REPORT NO. R-21.8

SALINITY MANAGEMENT ALTERNATIVES FOR THE RECHNA DOAB, PUNJAB, PAKISTAN

Volume Eight

Options for Sustainability: Sector Level Allocations and Investments

Abdul Rehman (Senior Engineer, Planning Division, WAPDA)
Gauhar Rehman (Civil Engineer, GIS Specialist)
Hassan Zia Munawar (Engineer, GIS)

APRIL 1997

PAKISTAN NATIONAL PROGRAM
INTERNATIONAL IRRIGATION MANAGEMENT INSTITUTE
LAHORE

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 Manager (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.

Gaylord V. Skogerboe
Director, Pakistan National Program
International Irrigation Management Institute

Table of Contents

List of Tables

List of Figures

SALINITY MANAGEMENT ALTERNATIVES FOR THE RECHNA DOAB, PUNJAB, PAKISTAN

Volume Eight

Options for Sustainability: Sector Level Allocations and Investments

I. INTRODUCTION

The wealth of information generated in the preceding volumes relates to the pieces of the the strategy developed under the Process Flow Chart shown in Figure 1, Volume Three. The component-wise inputs have been derived from diverse sources and pertain to both the physical and economic charateristics of the regime. The tangible assimilation of results from each of these components, has also been described in detail under Section II. E of Volume Three where an Analytical Flow Chart (Figure 13) shows the integrating network of information that initially combines all facets of information at the irrigation subdivision level (see Process Flow Chart) before leading to the final deliverables extrapolated across the entire Rechna Doab. From amongst the *five* component separations shown under Section II. E of Volume Three, only the Indus Basin Model Revised (IBMR) component is inflexible in scale of deliverables, i.e. its output cannot address levels of detail below the canal command. Hence, the Process Flow Chart shows its initial outputs to be somewhat detached from the respective subdivision level appropriations under the other components of the study. However, in lieu of the need to be adaptive to this comparative upscaling of information originating at the smaller subdivision level, the set of IBMR simulations (perceived under Section VII of Volume Three) were primarily meant to be a sensitizing exercise to the major strategic options available for sustainable irrigated agriculture within the Rechna Doab. In the context of the above-mentioned Process Flow Chart, Section I of this Volume is limited to the "INFERENCE II" box in its evaluation of the best choices from amongst the list of strategic options appearing under Section VII. D of Volume Three. In Section II, adjustments are proposed to the above sensitivity analysis in the context of the salient findings under Sections III and IV of Volume Seven. The contributions from these Sections of Volume Seven, limited to the Jhang and Gugera branch canals only, are critical to the understanding of the adjustments to the selected IBMR simulations wherein the impact could be evaluated across the other canal commands of the Rechna Doab as a major extrapolation of results. The constituting pieces of this extrapolation would then be in terms of the required increases in area and yield, available canal diversions, the contributions from private tubewell pumpage, and the availability of water at the root zone.

A. Simulation Strategies for the IBMR

The set of initial simulations for the IBMR could broadly be categorised under two different time periods; the first relates to the predicted outcome of results between the years 1990-2000 wherein a total of eleven simulations are evaluated for changes in production of major crops based on both the historic and desirable growth rates in yield and area. Assumptions have also been made for the available canal water supplies to the year 2000 based on the actual figures for the year 1990-91 and for the year 1994-95. The supplemental contributions from the public wells have been progressively decreased, and sometimes even eliminated, during the period of simulation. Both *extensive* and *intensive* area strategies have been contrasted for impact on production, and in one case (Scenario E) a combination of the two has also been assumed. IIMI's own field survey data on the yields of the major crops has been adopted (scenarios B-J) to supplement the reported figures by the Agriculture Statistics of Pakistan. As a management reprieve to the less than adequate surface water supplies, both field application and conveyance efficiencies have been improved in certain cases (scenarios E-J).

The second period of simulation compares the predicted production of major crops to the year 2010 by taking 1995 as the base year. There are only two simulations for this period (scenarios K and K1). The first one assumes a combination of both *extensive* and *intensive* strategies whereas the second has a constant areal growth rate of 0.5% per annum to the year 2010. Cumulative yield rates in both of the scenarios derive from the IIMI data, and are variated in the first of the two scenarios. Also, the first one eliminates public tubewell contributions by the year 2000, whereas the same reduction is not put into effect till the year 2010 in the second simulation. Perhaps the most significant difference is in the canal water availability, which in the first one is variated to increase by a maximum of 110%, whereas in the second simulation the much higher proportional allocations of average post-Tarbela diversions are assumed.

B. Initial Results

The following discussion highlights the salient features of the predicted outputs by the IBMR for the specified set of simulation characteristics for each of the two time periods. For ease of understanding, the comparisons have been drawn in the context of the principal constraints to sector level mobilization of resources. It is here that the inferences are drawn in the context of the most appropriate mix of results that could be used to fine tune the inputs leading to the final simulations that are described in the next section.

1) Performance Assessment (1990-95)

To assess the performance of irrigated agriculture during the last five years (1991-95) under the canal commands of the irrigation system in Rechna Doab, the model results for the years 1989-90 and 1994-95 were used taking 1989-90 as a base year and simulating the year

1994-95 such that the simulated results of different variables like crop area, yield and canal diversions at the canal head, match the actual data[1] of 1994-95. The 1990 base represents the situation in respect of the culturable command area (CCA), canal head capacity, irrigation system efficiencies (Annexure-A), as established under Revised Action Plan (RAP) by WAPDA and which also formed the basis for the Water Sector Investment Plan (WSIP) for the year 2000.

Cropped Area: The total cropped *area* under different crops during 1989-90 in Rechna Doab was reported as 6.783 Ma (Table 1) as against the CCA of 4.812 Ma (Table 7) resulting in an annual cropping intensity of 141%. From the reported cropped area of 7.296 Ma during 1994-95 (except fodder crops and chilies, for which data was not available and the data of 1990 was assumed), the proportionate area for each of the crops is shown in Figure 1, for the years 1989-90 and 1994-95. The total cropped area under the command of the LCC system increased from 4.109 Ma to 4.342 Ma (39% and 61% for Jhang and Gugera canal commands, respectively); 82% of this area is in fresh and 18% is in saline groundwater regimes. The change in cropping intensity of major crops like rice, cotton, wheat and sugarcane during this period is shown in Figure 2. All crops, except cotton, have an increasing trend in the Upper Rechna Doab canal commands (Raya, MR Link, UCC), whereas in the LCC System and the Haveli canal commands, there is an increasing trend for wheat, basmati and sugarcane, no change for IRRI rice, and a tremendous decrease in cotton cultivation.

Production: The *production* of major crops like wheat, rice (paddy rice), cotton (seed cotton) and sugarcane, with corresponding average yields, are shown in Table 2. There is no significant variation between the simulated yields and the yield data collected through the IIMI survey during 1995. The simulated production of total rice during the period 1991-1995 has increased by 3.65%, whereas the corresponding area under total rice has increased by more than 16%, thereby resulting in a decrease of average yield per acre (9% for basmati and 17% for IRRI) in the Rechna Doab. The decrease in production and yield (30%) of the cotton crop is due to serious virus attacks during this period. However, the yields of wheat and sugarcane crops have an increasing trend (12% and 19%, respectively).

The production and average crop yield in the Lower Chenab Canal (LCC) system is given in Table 3, which shows that the production of rice in areas under the LCC system has increased from 0.932 to 0.955 Mt (0.5 % per annum) whereas per acre yield has decreased. The production of sugarcane and wheat crops is showing an increase of 10% and 5% per annum, respectively, with a corresponding increase in yield per acre, but there is a substantial decreasing trend for the cotton crop.

---

[1] Data Sources: The cropped area and production data is from the Agricultural Statistics of Pakistan (ASP), and the canal diversions data from the Water Resources Management Directorate (WRMD) of WAPDA.

Table 1. Comparison of Cropped Area within the Rechna Doab, Punjab, Pakistan.

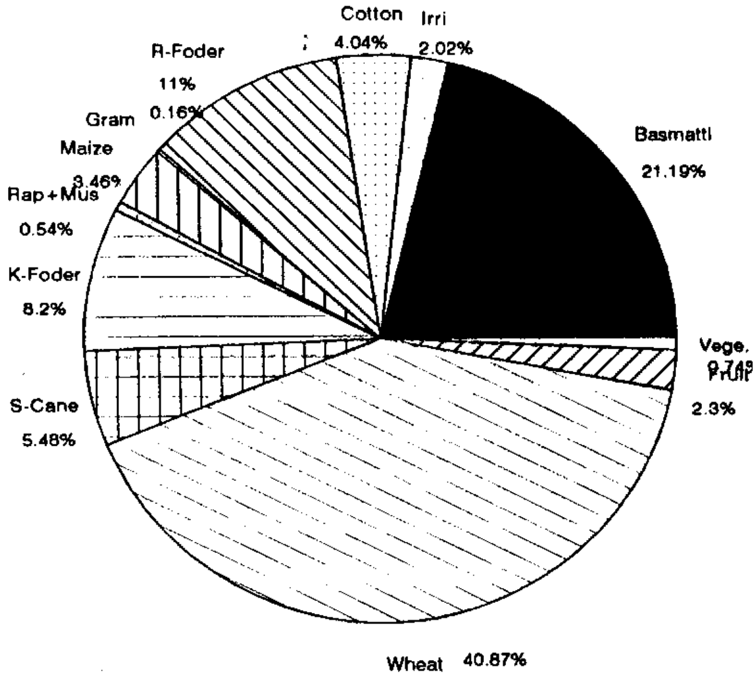
(000 acres)

Crop	Fresh		Saline		Total	
	1990	1995	1990	1995	1990	1995
Basmati	1368.48	1604.53	68.64	85.76	1437.13	1690.29
IRRI	131.47	133.73	5.46	4.51	136.93	138.24
Cotton	186.55	127.21	87.77	62.14	274.32	189.35
Rabi Fodder	633.6	633.6	112.19	112.19	745.79	745.79
Gram	9.27	8.19	1.64	1.6	10.91	9.79
Maize	176.02	157.16	58.63	53.23	234.64	210.39
Rape+Must.	28.64	24.8	7.8	8.71	36.44	33.51
Kharif Fodder	453.66	453.66	102.39	102.39	556.04	556.04
Sugarcane	279.02	357.39	92.54	129.25	371.55	486.64
Wheat	2334.44	2563.12	437.96	444.63	2772.4	3007.75
Fruits	118.28	123.74	38	40.15	156.28	163.89
Potato	34.82	47.78	4.16	4.04	38.99	51.82
Onions	6.27	7.74	1.04	1.21	7.3	8.95
Chilies	3.27	3.27	0.81	0.81	4.08	4.08
Total Crops	5763.79	6245.92	1019.03	1050.62	6782.82	7296.54

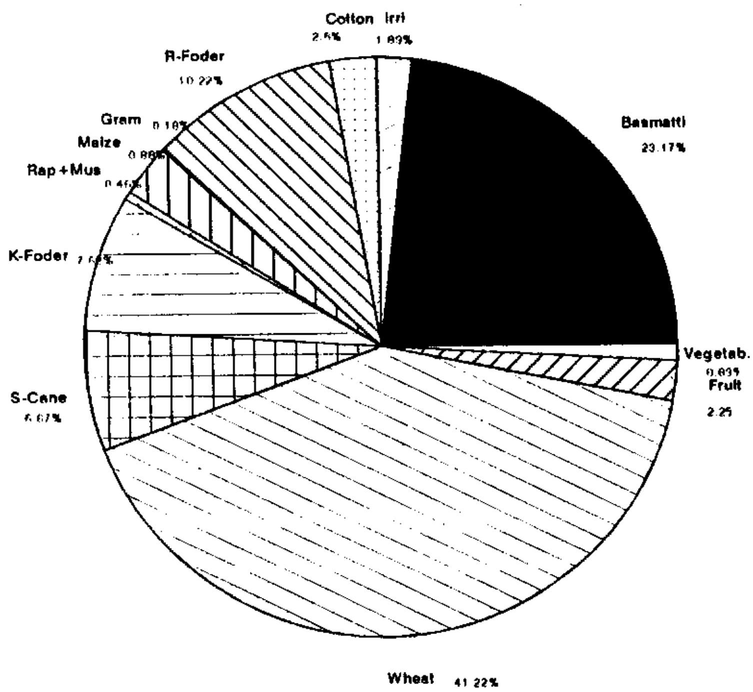
Table 2. Crop Production and Average Yield in the Rechna Doab, Punjab, Pakistan.

Crop	Production (million tons)		Average Yield (tons per acre)		
	1990	1995	1990	1995*	1995**
Basmati	1.842	1.964	1.281	1.162	1.016
IRRI	0.286	0.241	2.092	1.745	1.888
Cotton	0.156	0.075	0.568	0.396	0.391
Sugarcane	5.863	8.58	15.78	17.632	17.614
Wheat	2.329	3.005	0.84	0.999	0.998

Note * Crop yield trend calculated through IBMR model.
** Actual, through IIMI Survey (1995).



Distribution of Cropped Area for the Year 1989-90



Distribution of Cropped Area for the Year 1994-95

Figure 1 Distribution of Cropped Area within the Rechna Doab

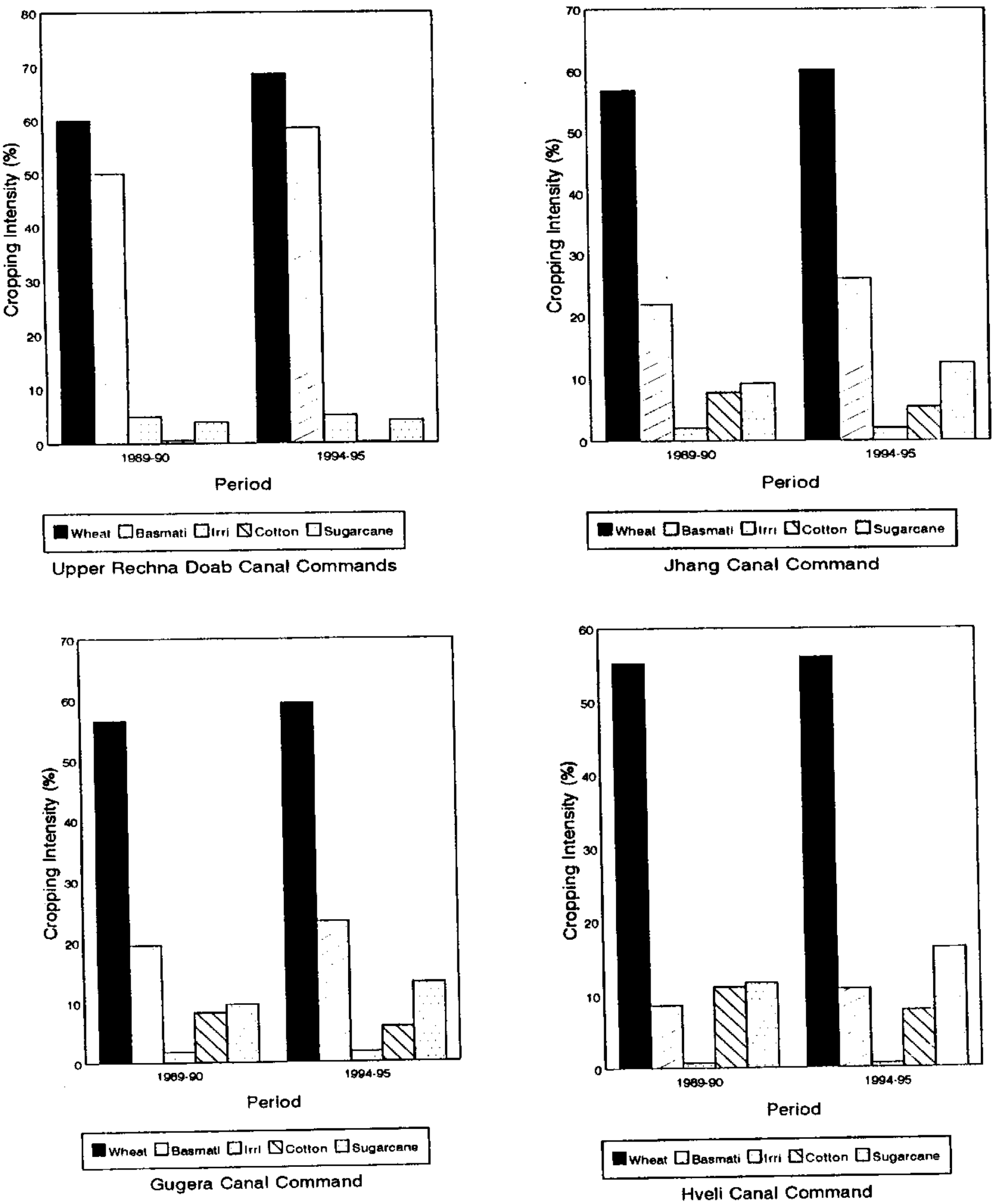


Figure 2. Comparison of Cropping Intensity for Major Crops within the Canal Commands of the Rechna Doab.

