u^{s}_{max}$:

$$\delta t = \delta t_{o}\left(0.2 + 0.8\frac{\delta u^{s}_{max}}{|\delta u_{max}|}\right) \qquad (20)$$

and For the case $\delta u_{max} = 0$:

$$\delta t = 1.5\delta t_{o} \qquad (21)$$

where u is the pressure or solute mass fraction; δu^{s}_{max} is the specified maximum change in u; δt is the new time step; δt_{o} is the previous time step; and $|\delta u_{max}|$ is the absolute value of the maximum-calculated change in u over the previous time step. The new time step is selected to be the minimum of the two calculated on the basis of change in the pressure and solute mass fraction. The time step is constrained to a user-specified range, and the maximum increase in time step is limited to a factor of 1.5. More detailed information about the HST3D model can be found in Kipp (1987).

E. Data Requirements for HST3D

The groundwater salinity model simulates changes in groundwater flow regimes and in groundwater salinity considering the recharge from the irrigated area and the pumpage from the groundwater system. This model needs data on physical dimensions of the aquifer, such as aquifer thickness; length and width of the simulation region; fluid density and fluid viscosity; data on initial salinity concentration distribution in the groundwater body (salinity concentration of the fluid at numerous locations with depth), and the chemical quality of recharge water entering the groundwater; fluid compressibility; molecular diffusivity for the solute in the porous medium; solute decay rate constant; porous-media properties, such as permeability, porosity, compressibility and density; solute dispersion data, such as longitudinal dispersivity and transverse dispersivity; and well data consisting of well depth, well radius, and well discharge; and data on groundwater quality of pumped water of the tubewells in the Rechna Doab. Employing the abovementioned data, the model simulates 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. A detailed discussion on model calibration, predictions on future tubewell salinity discharges in Rechna Doab, synthesis of findings, and conclusions and recommendations are provided in Volume Five.

V. SELECTION OF QUESTIONNAIRE INFORMATION FOR THE ECONOMIC SURVEY

A. INTRODUCTION

The role and importance of irrigation 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 one the 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 by the year 2013 (WSIP, 1990). Pakistan is the ninth most populous country in the world, having one of the highest population growth rates (2.82 percent per annum) in the region. Population growth rates in the countries of the region are: Bhutan 2.0 percent, India 2.1 percent, and Nepal 2.7 percent.

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. The survey of the literature reveals that under the current circumstances it is not possible to increase the productivity due to the constraints the farming communities are facing in the agriculture sector. These constraints range from the scarcity of irrigation water and poor ground water quality to the non-availability of required input resources (irrigation, fertilizer, improved seed, tractors and machinery etc.) at the proper time (Berry and Cline, 1979; Khan and Akbari, 1981).

The major physical constraint to irrigated farming in Pakistan is the threat of waterlogging and salinity. Despite the huge initial capital investment in the SCARPS, the desired results could not be attained due to faulty design and construction, poor maintenance, and mismanagement (Ahmad and Kutcher, 1992; Badruddin, 1986; Velde and Kijne, 1992; Chaudhary and Ali, 1989). Some of these SCARPS tubewells also created the problem of secondary salinization (Kijne and Vander Velde, 1991).

In lieu of this persistent loss of productive land, the total culturable waste area in Pakistan has increased from nearly 0.6 Mha in 1980 to 2.37 Mha during 1990 (GOP 1980 & GOP 1990). Different studies reported that the cultivated areas are approaching their limits in cropping intensity (Chaudhri et al, 1985; Khan and Akbari, 1986; Doelalikar, 1981; Hallam, 1991), and there lies the limitation to achieve horizontal expansion in the area. Hence, attempts at increase in the agricultural production have to focus on the horizontal and vertical expansion in area by bringing the culturable uncultivated areas under agriculture, and by increasing the cropping intensity of the existing cultivated area.

Sustainable efforts to reduce the problem of waterlogging and salinity from irrigated agriculture are essential because it means an assured crop, higher yields, more income and more employment in the farming sector. To Pakistan, it means 24.5 % of gross domestic product, 26% of public revenues and 64% of all exports provided by products originating in the agricultural sector (GOP, 1995-96).

In Pakistan, the literature review shows that all of the previous studies conducted in the arena of salinity management and resource productivity, either revolve around a specific crop or refer to cumulative descriptions of an area (Jilani et al, 1987; Ahmad et al, 1988; Hussain and Khan, 1988; Mujeeb et al, 1989; Usman, 1991; Siddiq 1994). None of the studies take into account the spatial variations in the salinity and sodicity and its impact on crop productivity. In fact, all of these studies assumed homogeneous saline and waterlogged conditions on large areas while the situation is not so. Actually, salinity and waterlogging are the localized constraints created either due to the nature of the parent material in the soil or due to the application of bad quality ground water (Mustafa, 1991).

To answer the issues of spatial differences in the inefficiencies in land use and spatial differences in the resource use productivities of different inputs in the major crops, the *Economic Component* of this study uses the Rechna Doab as the role model. It intends to document the historical changes in the productivity of the major crops, along with the spatial representation of the farmers perception about the problem of salinity, sodicity and waterlogging. Through studying the inefficiencies existing on different farms in the Rechna Doab regarding the land use intensity and the cropping intensity, it determines the limits for the possible horizontal and vertical expansion in the area under crops. This provides first-hand estimates of the spatial differences in yields, costs and net incomes from major crops being grown in the different areas of the Rechna Doab. Finally, the production function modeling provides estimates of the resource efficiency being used for producing the major crops on farms in different areas of the Rechna Doab.

B. OBJECTIVES

The specific objectives of the *Economic Component* of the present study are:

- To provide an overview of the historical trend and spatial differences in productivity of major crops (wheat, cotton, rice, and sugarcane) across farm-size groups at the Rechna Doab and district level;

- To study the farmers' perceptions about the ground water quality, soil conditions, land utilization, cropping intensity and drainage management in the Lower Rechna Doab;

- To estimate the total unused cultivable land in the sampled farms of the Lower Rechna Doab and to study the relationship between the size of holding and the level of unused cultivable land;

- To estimate the level of efficiency of land use across farm-size groups in each district and at the Rechna Doab level;

- To estimate the possible distribution of additional cultivable land through improvement in the culturable waste area across farm size in the Rechna Doab;

- To study the relationship between the output of major crops and input resource (labor, fertilizer/manure, irrigation, mechanization) utilization under different conditions at the Rechna Doab and district levels;

- To measure the differences in the profitability and returns to major crops in different regions of the Rechna Doab; and

- To suggests some policy measures to achieve full utilization of land and water resources.

The primary data set for the study comprised questionnaire information derived from a sample of 443 farms, predominantly scattered across the LCC irrigation system. Details on the typology and aggregation of this data are presented in Section VI of Volume Four. The secondary data was gathered from the Agricultural Census reports for the periods 1960, 1972, 1980 and 1990.

VI. THE INDUS BASIN MODEL

A. Background

Due to the layout of the land and other socio-economic compulsions, the initial work on water resources development (from late nineteenth to mid twentieth century) in the Indus Basin was primarily for the single purpose of irrigated agriculture. Therefore, the concept of basin planning was almost non-existant. The concept of multi-purpose planning started receiving attention during the tripartite water dispute negotiations during the 1950's under the aegis of the World Bank. Though conceding in principle, for the division of the Indus Basin river waters between India and Pakistan, the Bank brought in the concept of integrated planning/development on a multi-purpose basis. For instance, in the "Bank Plan of 1956," for the first time the concept of multi-purpose storages in the Indus Basin was introduced. The multi-purpose basin planning in Pakistan got a real boost with the establishment of WAPDA in 1958.

Right from the start of basin planning studies in the early 1960's, it was realised that the vast and complex nature of work required the use of computer-based digital programming/ modelling techniques. This set into motion the process of acquiring/developing computer models for system-level simulation of statistical and agro-economic evaluations. The computer models, such as Harza's Comprehensive System Simulation Model (COMSYM) and DELTA computer program were used in Harza's Master Plan of 1964 and the Indus Special Study of 1967.

