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WATERLOGGING AND SALINITY MANAGEMENT IN THE SINDH PROVINCE, PAKISTAN

VOLUME THREE

STRATEGY FOR RESOURCE ALLOCATIONS AND MANAGEMENT ACROSS THE HYDROLOGICAL DIVIDES

Abdul Rehman
Gauhar Rehman

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INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
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WATERLOGGING AND SALINITY MANAGEMENT IN THE SINDH PROVINCE

Volume III

Strategy for Resource Allocations and Management Across the Hydrological Divides

I INTRODUCTION

This study is part of an integrated assessment aimed at the remediation of the threat of waterlogging and salinity in the province of Sindh. The emphasis remains on non-capital intensive strategies that harken management-led reforms across the hydrological divides. This study, utilizing a digital modeling approach towards the determination of both ground and surface water balances, foresees adjustments to the cropped areas and yield growth rates as a balancing act between optimum crop production without the nemesis of environmental degradation. Such environmental safeguards are essential to the peculiar, but stable, cropping patterns that have emerged throughout the province. Recurrent emphasis on high consumptive use crops has grossly disturbed the groundwater balance across much of the irrigated areas in the Sindh province to an extent whereby many of the deep-rooted crops like cotton and wheat have been replaced by rice and sugarcane. This has further compounded the already derelict situation for equity of surface water supplies, especially during the early Kharif season. Accordingly, remedial measures must concentrate on altering the water use patterns and demands that account for the existing canal capacities; provision of additional supplies is a politically sensitive issue that will entail high capital costs. The digital model used in this study has been useful to the extent that it has allowed projection of simulation results to the year 2010 that compare increased water availability (through Water Apportionment Accord), canal lining of saline groundwater zones and changes to the cropping patterns across the agro-climatic divides.

Much of the discussion in this supplement is specific to the canal commands since it is at this level the interventions suggested in the study could be implemented. The area and yield growth rates, however, have been specified separately for each of the four agro-climatic zones containing whole, or part, of the canal commands. The results have been projected to the year 2010 in an effort to synchronize the findings to the projections already made in the past in lieu of the targets set aside in the Water Sector Investment Planning Study completed at the beginning of the decade, and also the potential requirements for crop growth and yield increases as set aside in the recommendations of the National Commission of Agriculture.

The province of Sindh has a total area of 14,091 Million Hectares (Mha) of which 5,786 Mha are cultivated and another 1,388 Mha are classified as culturable waste. The remainder is arid and used mostly as pasture land. The area of Sindh is irrigated through fourteen (14) canal commands offtaking from the Guddu, Sukkur and Kotri Barrages on the river Indus, with a cumulative Culturable Command Area (CCA) of 5,098 million ha.

The underground water in Sindh at most places (89%) has been found to be brackish (TDS > 3000 PPM according to WAPDA classification) and unfit for irrigation (Table 1).

Table 1. Culturable Command Area by Groundwater Quality in Thousand Hectares.

	Fresh	Saline	Total CCA
	157.824		157.824
Begari Feeder	170.369	170.369	340.738
Ghotki Feeder	184.128	184.128	368.256
North West Canal	46.376	262.968	309.174
Rice Canal	46.206	163.822	210.028
Dadu Canal	39.173	205.657	244.830
Khairpur West Canal	195.459		195.459
Khairpur East Canal		182.510	182.510
Rohri Canal	574.906	470.377	1045.283
Nara Canal		882.603	882.603
Kalri Begar Feeder		257.375	257.375
Lined Channel		220.145	220.145
Fuleli Canal		360.568	360.568
		323.338	323.338
Sindh Total	574.906	2696.916	5098.131

A. STUDY OBJECTIVES

By virtue of the capabilities of the model to simulate larger areas, the IBM-III has been selected for use as a tool for analysis of performance of irrigated agriculture by canal command through agricultural modeling techniques, to fulfil the following objectives:

- To ascertain subsystem-wide (canal command level) adequacy of irrigation supplies for sustainable agriculture production.
- To predict long term impact of remedial measures on agricultural production.
- Iterative determination of the non-degrading water balance (surface and groundwater) conditions at the root zone based on changes in the cropping pattern.

B. THE INDUS BASIN MODEL REVISED

The Indus Basin Model Revised (IBMR) is a hydrologic and agro-economic optimization model developed by the Development Research Centre of the World Bank for use by WAPDA to facilitate large scale planning and investigation studies specific to water and land resources. The model development efforts were initiated in 1976, whereby innumerable computer algorithms, written in the General Algebraic Modeling System (GAMS) language, linked the hydrologic details of the Indus Basin conjunctive stream aquifer system with an economic model of agricultural production based on farm level activities. The model was partitioned into nine agro-climatic zones (ACZ) representing the Indus Basin, together with a network model of the entire irrigation system. Both, linear and non-linear programming algorithms can be used for the solution of optimal problems relating to cropping and livestock activities at the zonal and national levels against different resource constraints. The objective function of IBMR is the

maximization of the production surpluses against costs, plus the value of exports less the cost of imports.

The IBMR was updated and streamlined according to 1988 conditions and subsequently transferred to WAPDA in 1989, ahead of the Water Sector Investment Planning Study (WSIPS). Here, the model was extensively used to evaluate the minimum and maximum plans for different water sector development scenarios leading to the year 2000. Further revisions to the model in 1992 resulted in the IBM-III that was deployed towards a ranking study of new irrigation projects in the aftermath of the Water Apportionment Accord. This latest revision not only increased the ACZs from 9 to 12 for greater conformity with the provincial boundaries, but also, the size of the model was reduced to 2000 equations and 5000 variables (after deleting some constraints relating to labor, tractor and livestock). The objective function targeted the value-added returns in terms of economic prices, considered to be the lynchpin in measuring the economic performance of development projects.

For the current study, limited to the province of Sindh, the IBMR retains four ACZ-based delimitations (RAP, WAPDA) that are peculiar to the local climatic conditions, agricultural practices and cropping patterns covering the over 6 Mha of gross canal commanded area served by 3 major barrages of Guddu, Sukkur and Kotri, all located on the river Indus (Annexure -A). For the ACZ-based simulations of the IBMR, necessary modifications were incorporated in the model programs in GAMS so that the zonal models could be run with the surface water network model (SWM) of the Indus Basin Irrigation System (IBIS); for the fourteen major canal commands, the results were to be obtained according to areas of groundwater quality (fresh and saline). This was achieved through weighting factors provided in the model based on ACZ-canal-subarea (fresh or saline) CCA mapping.

For the study, the model updates available against the WSIP ranking studies were used as a base for diverse inputs relating to agronomy, agricultural economics, surface and groundwater hydrology, reservoir and canal system operation, project planning characteristics, availability of resources, etc. For the year 1995-96 (coinciding with the initiation of the study), efforts were made to update the data as much as possible according to the availability and volume of data, as well as the time schedule of the study. The data updates are described below.

1) Agricultural Data

The agricultural input coefficients, like seed, fertilizer, crop water requirements, draft power, tractor and labor, etc. are based on the 1976 Extended Agricultural Economic survey (XAES) and the Farm Survey of 1988. These coefficients have remained unchanged for the study. The cropped area statistics, by canal command, were collected from the respective Chief Engineers of the Sindh Irrigation and Power Department; however, the data pertaining to crop production and average yield was updated from the district-wise records published by the Bureau of Statistics, Government of Sindh, for the year 1994-95 and the Ministry of Food and Agriculture, Govt. of Pakistan, for the year 1995-96. The district-wise data was converted to the respective ACZs according to the

district-to-ACZ mapping. Moreover, the crop yield data of some major crops, as collected by IIMI-Pakistan sample field surveys during the course of this study, was also used.

2) River and Tributary Inflows

The river flows data was collected from the Water Resource Management Directorate, Planning Division, WAPDA, as published in the report on the Indus Basin Irrigation System, Historic Rivers and Canals Discharge Data. The average and 80 percent probable inflows at rim stations (Indus at Tarbela, 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 up to 1995-96. Similarly, the historic river flows at different headworks/barrages of the Indus Basin Irrigation System were updated for the water year 1995-96 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 was also obtained from WAPDA (see publication above) for the period 1990-91 to 1995-96, whereby monthly and seasonal average post-Tarbela historic canal diversions covering the period 1976 to 1996 were computed. The daily actuals for canal operations were collected from the office records of the respective Chief Engineers of the Irrigation and Power Department, Sindh Province, for the year 1995-96, and subsequently converted to monthly and seasonal totals. These two sources of data allowed for the comparison of the actuals and the indented values.

4) Agro-Economic Data

The economic data includes the financial and economic prices of crop and livestock commodities and their by-products, miscellaneous inputs for crop production, O&M of private tubewells and tractors, farm labor wage rates, etc. These data were updated for the financial year 1995-96.

5) Projects Information Data

The public sector projects affect several aspects of the IBIS, like increasing canal command area (CCA), canal capacities, storage capacities, improving canal and farm level delivery efficiencies and watertable depths. 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 contingent information on public sector projects is based on the information provided by the World Bank was adopted in the IBMR.

6) Resource Inventory Data

The resources (except water) include farm households, farm workers, number of private tubewells and tractors, livestock population, etc. and their respective growth rates. This information is usually listed in the agriculture census or agro-economic farm surveys conducted by the government. The most recent update to this information, based on the Agriculture Census of 1990, has been incorporated by the World Bank in the IBM-III.

The data pertaining to private tubewells and tractors was updated from the Census of Agricultural Machinery, conducted by the Agricultural Census Organization during 1994.

7) Validation and Calibration

When a model is first constructed, or is substantially revised, it must be validated against the available data to ensure that it simulates the actual conditions with respect to the critical variables and constraint patterns before it is used to simulate policy and project options. The IBM-III has been extensively validated in respect of cropping pattern, crop production, canal diversions, etc. in the context of the ranking studies during 1992 and on the basis of the Agricultural Census conducted during 1990. Obtaining a close cropping pattern "fit" is extremely important when addressing water-related issues because water requirements differ widely among crops. The model was validated according to the actual cropped area and canal diversions for the year 1995-96, and the growth rates for crop area and yields were determined for the period 1991-1996.

8) Evaluation of Canal Command System Performance

To assess the performance of irrigated agriculture during the 1990-96 period under the canal commands of the irrigation system in the Sindh Province, the model results of the following variables on that canal command level, for the years 1989-90 and 1995-96, were used as a basis for comparison:

- Cropping intensity and average crop yield;
- Canal water diversions at canal head;
- Crop water requirements and supplies at root zone; and
- Groundwater inflows and outflows

The model results for these variables are compared for the years 1990 and 1996. The 1990 base year represents the situation in the context of the CCA, canal capacities (CCAP), irrigation system efficiencies, etc. as established under the Revised Action Plan (RAP) by WAPDA, and consequently formed the basis for the Water Sector Investment Plan (WSIP) related structural adjustment programs in the agriculture sector.

a. Cropping Pattern

The total area under different crops irrigated by all canals during 1989-90 has been reported as 3,41 Mha, with 55 percent in Rabi and 45 percent in Kharif seasons; the annual cropping intensity being 68 percent. The total cropped area reported by the Irrigation and Power Department of Sindh for the year 1995-96 is 3,49 Mha, with 45 percent in Rabi and 55 percent in Kharif seasons. Intensity-wise, there has been an overall annual increase of 2 percent during a six year period, with an increase of cumulative CCA from 5,022 Mha to 5,098 Mha. The seasonal cropping intensities across the hydrological divides have been illustrated in Figure 1, which shows that the Rabi cultivations have mostly decreased, whereas the Kharif cultivations are on the increase (except in the commands of Ghotki, Dadu, Khairpur West and East Canal systems). This is most significant for the rice crop, a principal contributor to the seasonal rise of groundwater levels in the Sindh Province. The change in the CCA of each canal

command, with a corresponding change in area under major crops of wheat, rice, cotton and sugarcane, is shown in Figure 2. The CCA of all canals has increased, except, the Begari Feeder, North West and Fuleli Canals; no change has been reported in the CCA of the Rice Canal command. The area under wheat and cotton has decreased in seven out of the fourteen canal commands, whereas there has been a tremendous increase in the area under rice crop across much of the commanded regime. The increase in the area under rice may partly have been responsible for the reduction in area observed for the sugarcane crop across all canal commands, except Dadu, Rohri and Lined Channel (Akram Wah) Canals, where the acreage has, instead, increased.

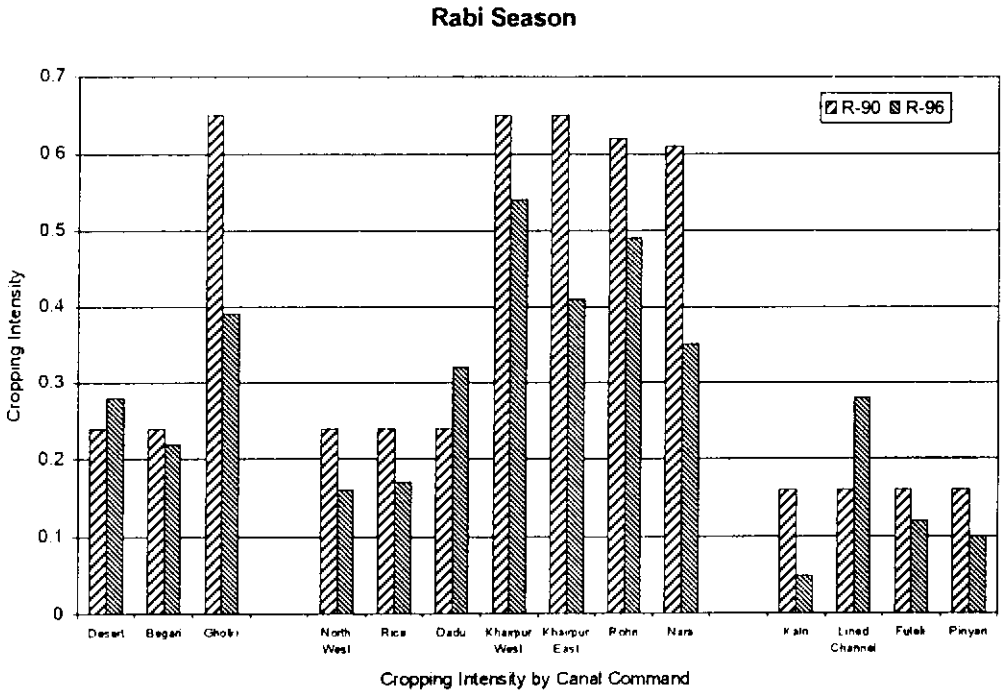
b. Crop Production and the Average Yields

The actual and simulated production of major crops (wheat, cotton, rice and sugarcane) for the year 1995-96 is shown in Figure 3. Figure 4 draws the comparison for the same major crops, but for the yield changes between 1990 and 1996; the average yield of rice has decreased from 2 percent to 32 percent in Ghotki, Desert, Begari and Rice Canal commands, whereas all other commands are showing an increasing trend from 21 percent to more than double the figure of 1990. The yield of cotton has declined only in Dadu and Kalri Canals (26% and 41%, respectively), whereas the remainder is showing an increasing trend. The yield of sugarcane is reported to be decreasing throughout the Kotri Barrage command from 8 percent to 10 percent. A substantial decline of up to 23 percent in yield has also occurred within the Begari Canal command. All other canal commands are showing an increasing trend, from 5 percent to 63 percent.

The yield of wheat, a major food grain crop, has decreased across the Desert (33%), Begari (6%), Dadu (40%), Khaipur West (30%), Rohri (36%), Nara (10%), Lined Channel (59%) and Fuleli (52%) canal commands; the remainder of the Sindh canal commands are showing an increase in average yield from 4 percent to 43 percent.

c. Canal Water Diversions at Canal Head.

The total annual canal diversions at canal head during 1995-96 were 5,221 Mhm (Rabi 33.6% and Kharif 66.4%) when compared to 5,412 Mhm in 1989-90 (Rabi 33.9% and Kharif 66.1%). The annual supplies to Sindh canals have decreased by 4 percent during this time, with some improvement reported for the Rabi season (0.3%). The graphical summary is shown in Annexure-B, together with the Water Apportionment Accord allocations. A decreasing trend in water diversions to the Indus Right Bank canals could be observed, except for the non-perennial Rice Canal, where there has been an improvement during the Kharif season of 1995-96. The Indus Left Bank canals, offtaking from the Guddu and Sukkur Barrages, show an increasing trend in supplies during the late Kharif and early Rabi crop seasons, the exception being the Ghotki Canal, where the water supplies have decreased throughout the year. The diversions during late Kharif and early Rabi are exceeding those apportioned under the Accord, a phenomenon also observed for the canals offtaking from the Kotri Barrage.



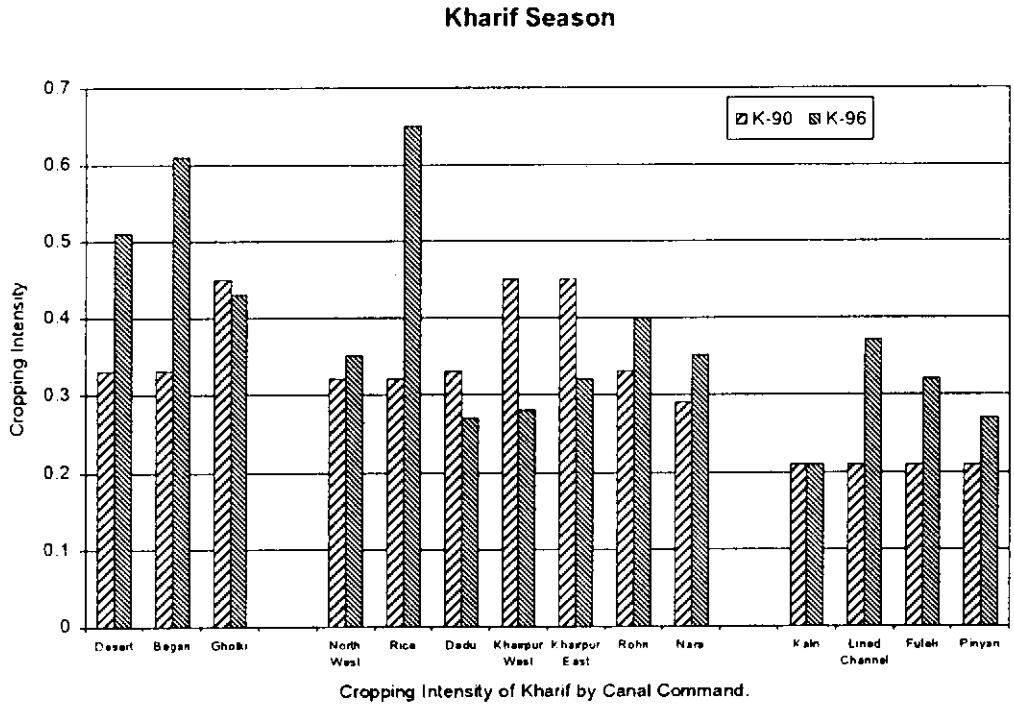


Figure 1. Comparison of the Cropping Intensity for the Years 1990 and 1996 within the Lower Indus Basin Canal Commands.