Table 3. Crop Production and Average Yield within the LCC System and Haveli Canal Command, Rechna Doab, Punjab, Pakistan.

Crop	Production (million tons)		Average Yield (tons per acre)	
	1990	1995	1990	1995
Jhang Branch				
Basmati	0.334	0.354	1.302	1.161
IRRI	0.05	0.041	2.105	1.743
Cotton	0.052	0.025	0.589	0.362
Sugarcane	1.709	15.891	2.559	16.09
Wheat	0.562	0.702	0.847	0.953
Gugera Branch				
Basmati	0.477	0.503	1.311	1.161
IRRI	0.071	0.057	2.112	1.743
Cotton	0.09	0.043	0.59	0.362
Sugarcane	2.874	4.327	15.923	16.047
Wheat	0.896	1.106	0.85	0.948
Haveli Canal				
Basmati	0.022	0.023	1.422	1.161
IRRI	0.003	0.002	2.211	1.743
Cotton	0.012	0.005	0.596	0.361
Sugarcane	0.335	0.514	16.023	15.906
Wheat	0.085	0.100	0.861	0.926

Canal Diversions: The total annual *canal diversions* during 1994-95 were 9.601 MAF (39 % in rabi and 61% in kharif seasons) as compared to 1989-90 diversions of 11.053 MAF. The monthly pattern of water diversions at the canal heads appear in Figure 3, which shows a decreasing trend across all of the canal commands in all months. A seasonal comparison of canal command diversions in Rechna Doab is given in Table 4. It is evident from the 5-year average diversions for each canal that the water supplies to all of the canals have been reduced at the rate of 2.5% per annum during the 1991-95 period; the exceptions being for the Raya Canal of BRBD and Marala Ravi (Internal) canals where there is an increase of 47% in the rabi season and 19% in the kharif season.

Water Balance at the Root Zone (Rechna Doab Level): The *water shortages or surpluses* are derived through water balance computations at the root zone, where the water requirements are met from supplies through surface (canal and rainfall) and groundwater sources (pumpage from tubewells and subirrigation through capillary action). Table 5, together with Figure 4, compare water requirements and supplies (MAF) at the root zone for the years 1990 and 1995 for the Rechna Doab. The annual crop water requirements have increased by 10 % (15.834 to 17.366 MAF) during the 1991-95 period (45% in rabi and 55% in kharif seasons) whereas the annual total water supplies increased by 8% (14.98 to 16.203 MAF). These requirements are met from different sources, like canal water (26% in rabi and 33% in kharif), groundwater (59% in rabi and 36% in kharif), rainfall (13% in rabi and 29% in kharif) and sub-irrigation (2% in rabi and kharif) for the year 1990. The groundwater pumpage is from public tubewells (15% in rabi and 24% in kharif) and from private tubewells (85% in rabi and 76% in kharif).

The total canal system in the Rechna Doab is showing a shortage of 0.841 MAF in rabi and 0.013 MAF in kharif during 1990 and this shortage has increased by the year 1995 (0.896 MAF and 0.267 MAF in rabi and kharif, respectively) which is due to a decrease of canal supplies by 3% in rabi and 6% in kharif. Thirty percent of these shortages are occuring in the fresh groundwater areas and 70% in saline areas.

Water Balance at the Root Zone (Canal Command Level): The water balance at the root zone by canal command is given in Table 6 for the LCC and the Haveli canal commands, and is illustrated in Figures 5-7. The Jhang Branch is showing a shortage of 0.144 MAF in saline areas and a surplus of 0.04 MAF in fresh areas during the rabi season (net shortage of 0.104 MAF). For the kharif season, there is a surplus of 0.145 MAF in fresh areas and a shortage of 0.04 MAF in saline areas (net surplus of 0.105 MAF) during the year 1990, resulting in net annual surplus of 0.001 MAF. The net shortage during 1994-95 is 0.022 MAF (shortage of 0.094 MAF in rabi and a surplus of 0.072 MAF in kharif).

Similarly, in 1990 the Gugera Canal command shows a shortage of 0.45 MAF in rabi (0.12 in fresh and 0.33 in saline areas) and 0.145 MAF in kharif (0.04 in fresh groundwater areas and 0.105 in saline areas). These shortages have an overall increase of 15% annualy from the base year 1990, which is due to the decrease in canal supplies during 1994-95.

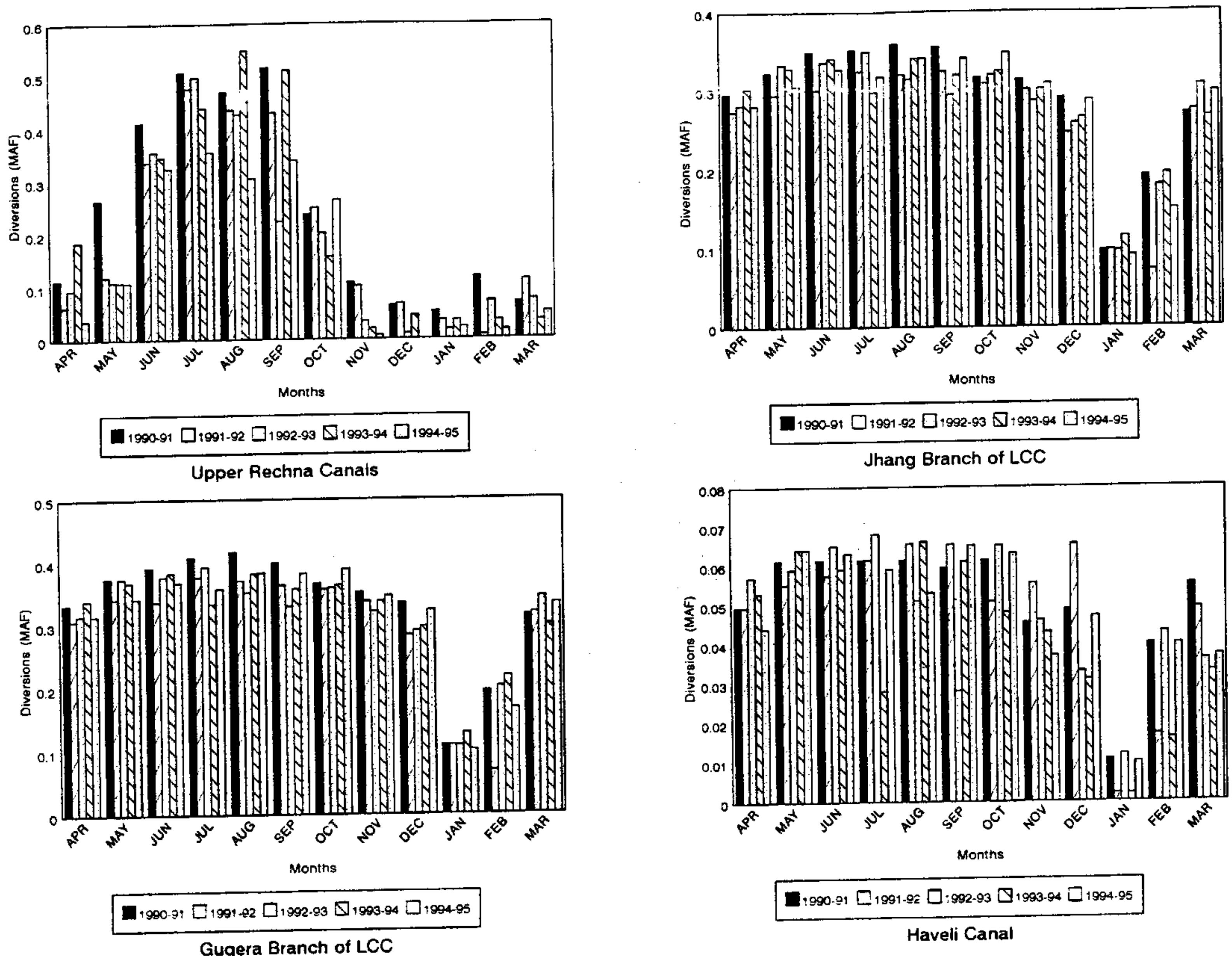


Figure 3.Monthly Canal Diversions (at Canal Head) during the Period 1991-95, Rechna Doab.

Table 4. Comparison of Seasonal Canal Diversions within in the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Canal Command	1989-90			1994-95			Average		
	Rabi	Kharif	Annual	Rabi	Kharif	Annual	Rabi	Kharif	Annual
Raya	0.036	0.394	0.43	0.064	0.361	0.425	0.053	0.391	0.444
M R (Internal)	0.049	0.205	0.255	0.008	0.25	0.258	0.012	0.243	0.255
UCC (Internal)	0.563	1.682	2.245	0.282	0.859	1.141	0.395	1.258	1.653
Jhang Branch	1.478	2.034	3.513	1.477	1.913	3.39	1.122	1.523	2.645
Gugera Branch	1.672	2.323	3.995	1.658	2.147	3.805	1.265	1.726	2.991
Haveli	0.261	0.354	0.615	0.233	0.348	0.581	0.228	0.343	0.571
Total	4.06	6.993	11.053	3.722	5.879	9.601	3.075	5.485	8.56

Table 5. Surface Water Balance at the Root Zone of Rechna Doab, Punjab, Pakistan.

(million acre feet)

Description	Rabi		Kharif		Annual	
	1990	1995	1990	1995	1990	1995
Crop Water Requirement	7.216	7.791	8.618	9.575	15.834	17.366
Water Supplies						
Canal	1.665	1.555	2.878	2.468	4.543	4.023
Effective Rainfall	0.825	0.898	2.481	2.705	3.306	3.603
Sub-Irrigation	0.132	0.141	0.177	0.191	0.309	0.332
Tubewell Pumpage						
Public	0.557	0.568	0.743	0.758	1.3	1.326
Private	3.196	3.733	2.326	3.186	5.522	6.919
Total	3.753	4.301	3.069	3.944	6.822	8.245
Total Supplies	6.375	6.895	8.605	9.308	14.98	16.203
Shortage	0.841	0.896	0.013	0.267	0.854	1.163
Surplus						
Water Stress	0.156	0.173			0.156	0.173

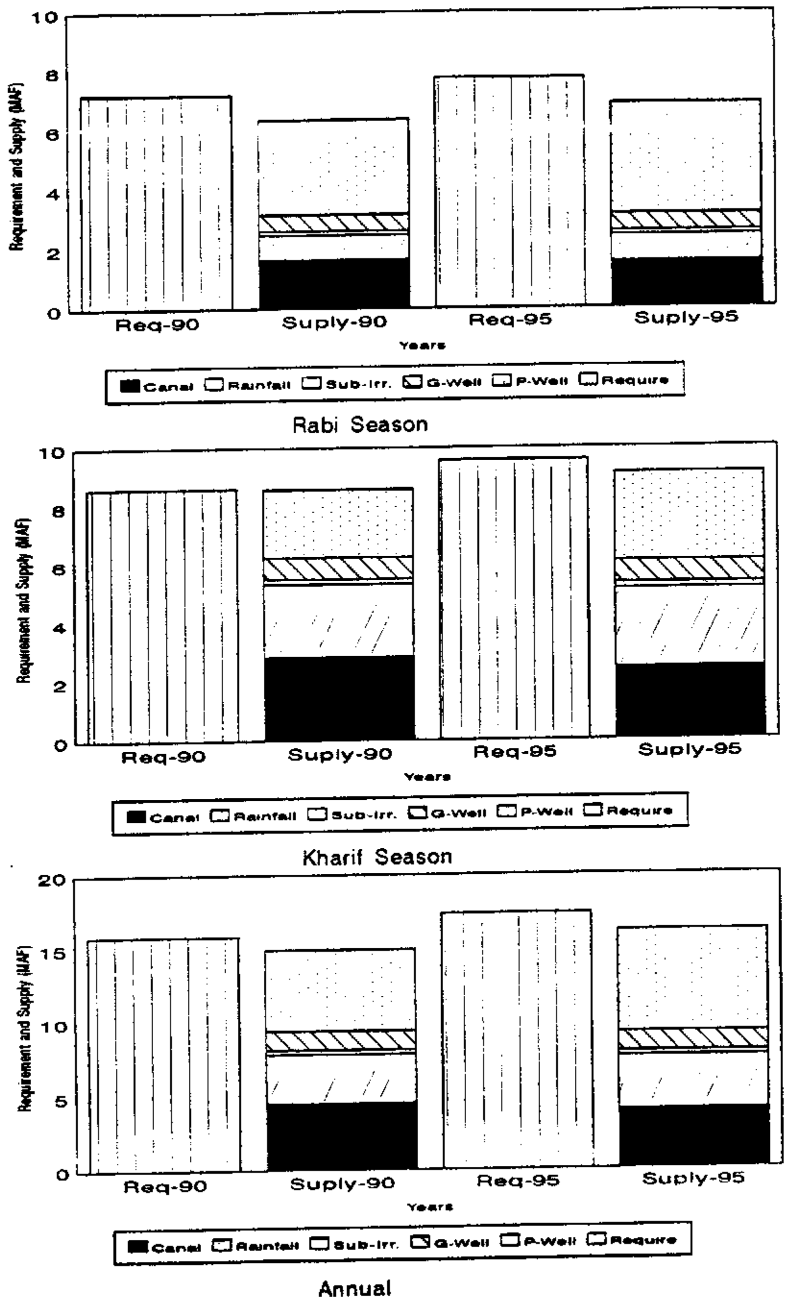


Figure 4. Seasonal Surface Water Balance for the Rechna Doab.