Based on the various investment opportunities identified by the Indus Special Study group consultants in the field of irrigation development, the study group constructed a linear programming model for optimum allocation of water and investment resources under specific resource constraints. All of this economic analysis using linear programming techniques was carried out by CEIR, a commercial computer service organization specializing in operations research. Similarly, various other computer models were developed for specific purposes during studies of WAPDA-Harza, IACA, Tipton and Kalmbach, and Lieftinck et. al. These studies were unanimous in recommending large-scale public tubewell development for vertical drainage and to achieve efficient conjunctive use of surface and ground water, although the long-term need for horizontal drainage (for flushing of salts in the root zone) was also recognized.

B. Development of the Indus Basin Model

1) The Farm Level Model (FLM)

In early 1975, a proposal was formalised for the preparation of a Revised Action Programme (RAP) by WAPDA under UNDP/World Bank technical and financial assistance for planning, preparation and implementation of irrigation, drainage, reclamation, surface storage and flood protection schemes during the next 15 years (1975-90). Under the proposal, titled **Preparation of Revised Action Programme and National Investment Scheme for Irrigated Farming Development and Land Reclamation in the Indus Basin and Adjoining Areas in Pakistan**, massive amounts of data were collected in the period 1975-79 that ultimately led to the recommendations constituting the RAP document. Meanwhile, the Development Research Centre (DRC) of the World Bank continued research into the development of an Indus Basin family of models for water sector investments; the Fram Level Model (FLM) was one of these developments. The FLM is a tool for optimising agricultural production on the farm(s), by applying linear programming techniques to estimate the farmer's response to the availble water and non-water inputs.

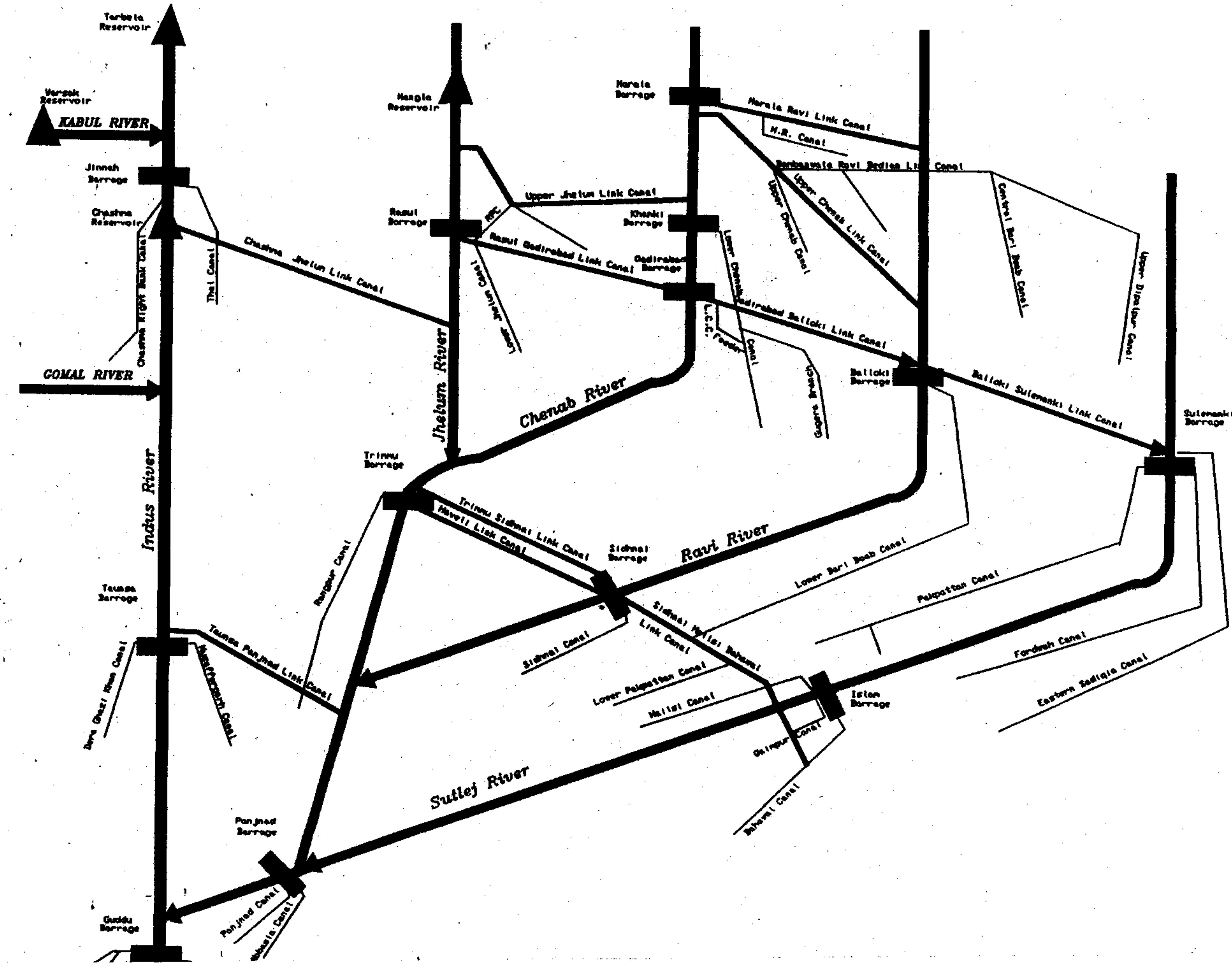
2) The Indus Basin Standard Model (IBM-I)

The computer models used by WAPDA and consultants in the Master Planning studies (1975-79) essentially routed surface water under different simulations. In order to convert the water inputs to agricultural outputs, a more versatile and powerfull tool was needed. In 1976, soon after starting work on RAP, the World Bank initiated work on the development of a large-scale linear programming model for the Indus Basin. WAPDA provided the necessary data to be used in the process of model development. The resulting model (IBM1) was based on 53 irrigated regions or "polygons," covering the entire Indus Basin with more than 20,000 constraints. Later on, some structural simplifications were made such that the entire model contained approximately 8000 constraints which could be solved using a large machine and commercial software. The resulting model, referred to as the Indus Basin Model (IBM), was completed in 1981-82 that could combine the standard agriculture modeling techniques with the surface water reservoirs and canal distribution network of the Indus Basin Irrigation System (Figure 19). The model also incorporated the conjunctive use of surface and ground water in the areas underlain by fresh groundwater.

The IBM was a valuable research tool investigating and analysing water related projects and agricultural policies where important factors with respect to groundwater quality and depth to water table were involved. However, the size of the model prevented the researchers from obtaining solutions beyond a limited number of alternatives. It was also recognised that partial analytical techniques adopted for the IBM did not prove adequate for modeling the large water resources projects like Kalabagh Dam Project.