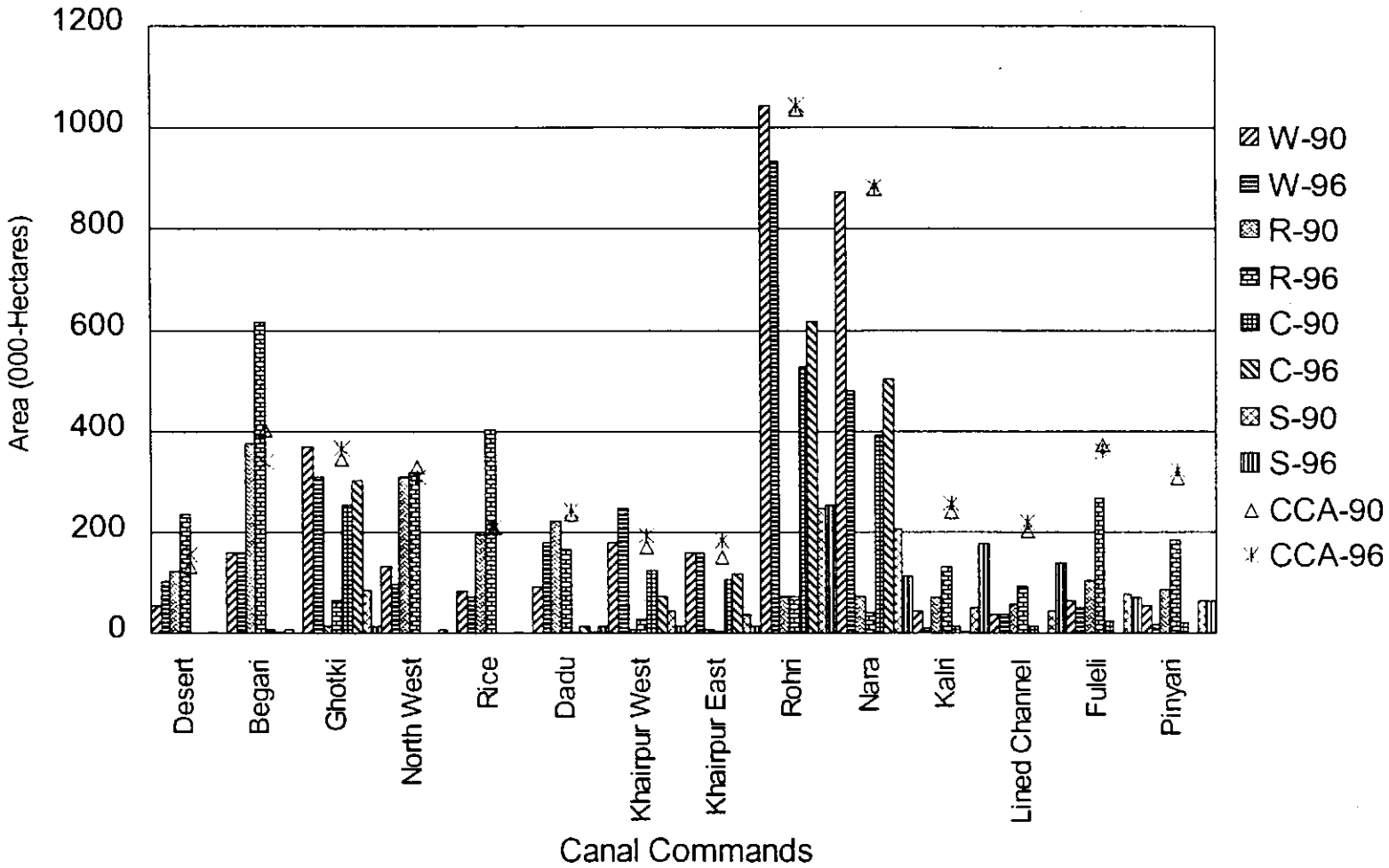


Figure 2. Comparison of CCA and Area under Major Crops during 1990 and 1996, Lower Indus Basin Canal Commands.

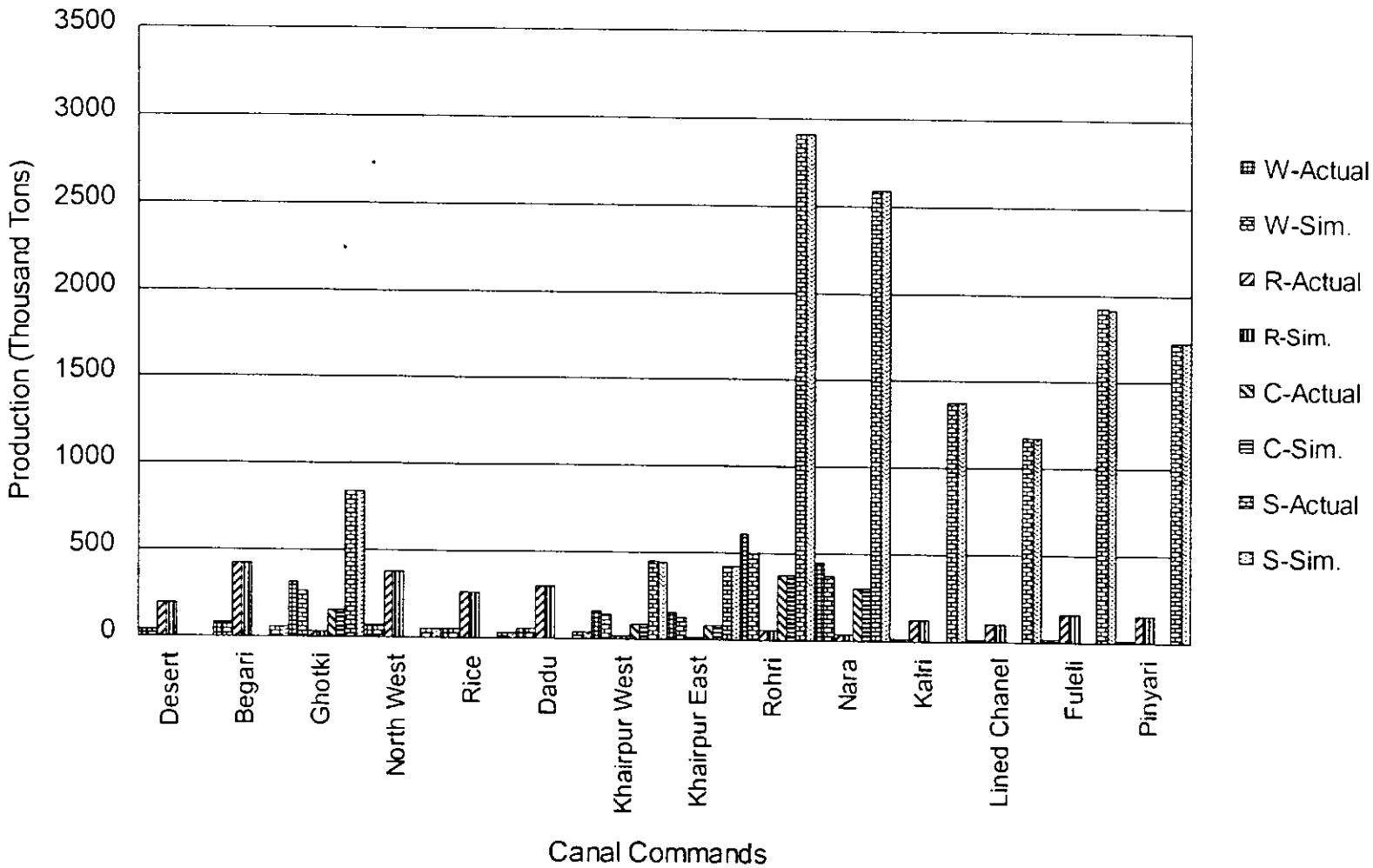


Figure 3. Comparison of Actual and Simulated Production of Major Crops for the Year 1995-96 in the Lower Indus Basin Canal Commands.

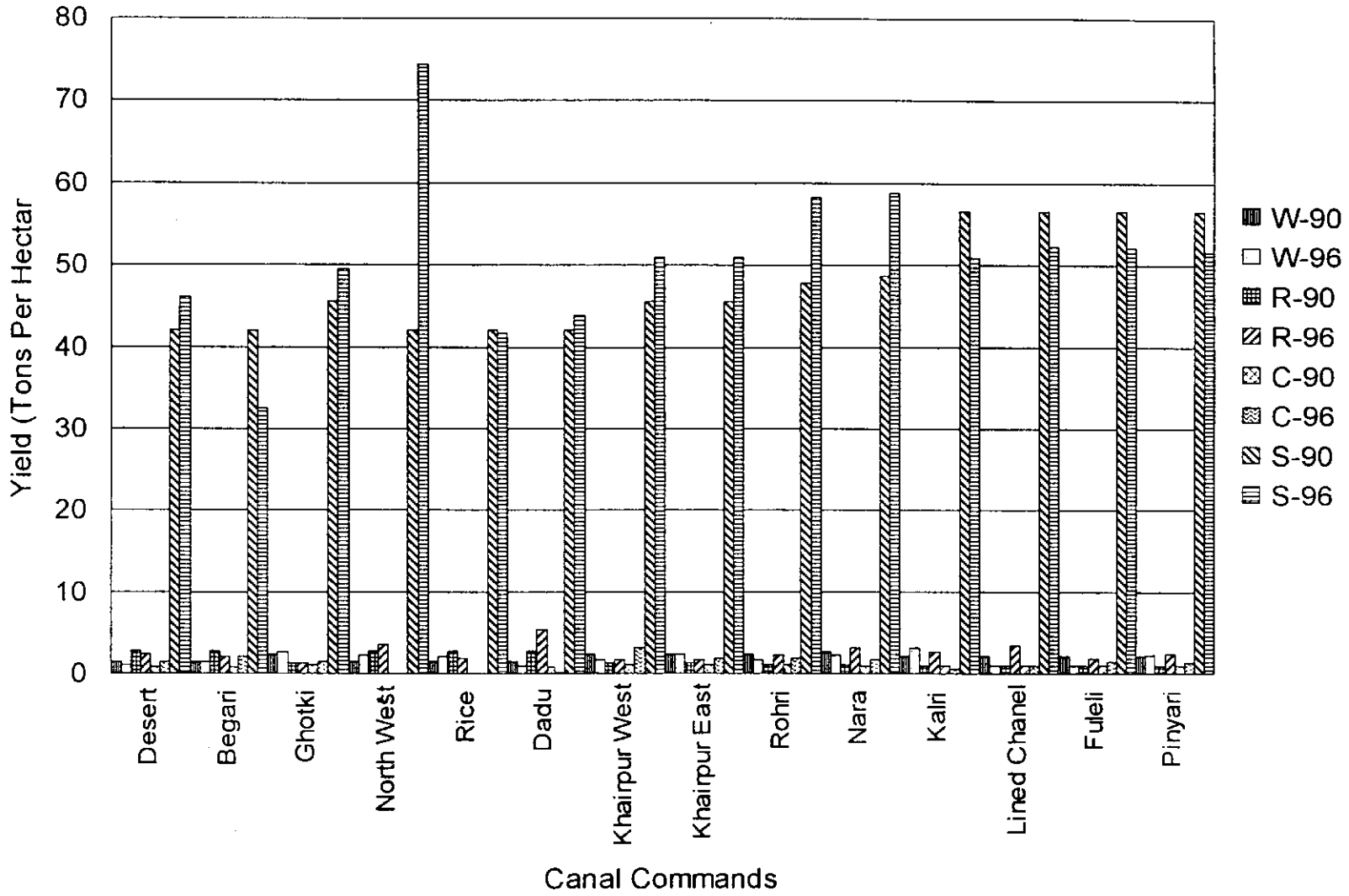


Figure 4. Comparison of Average Yield of Major Crops during 1990 and 1996 in the Lower Indus Basin Canal Commands.

d. Crop Water Requirements and Supplies at Root Zone

The water shortages or surpluses are derived through water balance computations at the root zone, where the water requirements are met from supplies through surface water sources (canal and rainfall) and the groundwater sources (pumpage from tubewells and sub-irrigation through capillary action). A comparison of water requirements and supplies at the root zone, for the years 1990 and 1996, is illustrated in Figure 5, wherein the total annual water requirements have increased by 5 percent (2,64 to 2,77 Mhm). Internally, this increase is adjusted as a 26 percent increase during Kharif and 21 percent decrease in the Rabi (see Figure 1). Similarly, the total water supplies have decreased by 8 percent (1,0026 to 0,9175 Mhm) during Rabi and increased by 2 percent (19,964 to 20,356 Mhm) during Kharif; overall, there has been an annual decrease of 1.5 percent (2,999 to 29,531 Mhm) due to the decrease in supplies from public tubewell pumpage during the Rabi season. Figure 5 also illustrates the contribution and trend of different water supply sources, like canal water (73 to 78% in Rabi and 80 to 83% in Kharif), groundwater (5 to 7% in Rabi and 1 to 2% in Kharif), rainfall (2 to 3% in Rabi and 6 to 8% in Kharif) and sub-irrigation (15 to 17% in Rabi and 10 to 12% in Kharif).

Province-wide, during 1991-96, shortages during the Rabi season have decreased by 96 percent and the total surpluses during the Kharif season have also decreased by 64 percent. This is due to changes in cropping intensity, which has decreased during Rabi and increased during Kharif seasons, with corresponding increases in canal supplies during Rabi and decreases during Kharif.

The canal command-wise comparison of net water requirements (crop water requirements besides rainfall and sub-irrigation) and water supplies (canal supplies and pumpage from tubewells), for the years 1990 and 1996, has been illustrated in Figures 6a and 6b for Rabi and Kharif seasons. For both time periods, Rabi shortages are persistent across all canal commands, except Dadu and North West Canals (on the Right Bank); contrastingly, the Kotri Barrage commands are showing surplus water, which is due to lower cropping intensities during Rabi.

During Kharif, water supplies are more than the demands for all the canals, except Dadu, North West and Khairpur West Canals. The Nara Canal and the Lined Channel have lost their surpluses during 1995 due to increases in area under cotton in the former, and sugarcane in the latter (Figure 7).

e. Groundwater Inflows and Outflows

The groundwater balance is the measure of imbalance between inflows through recharge to the aquifer system from different seepage sources, like irrigation canals, watercourses, farm fields, link canals, rainfall, rivers, etc. and outflows in the form of extractions from the subterranean aquifer through tubewells and evaporation from the groundwater surface. The recharge to the groundwater reservoir from different sources of percolation cannot be measured directly; but rather, can be estimated indirectly from the equation of hydrological equilibrium, which is based on the theory that a balance must exist between the quantity of water entering any given area and the amount stored within or leaving the same area for any period of time. These groundwater balance equations can be expressed as under:

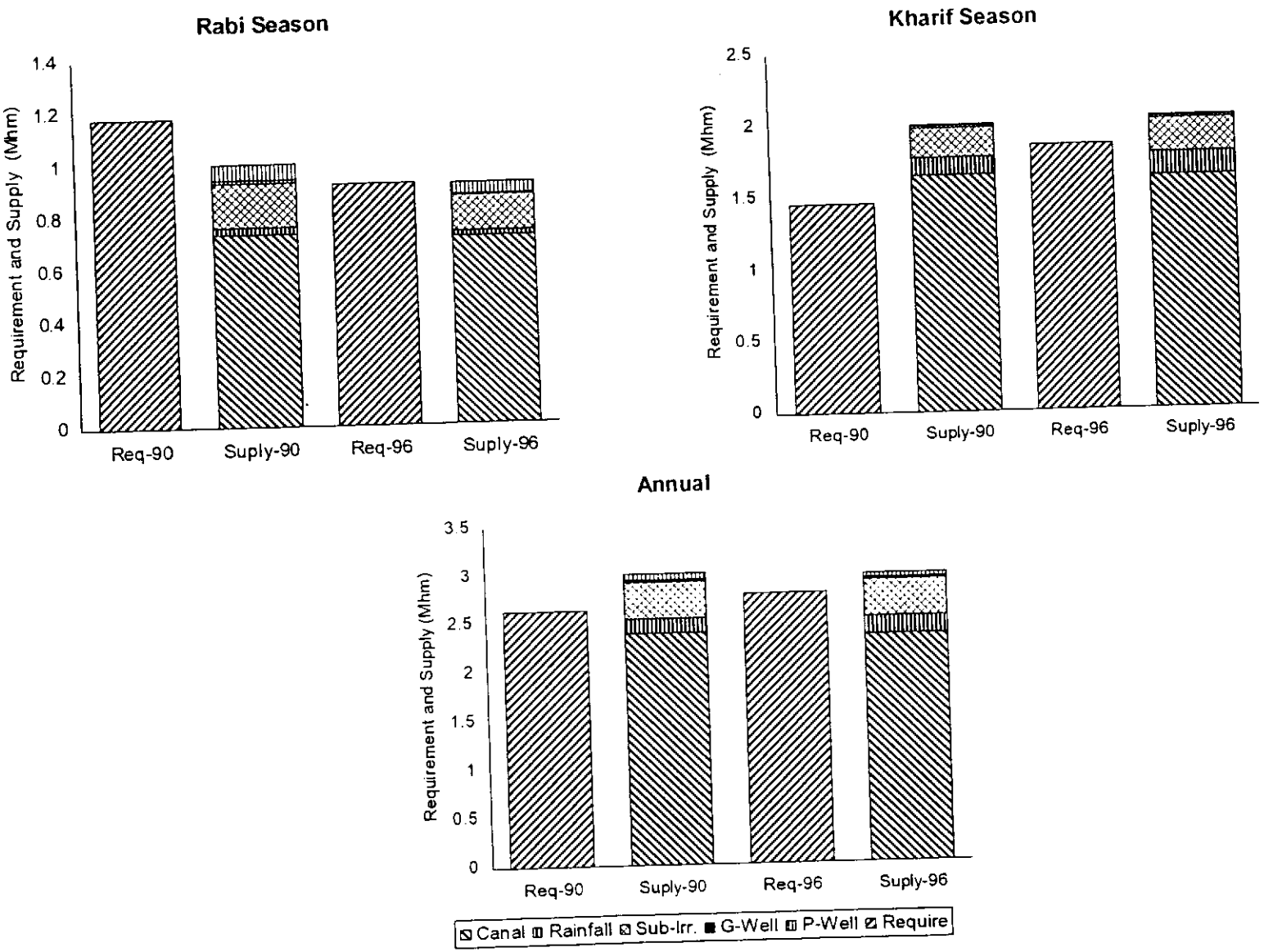
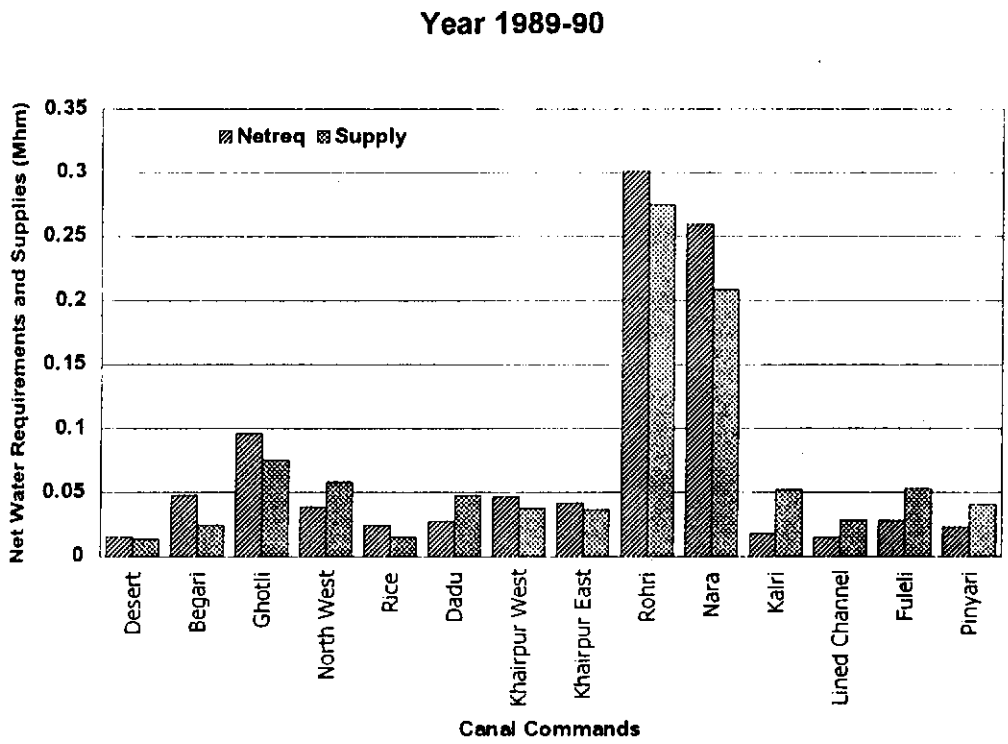


Figure 5. Comparison of Seasonal Surface Water Balance at Root Zone for the Years 1990 and 1996, within the Lower Indus Basin Canal Commands.