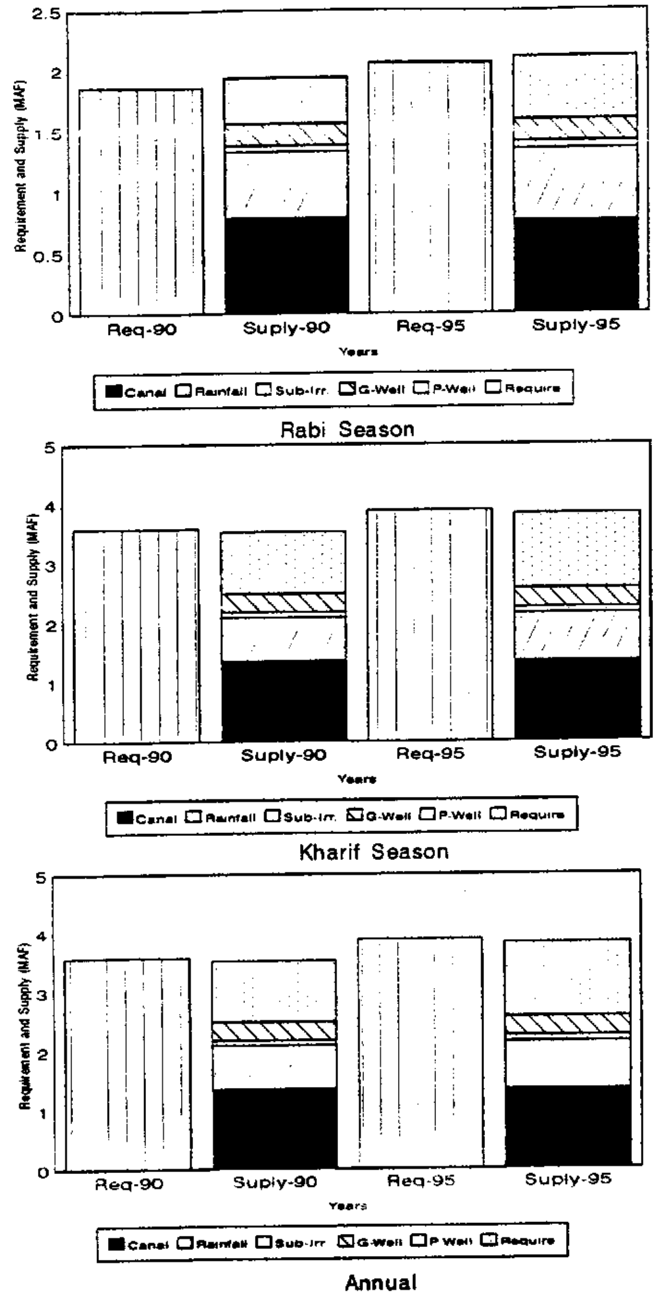


Figure 5. Seasonal Surface Water Balance for the Jhang Branch.

Table 6. Water Balance at the the Root Zone for LCC and Haveli Canal Commands, Rechna Doab, Punjab, Pakistan.

(million acre feet)

Description	Rabi		Kharif		Annual	
	1990	1995	1990	1995	1990	1995
Jhang Branch of LCC						
Crop Water Requirement	1.722	1.834	1.863	2.062	3.585	3.896
Water Supplies						
Canal	0.578	0.594	0.796	0.769	1.374	1.363
Effective Rainfall	0.196	0.211	0.547	0.59	0.743	0.801
Sub-Irrigation	0.043	0.046	0.058	0.063	0.101	0.109
Tubewell Pumpage						
Public	0.14	0.143	0.182	0.186	0.322	0.329
Private	0.661	0.746	0.385	0.526	1.046	1.272
Total	0.801	0.889	0.567	0.712	1.368	1.601
Total Supplies	1.618	1.74	1.968	2.134	3.586	3.874
Shortage	0.104	0.094				0.022
Surplus			0.105	0.072	0.001	
Water Stress	0.044	0.048			0.044	0.048
Gugera Branch of LCC						
Crop Water Requirement	2.736	2.901	2.863	3.163	5.599	6.064
Water Supplies						
Canal	0.692	0.703	0.962	0.911	1.654	1.614
Effective Rainfall	0.31	0.334	0.845	0.91	1.155	1.244
Sub-Irrigation	0.075	0.08	0.1	0.108	0.175	0.188
Tubewell Pumpage						
Public	0.222	0.226	0.288	0.294	0.51	0.52
Private	0.987	1.1	0.523	0.714	1.51	1.814
Total	1.209	1.326	0.811	1.008	2.02	2.334
Total Supplies	2.286	2.443	2.718	2.937	5.004	5.38
Shortage	0.45	0.458	0.145	0.226	0.595	0.684
Surplus						
Water Stress	0.077	0.086			0.077	0.086
Haveli Canal (Internal)						
Crop Water Requirement	0.256	0.266	0.227	0.249	0.483	0.515
Water Supplies						
Canal	0.115	0.105	0.156	0.157	0.271	0.262
Effective Rainfall	0.029	0.031	0.069	0.073	0.098	0.104
Sub-Irrigation	0.009	0.01	0.013	0.014	0.022	0.024
Tubewell Pumpage						
Total Supplies	0.153	0.146	0.238	0.244	0.391	0.39
Shortage	0.103	0.12		0.005	0.092	0.125
Surplus			0.011	-	0.011	
Water Stress	0.035	0.039			0.035	0.039

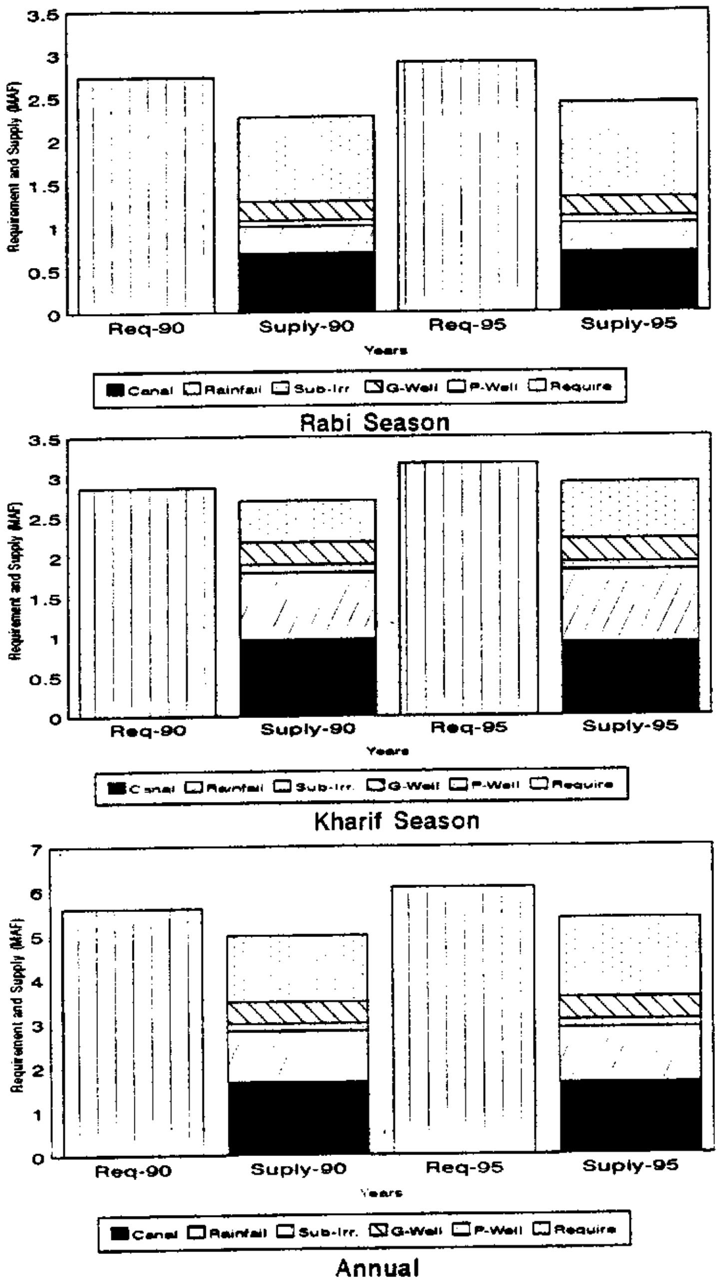


Figure 6. Seasonal Surface Water Balance for the Gugera Branch.

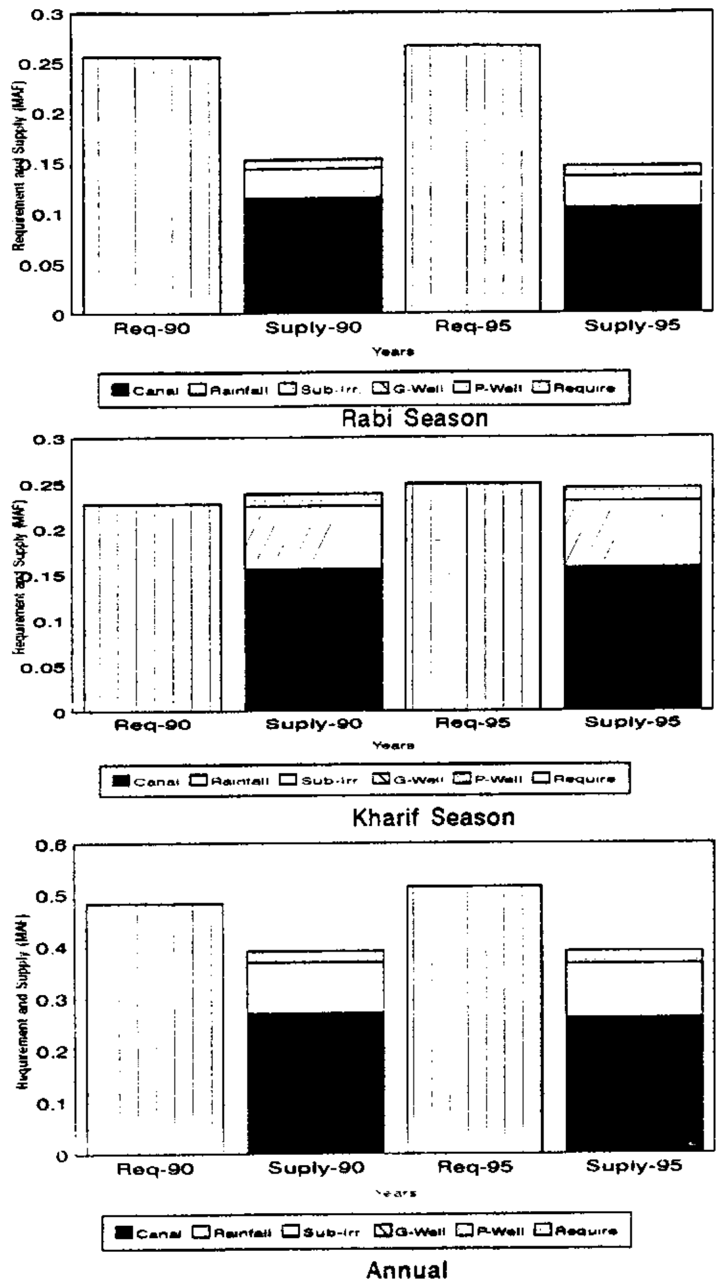


Figure 7. Seasonal Surface Water Balance for the Haveli Canal.

Since the groundwater regime in the Haveli Canal command is saline (Table 7), there is no pumpage to supplement the canal supplies. The resulting water shortages are exacerbated by the increase in annual water requirements of about 7%. There is a surplus of 0.011 MAF in kharif of 1990, but by 1995, this has been converted to a shortage due to decreased canal supplies.

Crop Stress: In the IBMR simulations, when the crop water requirements are not met from the available water supplies, then instead of reducing the crop area, the crops are stressed in particular months to a certain limit with associated lower yields and the embedded economic costs of incurring stress. The stress occurs only in the saline areas because fresh groundwater areas can always supplement the irrigation requirements through tubewell pumpage. A comparison of monthly water stress occuring in the saline areas of Rechna Doab, as well as in the canal commands of the LCC and the Haveli, during the years 1990 and 1995, is shown in Figure 8 where an increase in stress of 11% (Tables 5 & 6) is mostly distributed between the months of September and March.

Groundwater Balance: Table 8 gives the groundwater balance for the entire Rechna Doab based on the model results for the years 1990 and 1995. The positive numbers of net groundwater balance indicate net inflows (rising water table), whereas the negatives indicate net outflows due to excess pumping (falling water table). The total annual recharge to the groundwater from all sources in the irrigated areas of the Rechna Doab has been estimated to be 9.922 MAF in 1990 and has decreased to 9.636 MAF in 1995 due to decreased canal supplies, out of which 87% of the recharge occurs in fresh groundwater areas and the remaining 13% is in the saline groundwater areas (Table 9). The maximum (66%) recharge is occuring in the areas under the canal commands of the LCC system and the Haveli Canal. The annual recharge to the areas under the LCC system has decreased by 2% from 6.318 MAF (1990) to 6.193 MAF (1995) due to decreased canal water supplies. The contribution of recharge from various seepage sources for the whole of the Rechna Doab (Table 8) shows that the maximum recharge is from the irrigation and link canal network (60%), followed by the recharge from the tubewell pumpage used for irrigation purposes.

The total *annual pumpage* of groundwater in the irrigated areas of Rechna Doab has been estimated to be 10.105 MAF in 1990 out of which 2.45 MAF (24%) occurs with public sector tubewells and 7.64 (76%) with private sector tubewells. The total pumpage has increased to 11.967 MAF in 1995, out of which 9.509 MAF (79%) is from private sector tubewells and 2.458 (21%) is from public sector tubewells (Table 10). The groundwater pumpage is more in the upper Rechna canal commands (51%) where most of the areas receive non-perenial canal supplies. The annual pumpage in the areas of the LCC system has increased by 14% from 5.129 MAF to 5.833 MAF during 1991-1995 to supplement the surface supplies due to decreased diversions at canal heads during 1994-95. The pumpage from private tubewells has increased from 7.647 MAF (1990) to 9.509 MAF (1995) and the maximum pumpage from the private sector tubewells (55%) is occuring in the upper Rechna Doab areas, most of which are under the non-perenial canal commands.