3) The Indus Basin Model Revised (IBMR)

Because of the interdependence of the entire Indus Basin Irrigation System (IBIS) accomplished through re-routing of surface waters, the need for a model was realized which could simultaneously evaluate the benefits of additional water throughout the agroclimatic zones and among the major crops. Consequently, in 1985, a DRC team from the World


Tarbela Reservoir
Warsak Reservoir
KABUL RIVER
Jinnah Barrage
Chashma Reservoir
Chashma Right Bank Canal
Thal Canal
GOMAL RIVER
Indus River
Taunsa Barrage
Dera Ghazi Khan Canal
Muzaffargarh Canal
Taunsa Panjnad Link Canal
Guddu Barrage
Panjnad Barrage
Panjnad Canal
Abbasia Canal
Mangla Reservoir
Rasul Barrage
Upper Jhelum Link Canal
Rasul Qadirabad Link Canal
Lower Jhelum Canal
Chashma Jhelum Link Canal
Jhelum River
Marala Barrage
Marala Ravi Link Canal
M.R. Canal
Bambanwala Ravi Bedian Link Canal
Upper Chenab Canal
Upper Chenab Link Canal
Khanki Barrage
Qadirabad Barrage
Lower Chenab Canal
Qadirabad Balloki Link Canal
L.C.C. Feeder
Gugera Branch
Chenab River
Trimmu Barrage
Trimmu Sidhnai Link Canal
Haveli Link Canal
Rangpur Canal
Central Bari Doab Canal
Upper Dipalpur Canal
Balloki Barrage
Balloki Suleimanki Link Canal
Suleimanki Barrage
Sidhnai Barrage
Ravi River
Sidhnai Canal
Sidhnai Mailsi Bahawal Link Canal
Lower Bari Doab Canal
Pakpattan Canal
Fordwah Canal
Eastern Sadiqia Canal
Lower Pakpattan Canal
Mailsi Canal
Islam Barrage
Qaimpur Canal
Bahawal Canal
Sutlej River

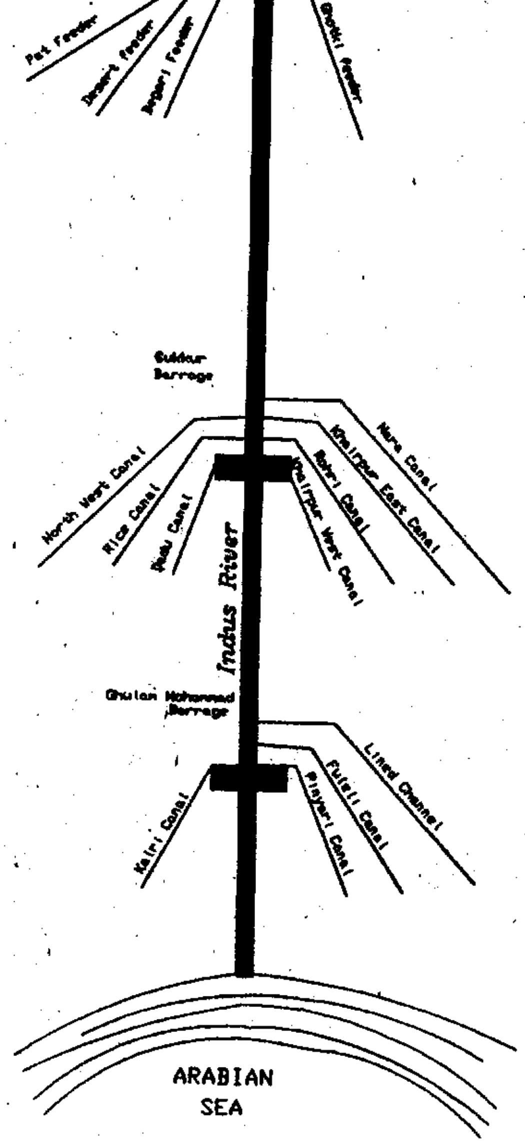


Figure 19 Schematic Diagram of the Indus Basin Irrigation System.

Bank, in association with consultants, undertook the assignment of updating the IBM. It included updating of the model's input data, structural modifications to the programme through rewriting the model in General Algebraic Modelling System (GAMS) language, reduction of the 53 groundwater homogeneous subareas (polygons) to nine agroclimatic zones (ACZ), deletion of a large number of constraints imposing groundwater equilibrium in favour of an accounting system, and replacing the farm-level linear expenditure system, originally based on consumption functions, with a price-endogenous structure which could simulate the material equilibrium of demand and supply. The resulting model, called the Indus Basin Model Revised (IBMR) contained about 2500 equations and was extensively used in 1986 by the World Bank for the analysis of the proposed Kalabagh Dam Project. The World Bank further updated and streamlined the model in 1989 during the Water Sector Investment Planning Study (WSIPS) using the agroeconomic field survey data collected by WAPDA in 1988. The model was eventually transferred to WAPDA in August 1989 and was extensively used for evaluation of alternative 10-year (1990-2000) water resources development plans presented in WSIPS.

4) The Indus Basin Model-III (IBM-III)

Though the IBMR was basically a planning tool, it could also be used with advantage for system management of the Indus Basin Irrigation System (IBIS). However, this additional versatility was of little use in the absence of an agreement for the apportionment of the Indus waters among the provinces of Pakistan. This impediment was removed through the Water Apportionment Accord of March 1991 that cleared the way for the efficient utilization of the water resources within the country.

Besides the abovementioned development requiring adjustments to the Model, the advances in personal computing and modelling softwares permitted revision and simplification of the linear programming code. Therefore, the model was further revised by the World Bank in 1992 and termed as IBM-III. This model was used in the context of a Ranking Study of new irrigation projects as a result of the Water Apportionment Accord of 1991. To make the Agroclimatic Zones (ACZ) delineation in conformation with provincial boundaries, the number of ACZs have been increased from 9 to 12 so that the model results can quantify the effects of any simulation for individual provinces (Figure 20). Moreover, the size of the model has been reduced to 2000 equations and about 5000 variables after deleting some constraints. The entire layout of the Model is given in Figure 21.

The Indus Basin Model Revised-III is an agro-economic and irrigation optimization model which, for any given set of inputs, constraints, parameters and objective functions, 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 crops produced. The objective function for IBM-III is value-added in terms of economic prices (VAEP) to access the economic benefit from the projects being simulated.