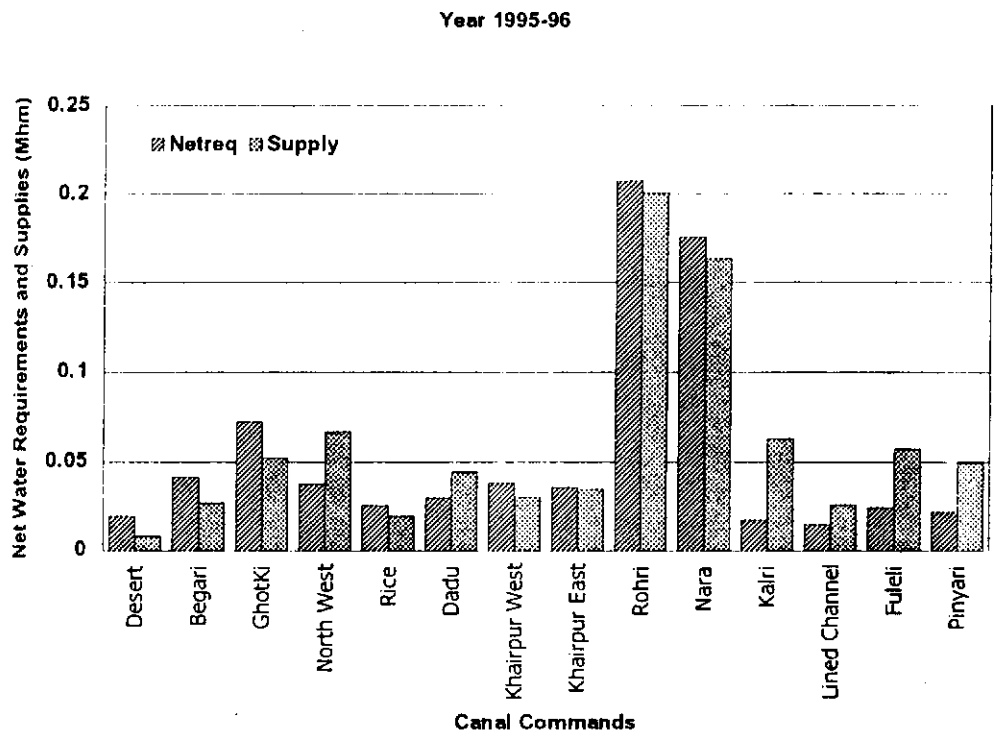
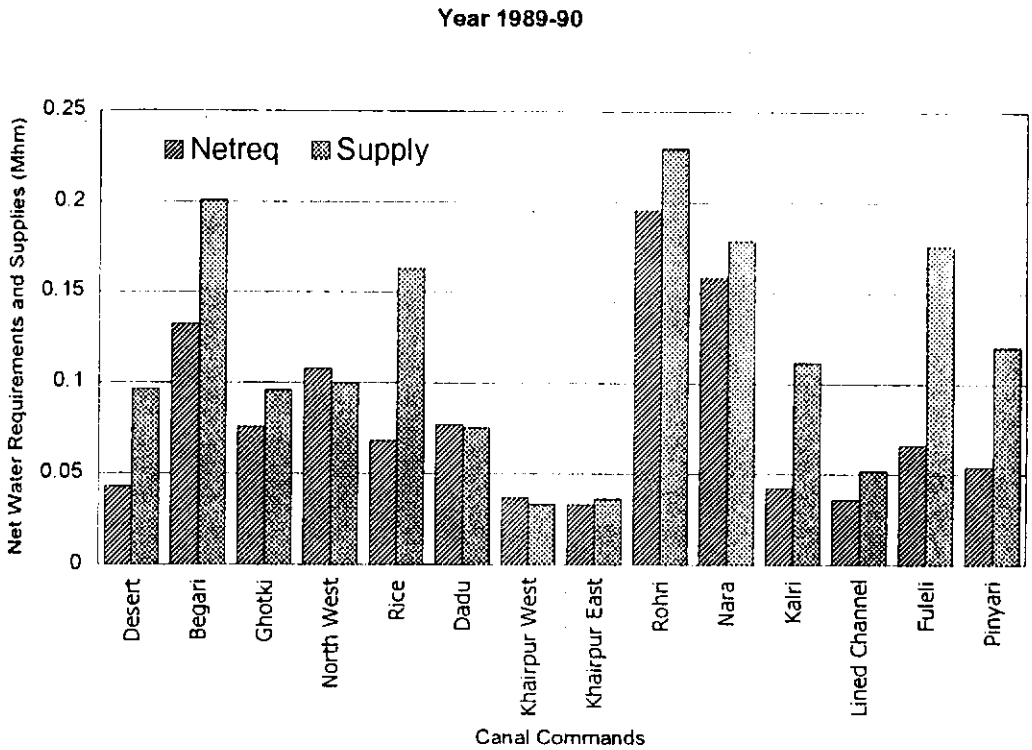


Figure 6a. Comparison of Net Water Requirements and Supplies at Root Zone by Canal Command during Rabi Season for the Years 1990 and 1996, Lower Indus Basin.



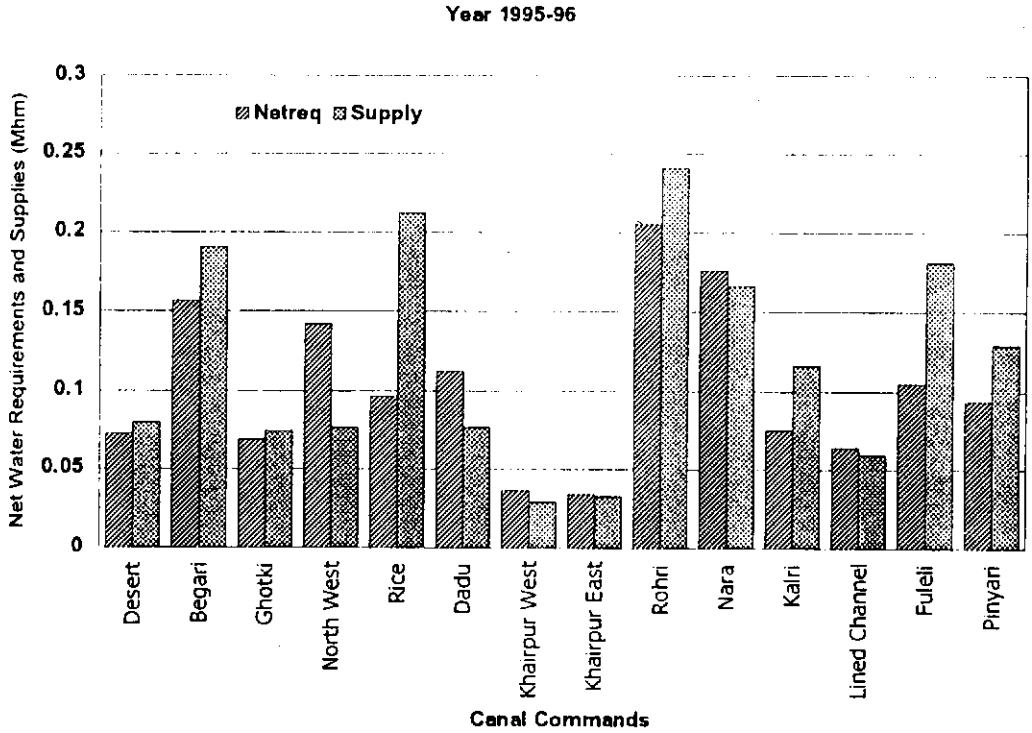
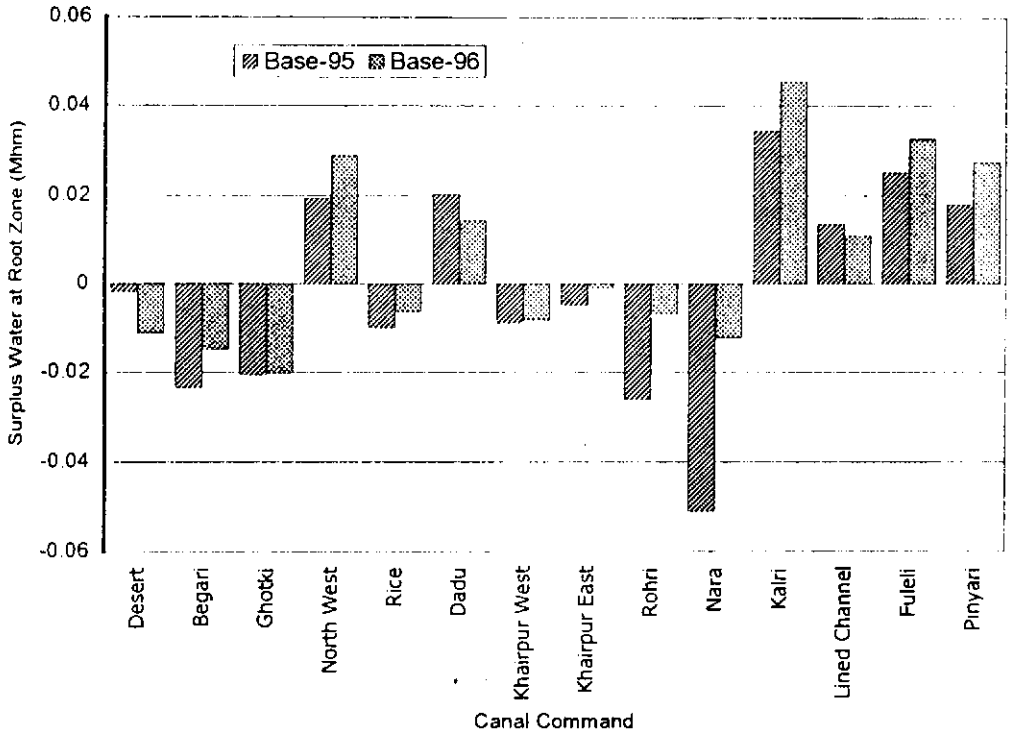


Figure 6b. Comparison of Net Water Requirements and Supplies at Root Zone by Canal Command during Kharif for the Years 1990 and 1996, Lower Indus Basin.



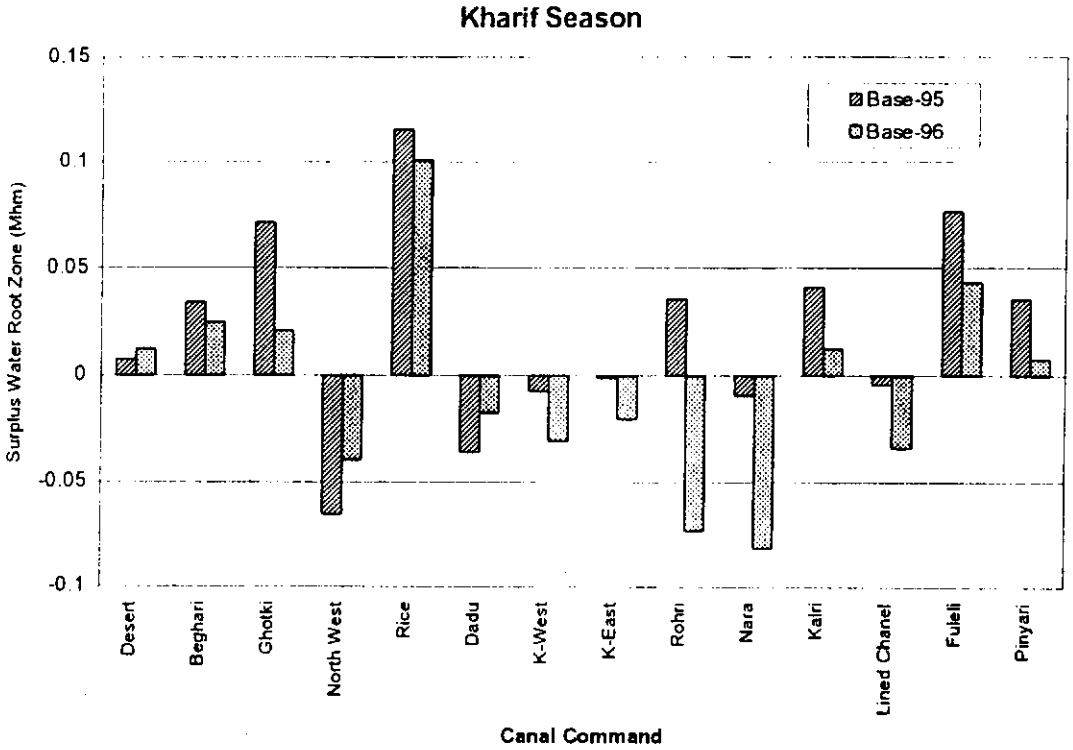


Figure 7. Comparison of Seasonal Surplus and Shortage of Water at Root Zone for the Years 1990 and 1996 by Canal Command.

Recharge to the groundwater:

Fresh Areas: $TR = R_r + R_c + R_w + R_p + R_i + R_t$ **(Eq. 1)**

Saline Areas: $TR = R_r + R_c + R_w + R_p + R_i$ **(Eq. 2)**

Discharge from the groundwater:

Fresh Area: $TD = D_e + D_t + D_x$ **(Eq. 3)**

Saline Areas: $TD = D_e + D_d + D_x$ **(Eq. 4)**

Groundwater balance:

$\Delta S = TR - TD$ **(Eq. 5)**

Watertable depth (meters):

$WTD_t = WTD_{t-1} + (\Delta S / A^g) / c$ **(Eq. 6)**

Where;

- R_r recharge from river seepage;
- R_c recharge from canal seepage;
- R_w recharge from watercourses and farm fields;
- R_t recharge from tubewell operations (R_{gt}-government + R_{pt}-private);
- R_i recharge from lateral flows from adjacent areas;
- R_p recharge from precipitation; and
- **TR** total recharge.
- D_e discharge from evaporation and subirrigation;
- D_t discharge from tubewell withdrawals (D_{gt}-government + D_{pt}-private);
- D_d discharge from subsurface drainage (subsurface drainage in saline areas);
- D_x discharge from lateral flows to adjacent areas;
- **TD** total discharge;
- ΔS change in volume of groundwater aquifer; and
- A^g the gross area and c is the storage coefficient.

Based on previous studies conducted by WAPDA across the Indus Plains, it is assumed that 70 percent of the water lost in the canal conveyance system, (R_c) contributes to the groundwater. Similarly, the contribution of recharge from watercourses, farm fields and rainfall (R_w and R_p) are 80 percent of the losses occurring through these sources (World Bank). These recharge parameters vary according to the mode of system operation, physical characteristics of the area affecting the seepage factors and the climatic conditions, and can be improved through system rehabilitation (canal lining, watercourse improvement, etc.).

Rt, the sum of Rgt and Rpt, depend directly on the level of tubewell operations in fresh groundwater areas only. Rpt is determined endogenously within the model as a function

of private investment in tubewells installation, whereas Rgt is given exogenously in the model as the function of investment in public sector. The seepage losses from public tubewell water are computed similar to that for canal water. The private tubewells are assumed to be closer to the fields where the water is used and the watercourse losses, therefore, are halved, but the same field losses are assumed.

The recharge from the river (Rr) is determined from the estimates of river losses and gains computed by the model endogenously through river routing for each of the river reaches. The losses contributing to groundwater are computed from the river reach, corresponding to the ACZ and canal command mapping provided in the model. The contribution of recharge (annual) from various sources, as computed by the model for each canal command, is given in Table 2 and illustrated in Figure 8 by areas of groundwater quality for the years 1990 and 1996.

Table 2. Contribution of Recharge to Groundwater from Various Sources (%).

(Right Bank Canals offtaking from Sukkur and Guddu Barrages)

Source of Recharge	Fresh Groundwater Areas	Saline Groundwater Areas
Rain	2	2
Private Tubewells	1	-
Government Tubewells	<1	-
Canals	30	32
Watercourses and Fields	60	60
Rivers	6	6

(Left Bank Canals offtaking from Sukkur and Guddu Barrages)

Source of Recharge	Fresh Groundwater Areas	Saline Groundwater Areas
Rain	2	2
Private Tubewells	4	-
Government Tubewells	4	-
Canals	25	28
Watercourses and Fields	58	63
Rivers	7	7

(Nara Canal and Kotri Barrage canal commands)

Source of Recharge	Nara Canal Command	Kotri Barrage Canal command
Rain	2	2
Canals	27	33
Watercourses and Fields	67	62
Rivers	4	-

The results in Table 2 show that the maximum recharge is from watercourses and farm fields (60%), followed by the irrigation canal network (30%). The contribution of recharge from the Indus River towards its Right Bank is less (< 6%) due to a high watertable forming a fresh water lens along the river bed, when compared to the Left Bank (> 7%). The Nara Canal system is receiving a smaller proportion of river recharge due to a greater distance from the Indus River.