Table 7. Groundwater Quality within the Canal Commands of the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Canal	Fresh	Saline	Total
Raya Canal	0.424		0.424
Marala Ravi (Internal)	0.158		0.158
Upper Chenab (Internal)	1.017		1.017
Jhang Branch (LCC)	0.946	0.222	1.168
Gugera Branch (LCC)	1.474	0.392	1.866
Haveli Canal (Internal)		0.179	0.179
Total Rechna Doab	4.019	0.793	4.812

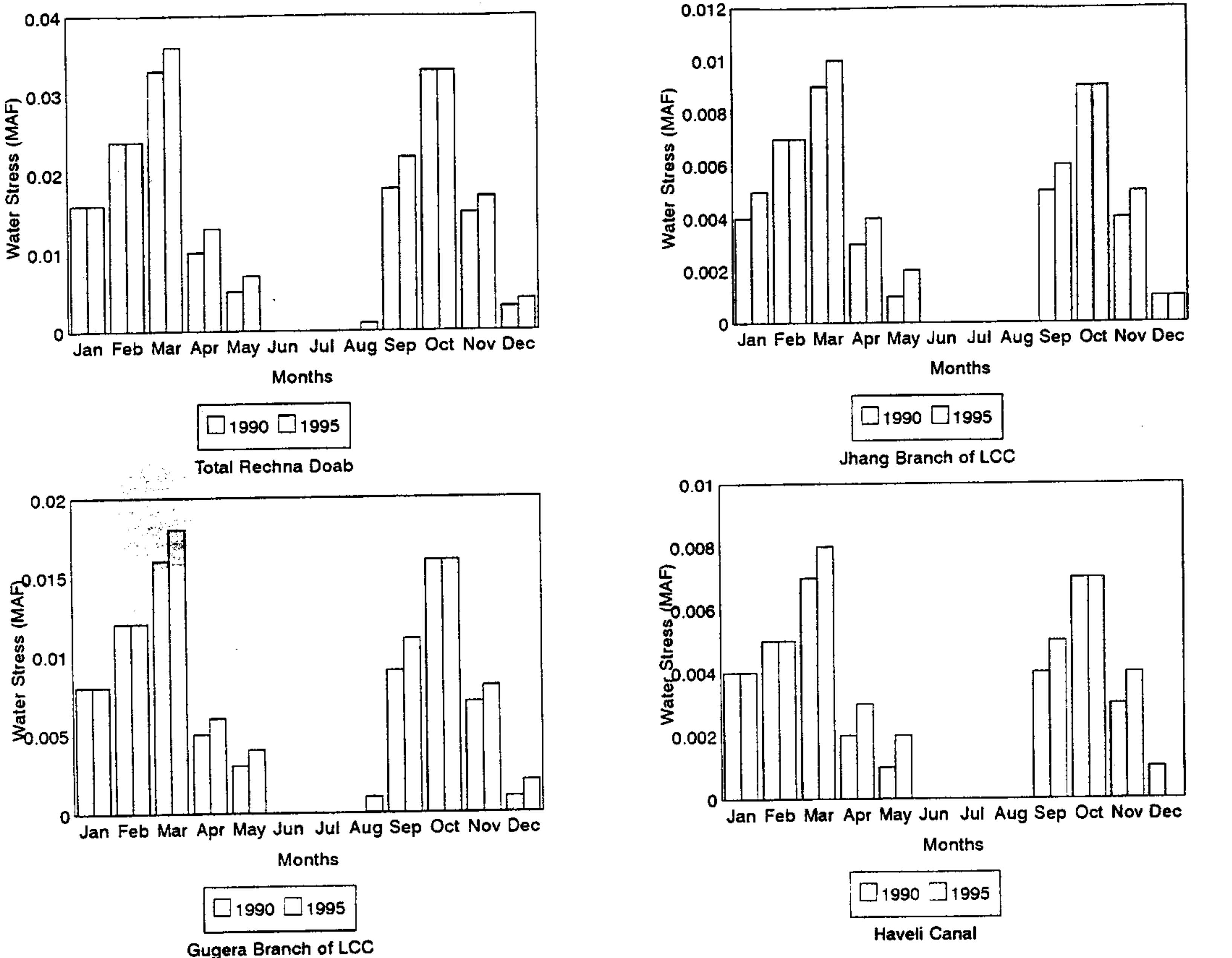


Figure 8. Comparison of Water Stress at the Root Zone during the Years 1990 and 1995.

Table 8. Annual Groundwater Balance for the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Inflows and outflows	1990		1995		Contribution (%)	
	Fresh	Saline	Fresh	Saline	1990	1995
Seepage Sources						
Rain	0.388	0.067	0.388	0.067	4	4
Private Tube wells	1.7		2.072		21	26
Public Tube wells	1.273		1.243		16	16
Irrigation Canals	2.772	0.765	2.524	0.781	30	28
Watercourses and Fields	1.763	0.281	1.437	0.263	19	16
Link Canals	0.975	0.153	0.93	0.132	10	10
Rivers	-0.225	0.01	-0.221	0.019	0.5	0.75
Pumpage						
Private Tubewells	7.647		9.509		76	79
Public Tubewells	2.458		2.458		24	21
Total Inflows	8.646	1.276	8.373	1.262		
Total Outflows	10.105		11.967			
Inflows-Outflows	**-1.459**	**1.276**	**-3.594**	**1.262**		
Groundwater Evaporation	0.513	0.143	0.382	0.098		
Net Groundwater Balance (MAF)	**-1.972**	**1.133**	**-3.976**	**1.164**		
(acre feet per acre of CCA)	-0.491	1.429	-0.989	1.468		

Table 9. Annual Recharge to Groundwater within Canal Commands of the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Areas of Recharge	Fresh		Saline		Total	
	1990	1995	1990	1995	1990	1995
Raya Canal	0.879	0.837			0.879	0.837
Marala Ravi	0.328	0.312			0.328	0.312
UCC (Internal)	2.109	2.009			2.109	2.009
Jhang Branch (LCC)	2.076	2.028	0.357	0.354	2.433	2.382
Gugera Branch (LCC)	3.254	3.187	0.631	0.624	3.885	3.811
Haveli (Internal)			0.288	0.285	0.288	0.285
Total Rechna Doab	8.646	8.373	1.276	1.263	9.922	9.636

Table 10. Annual Groundwater Pumpage in the Canal Commands of the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Areas of Pumpage	Public Sector		Private Sector		Total	
	1990	1995	1990	1995	1990	1995
Raya Canal	0.232	0.232	1.087	1.394	1.319	1.626
Marala Ravi	0.087	0.087	0.405	0.519	0.492	0.606
Upper Chenab (Internal)	0.557	0.557	2.607	3.344	3.164	3.901
Jhang Branch (LCC)	0.612	0.612	1.451	1.752	2.063	2.364
Gugera Branch (LCC)	0.97	0.97	2.096	2.499	3.066	3.469
Haveli Canal (Internal)						
Total Rechna Doab	2.458	2.458	7.647	9.509	10.105	11.967

Groundwater Development Potential: Having determined the recharge and the pumpage occuring in different areas of Rechna Doab, it is now possible to estimate the remaining development potential. Net recharge is the actual usable recharge minus evaporation from groundwater and the net pumpage is the actual pumpage from public and private tubewells minus the recharge that occurs from the pumped groundwater when the same is used for irrigation (recycled water). Actual pumpage potential is the overall development potential for a particular canal command. However, if the development potential of over-exploited canals is considered as zero and not a negative quantity, the adjusted development potential is obtained. This is the actual potential for development of groundwater that is available in the canal commands. The results in the Table 11 show that there is an over-exploitation of groundwater by 0.390 MAF during 1990 which has increased to 1.444 MAF (in 1995) in the canal commands of the Upper Rechna Doab. There still exists the groundwater development potential within the LCC and Haveli canal commands; however, it has decreased by 20%, i.e. from 2.741 MAF (1990) to 2.169 MAF (1995).

2) Simulation Period 1990-2000

a) Cropped Area

From the comparison of simulated cropped area under the **scenarios A-J** for the year 2000 (Figure 9), the maximum cropped area is obtained (based on ASP figures) during the 1991-95 period (except for cotton, for which the growth is based on the moving averages during this period), followed by the results based on a 0.5% growth rate (assumed for the year 2000), and lastly, based on the recommendations of the National Commission on Agriculture(NCA). The results for some major crops have been illustrated in Figure 10 as a comparison with the years 1990 and 1995, and the details are given in the Table 12 for the total Rechna Doab, as well as for the canals commands in the Lower Rechna Doab.

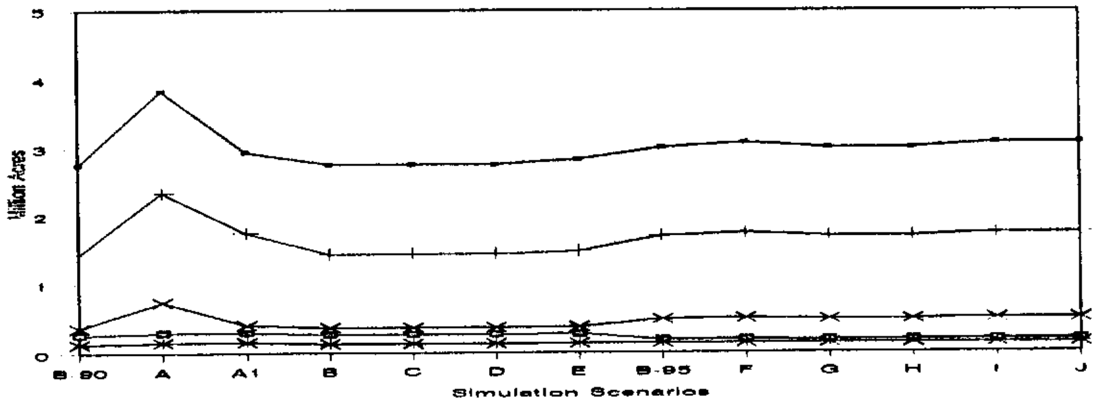
A comparison of the simulated area with the actual area for 1994-95 reveals that under historic growth rates, the increase in cropped area is high for all major crops (wheat 27%; basmati 38%; IRRI 13%; cotton 57%; and sugarcane 51%). The NCA growth rates are showing quite different results; there is a decrease in area for wheat and sugarcane by 2.5% and 17%, respectively. This anomaly is because the NCA projections are generalized for the entire irrigated area of the country. The 0.5% growth rate (**Scenario-J**) is showing approximately the middle values between the first two scenarios, *therefore, the same has been taken as an index for the future projections*.

The simulated crop area and the average yields of some of the major crops by the year 2000 are shown in Figure 11, where the cropped area has increased within all of the canal commands in the doab. For the LCC system, the Jhang Branch is showing higher increases as compared with the Gugera Branch, where there are more system-wide shortages of irrigation water.

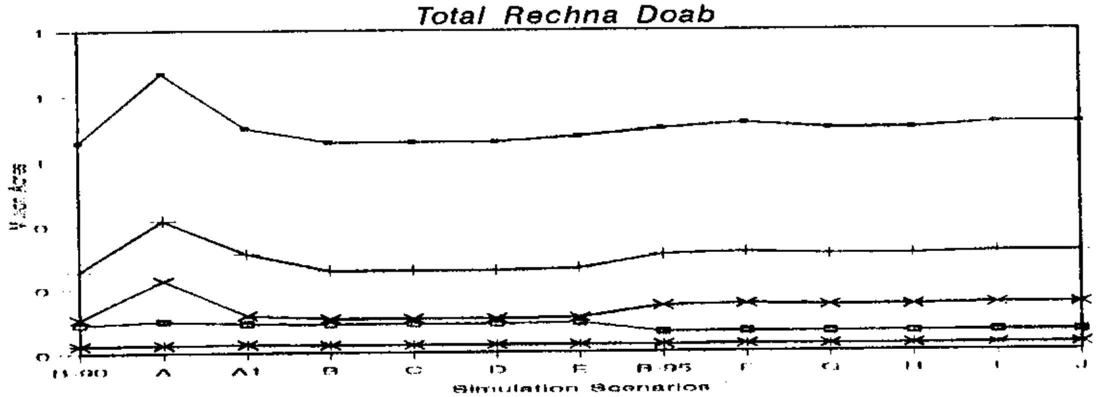
Table 11. Annual Groundwater Development Potential in the Canal Commands of the Rechna Doab, Punjab, Pakistan.

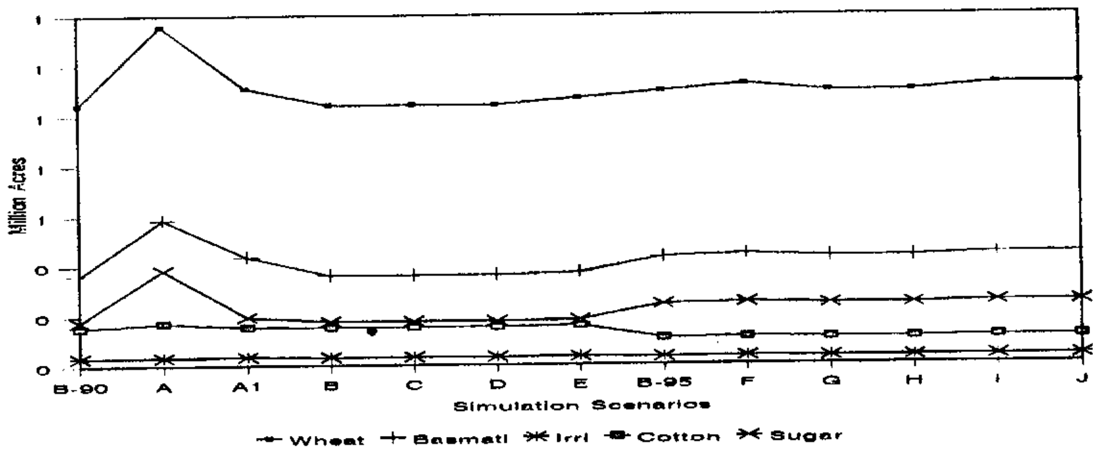
(million acre feet)

Canal Commands	Useable Net Recharge		Net Pumpage		Remaining Development (Actual)		Groundwater Potential (Adjusted)	
	1990	1995	1990	1995	1990	1995	1990	1995
Raya Canal	0.882	0.849	0.985	1.232	-0.103	-0.383		
Marala Ravi	0.328	0.317	0.367	0.459	-0.039	-0.142		
UCC (Internal)	2.115	2.037	2.363	2.956	-0.248	-0.919		
Jhang Branch (LCC)	2.281	2.281	1.389	1.639	0.892	0.642	0.892	0.642
Gugera Branch (LCC)	3.62	3.63	2.027	2.365	1.593	1.265	1.593	1.265
Haveli (Internal)	0.256	0.262			0.256	0.262	0.256	0.262
Total Rechna Doab	9.482	9.376	7.131	8.651	2.351	0.725	2.741	2.169



Total Rechna Doab





Gugera Branch Canal

Figure 9. Comparison of Simulated total Cropped Area under IBMR Simulations A-J.