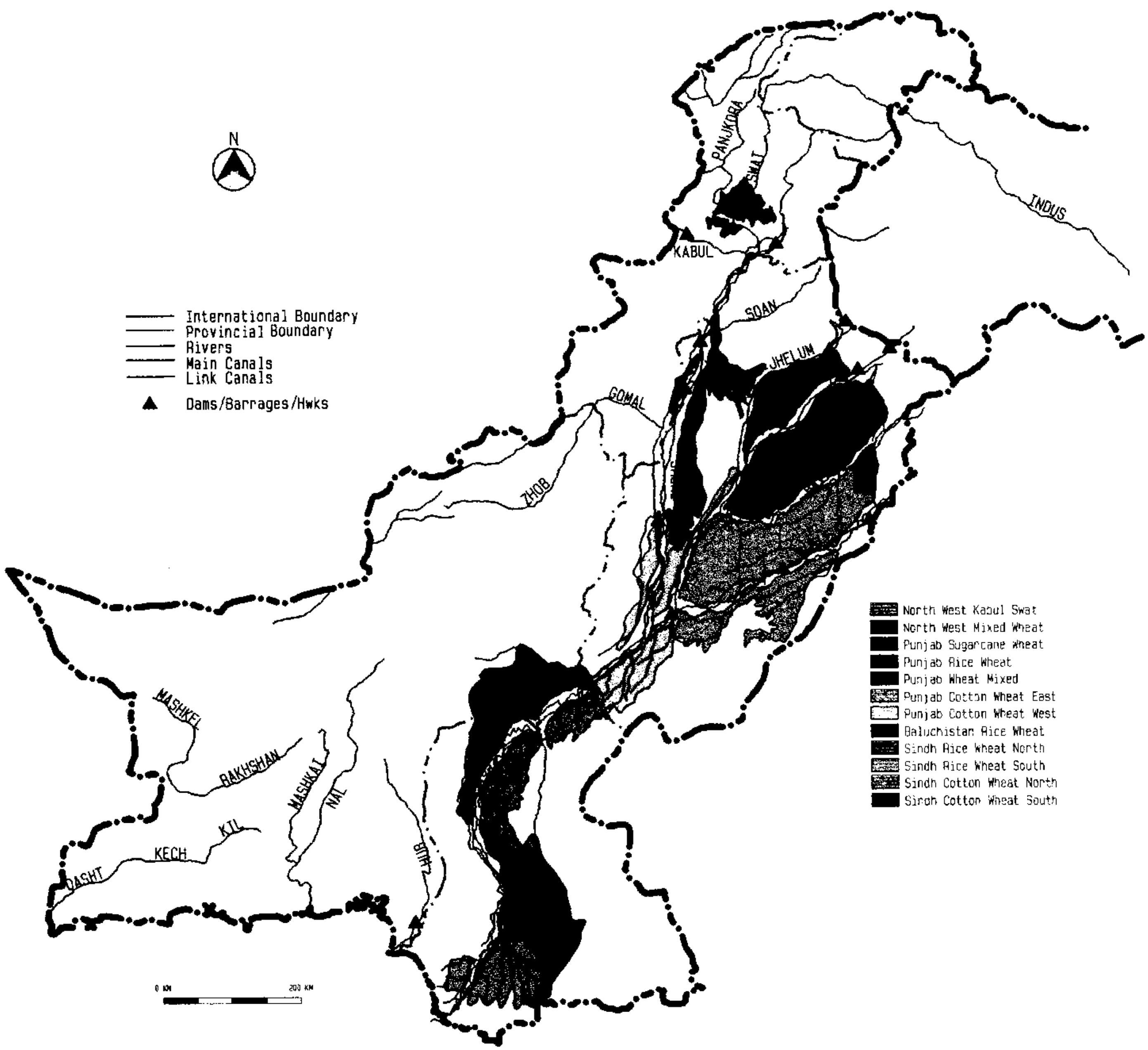


Figure 20 Geographical Layout of the Agroclimatic Zones within the Indus Basin Model-III.

For each crop and in each zone (where the crop applies), and each type of land (fresh or saline, where applicable), the IBM-III first seeks to match the base-period acreage cultivated, and then increases this area subject to land constraints and water availability. The increases in cultivated area will depend on the VAEP per acre by crop-zone-land classification. All solutions will report the cropped area by crop, zone, fresh-saline class, and the cropping intensities.

Water availability is much more complex. For each crop and zone combination, the total water requirements per acre, by month, are given. These requirements are first served by effective rainfall, given exogenously by zone and month. In only a few crop-zone combinations is rainfall sufficient to meet the water requirements. The model next uses "sub-irrigation," which is the evapotranspiration from soil moisture available through the capillary action of groundwater. Supplies from sub-irrigation vary significantly according to the water table depth, which in turn, varies by zone and fresh/saline classification.

The bulk of water supplies come from the surface water delivery system which is represented within the model. System inflows enter the model at rim stations and tributaries. The model routes these along river reaches and through the major reservoirs of Tarbela, Mangla, and Chotiari. Changes in storage at these reservoirs are endogenously determined within limits given by rule curves determined a priori for power and flood control needs. From the reservoirs and other control points (barrages and headworks), the model then routes surface water through link canals and main canals to its final destination for use by crops at the zone level. In saline areas, the above sources of water supply, i.e. rainfall, sub-irrigation, and surface water are the only recourse in meeting the demands as given by the cropping pattern and crop water requirements. If the requirements cannot be met from these sources, then crops must be stressed and the associated yield decline. Which crops are stressed, and when, will depend on the crop yield response (K_y) factors, the value added of the crop, and the timing of the shortages.

In "fresh" areas (named for the suitability of the underlying groundwater), farmers have an additional recourse, that of using tubewells. In virtually all fresh areas of the Indus Basin, farmers have invested in private tubewells for the purposes of supplementing untimely and insufficient surface water supplies. The use of these tubewells is determined by the model according to the shortages and the costs of using them vis-a-vis the return to the crops. Use of tubewells in any month is constrained by the capacity of the tubewells previously installed in the particular zone.

In addition to these private tubewells, a smaller but nevertheless significant quantity of groundwater is pumped by public tubewells installed by the government through several SCARP Projects in the last two decades. Although most of these are being phased out, or transferred to private operation, they remain a separate source in the model. Because their operation is largely pre-determined by capacity constraints, as well as given policy decisions, the pumping from public tubewells in exogenously fixed.

In sum, the model will attempt to match or exceed the cropping pattern in each zone and fresh/saline classification while making the most efficient use of the available water. Where necessary, it will resort to stressing the crops according to water shortages and the embedded economic costs of incurring stress. The solution of IBMR contains a great detail of information, but the solution listings (Table 2) are not well organized for comprehending the details and relationship contained in them. Therefore detailed reports are prepared towards understanding the results.

The model has been used for a number of studies, including the following:

- Appraisal of several World Bank assisted projects in Pakistan such as On Farm Water Management projects, Left Bank Outfall Drain and SCARP Transition Pilot project;

- The Agricultural Impact Assessment Study for the Kalabagh Dam Project and Raised Mangla Dam Project;

- The Water Sector Investment Planning Study (WSIPS) to develop a medium term investment plan in the water sector by year 2000;

- Environmental impact study under changing global climate, a case study of the Complex River Basin Management Project for the Indus Basin Irrigation System; and

- The ranking study of new irrigation projects, identified by provinces as a result of the Water Apportionment Accord of 1991.

VII. DEFINITION OF MANAGEMENT AND CAPITAL INVESTMENT SCENARIOS USING THE INDUS BASIN MODEL REVISED-III

A. Adaptations to the Model

The area within the Rechna Doab falls under two separate Agroclimatic Zones, i.e. the Punjab Sugarcane-Wheat (PSW) and Punjab Rice-Wheat (PRW) zones. Besides the Rechna Doab, these zones have partial overlap with areas contained within the Chaj and Bari doabs. Since the model simulation conforms to the ACZs, necessary modifications were incorporated in the model programs in GAMS such that the zonal model could be run with the surface water network model (SWM) of the Indus Basin Irrigation System (IBIS) and the results obtained at the canal command level (see Figure 14, Vol. II). This was achieved through weighting factors provided in the model according to ACZ-canal-subarea (fresh or saline groundwater) mapping provided in the model on the basis of CCA classification. Simulations were to be made on the MS/DOS version of the GAMS (GAMS/386), alongwith the GAMS Solver (MINOS5), for use on a personal computer. By virtue of the capabilities

Table 2 Listing of Results from Indus Basin Model-III.

- CCA of ACZ by groundwater quality.
- Actual cropped area (000-Acres).
- Simulated cropped area (000-Acres).
- Water balance at root zone by ACZ, month and groundwater quality.
- Slack-water at root zone by season, ACZ, and groundwater quality.
- For the ACZs, groundwater quality wise monthly area under all crops, net-requirement, canal supplies, groundwater supplies, water stress, total supply and shortages.
- Production comparison, actual and simulated, of each crop by ACZ.
- Yield of crops, by ACZ.
- Yield reduction factors due to water stress.
- Monthly water balance at watercourse head, by ACZ & groundwater table.
- Surface water diversion by model at canal head, by canal command.
- Surface water diversion by model at canal head, by regions.
- Monthly prescribed diversions at canal head, by canal.
- Monthly difference of canal diversions, by model and prescribed releases.
- Monthly surface water diversion at the canal head, by ACZ and groundwater quality.
- Surface water flow between nodes, by month and season.
- Ground water balance, by ACZ and groundwater quality.
- Water losses in the link canals, by month and season.
- River losses and gains between reaches, by month and season.
- Reservoir contents at the end of the month.
- Report on monthly system inflows and outflows.

of the model to simulate larger areas, the IBMR was applied for studying the following parameters in the Rechna Doab:

- The effect of groundwater balance constraints on cropping patterns;
- Qualitative impact of the variations in the groundwater balance;
- Groundwater recharge and quality; and
- Optimized cropping patterns for Rechna Doab.