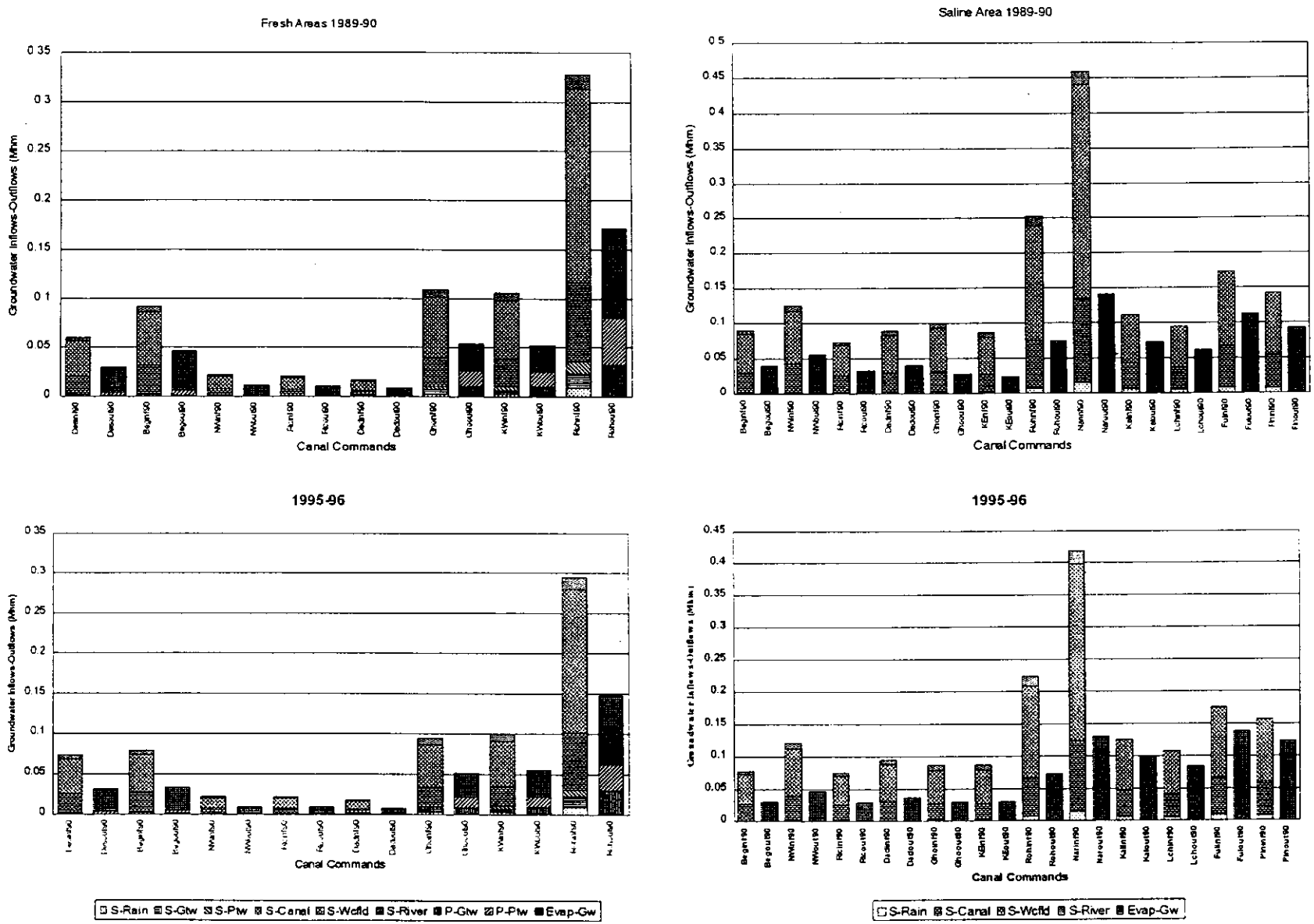


Figure 8. Canal Command-wise Annual Groundwater Balance by Areas of Groundwater Quality for the Years 1990 and 1996, Lower Indus Basin.

From Equations 3 & 4 above, De is the function of the pan evaporation and the watertable depth, whereas Dd depends on the installed subsurface drainage in saline areas and is assumed to equal:

$$D_d = TR - D_e - D_x \qquad \text{(Eq. 7)}$$

De, in this case, is estimated at the watertable depth with the drains installed. The comparison of Equations 4, 6 and 7 reveals that ΔS for areas with subsurface drainage will be zero as any net recharge will be exported as drainage effluent. Similarly, Ri and Dx, the subsurface inflows and outflows from neighboring areas, depend on a host of physical and geological factors in addition to hydraulic head (difference in watertable depth between adjacent areas). These flows must be ignored given the limited scope of this study.

ΔS, the difference between recharges (inflows) and discharges (outflows) in any given period, is of particular interest because, except in drained (saline) areas for which ΔS is zero by assumption (i.e., all net recharge is drained), it determines the change in watertable depth. A positive ΔS indicates progressing waterlogging, and probably salinity, whereas a negative ΔS indicates a falling watertable. The watertable varies considerably during the year, being higher towards the end of Kharif due to higher canal deliveries and rains. This phenomenon of changing watertables, in both fresh and saline areas of Sindh canal commands, has been presented in Tables 3 and 4 for the years 1990 and 1996, which show the mean annual change in storage (as a trend of rising watertables).

Most of the contamination of fresh groundwater areas occurs through lateral movement of saline groundwaters, spurred by differing watertable depths. The higher the head (difference in watertable depth between adjacent fresh and saline groundwater areas), the greater the pressure for lateral movement and more likely, the possibility of occurrence of contamination (assuming no vertical hydrological barriers). Too little is known about these barriers, or the characteristics of groundwater movement to make these predictions.

The water tables are rising, on average, in all canal commands, apart from natural drainage (surface drains and/or nearby passing rivers or creeks). A presumably small and only outlet for positive recharge is evaporation. The watertable, thus, rises to the level where all the recharge is balanced by evaporation, moving substantial quantities of salts to the soil surface, causing salinity.

Table 3. Annual Groundwater Balance by Canal Command for the Year 1989-90 (Mhm).

Fresh Groundwater Areas								
Description	Desert	Begari	North West	Rice	Dadu	Ghotki	Khairpur West	Rohri
Gross Area (Mha)	0.1300	0.2210	0.0660	0.0510	0.0380	0.1910	0.1240	0.6360
Seepage to Groundwater								
Rainfall	0.0012	0.0018	0.004	0.0004	0.0003	0.0023	0.0022	0.0091
Private Tubewells	0.0008	0.0013	0.0003	0.0003	0.0002	0.0044	0.0042	0.0132
Government Tubewells	0.0001	0.0002	0.0000	0.0000	0.0000	0.0044	0.0043	0.0140
Canal System	0.0188	0.0287	0.0070	0.0065	0.0053	0.0286	0.0277	0.0802
Watercourses & Fields	0.0359	0.0548	0.0134	0.0125	0.0102	0.0612	0.0595	0.1971
River	0.0034	0.0053	0.0013	0.0012	0.0009	0.0079	0.0077	0.0142
Total Inflows	0.0602	0.0921	0.0224	0.0209	0.0169	0.1088	0.1056	0.3278
Groundwater Outflows								
Pumpage from Ptw	0.0035	0.0054	0.0013	0.0012	0.0010	0.0159	0.0155	0.0480
Pumpage from Gtw	0.0004	0.0006	0.0001	0.0001	0.0001	0.0104	0.0101	0.0323
Total Pumpage	0.0039	0.0060	0.0014	0.0013	0.0011	0.0263	0.0256	0.0803
Evaporation from G.W.	0.0265	0.0405	0.0099	0.0092	0.0075	0.0274	0.0267	0.0914
Total Ourflows	0.0304	0.0465	0.0113	0.0105	0.0086	0.0537	0.0523	0.1717
Net Recharge	0.0298	0.0456	0.0111	0.0104	0.0083	0.0551	0.0533	0.1561
(Change in Storage)								
Net Recharge Per Hectare	0.2292	0.2063	0.1682	0.2039	0.2184	0.2885	0.4296	0.2454

Saline Groundwater Area												
Description	Begari	North West	Rice	Dadu	Ghotki	Khairpur East	Rohri	Nara	Kalri	Lined Channel	Fuleli	Pinyari
Gross Area (Mha)	0.2210	0.3720	0.1820	0.1970	0.1910	0.2080	0.5200	1.0480	0.2740	0.1870	0.4050	0.4450
Seepage to Groundwater												
Rainfall	0.0018	0.0025	0.0015	0.0018	0.0023	0.0020	0.0071	0.0143	0.0053	0.0045	0.0082	0.0068
Canal System	0.0287	0.0397	0.0232	0.0281	0.0286	0.0248	0.0687	0.1213	0.0373	0.0317	0.0582	0.0478
Watercourses & Fields	0.0548	0.0759	0.0443	0.0536	0.0612	0.0532	0.1622	0.3038	0.0687	0.0583	0.1072	0.0880
River	0.0053	0.0073	0.0042	0.0052	0.0079	0.0069	0.0143	0.0196	0.0000	0.0000	0.0000	0.0000
Total inflows	0.0906	0.1254	0.0732	0.0887	-0.1000	0.0869	0.2523	0.4590	0.1113	0.0945	0.1736	0.1426
Groundwater Outflows												
Evaporation from G.W.	0.0405	0.0562	0.0327	0.0397	0.0274	0.0238	0.0745	0.1415	0.0724	0.0614	0.1129	0.0927
Net Recharge	0.0501	0.0692	0.0405	0.0490	0.0726	0.0631	0.1778	0.3175	0.0389	0.0331	0.0607	0.0499
Net Recharge Per Hectare	0.2267	0.1860	0.2225	0.2487	0.3801	0.3034	0.3419	0.3030	0.1420	0.1770	0.1499	0.1121

Table 4. Annual Groundwater Balance by Canal Command for the Year 1'995-96 (Mhm.).

Fresh Groundwater Areas								
Description	Desert	Begari	North West	Rice	Dadu	Ghotki	Khairpur West	Rohri
Gross Area (Mha)	0.1300	0.2210	0.0660	0.0510	0.0380	0.1910	0.1240	0.6360
Seepage to Groundwater								
Rainfall	0.0014	0.0015	0.004	0.0004	0.0003	0.0024	0.0025	0.0091
Private Tubewells	0.0008	0.0009	0.0002	0.0002	0.0002	0.0035	0.0037	0.0087
Government Tubewells	0.0001	0.0002	0.0000	0.0000	0.0000	0.0037	0.0039	0.0131
Canal System	0.0227	0.0245	0.0067	0.0066	0.0056	0.0241	0.0256	0.0715
Watercourses & Fields	0.0433	0.0467	0.0127	0.0127	0.0107	0.0522	0.0554	0.1771
River	0.0047	0.0050	0.0014	0.0014	0.0012	0.0085	0.0091	0.0150
Total Inflows	0.0730	0.0788	0.0214	0.0213	0.0180	0.0944	0.1002	0.2945
Groundwater Outflows								
Pumpage from Ptw	0.0036	0.0038	0.0010	0.0010	0.0010	0.0129	0.0137	0.0318
Pumpage from Gtw	0.0005	0.0005	0.0001	0.0001	0.0001	0.0086	0.0091	0.0302
Total Pumpage	0.0041	0.0043	0.0011	0.0011	0.0011	0.0215	0.0228	0.0626
Evaporation from G.W.	0.0276	0.0298	0.0081	0.0081	0.0068	0.0302	0.0321	0.0858
Total Ourflows	0.0317	0.0341	0.0092	0.0092	0.0079	0.0517	0.0549	0.1478
Net Recharge	0.0413	0.0447	0.0122	0.0121	0.010	0.0427	0.0453	0.1467
(Change in Storage)								
Net Recharge Per Hectare	0.3177	0.2023	0.1848	0.2373	0.2658	0.2236	0.3653	0.2307

Saline Groundwater Area												
Description	Begari	North West	Rice	Dadu	Ghotki	Khairpur East	Rohri	Nara	Kalri	Lined Channel	Fuleli	Pinyari
Gross Area (Mha)	0.2210	0.3720	0.1820	0.1970	0.1910	0.2080	0.5200	1.0480	0.2740	0.1870	0.4050	0.4450
Seepage to Groundwater												
Rainfall	0.0015	0.0024	0.0015	0.0018	0.0024	0.0024	0.0071	0.0143	0.0057	0.0049	0.0079	0.0071
Canal System	0.0245	0.0378	0.0236	0.0296	0.0241	0.0239	0.0594	0.1089	0.0420	0.0358	0.0587	0.0526
Watercourses & Fields	0.0467	0.0721	0.0449	0.0564	0.0522	0.0518	0.1420	0.2747	0.0775	0.0663	0.1086	0.0974
River	0.0050	0.0078	0.0048	0.0061	0.0086	0.0085	0.0149	0.0207	0.0000	0.0000	0.0000	0.0000
Total inflows	0.0777	0.1201	0.0748	0.0939	0.0873	0.0866	0.2234	0.4186	0.1252	0.1070	0.1752	0.1571
Groundwater Outflows												
Evaporation from G.W.	0.0298	0.0460	0.0286	0.0360	0.0302	0.0300	0.0722	0.1301	0.0983	0.0841	0.1377	0.1235
Net Recharge	0.0479	0.0741	0.0462	0.0579	0.0571	0.0566	0.1512	0.2885	0.0269	0.0229	0.0375	0.0336
Net Recharge Per Hectare	0.2167	0.1992	0.2538	0.2939	0.2990	0.2721	0.2908	0.2753	0.0982	0.1225	0.0926	0.0755

II STRATEGIC OPTIONS FOR IBMR SIMULATIONS FOR THE YEAR 2010

The single-most important variable leading to waterlogging and salinity problems is annual net recharge to groundwater (recharge from various sources minus groundwater pumpage and subsurface evaporation). Where this variable has been positive over an extended period of time, waterlogging has occurred in tandem with soil salinity (induced by high evaporation from the groundwater). Salinity can also occur in isolation, wherein groundwater salts have been added to the root zone through tubewell pumpage. The main source of recharge is the irrigation canal system network and the irrigation practices at the farm level. Theoretically, there exists a pattern of canal water diversions, which could bring recharge into balance in each fresh/saline groundwater area zone. This phenomenon of impact of changes in canal diversions to achieve groundwater balance in fresh and saline groundwater areas of the Sindh canal commands has been shown in Table 5, which reports the steps involved in determining such a pattern.

The "Total Seepage" is that component of canal diversions that reaches the groundwater; the "Desired Seepage" is what would permit zero net recharge; and, "Required diversions" are those that are necessary to reduce the seepage to achieve the required recharge. Finally, the percentage changes in diversions and their magnitudes are reported, which indicate the requirement for substantial reductions in canal diversions, both in fresh as well as saline groundwater areas, to arrest waterlogging. These calculations assume, theoretically, that other things would remain constant. However, in actual practice, when canal diversions change, virtually all other variables change as well (notably cropping pattern, intensities, and tubewell operations). The results should only be considered as indicative of the directions and crude magnitudes that would be required. Moreover, politically, they are also difficult to bear and hence, canal diversion policies alone cannot provide a solution.

An alternative is to increase the tubewell withdrawals in fresh as well as saline groundwater areas to check the increasing net recharge to groundwater aquifer (see Table 4 and Figure 9), which requires a heavy capital investment in the public and private sectors. Another capital-intensive option is the increase of delivery efficiency by canal lining (to reducing the seepage losses) in saline groundwater areas only. The provision of subsurface drainage in saline areas is also another capital-intensive option to intercept the seepage losses and maintain the watertable at a specified level, but it is commonly recommended for non-rice areas. From the above discussion, it can be conceived that no panacea exists for correcting the imbalances leading to, or perpetuating, waterlogging and salinity. But, it indicates the existent scope through some carefully conceived combination of policies to redress the imbalances.

To study the effects of resource allocation and capital investment under the existing irrigation constraints and identification of different options for improvement of irrigated agriculture, the following IBMR simulations have been generated for year 2010 under a set of scenarios (Annexure- C), which aim towards favorable changes to the groundwater balance and concurrently minimize the inequities in surface water supplies.

Table 5. Changes in Canal Diversions to Achieve Groundwater Balace by Canal Command (in 000 hectare meters).

			(Fresh Groundwater Areas)					
Descriptions	Desert Canal	Begari Canal	N.W. Canal	Rice Canal	Dadu Canal	Ghotki Canal	K-West Canal	Rohri Canal
Net Recharge	42.080	45.425	12.365	12.320	10.444	42.898	45.537	146.786
Canal Efficiency	0.830	0.820	0.801	0.854	0.804	0.765	0.748	0.810
W.C.Command Efficiency	0.575	0.610	0.585	0.655	0.585	0.470	0.460	0.470
Canal Diversions	172.073	198.408	43.728	80.079	38.905	141.051	133.465	536.844
at Canal Head								
Total Canal System Losses	89.951	99.165	23.237	35.285	20.606	90.336	87.542	332.467
Seepage from Canal, W.C. and Fields								
Canals	22.707	24.512	6.672	6.648	5.636	24.159	25.646	71.476
WC&Flds.	43.289	46.730	12.720	12.674	10.745	52.230	55.445	177.136
Total	65.996	71.242	19.393	19.322	16.381	76.390	81.091	248.612
Desired Seepage	23.916	25.818	7.028	7.002	5.936	33.492	35.553	101.826
Required Diversions	62.358	71.902	15.847	29.020	14.099	61.842	58.516	101.016
Change in Diversions	-109.715	-126.507	-27.881	-51.059	-24.806	-79.209	-74.949	-435.828
Percent Change	-64	-64	-64	-64	-64	-56	-56	-81

Saline Groundwater Areas												
Descriptions	Begari Canal	N.W. Canal	Rice Canal	Dadu Canal	Ghotki Canal	K-East Canal	R[illegible]ri Canal	Nara Canal	Kalri Begar	L.Chanel	Fuleli Canal	Pinyari Canal
Net Recharge	48.082	74.167	46.234	58.040	57.197	56.694	151.113	288.845	26.841	22.959	37.603	33.721
Canal Efficiency	0.820	0.801	0.854	0.804	0.765	0.738	0.810	0.811	0.800	0.800	0.800	0.821
W.C.Command Efficiency	0.610	0.585	0.585	0.655	0.480	0.465	0.470	0.459	0.585	0.590	0.605	0.595
Canal Diversions	198.408	247.748	460.219	204.218	141.051	179.228	439.225	794.004	377.944	177.377	475.761	357.345
at Canal Head												
Canal Irrigation System Losses	99.165	131.657	230.298	96.673	89.257	117.722	272.012	498.437	201.066	93.655	245.493	182.784
Seepage from Canal, W.C.and Fields												
Canals	24.512	37.810	23.570	29.589	24.159	23.947	59.384	108.951	41.916	35.853	58.722	52.659
WC&Flds.	46.730	72.082	44.934	56.409	52.230	51.771	141.719	274.708	77.538	66.322	108.627	97.410
Total	71.242	109.892	68.504	85.998	76.390	75.718	201.102	383.660	119.454	102.175	167.349	150.069
Desired Seepage	23.160	35.725	22.270	27.958	19.193	19.024	49.989	94.815	92.613	79.216	129.745	116.348
Required Diversions	22.340	34.924	21.416	27.154	18.428	18.286	49.179	94.004	91.813	78.416	128.945	115.527
Change in diversions	-176.068	-212.824	-438.803	-177.065	-122.623	-160.941	-390.045	-700.000	-286.132	-98.961	-346.816	-241.818
Percent Change	-89	-86	-95	-87	-87	-90	-89	-88	-76	-56	-73	-68

Note:--

1- Total Seepage is that component of canal diversions that reaches the groundwater.

2- Desired Seepage is that that would permit zero net recharge

3- Required Diversions are those necessary to reduce or increase the seepage to achieve the required recharge.