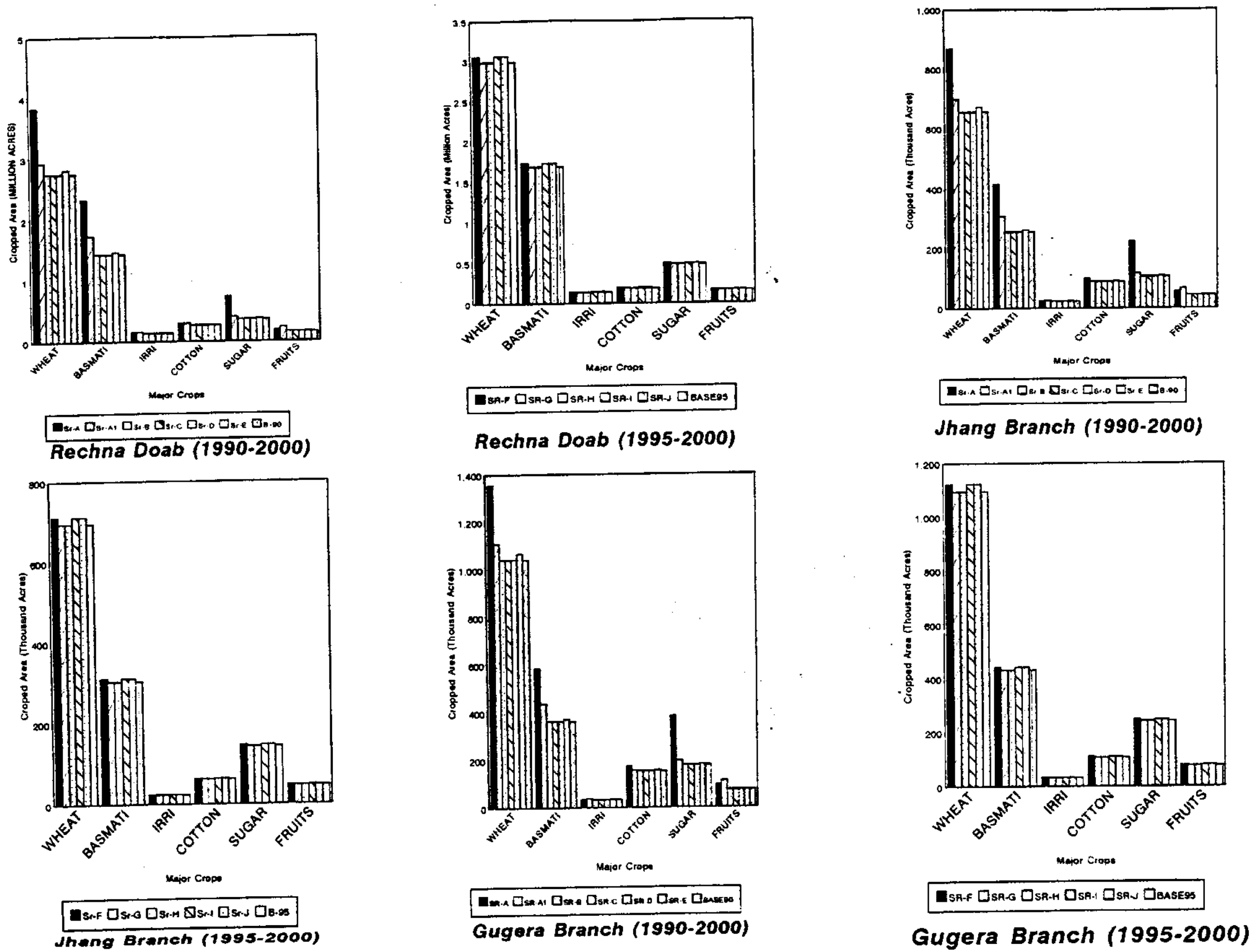
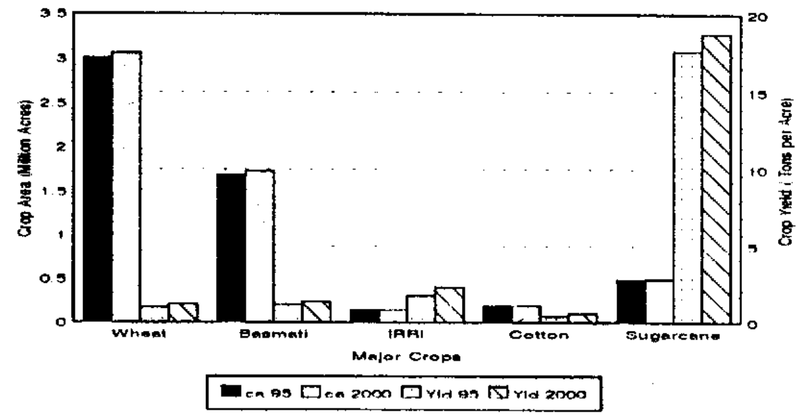


Figure 10.Simulated Cropped Area of Major Crops under IBMR Simulations A-J.

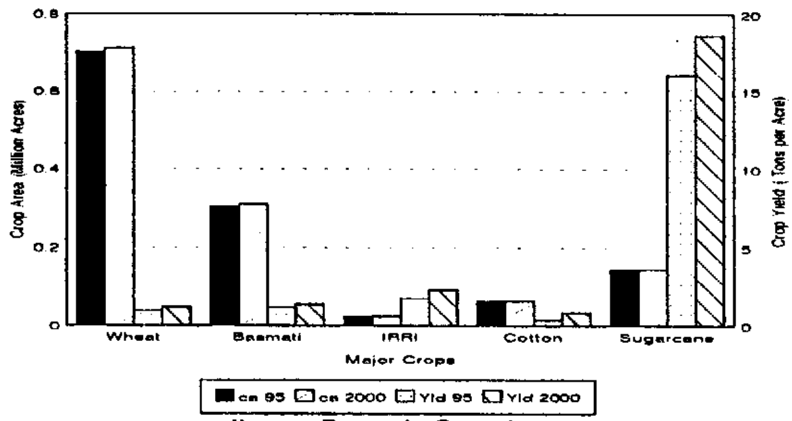
Table 12. Simulated Cropped Area by Year 2000 within Rechna Doab, Punjab, Pakistan.

(million acres)

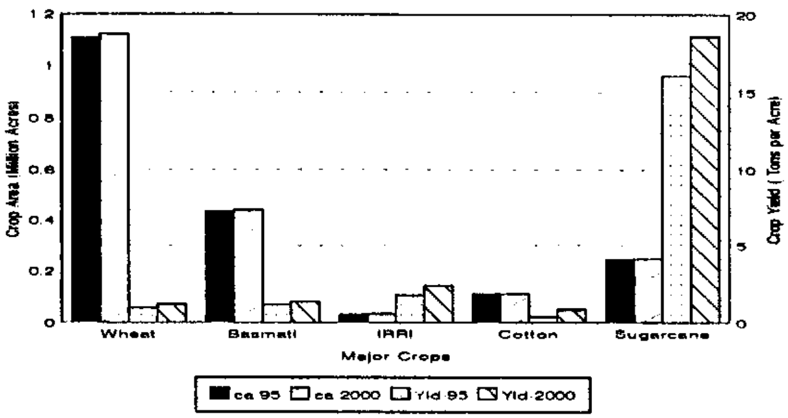
Major Crops	Growth during 1991-95 (Scenario-A)	NCA Growth Rates (Scenario-A1)	0.5% Growth Rate (Scenario-J)
Rechna Doab			
Wheat	3.83	2.931	3.061
Basmati Rice	2.33	1.735	1.729
IRRI Rice	0.156	0.16	0.141
Cotton	0.297	0.297	0.191
Sugarcane	0.735	0.404	0.492
Jhang Canal Command of LCC			
Wheat	0.868	0.698	0.712
Basmati Rice	0.414	0.308	0.31
IRRI Rice	0.025	0.027	0.024
Cotton	0.099	0.09	0.064
Sugarcane	0.225	0.117	0.147
Gugera Canal Command of LCC			
Wheat	1.357	1.109	1.122
Basmati Rice	0.585	0.435	0.441
IRRI Rice	0.034	0.037	0.033
Cotton	0.172	0.155	0.11
Sugarcane	0.383	0.196	0.248
Haveli Canal Command			
Wheat	0.117	0.104	0.1013
Basmati Rice	0.024	0.018	0.0195
IRRI Rice	0.001	0.001	0.001
Cotton	0.022	0.02	0.0141
Sugarcane	0.046	0.023	0.0294



Rechna Doab



Jhang Branch Canal



Gugera Branch Canal

Figure 11. Simulated Crop Area and Average Yield under IBMR Simulation J..

b) Production and Yield

The simulated crop production, and the corresponding average yields of the major crops, appears in Table 13 for each of the three crop yield growth scenarios; a comparison with the year 1995 has been shown in Table 13(a). The simulations show a lower trend for wheat and sugarcane crops under the historical growth rates. The difference between the NCA and 3% growth scenarios are due to two reasons; firstly, the per annum growth rate for each crop under NCA is different, whereas for Scenario J a 3% growth rate for all major crops has been assumed. Secondly, the crop yields and production under the NCA recommended projections are for the entire country which invariably leads to a generalized figure. *Therefore, the 3% growth rate (Scenario J) has been taken an index for future projections*.

The simulated average crop yields for the major crops are shown in Figure 11 where the projected values have increased. For the LCC system, the Jhang Branch is showing an increase in crop yields for wheat(11%), basmati(15.9%), IRRI(14.7%), cotton(10%) and sugarcane(5.5%). For the Gugera Branch, the respective increases are 10.8%, 15.9%, 15.7%, 12.9%, and 5.4%. The Haveli Canal is showing higher increases in crop yields for wheat (17.6%), basmati(17.8%), IRRI(14.7%), cotton(18.5%), and sugarcane (17.5%) because of a maximum reduction in water shortages at the root zone.

c) Canal Diversions

Canal diversions are made against the indents placed by the Provincial Irrigation and Power Departments (PIDs) which are met subject to the availability of river flows or storage reserves. There has been a lot of variations in canal diversions during the last five year (1991-1995) period, even after the Water Apportionment Accord of 1991 (Figure 3). Therefore, it is difficult to predict with confidence about the availability of water at each canal head by the year 2000. The projections for canal diversions by year 2000 are based on an increase of actual canal diversions during 1994-95 from 10-20% (Scenarios A-J). From the results of these scenarios, the actual diversions during the water year 1994-95 are the lowest, whereas the maximum are from the 20% increase (Scenario J), as given in Table 14. The intermediate values are derived from the 10% increase over the actual 1994-95 canal diversions (Scenario D). These canal diversions are within the designed capacity, as well as the Authorised Full Supply (AFS) at the canal head of each canal as shown in Figure 12. The figure shows that even after a 20% increase in canal supplies (1994-95), the diversions are within the designed capacities, except for Raya and UCC canals where these are increasing during the month of July and for the Gugera Branch, where the diversions are in excess of the design capacity between August-October. The diversions to Haveli Canal are much less than the design.

Table 13. Simulated Crop Production and Average Yield by Year 2000 within Rechna Doab, Punjab, Pakistan.

Major Crops	Growth during 1991-95 (Scenario-A)		NCA Growth Rates (Scenario-A1)		3 % Growth Rate (Scenario-J)	
	Production (Mt.)	Yield (T/A)	Production (Mt.)	Yield (T/A)	Production (Mt.)	Yield (T/A)
Rechna Doab						
Wheat	3.765	0.983	3.337	1.138	3.444	1.125
Basmati Rice	3.330	1.429	3.548	2.045	2.327	1.346
IRRI Rice	0.524	3.359	0.415	2.594	0.286	2.028
Cotton	0.220	0.741	0.205	0.690	0.084	0.440
Sugarcane	12.316	16.756	8.086	20.000	9.288	18.878
Jhang Canal Command of LCC						
Wheat	0.853	0.983	0.802	1.149	0.791	1.111
Basmati Rice	0.591	1.427	0.64	2.078	0.418	1.348
IRRI Rice	0.086	3.440	0.07	2.593	0.048	2.000
Cotton	0.074	0.747	0.068	0.756	0.028	0.437
Sugarcane	3.730	16.778	2.352	20.102	2.735	18.605
Gugera Canal Command of LCC						
Wheat	1.333	0.982	1.278	1.152	1.241	1.106
Basmati Rice	0.834	1.426	0.911	2.094	0.594	1.347
IRRI Rice	0.116	3.412	0.097	2.622	0.067	2.030
Cotton	0.128	0.744	0.118	0.761	0.049	0.445
Sugarcane	6.332	16.533	3.953	20.168	4.61	18.589
Haveli Canal Command						
Wheat	0.115	0.982	0.121	1.163	0.11	1.089
Basmati Rice	0.035	1.458	0.042	2.333	0.026	1.368
IRRI Rice	0.003	4.347	0.003	3.000	0.002	2.000
Cotton	0.017	0.743	0.015	0.750	0.006	0.428
Sugarcane	0.762	16.213	0.461	20.043	0.542	18.689

Table 13a. Comparison of Crop Production and Average Yield within Rechna Doab, Punjab, Pakistan.

Major Crops	Production (million tons)		Average Yield (tons per acre)	
	1995	2000	1995	2000
Total Rechna Doab				
Wheat	3.005	3.444	0.999	1.125
Basmati	1.964	2.327	1.162	1.346
IRRI	0.241	0.286	1.745	2.028
Cotton	0.075	0.084	0.396	0.440
Sugarcane	8.580	9.288	17.632	18.878
Jhang Branch				
Wheat	0.702	0.791	1.000	1.111
Basmati	0.354	0.418	1.163	1.348
IRRI	0.041	0.048	1.744	2.000
Cotton	0.025	0.028	0.397	0.437
Sugarcane	2.559	2.735	17.634	18.605
Gugera Branch				
Wheat	1.106	1.241	0.998	1.106
Basmati	0.503	0.594	1.162	1.347
IRRI	0.057	0.067	1.754	2.030
Cotton	0.043	0.049	0.394	0.445
Sugarcane	4.327	4.610	17.631	18.589
Haveli Canal				
Wheat	0.100	0.110	0.861	1.089
Basmati	0.023	0.026	1.161	1.368
IRRI	0.002	0.002	1.743	2.000
Cotton	0.005	0.006	0.361	0.428
Sugarcane	0.514	0.542	15.906	18.689

Table 14. Simulated Canal Diversions at Canal Head by Year 2000 within Rechna Doab, Punjab, Pakistan.