B. Updating the Input Data

The input to the model consists of multi-disciplinary data relating to agronomy, agricultural economics, surface and groundwater hydrology, reservoir and canal system operation, project planning, availability of resources and other miscellaneous considerations. The input data had been last revised in 1992, and therefore, in the context of the Rechna Doab, there was a need to update the data to represent conditions existing as of 1995-96. The data which was updated, as described as below:

1) Agricultural Data

For IBMR-III, the agricultural data (like seed inputs, fertilizer inputs, crop water requirements, draft power, tractor and labor requirements) is based on the 1976 Extended Agricultural Economic Survey (XAES) and the Farm Survey of 1988. This data, as incorporated by the World Bank, was used as such. However, the data relating to cropped area and production were updated from the district-wise data of crop area production for the year 1994-95 (Ministry of Food and Agriculture, Govt. of Pakistan). The district-wise data was converted to PSW and PRW zones according to the overlap between the district(s) and the ACZ. For crop yield, IIMI's data, collected during surveys in 1995, was used.

2) River and Tributary Inflows

The data on river flows was obtained from WAPDA's publication titled Indus Basin Irrigation System, Historic Rivers and Canals Discharge Data. The average and 80% probable inflows at rim stations (Indus at Tarbella, Jhelum at Mangla, Chenab at Marala, Ravi at Balloki, Sutlej at Sulemanki, Swat at Chakdara, Harro at Gariala and Soan at Dhok Pathan) were updated from the historic flows upto 1991-92. Similarly, the historic river flows at different headworks/barrages of the Indus Basin Irrigation System network were updated upto 1991-92 to determine the river loss and gain coefficients used in the surface water network model of the IBMR.

3) Canal Head Diversions

The 10-day canal diversions data were collected from WAPDA through the publication mentioned above and the monthly and seasonal average post-Tarbella historic canal diversions covering the period 1976 to 1992 were computed. However, the monthly and seasonal actual canal diversions for the water year 1994-95 were computed only for canals located under the PSW and PRW agroclimatic zones. A comparison has been shown in Figures 22(a)-(g) with the Water Apportionment Accord allocations of 1991.

4) Agro-Economic Data

The economic data includes the finanacial and economic prices of crop and livestock commodities and their byproducts, miscellaneous inputs for crop production, O & M of private tubewells and tractors, farm labor wage rates, etc. Data for all of the economic parameters was not available. Thus, it was decided not to use the partial information and therefore, the World Bank data against which the model had been calibrated for the base year 1990 was adopted.

5) Projects Information Data

Construction and rehabilitation activities affect several aspects of the system, like increasing canal command area (CCA), canal capacities, storage capacities, improving canal and farm level delivery efficiencies, etc.. The IBMR has been designed in such a way that it simulates the 'without' and 'with' project scenarios on the basis of project information as provided in the Water Sector Investment Planning Study (WSIPS) for all of the identified projects. The projected benefits, incorporated into the Model by the World Bank in lieu of completed and ongoing projects, were assimilated into the simulations for the Rechna Doab study.

6) Resource Inventory Data

The resources (except water) include farm households, farm workers, number of private tubewells and tractors, livestock population, and growth rates of resources. This level of information is realized either through a census or agro-economic farm surveys, both of which involve heavy investment in time and finances. Therefore, the resource data as updated by the World Bank for IBM-III has been adopted, which is based on the Agriculture Census of 1990.

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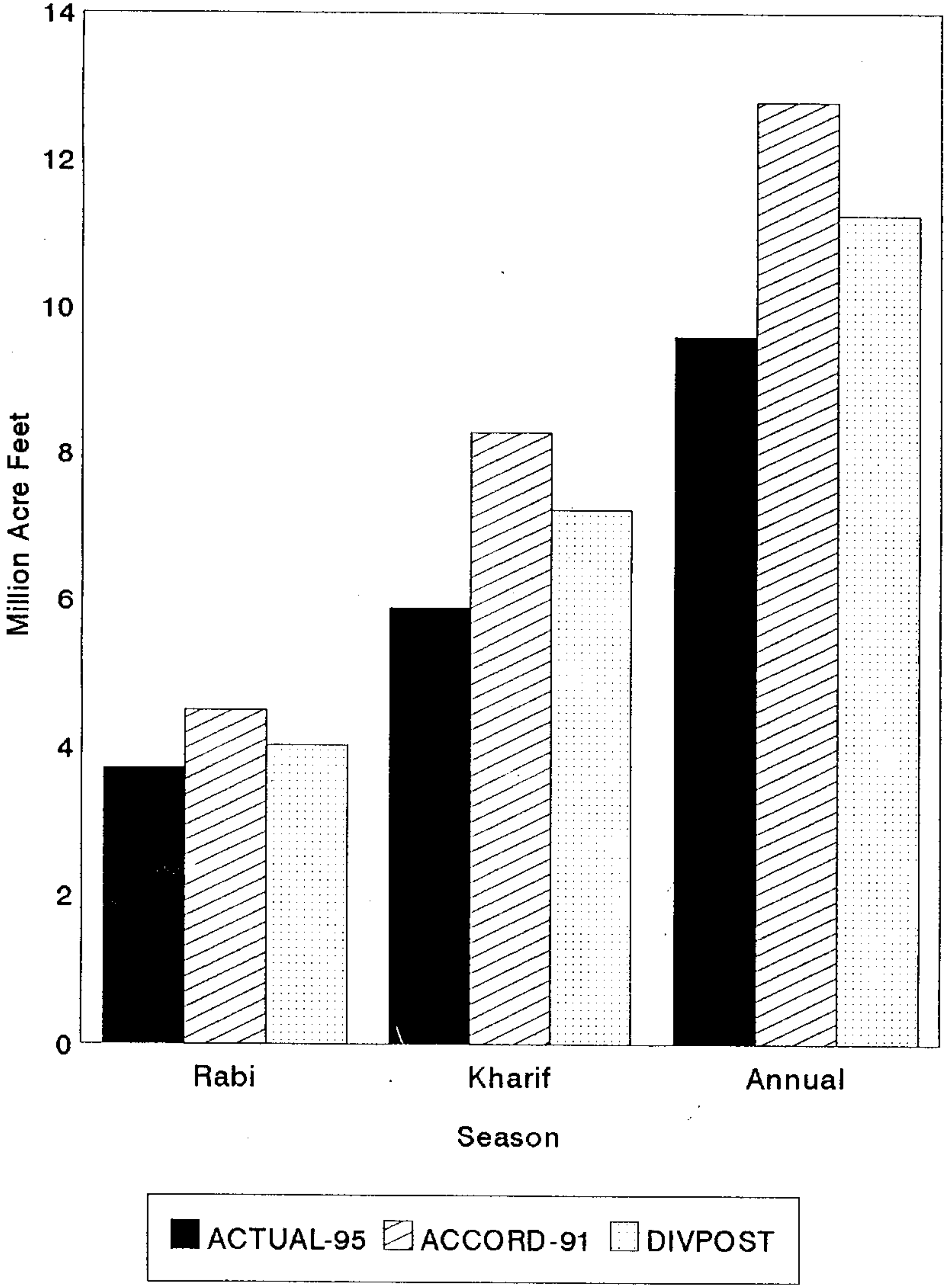