A. CROP AREA MANAGEMENT

This simulation is based on a set of six scenarios (Scenario-I to Scenario-III(c) in Annexure-C) that define the key variations in cropping pattern towards favorable changes to the groundwater balance and minimize the inequities in surface water supplies. The crop area and yield growth rates of four major crops (wheat, cotton, rice and sugarcane) for the year 2010 were determined according to the ACZ divides. The area under rice has been decreased from 0.25 percent to 2.5 percent per annum across the traditional zones; similar adjustments for other major crops also aimed to minimize the gap between net crop water requirements and supplies as well as the recharge to the aquifer system. These growth rates (Table 6) were established according to IIMI's on-farm estimates of fallow and culturable waste area that could benefit from the redistribution of irrigation supplies (estimated through agro-economic sample surveys conducted during 1997-98). The figures for crop area and average yields for the year 1995-96 have been used as a base for simulation results targeting the year 2010. The surface water supplies are set equal to the monthly average canal diversions at canal head during 1990-91 and 1995-96 periods. The growth rate for private tubewell development has been varied from 2 to 6 percent per annum and the pumpage from government tubewells for irrigation purposes in fresh areas has been assumed to be zero by year 2010 (in keeping with historic rates of deterioration, abandonment and the GoP policy of proceeding with the program of SCARP transition).

For the private tubewell extractions, the fresh groundwater lenses along the Right Bank of River Indus have been included in the program for development. The groundwater pumpage in saline areas has also been assumed under Scenarios III(a–c) to see the effect of lowering the watertable on the groundwater balance. From amongst these six simulation scenarios, III(c) is showing less shortages and more surpluses within the entire system. According to this scenario, the surplus in the Rice Canal during both seasons can be reallocated to other Sukkur Right Bank canals, which are showing shortages within the same season. Similarly, the surplus of the Kalri Beghar Feeder can be reallocated to other Kotri Barrage canals in both seasons; the Fuleli Canal surplus can be reallocated during Kharif season only. The groundwater inflow-outflow analysis for these simulation scenarios has been depicted in Figure 10, which shows that the net annual recharge to the groundwater has been minimized under scenario III(c) for all canal commands, especially in the rice-growing areas because the decrease of area under rice crop has been allocated to the cotton crop, together with the pumping of saline groundwaters for lowering the watertables only.

B. CAPITAL INVESTMENT OPTIONS

This option targets increases in the delivery efficiency of canals and watercourses through lining in areas affected by waterlogging and soil salinity. Concurrent improvements are also sought in the prevailing irrigation practices at the farm through better on-farm water management. The canal losses (70% of which enter the aquifer as recharge) depend on the length of the canal, soil type of the earthen bed and flow conditions (World Bank). Prevention of these delivery losses in fresh groundwater areas is not desirable since they replenish the fresh groundwaters being extracted through tubewells.

Table 6. Growth Rates of Crop Area, Average Yield and private Tubewells Under Different IBMR simulation Scenarios for the Year 2010 by Agroclimatic Zones (in percent).

Crop Area

Name of Crop	Scenario	Agroclimatic Zones			
		SCWN	SRWN	SCWS	SRWS
Wheat	I	3.16	6.54	3.49	13.97
	II	3.16	6.54	3.49	13.97
	III	2.75	6.54	2.50	13.00
	III-a	2.75	6.00	2.50	13.00
	III-b	2.75	6.00	2.50	13.00
	III-c	2.50	6.00	2.00	12.00
	IV	3.16	6.54	3.49	13.97
	V	3.16	6.54	3.49	13.97
Cotton	I	5.10	18.42	6.94	18.53
	II	5.00	18.42	5.00	23.47
	III	5.00	15.00	3.00	19.00
	III-a	5.00	15.00	3.00	19.00
	III-b	5.00	15.00	3.00	19.00
	III-c	5.00	18.0	3.00	20.00
	IV	5.10	18.42	6.94	18.53
	V	5.10	18.42	6.94	18.53
Rice	I	0.00	-1.00	0.00	0.00
	II	0.00	-1.00	0.00	-0.25
	III	0.00	-1.25	0.00	-0.40
	III-a	0.00	-1.50	0.00	-0.40
	III-b	0.00	-1.50	0.00	0.40
	III-c	0.00	-2.50	0.00	-0.60
	IV	0.00	-1.00	0.00	0.00
	V	0.00	-1.00	0.00	0.00
Sugarcane	I	3.49	15.00	3.49	7.59
	II	3.49	14.00	2.51	7.00
	III	3.25	14.00	2.00	7.00
	III-a	3.25	14.00	2.00	7.00
	III-b	3.25	14.00	2.00	7.00
	III-c	2.75	14.00	0.75	7.00
	IV	3.49	15.00	2.51	7.59
	V	3.49	15.00	2.51	7.59

Average Crop Yield

Name of Crop	Scenario	Agroclimatic Zones			
		SCWN	SRWN	SCWS	SRWS
Wheat	All	2.78	5.53	4.61	4.81
Cotton	All	4.96	1.00	6.19	1.84
Rice	All	5.65	4.57	5.84	6.69
Sugarcane	All	4.16	2.46	4.23	5.28

Private Tubewells

Name of Crop	Scenario	Agroclimatic Zones			
		SCWN	SRWN	SCWS	SRWS
Wheat	I	2.00	2.00	2.00	2.00
	II	3.00	2.25	3.00	2.00
	III	3.00	1.00	5.00	2.00
	III-a	3.00	1.00	5.00	2.00
	III-b	5.00	3.00	6.00	4.00
	III-c	6.00	5.00	6.00	4.00
	IV	2.00	2.00	2.00	2.00
	V	2.00	2.00	2.00	2.00

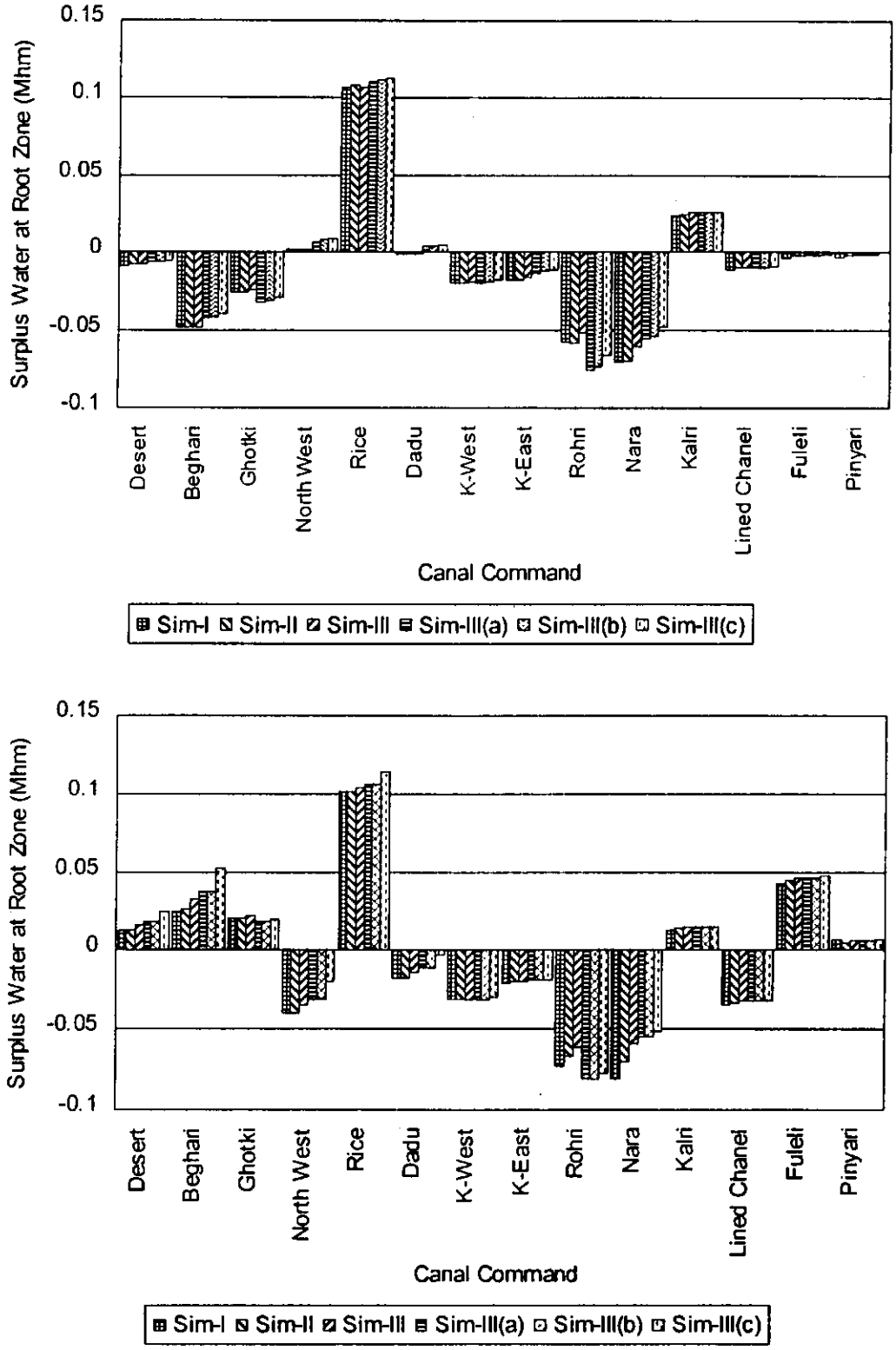


Figure 9. Results of IBMR Simulation Scenarios for Seasonal Surpluses and Shortages of Water at Root Zone in the Year 2010, Lower Indus Basin.

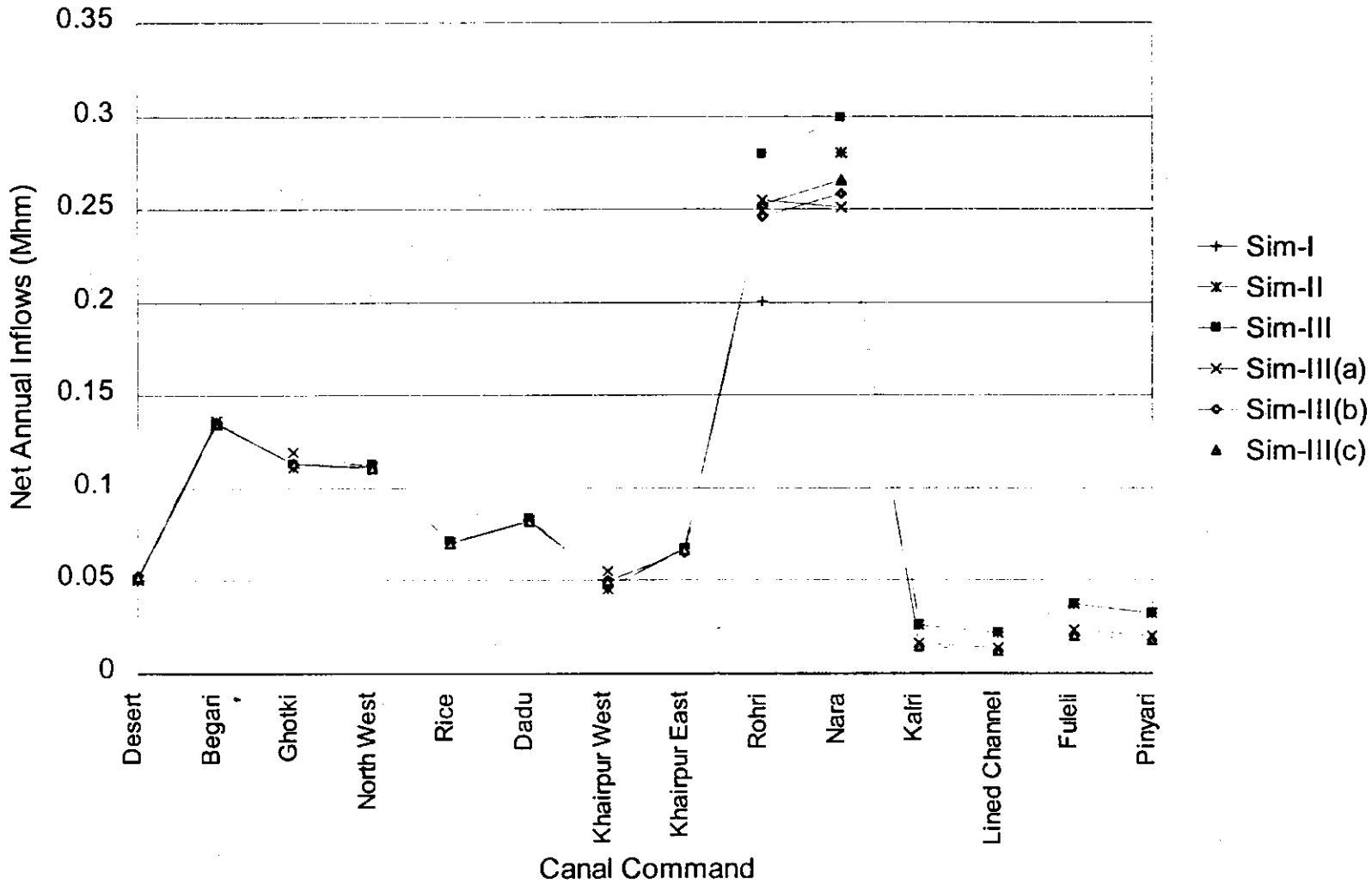


Figure 10. Results of IBMR Simulations for the Year 2010 for Annual Groundwater Balance under Crop Management Scenarios.

The canal losses through saline areas are very undesirable since the water is not only lost to recycled use for irrigation, but also contributes to environmental deterioration through raising the saline groundwaters to cause waterlogging. The canals passing through saline groundwater areas of Sindh, along with their current efficiencies and those expected to prevail if remodeled with concrete lining, are listed in Table 7. These, of course, are main canals, and each has a number of associated branches minors and distributaries.

Table 7. Saline Groundwater Canal Commands for the IBMR Simulation on Canal Lining Option.

Canal Name	Length (000-meters)	Efficiency Without	Efficiency With	Canal Name	Length (000-meters)	Efficiency Without	Efficiency With
Begari	294	0.820	0.946	Rohri	1523	0.811	0.943
Ghotki	751	0.765	0.929	Nara	2609	0.816	0.945
North West	1148	0.804	0.941	Kalri	1009	0.800	0.940
Rice	772	0.854	0.956	Lined Channel	717	0.800	0.800
Dadu	981	0.804	0.941	Fuleli	1078	0.800	0.940
Khairpur East	727	0.738	0.921	Pinyari	1221	0.821	0.946

Much of the irrigation system seepage-related losses occur below the main canal level, i.e. in the watercourses and farmers' fields. The history of successive On-Farm Water Management attests to the desirability of pursuing strategies that aim to reduce these delivery losses at the sub-system and farm levels. To account for the seepage losses in saline areas from the above-mentioned sources, water loss recovery factors (the proportionate saving of water losses through canal lining and /or improvement of watercourse command efficiency, as shown in Annexure–D) were computed and used in the IBMR Simulation specific to this scenario. The growth rates for crop areas, yield and private tubewell development (only in the fresh groundwater areas) are maintained as per Scenario I.

The canal water supplies at canal head are set equal to the monthly averages of canal diversions during 1990-91 and 1995-96 periods. The pumpage from government tubewells has been assumed to zero by the year 2010. From Figure 11, shortages in the Sukkur Right Bank command and the entire Kotri Barrage command, having maximum saline groundwater zones, have decreased or become surplus in both seasons (although the area of cotton and sugarcane has been increased tremendously). The exception is the Lined Channel, for obvious reasons. The surplus water availability is owed to the improvement in system delivery efficiencies and reduction in areas sown to rice crop. The remaining canal commands are showing an increase in shortages during the Rabi season and decrease in surpluses during Kharif. There is no improvement in water shortages under Rohri and Nara Canal commands under this scenario because the system cannot sustain the higher growth rates for sugarcane and cotton crops. The water saved through the lining process is consumed in reducing the water stress occurring across saline groundwater zones; and, since there is no assumption of lining in fresh areas, the

Next >>

shortages have increased. The groundwater inflow–outflow analysis under this scenario (Figure 12) shows that the net annual recharge to the groundwater aquifer has been minimized under all the rice-growing areas, especially in the Kotri Barrage commands, in addition to the Rohri and Nara anal commands.

Given the argument that the process of canal lining is highly disruptive to the production process due to lengthy closure periods, an alternative method of intercepting the seepage losses from main canals is the installation of interceptor drains, which probably costs less. The interceptor drains serve to retrieve the lost water before it becomes contaminated, and return it to the system. Their installation would not require canal closure, and thus, would not suffer from the same disruptive effects as canal lining. If the water loss recovery factors, as mentioned earlier for canal lining, are assumed to be the same for interceptor drains, these results can be applied under this option also.

C. Canal Diversion Regulation to Match the Water Apportionment Accord Allocations

This simulation is based on setting the water diversions at canal head equal to the Water Apportionment Accord allocations for each canal command of the Sindh Province. The growth rates for crop area, yield and private tubewell development (only in fresh groundwater areas) are kept the same as used under Scenario I. The pumpage from government tubewells has been assumed to zero by the year 2010. A comparison of the Accord allocations and the actual diversions during 1995-96 (Figure 13) indicates that during rabi season, out of the 14 major canals, 10 are drawing more water than apportioned (from 2 to 87%); the exceptions being the Desert, Begari, Rice and Pinyari Canals. During the kharif season, only 4 canals, i.e. Rohri, Kalri Beghar, Lined Channel and Fuleli are drawing excess water supplies (4 to 18%) than permitted under the Accord.

The impact of this deviation in canal diversions, on a seasonal water balance at the root zone, is depicted in Figure 14, which shows the surpluses and shortages of irrigation waters at the root zone. According to this scenario, the shortages have increased and surpluses have decreased under all canal commands during the rabi season, except for the Desert and Rice Canals. Similarly, during the kharif season, the shortages have reduced under all canal commands, except the commands native to the cotton and sugarcane-growing areas (because of the proposed higher crop area growth rates for these crops). The groundwater inflow–outflow analysis, resulting in net annual inflow (net annual recharge) under this scenario, has been illustrated in Figure 15 and compared with the base year of 1995-96. The net annual recharge to groundwater has decreased in the Ghotki, Khairpur West and Rohri anal commands, due only to pumpage from private tubewells in the fresh groundwater areas, to meet the net crop water requirements at the root zone during the rabi season. The remaining canal commands are showing an increase in net annual recharge to the groundwater aquifer whereby watertables would be expected to rise in the absence of adequate drainage.