(million acre feet)

Canal Command	Maximum (20% Increase)			Minimum (1994-95)			Medium (10% Increase)		
	Rabi	Kharif	Annual	Rabi	Kharif	Annual	Rabi	Kharif	Annual
Raya (BRBD)	0.077	0.434	0.511	0.064	0.361	0.425	0.070	0.398	0.468
MR (Internal)	0.010	0.300	0.310	0.008	0.250	0.258	0.009	0.275	0.284
UCC (Internal)	0.339	1.031	1.370	0.282	0.859	1.141	0.311	0.945	1.256
Jhang Branch	1.772	2.295	4.068	1.477	1.913	3.390	1.625	2.104	3.729
Gugera Branch	1.990	2.577	4.567	1.658	2.147	3.805	1.824	2.362	4.186
Haveli (Internal)	0.280	0.418	0.698	0.233	0.348	0.581	0.256	0.383	0.639
Total Rechna Doab	4.467	7.055	11.522	3.722	5.878	9.600	4.095	6.467	10.562

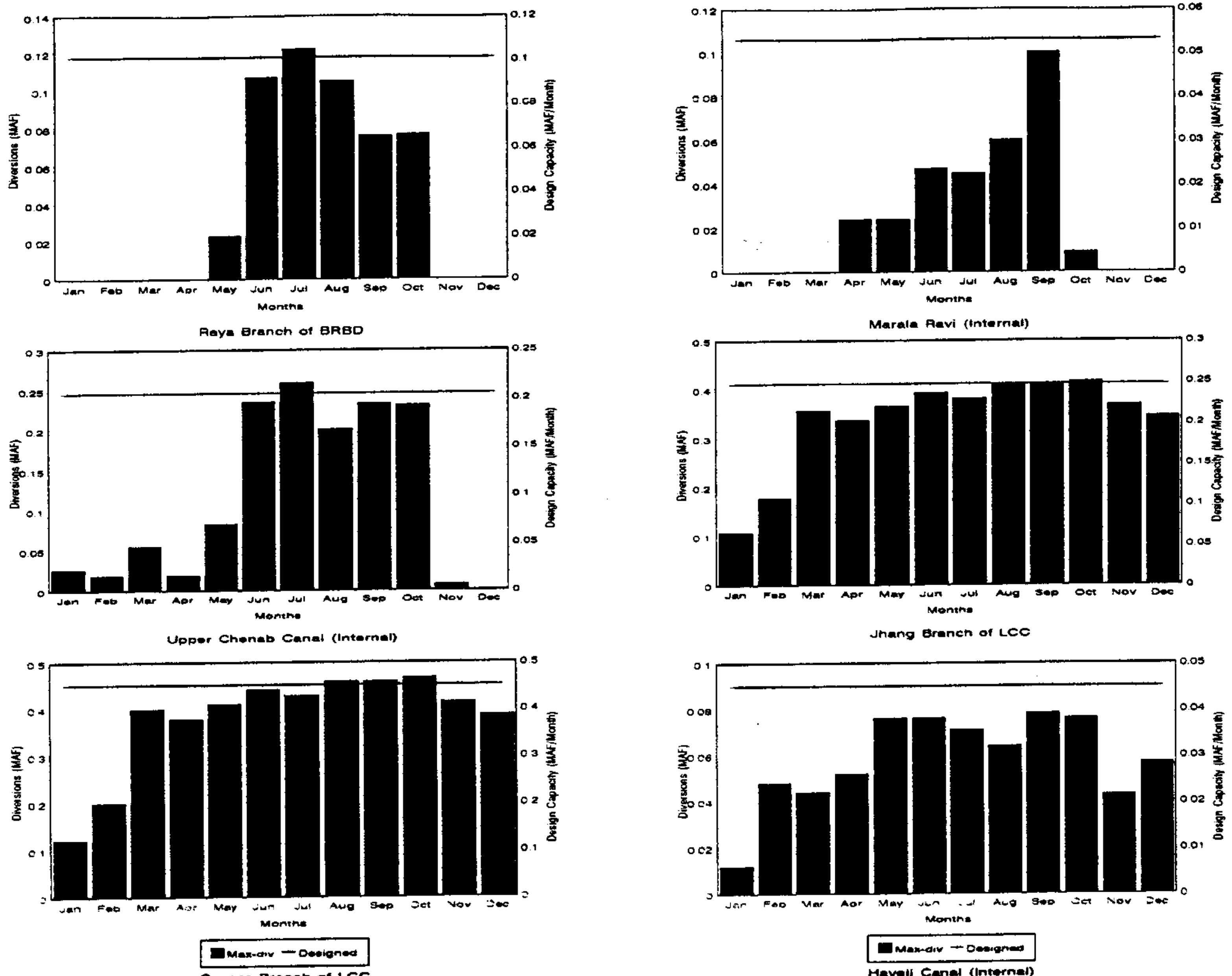


Figure 12. Comparison of Maximum Canal Diversions and Design Capacity at Canal Head under IBMR Simulation J.

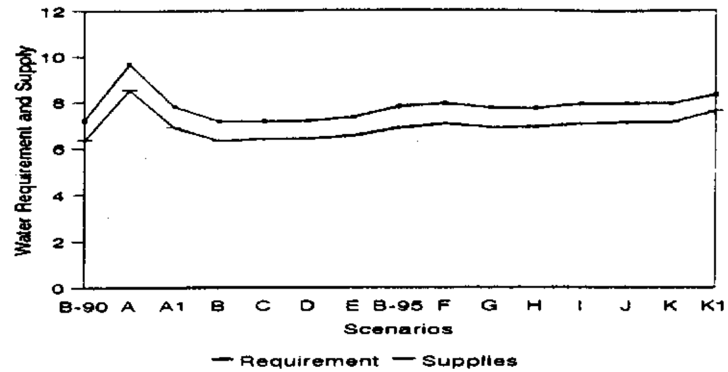
d) Water Balance at the Root Zone

A comparison of simulation results for water requirements and supplies from different sources, according to scenarios A-J, has been illustrated in Figure 13, which shows how the difference between water requirements and supplies can be minimised. It is apparent that the shortages have been minimised under Scenario D, where the cropped area of 1994-95 has been maintained up to year 2000 (which is unrealistic) and the canal supplies have been increased by 10%. Acceptable results are based on the Scenario J assumptions, where the cropped area has been increased by 0.5 % per annum and canal supplies, as of 1994-95, have been increased by 20%, along with improvements in designed field application and conveyance efficiencies by 5% and 10%, respectively. Hence, *the results of the scenario J have been used for the simulations to the year 2000*.

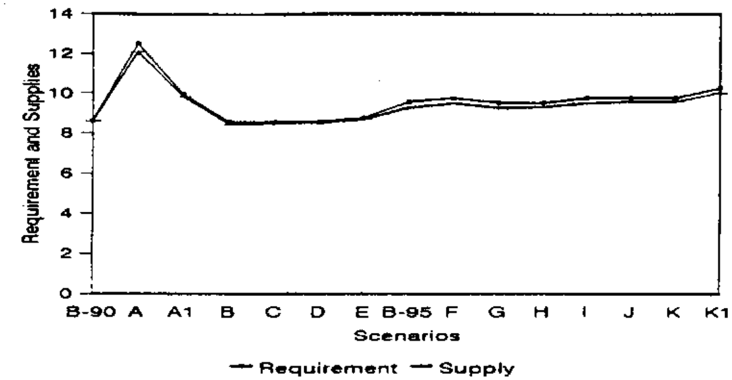
A comparison of annual water shortages and surpluses is shown in Figures 14-19, which show the crop water requirements and supplies from all sources by seasons and by areas of groundwater quality (fresh or saline). From the results, it is apparent that both shortages (as measured by crops grown under stress) and surpluses (as measured by the excess of water available over net requirements) exist in the canal commands of Rechna Doab at various times during the year. A summary of annual net water requirements (net of effective rainfall and sub-irrigation) and water supplies from canal and groundwater pumpage is presented in Table 15. The groundwater pumpage by the year 2000 is only from private tubewells because the contribution from public tubewells has been assumed to be zero due to the Government policy of transition of SCARP tubewells to the private sector.

The above results have been summarized in Figure 20, which shows that the annual water shortages have been alleviated by 45% in all of the canal systems of Rechna Doab (54% in fresh areas and 40% in saline areas). The Upper Rechna canals are showing increased shortages by 41% because the water requirements have increased by 2.52%, whereas the total water supplies (canal and tubewell) have not increased because most of the canals are nonperennial, and during the Rabi season the only source of water supply is the tubewell pumpage (which has reduced by 7%).

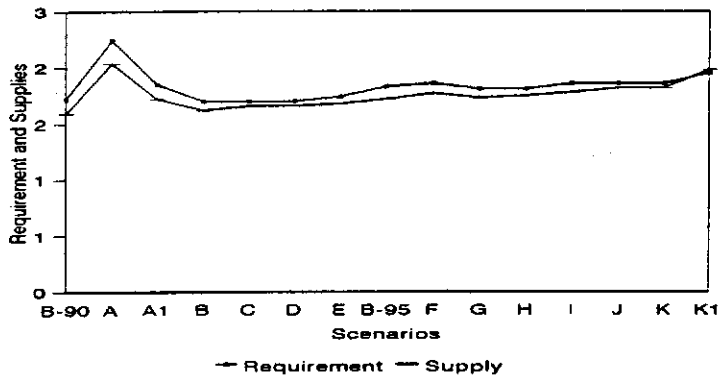
The surplus water in the Jhang Branch has been increased by 94% in fresh groundwater areas, along with a decrease in shortages by 47% in saline areas, resulting in a net annual surplus of 0.270 MAF by year 2000. The shortages in the Gugera Canal command have decreased by 37% (67% in fresh areas and 26% in saline areas). The Haveli Canal is showing a maximum reduction in water shortages (84%), along with a reduction in water stress (31%) by the year 2000. The results listed in Table 16 show that with the increased water supply for crops like cotton, kharif fodder, sugarcane, wheat and fruits (orchards), there are corresponding increases in crop yield by 43%, 22%, 7%, 41% and 28%, respectively, thereby indicating a linear relationship between the increase in water supply and corresponding crop yields (Figure 21).



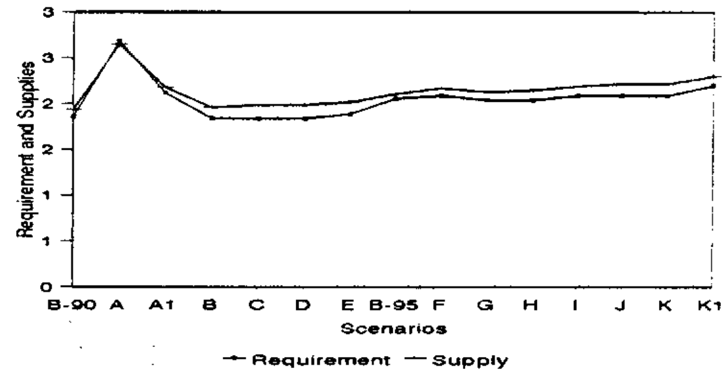
Rechna Doab (Rabi Season)



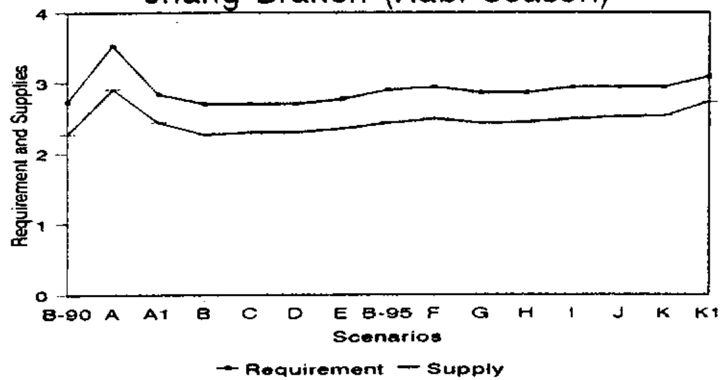
Rechna Doab (Kharif Season)



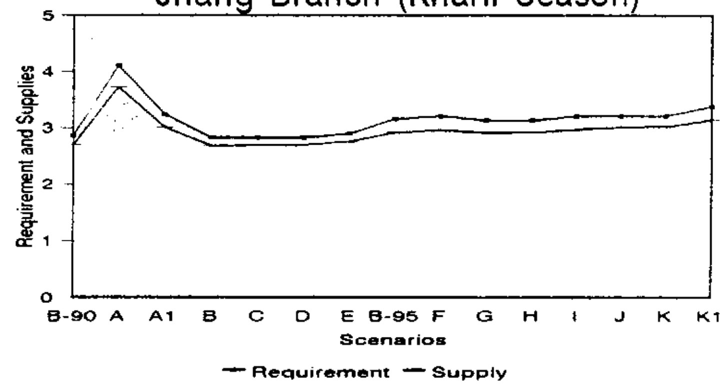
Jhang Branch (Rabi Season)



Jhang Branch (Kharif Season)



Gugera Branch (Rabi Season)



Gugera Branch (Kharif Season)

Figure 13.Comparison of Simulated Water Requirementsand Supplies at the Root Zone (MAF).

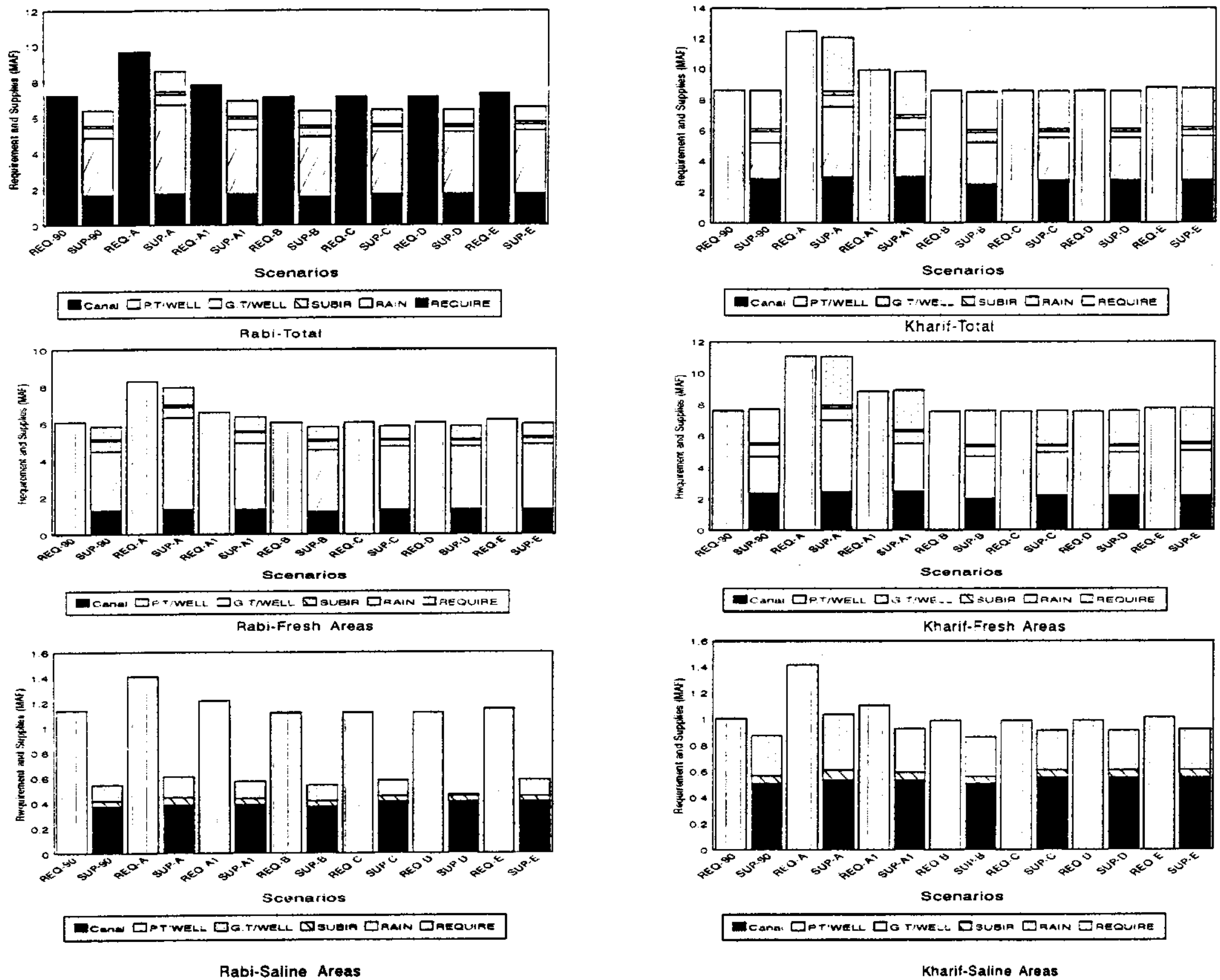


Figure 14. Water Balance during Rabi and Kharif seasons of Rechna Doab for the Period 1990-2000.