Figure 22(a) Water Allocation for Rechna Doab Canals at Canal Head

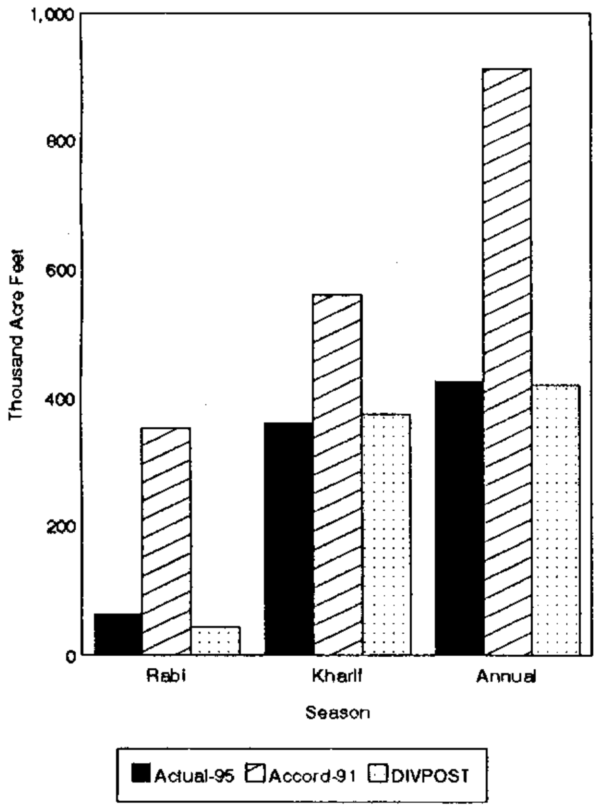

Figure 22(b) Water Allocation for Raya Branch (BRBD-Int.) Canal at Canal Head

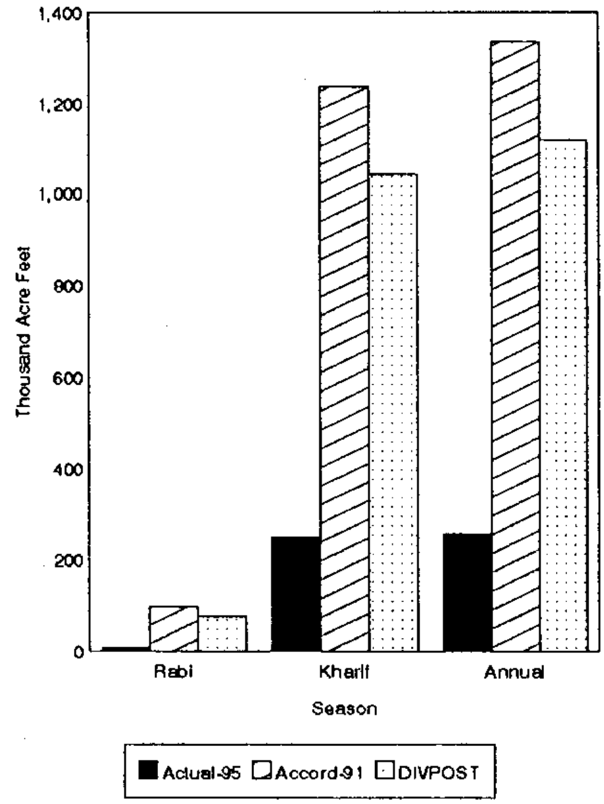

Figure 22(c) Water Allocation for Marala Ravi(Internal) Canal at Canal Head

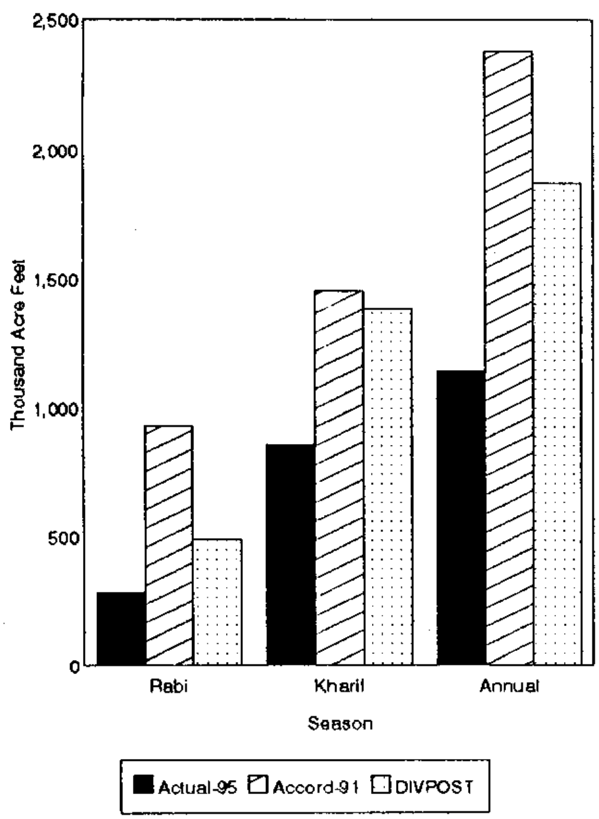

Figure 22(d) Water Allocation for Upper Chenab Canal (Internal) at Canal Head

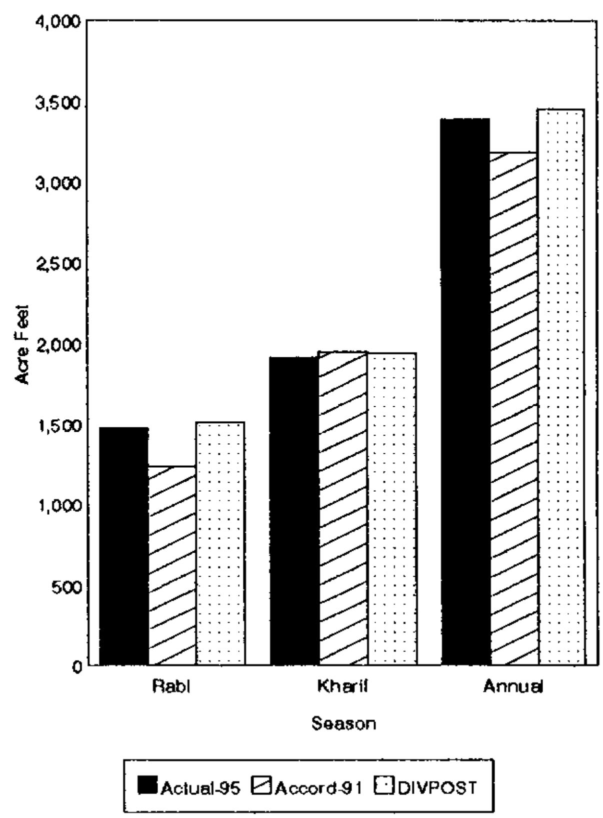

Figure 22(e) Water Allocation for Jhang Branch of Lower Chenab Canal at Canal Head