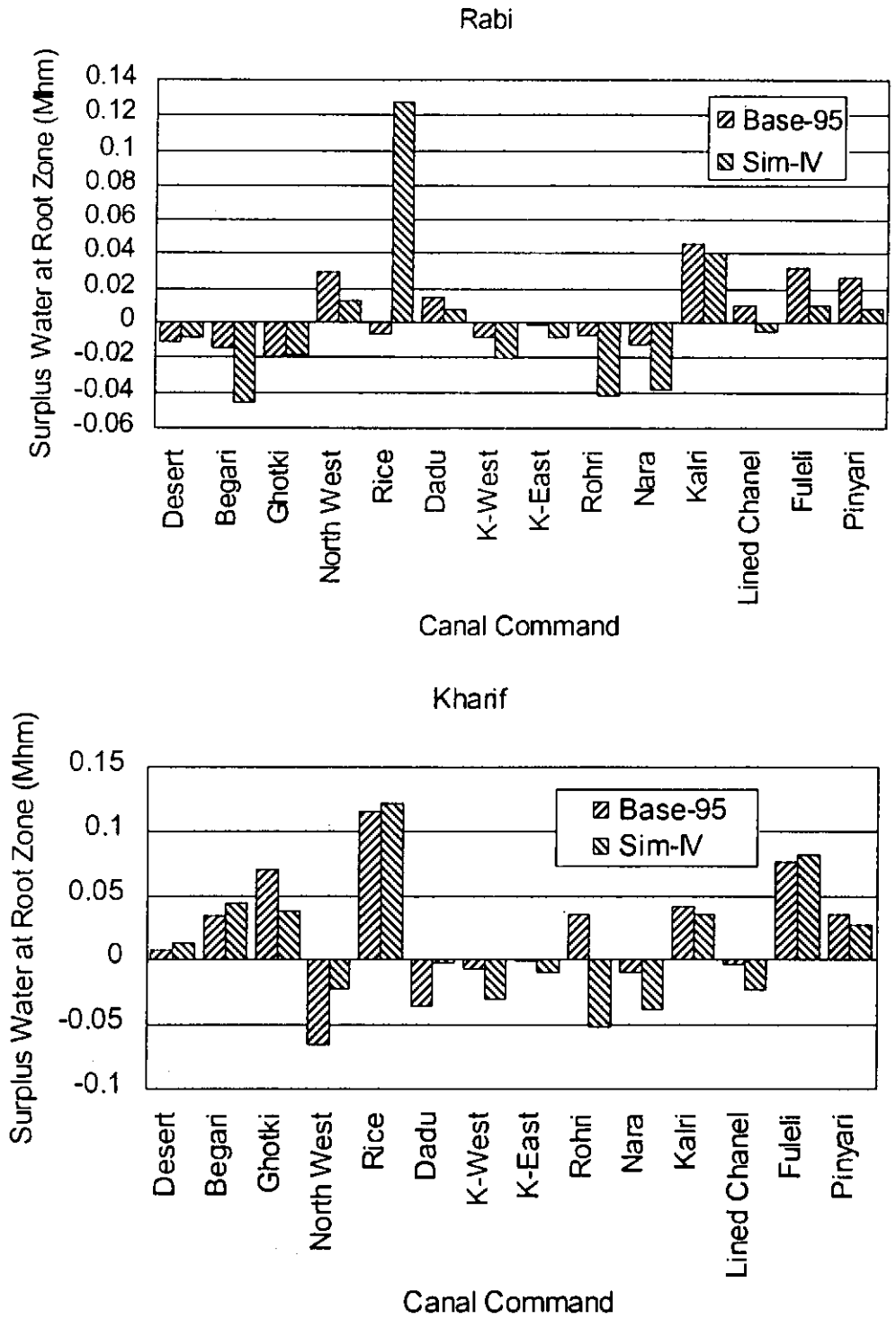


Figure 11. Results of IBMR Simulation for the Comparison of Capital Investment Scenario (to the Year 2010) with Base Year 1995-96 for Seasonal Surpluses and Shortages of Water at the Root Zone, Lower Indus Basin Canal Commands.

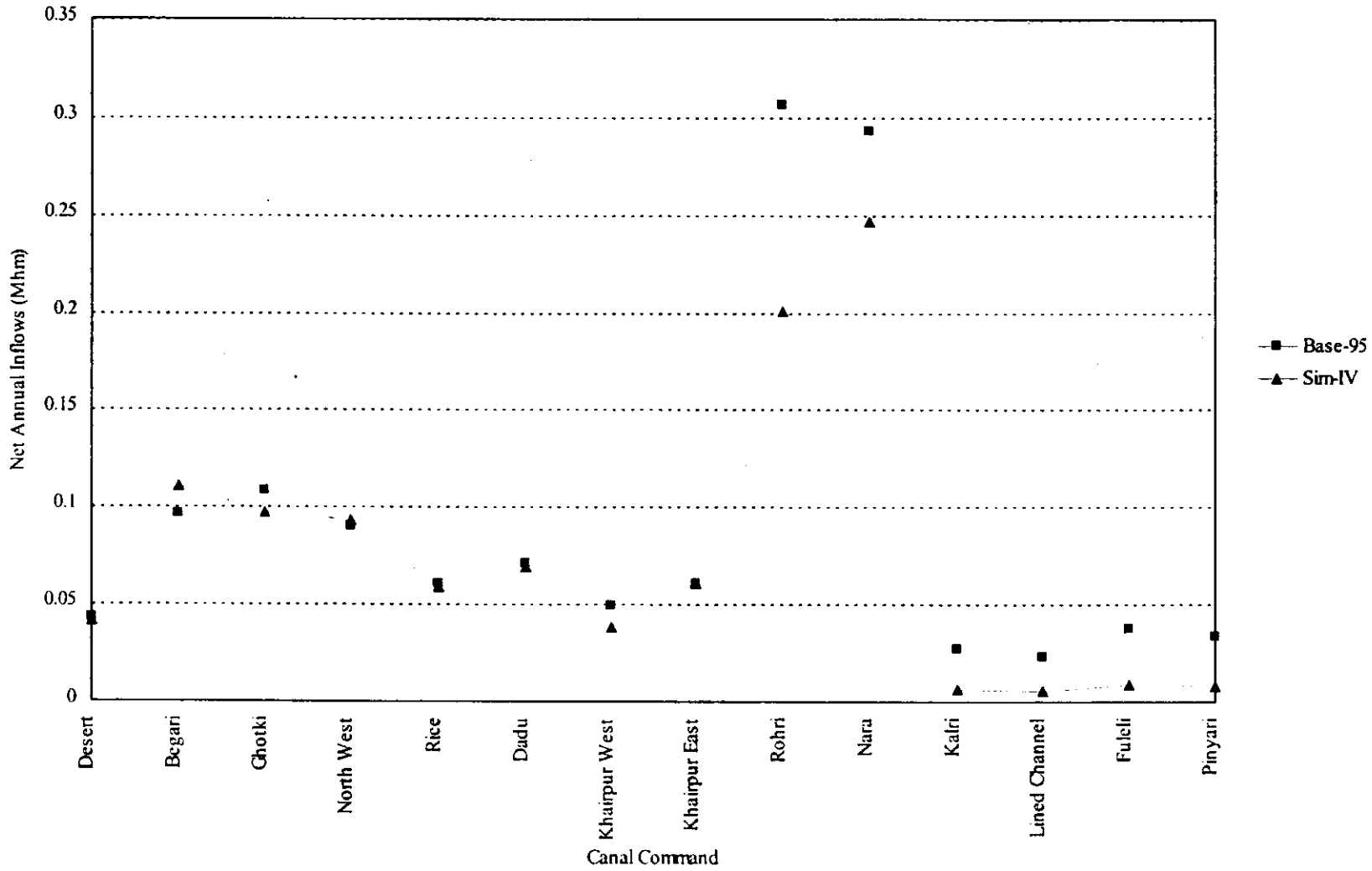
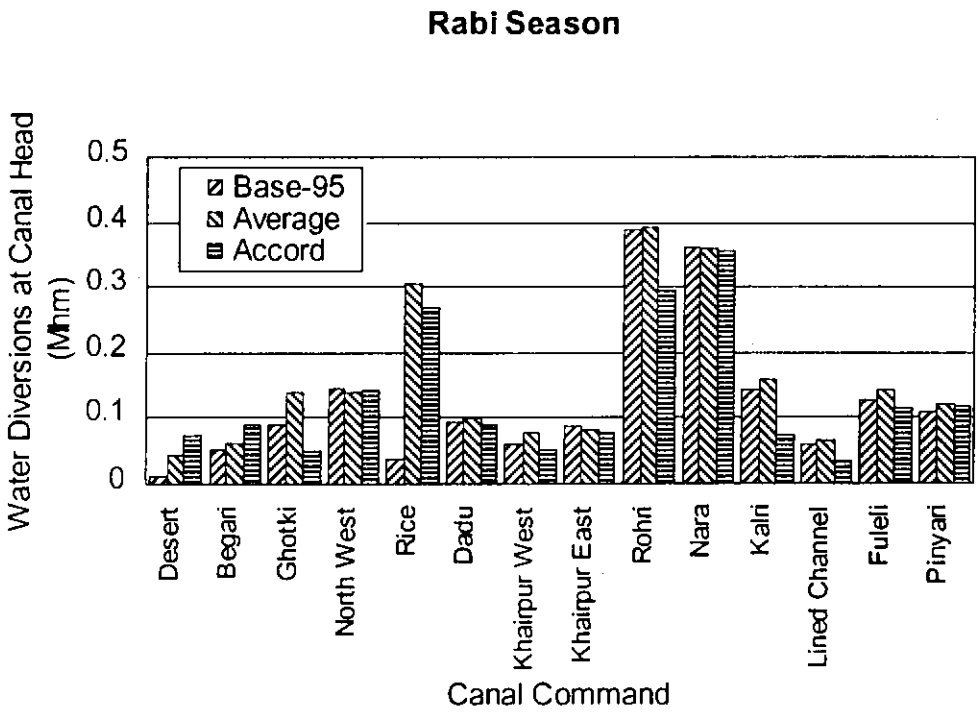


Figure 12. Results of the IBMR Simulations Annual Groundwater Balance under Capital Investment Scenarios by Year 2010, Lower Indus Basin Canal Commands.



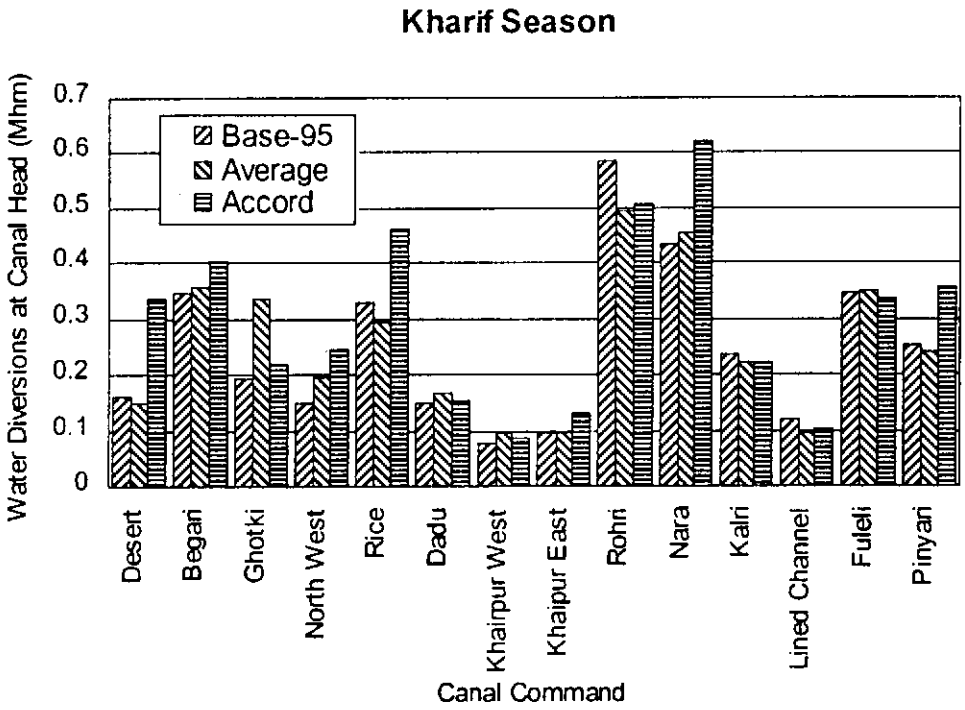


Figure 13. Comparison of the 5-Year Average Canal Diversions with the Base Year (1995-96) and the Water Apportionment Accord Allocations, Lower Indus Basin Canal Commands.

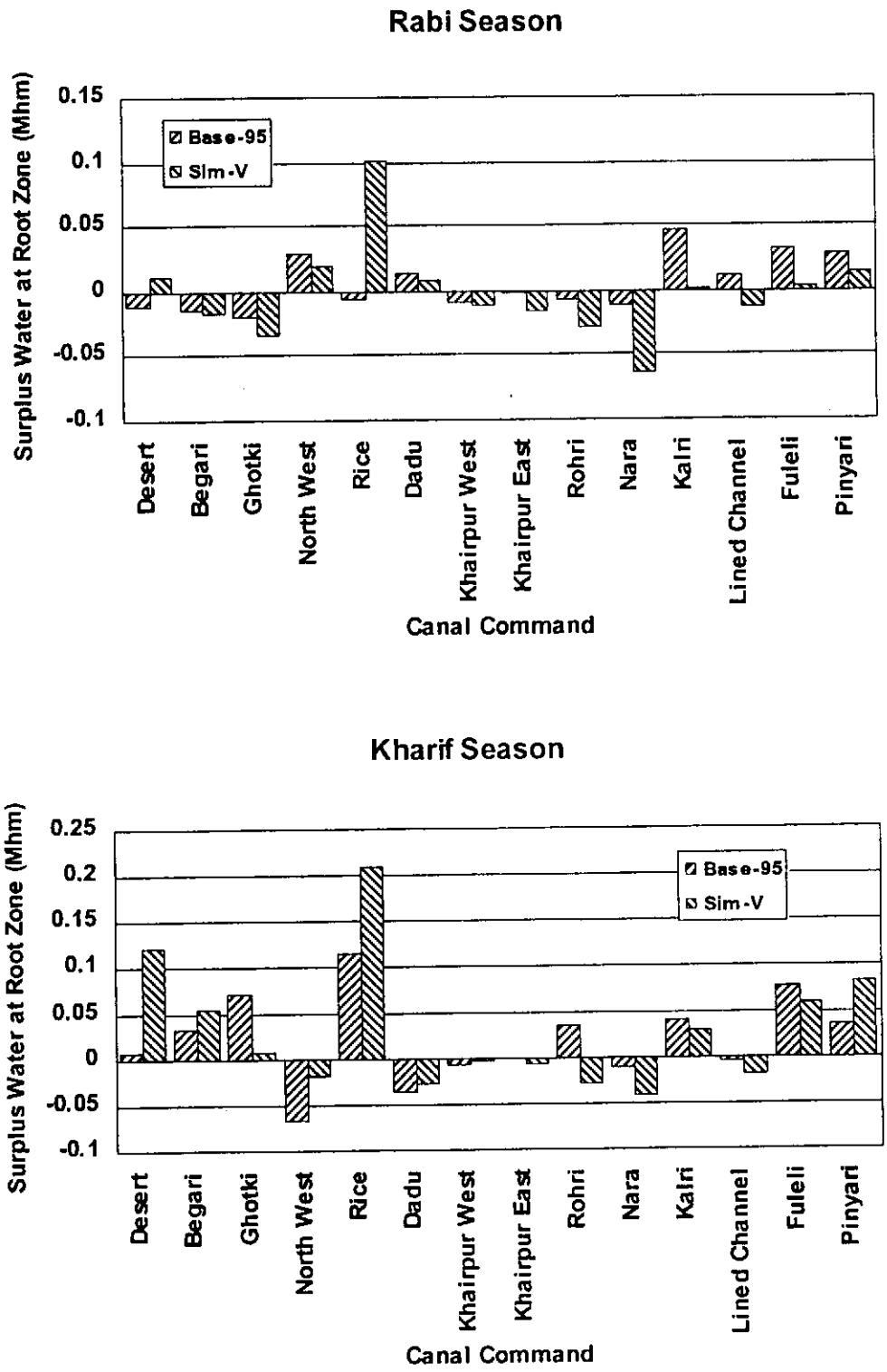


Figure 14.IBMR Simulation Results for the Comparison of Diversion Regulation Scenario with the Base Year 1995-96, Lower Indus Basin Canal Commands.

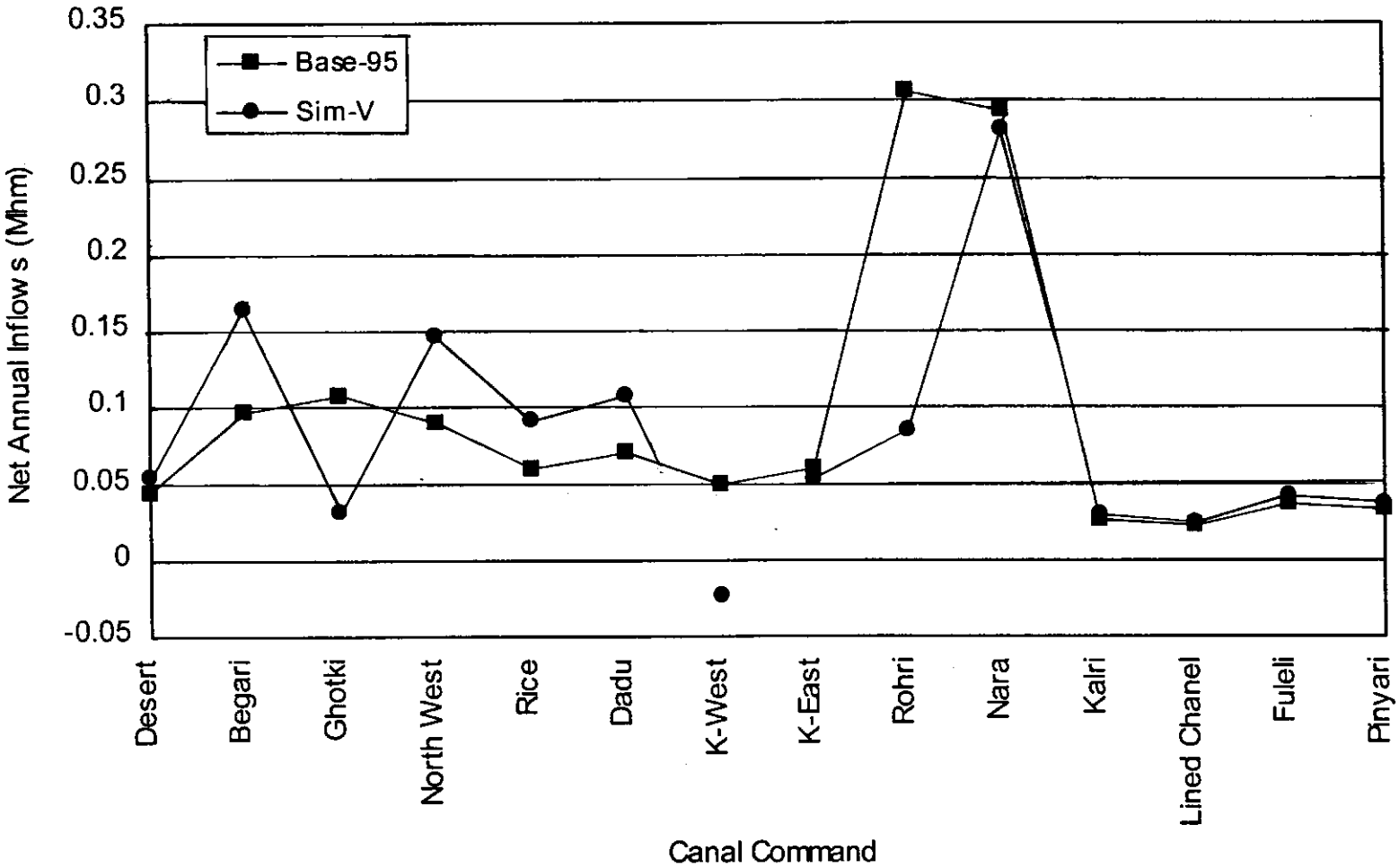


Figure 15. Results of IBMR Simulation for the Comparison of Diversion Regulation Scenario(s) to the Year with Base Year 1995-96 for Annual Groundwater Balance, Lower Indus Basin Canal Command.