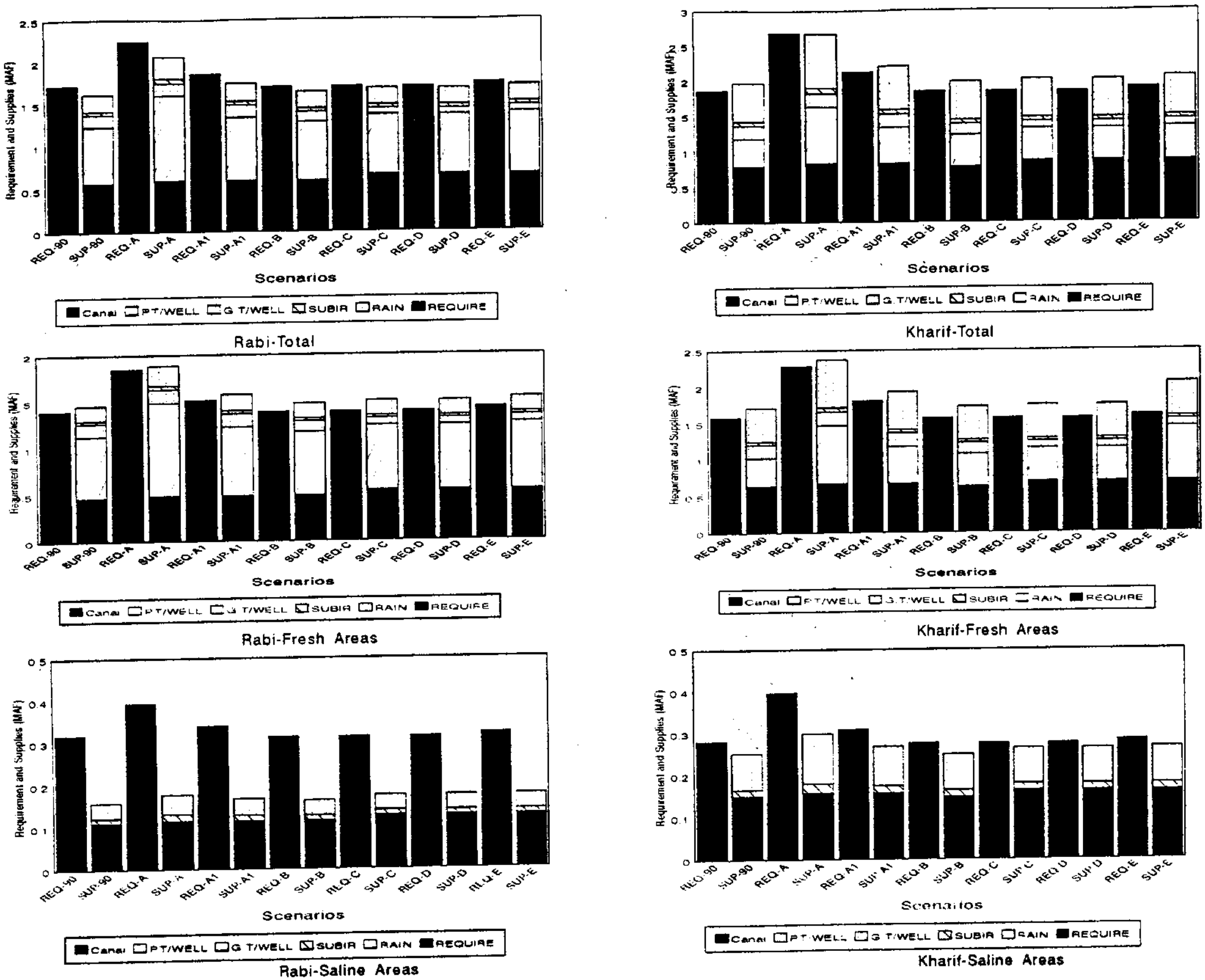


Figure 15. Water Balance during Rabi and Kharif seasons within Jhang Branch for the Period 1990-2000

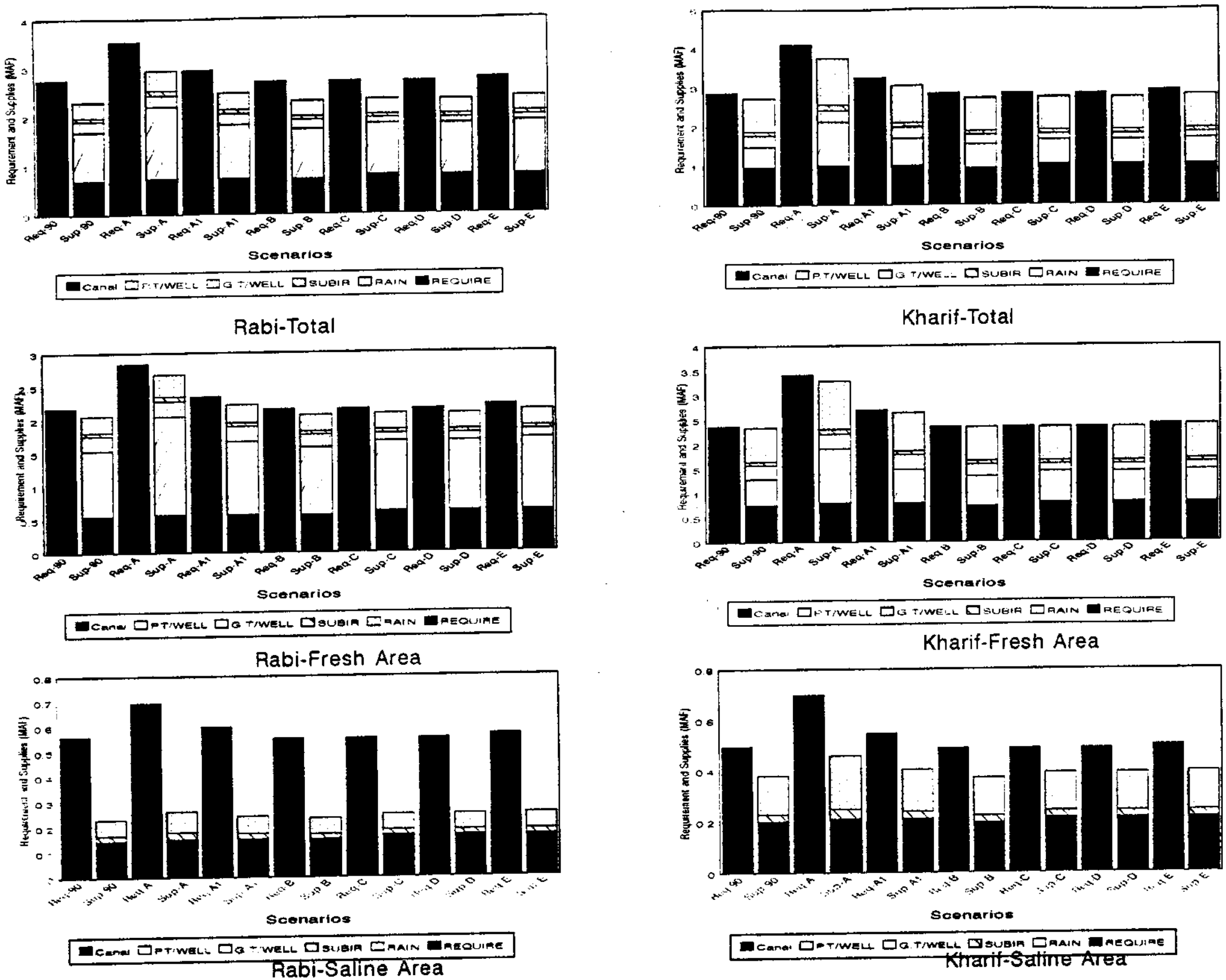


Figure 16. Water Balance during Rabi and Kharif seasons within Gugera Branch for the Period 1990-200

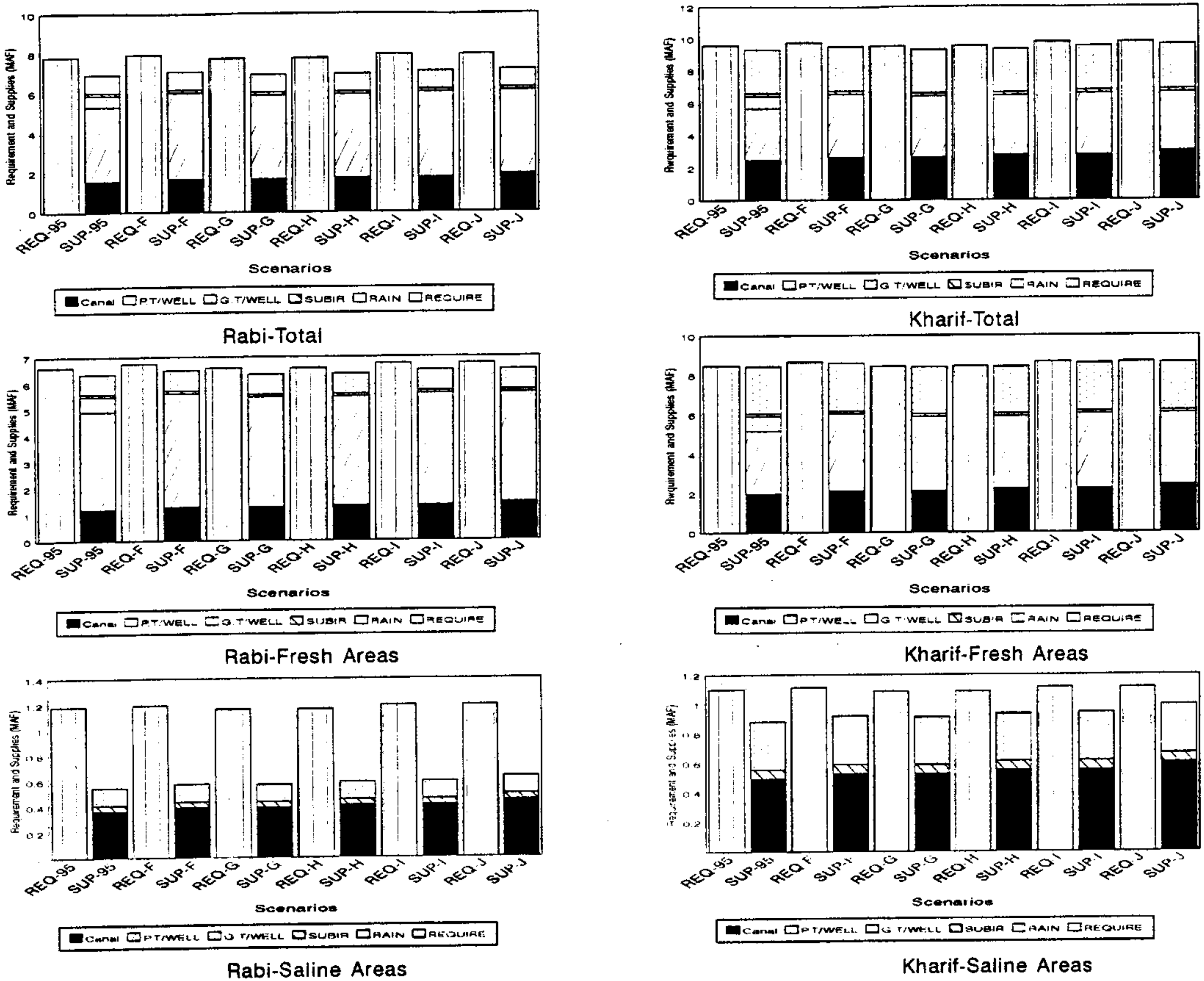


Figure 17. Water Balance during Rabi and Kharif seasons of Rechna Doab for the Period 1995-2000.

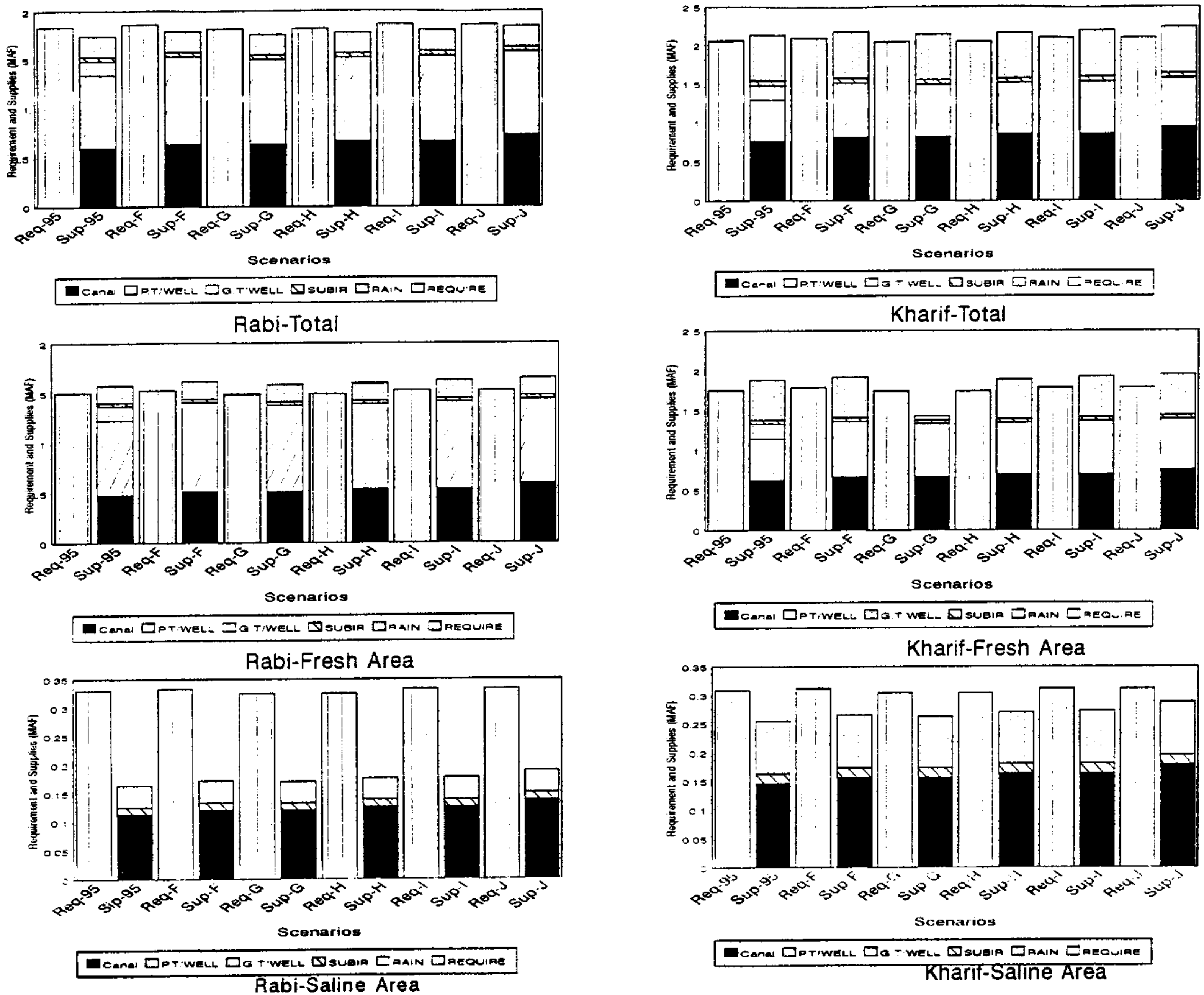


Figure 18. Water Balance during Rabi and Kharif seasons within Jhang Branch for the Period 1995-2000