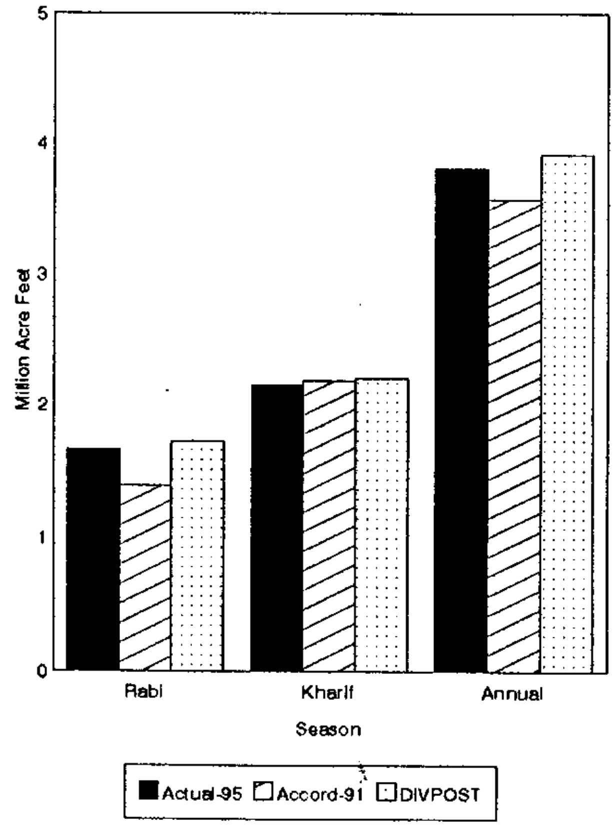

Figure 22(f) Water Allocation for Gugera Branch of LCC at Canal Head

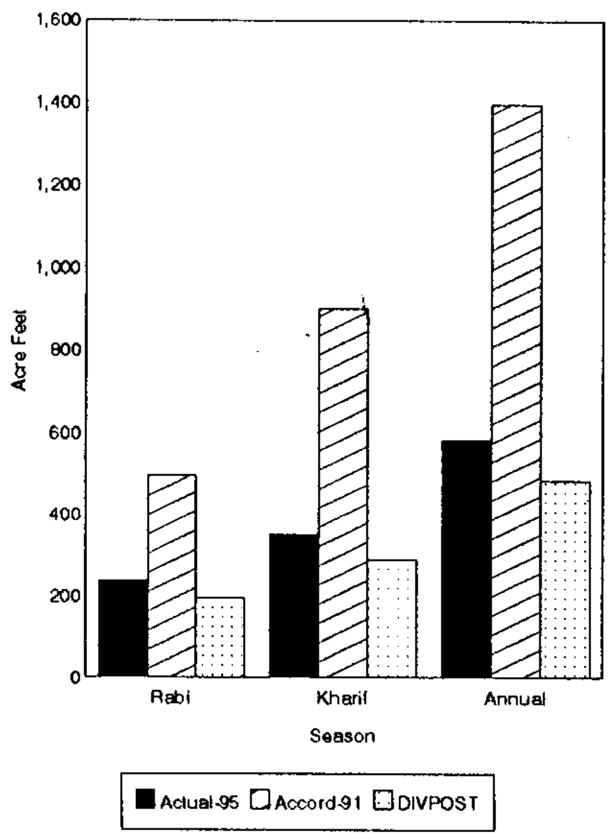

Figure 22(g) Water Allocation for Haveli (Internal) Canal at Canal Head

C. Validation and Calibration

The IBMR-III has been extensively validated in respect of cropping pattern, crop production, canal diversions, etc. in the context of the ranking study during 1992, and on the basis of the Agricultural Census conducted during 1990. Simulating a close cropping pattern "fit" is extremely important when addressing water requirements that differ widely amongst crops. The model was validated according to the actual cropped area and yields for the year 1994-95, and the growth rates for crop area and yields were determined for the period 1990-1995 (Figures 23(a)-(d)) for the PSW and PRW zones. Similarly, the model was validated for the canal water allocations according to the actual canal diversions during 1994-95.

D. Selection of Simulation Scenarios

To study the effects of resource allocations and capital investment under the existing irrigation system constraints, and to fulfill the objectives of the study, three simulation periods were selected. The simulations corresponded to the priorly established scenarios for sensitivity analysis.

Scenario A: A base year, or benchmark run starting from the year 1990 using 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 yield taken according to the growth rates for the period 1991-95, and projected for the year 2000.

Scenario A1: A base year, or benchmark run, starting from the year 1990 using 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 based on the reported figures as recommended by the National Commission on Agriculture for the year 2000.

Scenario B: There is 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.

Scenario C: There is no change in crop production area; average canal diversions for 1991-95 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 the year 2000. Public tubewell contribution for 1991-95 is no more than 30% of the total groundwater contribution, and thereafter less than 10% by the year 2000.

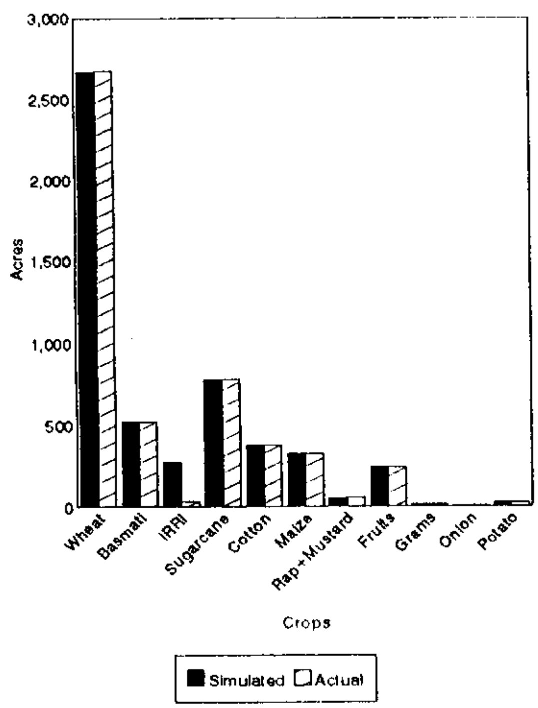

Figure 23(a) Simulated and Actual Crop Area for PSW Zone

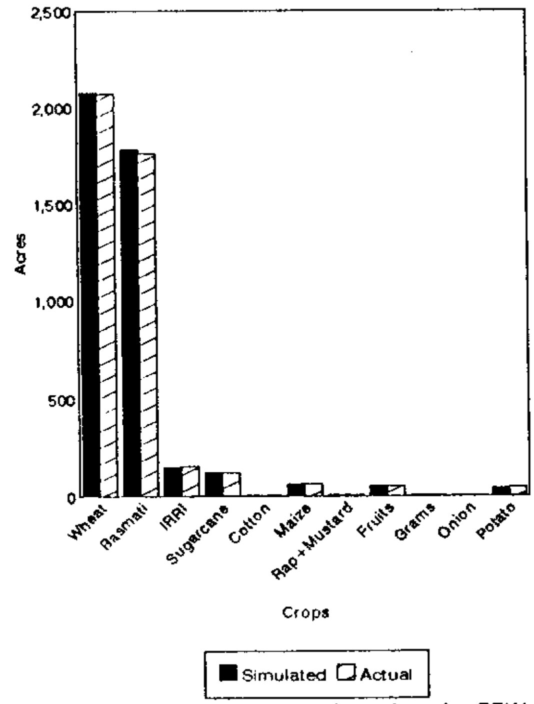

Figure 23(b) Simulated and Actual Crop Area for PRW Zone

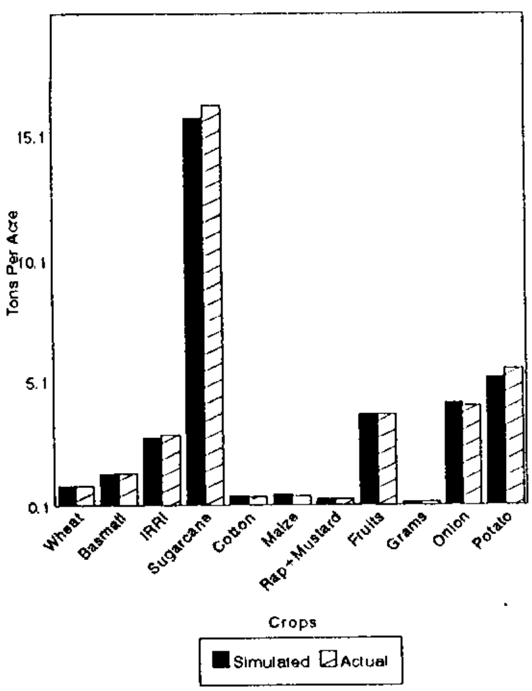

Figure 23(c) Simulated and Actual Crop Yield for PSW Zone

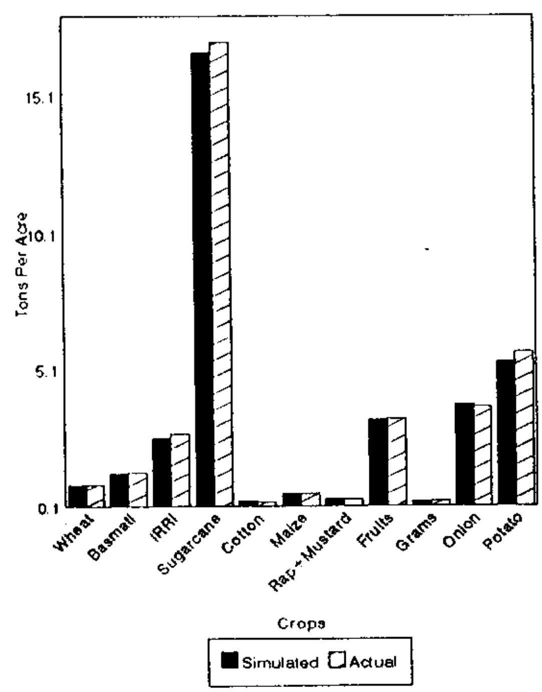

Figure 23(d) Simulated and Actual Crop Yield for PRW Zone

Scenario D: There is no change in crop production area; average canal diversions for 1991-95 are the ones reported for 1994-95, and 10% higher for the period 1995-2000. 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% by the year 2000.