D. WATERTABLE CONTROL UNDER RESOURCE MANAGEMENT OPTION

The effect of resource allocation and capital investment on the changes in groundwater balances (net recharge to groundwater aquifer system) and the equitable distribution of surface water supplies has been discussed in the preceding paragraphs under Simulations A to C. A comparison of the seasonal surplus at the root zone and the net annual recharge to the groundwater, under the three simulations, is illustrated in Figures 16 and 17, respectively. The net annual recharge is minimum under the Capital Investment Option (Sim-IV), which is based on the option of canal lining in saline groundwater areas. The option of maintaining canal diversions as per Water Apportionment Accord allocations has socio-political repercussions since the allocations can only be met if new surface water storages are added to the IBIS. The remaining option of "Crop Area Management" under Simulation "A", which is based on changes to the existing cropping pattern of major crops, reveals that Simulation III(c) is showing the acceptable results by minimizing the net recharge to the groundwater, as well as the inequities in surface water supplies, by reducing the shortages and surpluses at the root zone. This has been achieved through reducing the area under rice in the rice-wheat zone, increasing the area under cotton crop in the cotton-wheat zone, with an across-the-board increase in the area under wheat and sugarcane crops. With these adjustments, the changes in area under the major crops by the year 2010 are shown in Table 8.

Table 8. Barrage Command Level Changes in Cropped Area by the Year 2010.

Name of Crop	Barrage Command	Change (%)
Wheat	Sukkur	54
	Guddu	94
	Kotri	>100
Rice	Sukkur	- 29
	Guddu	-25
	Kotri	- 8
Cotton	Sukkur	90
	Guddu	>100
	Kotri	>100
Sugarcane	Sukkur	43
	Guddu	42
	Kotri	>100

Given the objective of minimizing the surplus water at the root zone to control the seepage loss contributions (as net recharge to the groundwater), the surpluses during both growing seasons have been minimized, from 0,0836 Mhm in Rabi 1996 to a shortage of 0,0748 Mhm in Rabi 2,010 and from 0,2447 Mhm in Kharif 1996 to 0,0504 Mhm in Kharif 2010 (Table 9). The shortages during the rabi season, which are maximum under the Sukkur Barrage command, can be alleviated through re-allocation of surpluses native to the Rice and Dadu Canals, as part of the adjustment within the same barrage command.

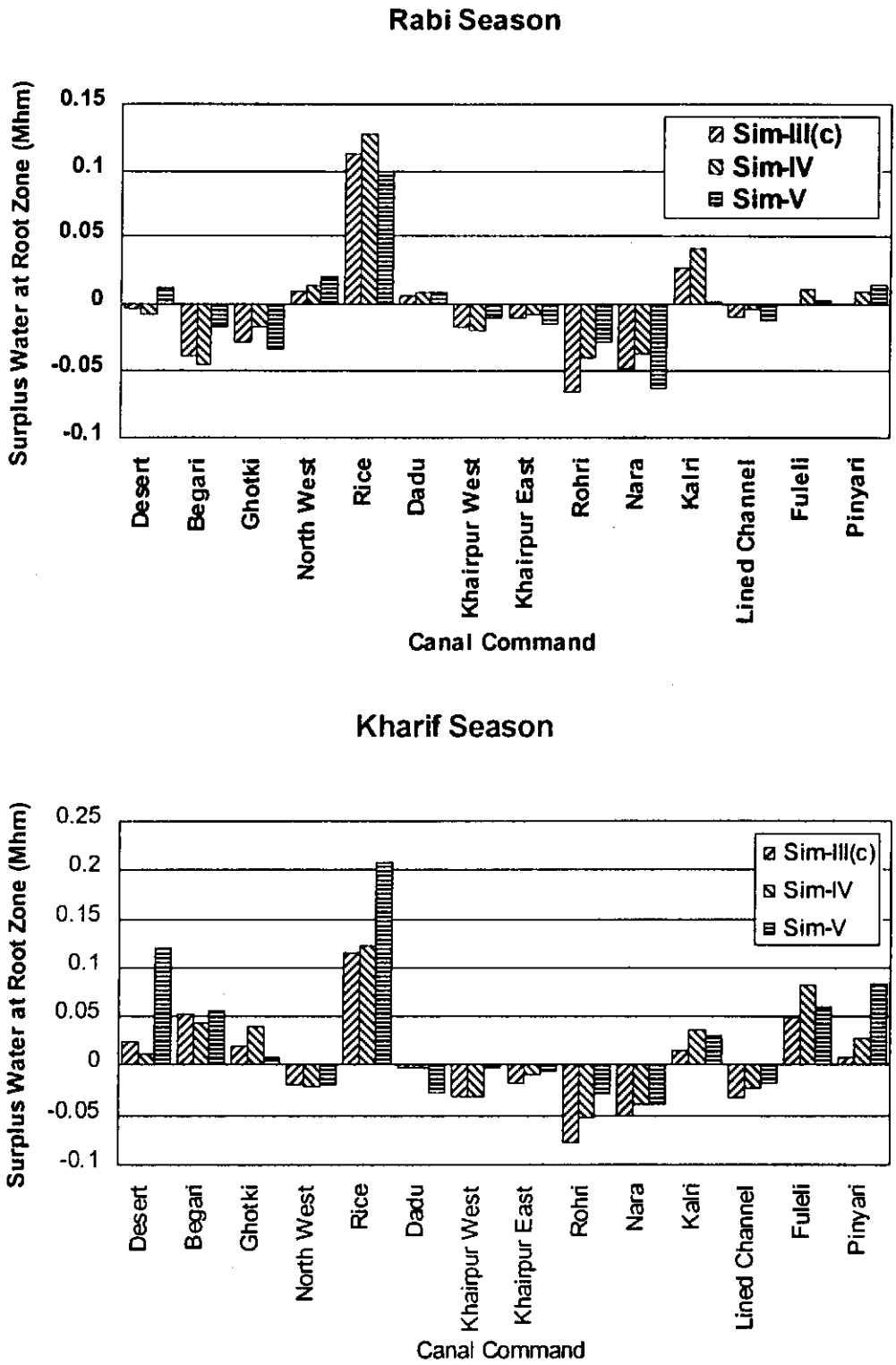


Figure 16. Comparison of Selected IBMR Simulation Scenarios to the Year 2010 for Seasonal Surplus or Shortage of Water at Root Zone, Lower Indus Basin Canal Commands.

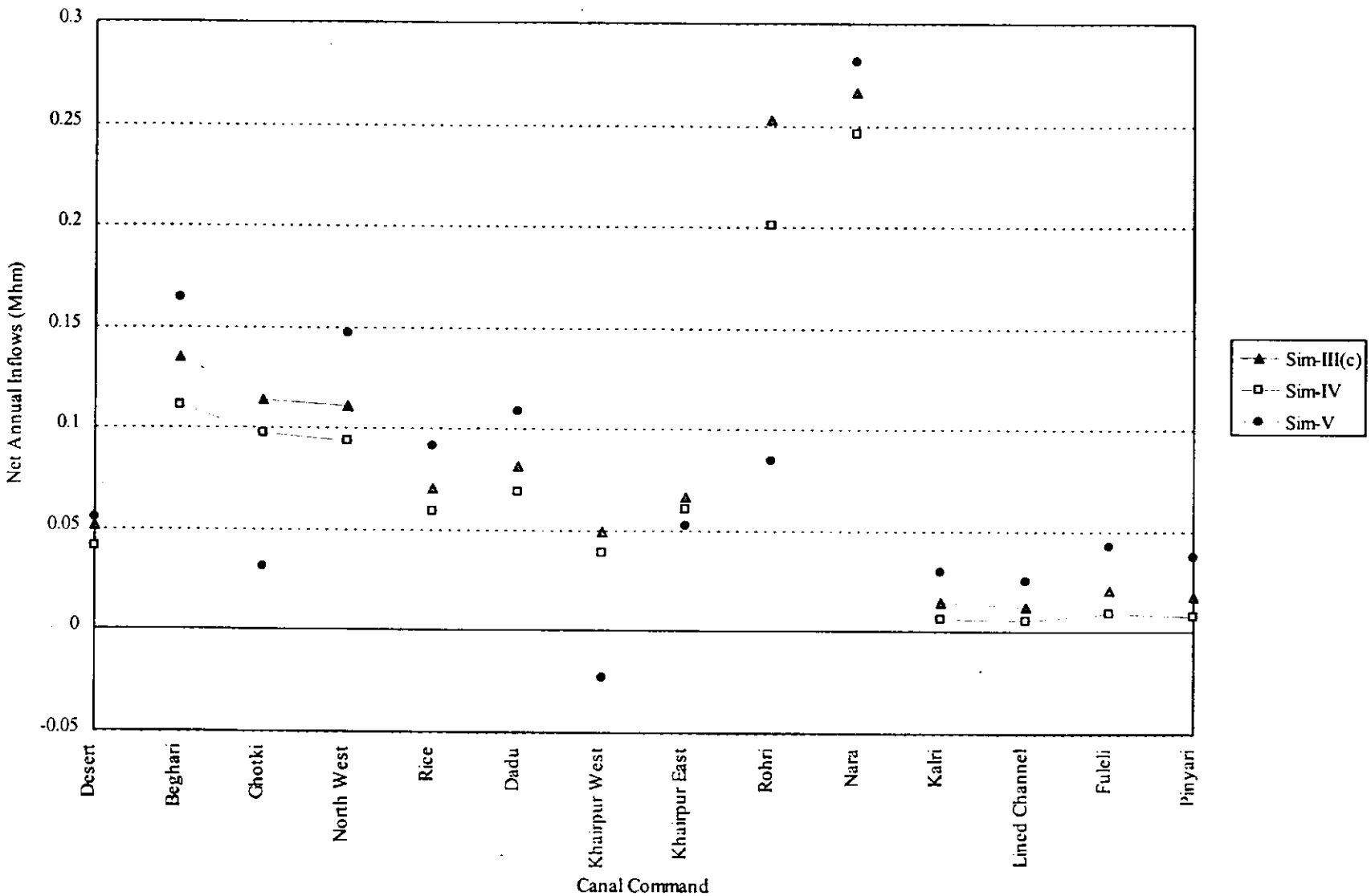


Figure 17. Comparison of Capital Investment and Crop Area Management Options in the IBMR Simulations to the Year 2010, Lower Indus Basin Canal Commands.

Table 9. Comparison of Water Surpluses (+) and Shortages (-) at Root Zone in Million Hectare Meters for Years 1995-96 and 2010 under IBMR Simulation III (c).

Canal Command	Rabi	Season	Kharif	Season
	1996	2010	1996	2010
Desert	-0.0112	-0.0051	0.0056	0.0254
Begari	-0.0137	-0.0393	0.0339	0.0529
Ghotki	-0.0201	-0.0293	0.0058	0.019
North west	0.0304	0.0089	-0.0582	-0.0199
Rice	-0.0053	0.1126	0.1208	0.1139
Dadu	0.0155	0.0049	-0.0303	-0.0032
Khairpur-West	-0.0082	-0.0179	-0.0072	-0.0298
Khairpur-East	-0.0010	-0.0113	-0.0011	-0.0182
Rohri	-0.0069	-0.0667	0.0360	-0.0775
Nara	-0.0122	-0.0485	-0.0095	-0.0508
Kalri	0.0453	0.0266	0.0414	0.0152
Lined-Chanel	0.0109	-0.0093	-0.0044	-0.0317
Fuleli	0.0326	-0.0004	0.0765	0.0477
Pinyari	0.0275	0.0000	0.0354	0.0074
Total for Sindh	0.0836	-0.0748	0.2447	0.0504

The effect of these reductions in surpluses on groundwater balance (net recharge) can be visualized from Figure 18 and Table 10, where a comparison has been made with the base year of 1995-96. The net annual recharge in the overall Sindh canal command system has decreased by 3 percent from 1,2989 Mhm to 1,2612 Mhm, especially within the Rohri, Nara and the entire Kotri Barrage canal commands. Across the Indus Right Bank canals, the net recharges are little more than the base year values due to higher growth rates of the sugarcane crop (itself a high delta crop). This higher growth rate of sugarcane within the otherwise traditional rice growing areas has resulted in a tremendous increase in the area under this crop (from 3,700 ha to 12,800 ha).

Table 10. Comparison of Net Annual Recharge to Groundwater (in Mhm).

Canal Command	Net Recharge during 1996	Net Recharge during 2010
Desert	0.0432	0.0517
Begari	0.0965	0.1345
Ghotki	0.1080	0.1135
North West	0.0897	0.1104
Rice	0.0606	0.0699
Dadu	0.0709	0.0817
Khairpur West	0.0497	0.0495
Khairpur East	0.0606	0.0662
Rohri	0.3063	0.2528
Nara	0.2925	0.2659
Kalri Beghar	0.0268	0.0143
Lined Channel	0.0229	0.0122
Fuleli	0.0375	0.0207
Pinyari	0.0337	0.0179
Total Sindh	1.2989	1.2612

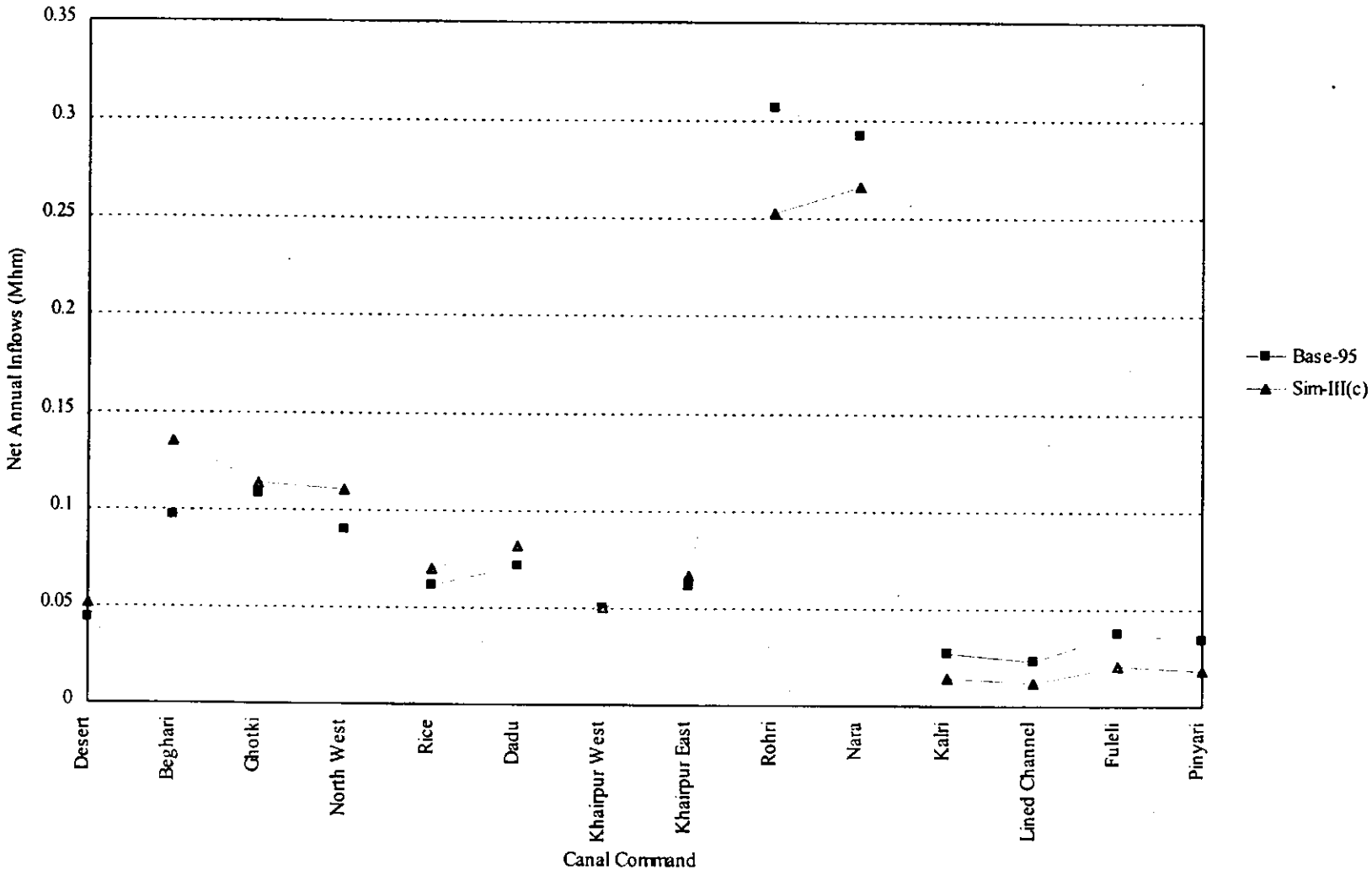


Figure 18. Comparison of Crop Area Management Options in the IBMR Simulations (to the Year 2010) with the Base Year (1996), Lower Indus Basin Canal Commands.

III CONCLUSIONS

On the basis of the assessment of the performance of irrigated agriculture during the 1991-96 period under the canal commands of the Sindh Province and the IBMR simulations to the year 2010 (to favor changes in the groundwater balance to control waterlogging and salinity, and minimizing the inequities in water supplies at root zones of crops), the results are concluded as under:

1. The cropping intensity during rabi season is showing a decreasing trend, but increasing in kharif. This indicates an increasing preference towards rice cultivation.
2. The canal head diversions for the Indus Right Bank canals (excepting the non-perennial Rice Canal) have decreased by 4 percent. The diversions to the Indus Left Bank canals, including all of the Kotri Barrage canals, are showing an increasing trend during the late kharif and early rabi seasons.
3. From the performance assessment comparison of water requirements and supplies at the root zone, both rabi seasons of 1990 and 1996 show water shortages to be prevalent across most of the canal commands. During the kharif season, water supplies are more than the demand, except in the Sukkur Right Bank canals. The Nara Canal and the Lined Channel have become water-short environments since1996, which is due to the increase in area under cotton (Nara Canal command) and sugarcane (Lined Channel command).
4. The groundwater balance for the years 1990 and 1996 shows a rising trend in the watertable depths in all canal commands.
5. From amongst the proposed set of strategic options for the IBMR simulations targeting the year 2010 (to control the watertable and minimize the inequities in surface supplies), the net annual recharge to the groundwater is at a minimum under canal lining or installation of interceptor drains (in saline groundwater areas only). But, this option is highly capital-intensive, time-consuming and disruptive to the production process. The Water Apportionment Accord allocations option entails socio-political consequences and is linked to upstream storage projects (presently uncertain to be realized in the near future).
6. The Crop Area Management option, which is based on changes to the existing cropping pattern by shifting from high delta crops to crops that require less water up to the stage of crop maturity, requires modifications to the traditional culture of rice cultivation to that of a system of mixed cropping. This option oversees the installation of tubewells (of 28 lps capacity) in the private sector to harvest fresh groundwater regimes as a supplement to the canal supplies. There is concurrent stress on watertable control through fractional scavenger and compound wells (of 14 lps capacity) exclusive to the saline groundwater areas. Based on the simulation results, the surpluses during both seasons have been minimized (Table 9). The shortages during the rabi season, which are maximum under the Sukkur Barrage command, can be alleviated through the re-allocation of surpluses of the

Rice and Dadu Canals (as part of the adjustment within the same barrage command).

7. The simulated net crop water requirements and total supplies at the root zone for the year 2010, by canal command as well as barrage command, are given in Annexure-E. Under the Crop Area Management option (Simulation III(c)), the annual net water requirements are increasing across the Guddu Barrage command (28%), Sukkur Left Bank command (64%) and Kotri (73%), while there is a decrease of 4 percent within the Sukkur Right Bank commands because of a reduction in area under the rice crop. Similarly, the annual supplies are increasing at Guddu (33%), Sukkur (30%) and Kotri (13%) Barrages, based on the average volume of canal supplies for the period 1991-96, and contributions from private tubewells. The gap between requirements and supplies is due to the reduction in surpluses, as mentioned earlier.

8. The reduction in surpluses has affected the groundwater balance through an overall reduction in net annual recharge to the groundwater aquifer (particularly in the commands of the Rohri and Nara Canals, and all of the Kotri Barrage canal commands). For the other Indus Right Bank canal commands, the net recharges are little more than the base year because of a higher growth rate assumed for the sugarcane crop.

IV RECOMMENDATIONS

Based on the findings of the irrigation system performance of canal commands during the 6-year period between 1991-96, and the IBMR simulation results to the year 2010, the emergent conclusion is that reliance on management-related interventions provide the best mix of returns in terms of long term investment considerations. For the management option to be successful, an integrated approach must focus on modifying the traditional cropping patterns to suit regional lowering of the groundwater tables, especially across saline groundwater zones. The emphasis should be on shifting from the cultivation of high delta crops to low delta crops with favorable economic and farm level returns. The IBMR simulations have shown that if, for the Sukkur Right Bank canal commands, the rice area is decreased by 30 percent and the area under cotton is increased by 90 percent (over the 1995-96 estimates), the net irrigation water requirements can be decreased to the extent that possible surplus could be reallocated to other canal commands under the same barrage command. This will also result in decreasing the net recharge to the groundwater and controlling the watertables. Similarly, under the Kotri Barrage command, where the existing cropping intensities are low, if the rice cultivation is reduced by 10 percent and the area under cotton increased, there will be a net reduction in recharge to the otherwise saline aquifer.

Apart from other supportive details already summarized as part of the foregoing analysis, it is highly desirable that a conscious effort be made to introduce a system of crop zoning and typical cropping patterns for different canal commands that, in terms of consumptive use requirements, match the current canal capacities and maximum deliverable volumes. This would require detailed evaluation of the existing cropping patterns, the cropping calendar and other socio-economic factors, including the need for coordination between the provincial Irrigation and Agriculture Departments.

From the canal operation data for the year 1995-96, it is evident that almost all of the canals designed to operate as non-perennial have, in effect, been converted into perennial systems. These include the Desert, Begari and Ghotki Canals offtaking from the Guddu Barrage, and Fuleli and Pinyari Canals within the Kotri Barrage command. Current operational procedures cannot sustain full supply levels to match the perennial demands, and are likely to receive only sporadic supplies amounting to a relatively small portion of their designed full supply depth. This mode of operation is not conducive to maintaining the canals in the regime.

In lieu of the above-mentioned crop area adjustments, water budgeting is an emergent requirement that will be needed to suit the introduction of demand-sensitive irrigation scheduling. These budgets would constitute a rolling mechanism for modifying the canal system allocations based on the changing pattern of water availability and cropping pattern. A significant benefit of water budgeting is the possibility of agreeing to mutually beneficial sales or exchanges of water supplies so as to supplement the shortages during the critical demand periods, which may be experienced at different times in various parts of the province.

Related to the proposed adoption of demand-sensitive irrigation scheduling, it would be appropriate to prepare annual rule curves for operational control of each canal system, on the lines used for reservoir operations. The rule curves will set the upper and lower limits of indents to be made for the system for each 10-day period of the cropping season, based on the projected climatic trends for the year, as well as the cropping pattern and intensity approved for the system. The rule curves would be accompanied by a system operation manual defining the authorized shares of each distributary canal. The integration of rule curves for all the canal systems would provide a logical framework for the formulation of provincial water budgets as described above.

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

Under the crop area management interventions cited in Simulation III(c), the significant contributions from private tubewells and skimming wells cannot be overlooked. The skimming wells are suitable for recovering fresh groundwater from thin layers or lenses of limited thickness and sizes. Technologically, they are difficult to implement in the absence of site-specific data on aquifer geometry, aquifer properties, lens geometry, salinity concentrations and dominant recharge mechanisms. Such data are seldom available from regional investigations, such as the ones covering the Sukkur Right Bank commands where skimming wells may also help towards lowering the watertables, as well as supplement irrigation supplies towards meeting the crop water requirements.

In contrast to the skimming wells, the scavenger wells produce both fresh and saline discharges from aquifers having as little as a 25-m interface. The former can be used for crop irrigation and the latter has to be disposed of. Some of the scavenger well systems have been installed in the Left Bank Outfall Drain project on a pilot basis. Based on their performance, their installation could be extended to cover areas of shallow fresh-saline groundwater divides elsewhere.

Any development regime imposed on a groundwater system also affects the recharge. The increased groundwater abstractions lead to a decline in the groundwater levels, which tend to increase the inflows from recharge sources and decrease some outflows, such as evaporation from groundwater surface. A detailed study is required to determine the extent and magnitude of this interaction on a sub-basin level, like the area irrigated by the Right Bank canals offtaking from the Guddu and Sukkur Barrages. The scope of such investigations will be crucial to the conscripts of the policy formulation antecedent of a regional groundwater development and management program.

In saline groundwater areas of the lower Sindh Province, poor drainage has been the primary cause of rising watertables with negative impacts on the expansion of cultivable areas and a concomitant decline in cropping intensities and crop yields. Where local relief limitations inhibit the provision of carrier drains for the agricultural effluent, the

construction of evaporation ponds over the un-culturable patches of land offers a viable alternative.

Some of the input parameters used in the IBMR will also need to be updated, like the recharge coefficients, which are currently based on the studies undertaken by WAPDA during 1976-78 for the formulation of the Revised Action Plan (RAP) for the Indus Basin irrigated agriculture. The update is more desirable at the canal command level for more accurate determination of some recharge components. Relatedly, across the history of public sector projects implemented by WAPDA, there is a tremendous volume of data on groundwater development, that is either not readily available or has not been computerized for modeling purposes. Therefore, there is a strong need to develop a computerized data base, whereby much of the unutilized information could be usefully deployed.

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ANNEXURES

A. MAIN FEATURES OF SINDH IRRIGATION SYSTEM

IBMR Agroclimatic Zones (ACZ)	Political Districts:
Sindh Cotton-Wheat North (**SCWN**)	Khairpur, Sukkur, Nawabshah, Nowshera Feroze
Sindh Cotton-Wheat South (**SCWS**)	Sanghar, Mirpurkhas Hyderabad, Tharparkar, Badin
Sindh Rice-Wheat North (**SRWN**)	Jacobabad, Shikarpur, Larkana, Dadu
Sindh Rice-Wheat South (**SRWS**)	Thatta, Hyderabad, Badin

Canal Command and ACZ Mapping

ACZ	Canal Command (Mha.)	% CCA	CCA (Mha)	CCAP (Mhm/M)	Canal Efficiency (%)
SCWN	Ghotki Feeder	100	0.368	0.0799	76
	Khairpur West	100	0.195	0.0194	75
	Khairpur East	100	0.182	0.0264	74
	Rohri Canal	59	0.617	0.1210	81
	Nara Canal	20	0.176	0.1077	80
SCWS	Rohri Canal	41	0.428	0.1210	81
	Nara Canal	80	0.706	0.1077	81
SRWN	Desert Feeder	100	0.158	0.0372	83
	Begari Feeder	100	0.341	0.1425	82
	North West	100	0.309	0.0470	80
	Rice Canal	100	0.210	0.1022	85
	Dadu Canal	100	0.245	0.0393	80
SRWS	Kalri Begar	100	0.257	0.0673	80
	Lined Channel	100	0.220	0.0253	80
	Fuleli Canal	100	0.361	0.1103	80
	Pinyari Canal	100	0.323	0.1025	82

B. WATER DIVERSIONS AT CANAL HEAD IN MILLION HECTARE METERS (MHM)

	1989-90			1995-96		
	Rabi	**Kharif**	**Annual**	**Rabi**	**Kharif**	**Annual**
Desert Feeder	0.025	0.193	0.218	0.013	0.159	0.172
Begari Feeder	0.041	0.370	0.410	0.051	0.346	0.397
Ghotki Feeder	0.133	0.256	0.389	0.090	0.193	0.282
North West	0.121	0.203	0.324	0.143	0.149	0.291
Rice Canal	0.026	0.254	0.280	0.037	0.327	0.364
Dadu Canal	0.100	0.152	0.253	0.093	0.150	0.243
Khairpur West	0.075	0.089	0.164	0.058	0.075	0.133
Khairpur East	0.088	0.105	0.193	0.086	0.093	0.179
Rohri Canal	0.470	0.571	1.041	0.390	0.586	0.976
Nara Canal	0.377	0.480	0.857	0.361	0.433	0.794
Kalri Beghar	0.115	0.229	0.343	0.140	0.238	0.378
Lined Channel	0.062	0.105	0.167	0.057	0.120	0.177
Fuleli Canal	0.115	0.339	0.454	0.127	0.348	0.476
Pinyari Canal	0.086	0.232	0.319	0.107	0.250	0.357

Cropped Area of major crops during 1995-96 (in thousand hectares)

	Wheat	**IRRI**	**Cotton**	**Sugarcane**
Desert Feeder	34.60	79.43	0.23	0.00
Begari Feeder	53.24	206.29	0.63	0.01
Ghotki Feeder	102.73	22.38	100.90	4.79
North West	31.94	107.49	0.00	0.34
Rice Canal	23.70	135.40	0.00	0.02
Dadu Canal	59.89	56.08	5.21	4.38
Khairpur West	81.81	9.15	25.08	4.76
Khairpur East	52.90	0.90	38.71	4.00
Rohri Canal	310.87	25.39	206.24	84.21
Nara Canal	159.88	13.39	167.91	38.18
Kalri Beghar	3.67	43.25	0.82	5.96
Lined Channel	12.01	30.63	0.16	47.33
Fuleli Canal	17.02	89.43	0.03	22.88
Pinyari Canal	6.20	61.15	0.02	20.95

C. SIMULATION SCENARIOS FOR THE YEAR 2010

The generation of IBMR simulations for year 2010 corresponds to a host of scenarios that independently define the key variations in cropping pattern that would induce favorable changes to the groundwater balance and minimize the inequities in the surface supplies. The stress was on the alternative cropping pattern, or the most judicious distribution of the same, in lieu of the physical constraints specified for a canal command. The scenarios were formulated based on IIMI's on-farm estimates of the fallow and cultural waste area that could benefit from redistribution of irrigation supplies. For each of the scenarios, growth rates of crop area and average yield of major crops were established for the year 2010 (**Table 6**) according to the IIMI sample surveys of 1997-98. These surveys benchmarked the potential for crop area and yield of major crops (wheat, cotton, rice and sugarcane) under existing conditions, for each canal command. Estimates of the current CCA and crop area were obtained from the 1995-96 figures of the Sindh Irrigation and Power Department, whereas crop yield statistics were owed to the Development Statistics of Sindh. Consequently, the following simulation scenarios were formulated within the IBMR for projection to the year 2010.

Crop Area Management

Scenario I:

A base year, or benchmark starting from the year 1995-96; the growth rates of crop area and average yield from IIMI surveys (**Table B.1**) set as target for the year 2010. Surface water supplies are set equal to monthly average diversions at canal head during 1990-91 and 1995-96 periods. The pumpage from Government tubewells is assumed to be zero by the year 2010. The growth rates for private tubewell investment were set equal to 2 percent. The area of fresh water lenses along the Right Bank of the river Indus were included.

Scenario II:

No change in growth rates of crop yield of all major crops, and, the crop area of wheat. The growth rates for cotton area were decreased in SCWN and SCWS, but increased in SRWS. The rice area was also decreased in SRWS, and sugarcane area was decreased in SRWN, SRWS and SCWS. The private tubewell growth rates were set equal to 2 percent in all zones, except in SRWN, where it was set equal to 2.25 percent per annum. All other parameters remained the same as under Simulation I.

Scenario III:

The growth rates were further reduced for crops like wheat (SCWN, SCWS and SRWS, but no change in SRWN), cotton (SRWN, SCWS, and SRWS and no change in SCWN), rice (SRWN and SRWS) and sugarcane (SCWN and SCWS). The growth rates of private tubewell development were set as SCWN=3 percent, SRWN=1 percent, SCWS=5 percent and SRWS=2 percent per annum. Other parameters remained the same.

Scenario III (a):

The crop area growth rates were kept the same as under Simulation III, except that the area of wheat and rice was further reduced. No change was made in the per annum growth rates of yield of major crops. The growth rate of private tubewells in fresh areas was kept the same as under Simulation III. The pumpage in saline groundwater areas was also included via skimming wells (14 lps capacity). All other parameters relating to canal diversions, yields etc., were the same as under Simulation III.

Scenario III (b):

There was no change in the growth rates of cropped area. The growth rates of private tubewells were increased as follows; SCWN=5 percent, SRWN=3 percent, SCWS=6 percent and SRWS=4 percent. The pumpage in saline areas was also allowed as under Simulation III(a). All other parameters relating to canal diversions, yields, etc., were the same as under Simulation III.

Scenario III (c):

The areal growth rate of wheat was decreased in SCWS and SRWS; increased for cotton in SRWN and SRWS; further decreased for rice in SRWN and SRWS; and sugarcane was decreased in SCWS. The growth rates of private tubewell development were set as SCWN=6 percent, SRWN=5 percent, SCWS=6 percent and SRWS=4 percent per annum. Other parameters relating to groundwater pumpage in saline areas, growth rate of crop yield, canal diversions, etc., remained the same as under Simulation III(c).

Scenario IV (Capital Investment Option):

This simulation accounts for lining of the irrigation canals passing through waterlogged and saline areas, along with remodeling watercourses and the improvement of irrigation practices at the farm level through OFWM Program. The WAPDA and World Bank figures for canal delivery and watercourse command efficiencies, with and without project conditions, were used for the year 2010. All the annual growth rates relating to crop area, yield, private tubewell development in fresh areas, and the canal diversions were kept the same as under simulation Scenario I. Saline groundwater pumpage is not permitted.

Scenario V (Canal Water Regulations):

This simulation scenario is based on the assumption that all the canals receive supplies at their diversion points according to the agreed formula of the Water Apportionment Accord of 1991. All the annual growth rates relating to the cropped area, yield, private tubewell development in fresh areas, etc., were kept the same as under simulation Scenario I. Once again, pumpage in saline areas is not permitted.

D. WATER LOSS RECOVERY FACTORS IN SALINE AREAS

Canal Water Loss Recovery Factors in Saline Areas by Canal Command (in the Context of IBMR).

Canal Command	Canal Efficiency (Without Lining)	Canal Efficiency (Canal Lining)	Loss Factors (With Lining)
Begari Feeder	0.820	0.946	0.70
Ghotki Feeder	0.765	0.929	0.70
North West Cana	0.804	0.941	0.70
Rice Canal	0.854	0.956	0.70
Dadu Canal	0.804	0.941	0.70
Khairpur East	0.738	0.921	0.70
Rohri Canal	0.811	0.943	0.70
Nara Canal	0.816	0.945	0.70
Kalri Begar	0.800	0.940	0.70
Lined Channel	0.800	0.800	0.70
Fuleli	0.800	0.940	0.70
Pinyari	0.821	0.946	0.70

Watercourse Command Water Loss Recovery Factors in Saline Areas by Canal Command (in the Context of IBMR).

Canal Command	Canal Efficiency (Without Lining)	Canal Efficiency (Canal Lining)	Loss Factors (With Lining)
Begari Feeder	0.600	0.620	0.05
Ghotki Feeder	0.450	0.480	0.05
North West Cana	0.575	0.595	0.05
Rice Canal	0.625	0.660	0.09
Dadu Canal	0.575	0.595	0.05
Khairpur East	0.455	0.475	0.04
Rohri Canal	0.456	0.490	0.06
Nara Canal	0.450	0.479	0.05
Kalri Begar	0.575	0.590	0.04
Lined Channel	0.555	0.595	0.09
Fuleli	0.600	0.610	0.03
Pinyari	0.585	0.600	0.04

E. ANNUAL NET WATER REQUIREMENTS AND SUPPLIES AT ROOT ZONE (Mhm.)

A Comparison of 2010 Simulations with Base 1995-96.

Canal Command		Base-96	Sim-IIIc	Sim-IV	Sim-V
Desert	Requirements	0.0918	0.0861	0.1026	0.1026
	Supplies	0.0880	0.1062	0.1066	0.2345
Begari	Requirements	0.1981	0.2211	0.2635	0.2635
	Supplies	0.2174	0.2347	0.2612	0.3016
Ghotki	Requirements	0.1410	0.2453	0.2561	0.2561
	Supplies	0.1263	0.2350	0.2763	0.2299
North West	Requirements	0.1797	0.1803	0.2149	0.2149
	Supplies	0.1433	0.1692	0.2059	0.2151
Rice	Requirements	0.1221	0.1139	0.1365	0.1365
	Supplies	0.2316	0.3409	0.3855	0.4459
Dadu	Requirements	0.1424	0.1335	0.1591	0.1591
	Supplies	0.1207	0.1352	0.1638	0.1401
Khairpur West	Requirements	0.0748	0.1302	0.1359	0.1359
	Supplies	0.0593	0.0825	0.0845	0.1215
Khairpur West	Requirements	0.0699	0.1216	0.1270	0.1270
	Supplies	0.0676	0.0920	0.1092	0.1045
Rohri	Requirements	0.4127	0.6728	0.7223	0.7772
	Supplies	0.4413	0.5286	0.6293	0.7211
Nara	Requirements	0.3515	0.5622	0.6091	0.6685
	Supplies	0.3296	0.4629	0.5309	0.5658
Kalri	Requirements	0.0921	0.1573	0.1700	0.1740
	Supplies	0.1789	0.1993	0.2466	0.2042
Lined Channel	Requirements	0.0788	0.1346	0.1454	0.1488
	Supplies	0.0852	0.0936	0.1168	0.1181
Fuleli	Requirements	0.1290	0.2283	0.2466	0.2525
	Supplies	0.2383	0.2756	0.3398	0.3140
Pinyari	Requirements	0.1157	0.1977	0.2135	0.2186
	Supplies	0.1786	0.2052	0.2498	0.3163

Net Requirements and Supplies by Barrage Command.

Barrage		Base-96	Sim-IIIc	Sim-IV	Sim-V
Guddu Barrage	Requirements	0.4309	0.5525	0.6222	0.6222
	Supplies	0.4317	0.5759	0.6441	0.7660
Sukkur Barrage	Requirements	1.3531	1.9145	2.1048	2.2191
	Supplies	1.3934	1.8113	2.1091	2.3140
Sukkur Barrage (Right Bank)	Requirements	0.4442	0.4277	0.5105	0.5105
	Supplies	0.4956	0.6453	0.7552	0.8011
Sukkur Barrage (Left Bank)	Requirements	0.9089	1.4868	1.5943	1.7086
	Supplies	0.8978	1.166	1.3539	1.5129

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