Scenario E: There is no change in crop production area 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 10% higher for the period 1995-2000. 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% by the year 2000. Both field application efficiency and conveyance efficiency improved by 5% each.

Scenario F: The crop production area increases by 0.5% per annum from the base year. 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 the period 1995-2000. Field application efficiency is improved by 5%.

Scenario G: There is no change in cropped area; 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%.

Scenario H: There is 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.

Scenario I: The cropped area increases by 0.5% per annum from the base year. 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.

Scenario 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%.

Scenario K: The cropped area increases by 0.5% per annum from the base year 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.

Scenario 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 Tarbela flows 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.

REFERENCES

Ahmad, M., A. Brooke, and Gary P. Kutcher, 1990, Guide to the Indus Basin Model Revised, The World Bank, Environment Operations and Strategy Division.

Ahmad, M., Gary P. Kutcher, 1992, Indus Basin Model III, Preliminary Discussion and results from the 1990 Base Case, Paper on Water Shortages and Surpluses in the context of the Ranking Study on New Irrigation Projects.

Ahmad, M., Gary P. Kutcher, 1992, Irrigation Planning with Environmental Considerations: A Case Study of Pakistan's Indus Basin. World Bank Technical Paper No. 166, Washington, D.C..

Ahmed, B., M. R. Chaudhry and M. A. Hamid, 1988, Role of Industrial Wastes in Soil Reclmamation. Proceedings of the Second national Congress of Soil Siences, Faisalabad, pp. 43-48.

Aslam, M. 1994, Summary Report on Research Activities and their Findings for the Waterlogging and Salinity Project, Phase-I, IIMI-Pakistan.

Badruddin, M., 1986, Waterlogging and Salinity in Pakistan. ODU Bulletin, July 8-10.

Berry, A. R., W. R. Cline, 1979, Agrarian Structure and Productivity in Developing Countries, Johns Hopkins University Press, Baltimore.

Chaudhry, M. G., M. A. Gill and G. M. Chaudhry, 1985, Size-Productivity Relationship in Pakistan's Agriculture in the Seventies. The Pakistan Development Review, Vol. XXIV, No. 3 & 4, Islamabad.

Chaudhri, M. A., M. Ali, 1989, Economics of Past and Prospective O&M Investment in Different Components of Irrigation System in Pakistan's Punjab. ODI-IIMI, Economic Analysis Network, Paper No. 89, Islamabad.

Deolalikar, A. B., 1981, The Inverse Relationship Between Productivity and Farm Size: A Test Using Regional Data from India. American Journal of Agricultural Economics, Vol. 63, No. 2, pp. 275-279.

Government of Pakistan, 1996, Pakistan Economic Survey 1995-96, Finance Division, Economic Advisor's Wing, Islamabad.

Government of Pakistan, 1994-95, Agricultural Statistics of Pakistan, Food and Agriculture Division, Ministry of Food, Agriculture and Cooperatives, Islamabad.

Government of Pakistan, 1991, Federal Planning Cell, Water Sector Investment Planning Study, Main Volune.

Government of Pakistan, 1981, Pakistan System Analysis Approach to Management of Water Resources in Indus Basin, A Paper for Working Group Meeting during XIth ICID World Congress.

Hallam, A., 1991, Economics of Size and Scale in Agriculture: An Interpretive Review of Emperical Measurement. Review of Agricultural Economics, Vol. 13, No. 1.

Hussain, N., G. D. Khan, 1988, Effect of Amendments with and without Farmyard Manure on the Restoration of Physical Properties of Sodic Soils, Annual Report 1987-88, Soil Salinity Research Institute, Pindi Bhattian, pp. 62-67.

INTERCOMP Resource Development and Engineering, Inc., 1976, A model for calculating Effects of Liquid Waste Disposal in Deep Saline Aquifers, Part I: Development, and Part II: Documentation. U.S. Geological Survey Water-Resources Investigations Report 76-61. 253p.

Irrigation, Drainage and Flood Management, 1979, Volume II, Supporting Report to the Revised Action Programme, Master Planning and Review Division, WAPDA, 1979.

Irrigation, Drainage and Flood Control Research Council, IDFCRC, 1975, International Conference on Waterlogging and Salinity. Country Report, Pakistan.

Jilani, G., A. Rustam, A. Cheema, and M. Saleem, 1987, Efficiency of Manuring under Brackish Water Irrigation for Wheat and Maize Crops, Soil Salinity Research Institute, Pindi Bhattian.

Khan, M. H., A. H. Akbari, 1986, Impact of Agricultural Research and Extension on Crop Productivity in Pakistan, World Development, Vol. 14, No. 6, pp. 757-762.

Khan, M. H., A. H. Akbari, 1981,

Kijne, J. W., Vander Velde, E. J., 1991, Secondary Salinity in Pakistan---Harvest of Neglect, IIMI Review, 5(1):15-16.

Kijne, J. W., E. J. Vander Velde, 1992, Salinity in Punjab Watercourse Commands and Irrigation Systems Operations: The Imperative Case for Improving Irrigation Management in Pakistan. IIMI Discussion Paper No. 2.

Kipp, K.L., 1987, A Computer Code for Simulation of Heat Transport and Solute Transport in Three-Dimensional Groundwater Flow Systems. U.S. Geological Survey, Water Resources Investigations Report 84-4095, Washington, D.C..

McWhorter, D.B., 1980, Summary of Skimming Well Investigations. Water Management Technical Report No. 63, Colorado State university, Fort Collins, Colorado.

Mujeeb, F., M. S. Dogar and M. Younis, 1989, Efficiency of Graded Doses of Gypsum in Saline Sodic Soil Using Different Methods of Application, Annual Technical Report, Soil Salinity Research Institute, Pindi Bhattian, pp. 42-43.

Mustafa (1991)

PC-II Proforma for System Management through Modeling, 1979, System Analysis Organization, Perspective Planning Division, WAPDA, Lahore, November,1979.

Reilly, T.E., A.S. Goodman, 1987, Analysis of Saltwater Upconing beneath a Pumping Well. Journal of Hydrology 89:169-204..

Sahni, B.M., 1972, Salt Water Coning beneath Fresh Water Wells. Water Management Technical Report No. 18, Colorado State University, Fort Collins, Colorado.

Siddiq, A., 1994, Sustainability of the Indus Basin: Impact of Tertiary Salinity/ Sodicity on Wheat Productivity, Damage Assessment and Future Public Policy, Ph.D. Dissertation, University of Illinois, Urbana-Champaign.

Usman, M., 1991, Economic Impact of Land Degradation (Waterlogging and Salt Affected Soils) on Rice Production in Pakistan's Punjab. Ph.D. Dissertation , University of the Phillipines at Los Banos.

Vander Velde, E. J., R. L. Johnson, 1992, Tubewells in Pakistan Distributary Canal Commands, Lagar Distributary, Lower Chenab Canal System, Punjab. IIMI Working Paper 21.

Vander Velde, E. J., J. W. Kijne, 1992, Salinity and Irrigation Operations in Punjab, Pakistan: Are there Management Options? Proceedings of the Workshop on IIMI-India Collaborative Research in Irrigation Management, New Delhi, pp. 205-237.

Wang, H.F., M.P. Anderson, 1982, Introduction to Groundwater Modeling Finite Difference and Finite Element Methods, W.H. Freeman, San Francisco, California. 237 p.

Water And Power Development Authority, 1979, Irrigation, Drainage and Flood Management Report. Revised Action Plan, Vol. 2, Lahore.

Water Resource Management Directorate, 1994-95, Indus Basin Irrigation System, Historic Rivers and Canals Discharge Data, Planning Division, WAPDA.

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