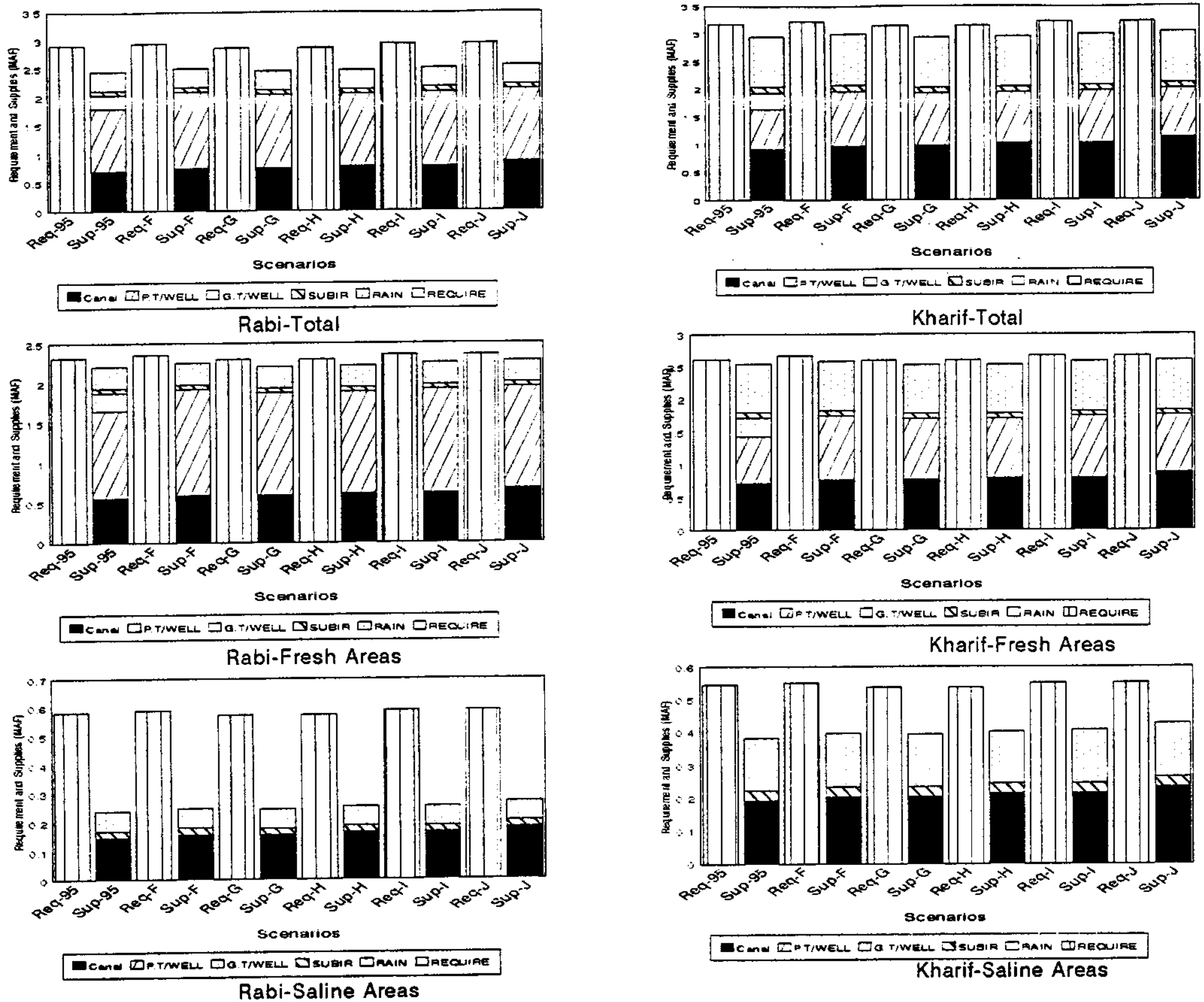


Figure 19. Water Balance during Rabi and Kharif seasons within Gugera Branch for the Period 1995-200

Table 15. Comparison of Annual Net Water Requirements and Supplies at the Root Zone for IBMR Scenario J.

(million acre feet)

Description	Fresh		Saline		Total	
	1995	2000	1995	2000	1995	2000
Rechna Doab						
Net Requirements	11.716	11.958	1.714	1.73	13.43	13.688
Water Supplies						
Canal	3.164	4.478	0.859	1.218	4.023	5.696
Tubewell Pumpage	8.245	7.34			8.245	7.34
Total Supplies	11.409	11.818	0.859	1.218	12.268	13.036
Shortage	0.307	0.140	0.855	0.512	1.162	0.642
Surplus						
Total Water Stress			0.174	0.119	0.174	0.119
Upper Rechna Canal Commands						
Net Requirements	5.426	5.563			5.426	5.563
Water Supplies						
Canal	0.784	1.111			0.784	1.111
Tubewell Pumpage	4.309	3.982			4.309	3.982
Total Supplies	5.093	5.093			5.093	5.093
Shortage	0.333	0.470			0.333	0.47
Surplus						
Total Water Stress						
Jhang Canal Command of LCC						
Net Requirements	2.506	2.549	0.48	0.484	2.986	3.033
Water Supplies						
Canal	1.104	1.559	0.259	0.366	1.363	1.925
Tubewell Pumpage	1.602	1.378			1.602	1.378
Total Supplies	2.706	2.937	0.259	0.366	2.965	3.303
Shortage			0.221	0.118	0.221	0.118
Surplus	0.200	0.388			0.2	0.388
Total Water Stress			0.049	0.033	0.049	0.033
Gugera Canal Command of LCC						
Net Requirements	3.785	3.846	0.847	0.855	4.632	4.701
Water Supplies						
Canal	1.276	1.808	0.339	0.481	1.615	2.289
Tubewell Pumpage	2.334	1.980			2.334	1.98
Total Supplies	3.610	3.788	0.339	0.481	3.949	4.269
Shortage	0.175	0.058	0.508	0.374	0.683	0.432
Surplus						
Total Water Stress			0.086	0.059	0.086	0.059
Haveli Canal Command						
Net Requirements			0.387	0.391	0.387	0.391
Water Supplies						
Canal			0.262	0.371	0.262	0.371
Tubewell Pumpage						
Total Supplies			0.262	0.371	0.262	0.371

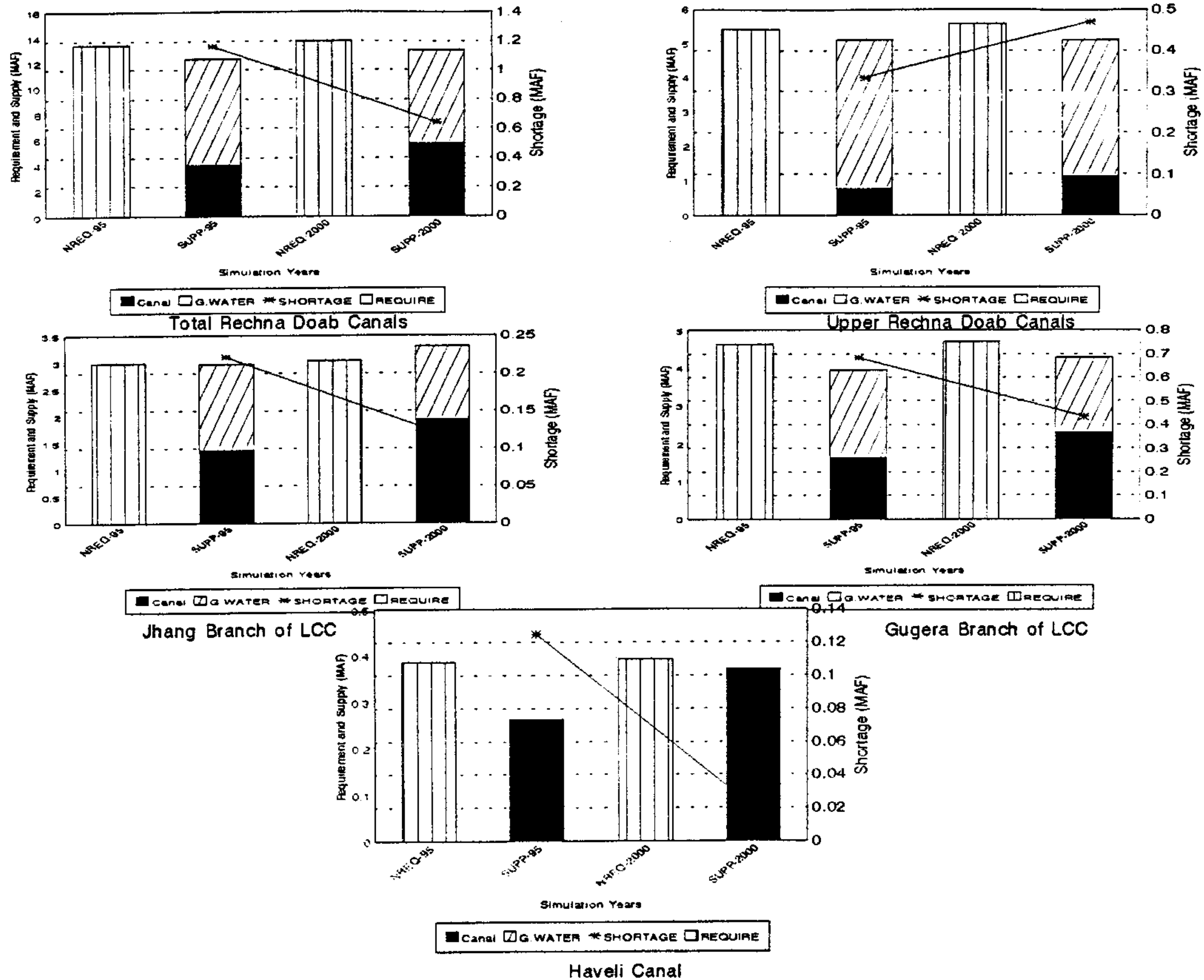


Figure 20. Simulated Water Balance at the Root Zone by Year 2000, under IBMR Simulation J.

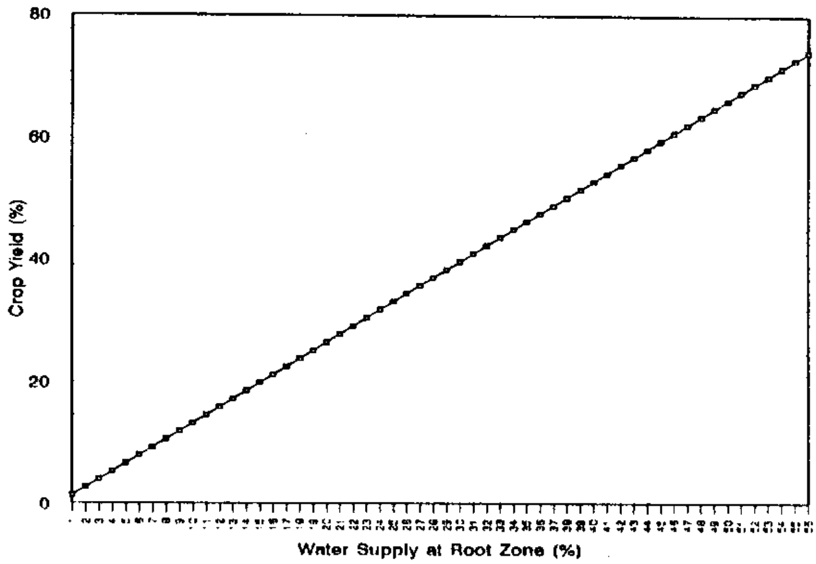
Table 16. Water Supply and Crop Yield Relationship for Scenario J, Rechna Doab, Punjab, Pakistan.

Crop	1995		2000	
	Water Supply (%)	Crop Yield (%)	Water Supply (%)	Crop Yield (%)
Cotton	40	70	100	100
Rabi Fodder	30	65	30	65
Maize	40	70	40	70
Kharif Fodder	74	82	100	100
Sugarcane	60	68	67	73
Wheat	50	70	66	80
Fruits	70	78	100	100

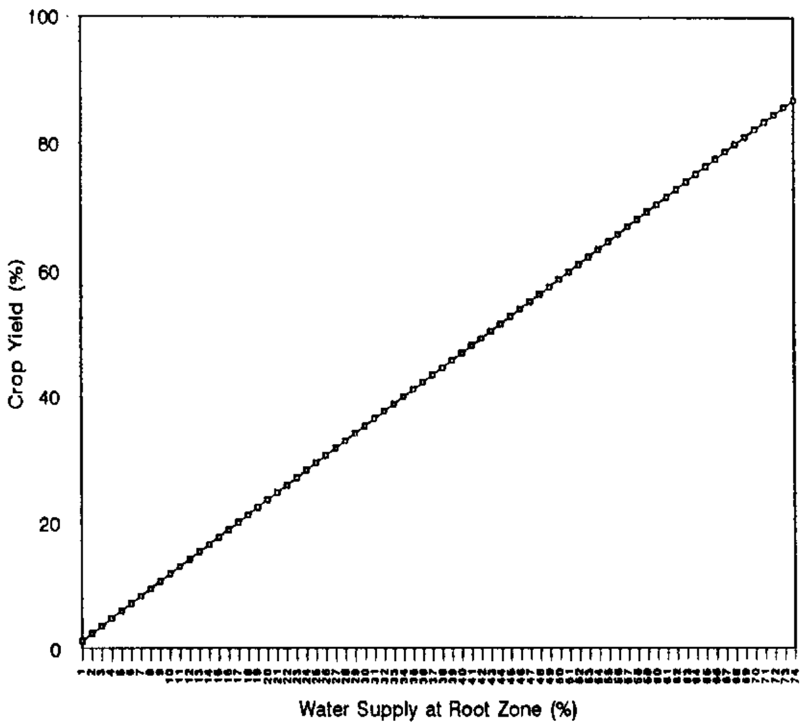
Table 17. Groundwater Balance for the Rechna Doab by Areas of Groundwater Quality (Scenario J).

(million acre feet)

Inflows and Outflows	Maximum (Scenario A)		Minimum (Scenario F)		Average (Scenario J)	
	Fresh	Saline	Fresh	Saline	Fresh	Saline
Seepage to Groundwater						
Rainfall	0.388	0.067	0.388	0.067	0.388	0.067
Private Tubewells	2.779		2.419		2.132	
Public Tubewells	1.217					
Irrigation Canals	2.726	0.749	2.624	0.807	2.68	0.863
Watercourses and Fields	1.683	0.264	1.466	0.266	1.684	0.305
Link Canals	1.002	0.131	1.048	0.157	0.918	0.15
Rivers	-0.174	0.028	-0.258	0.018	-0.51	-0.001
Pumpage from Tubewells						
Private Tubewells	12.982		11.294		9.963	
Public Tubewells	2.44					
Total Inflows (Recharge)	9.621	1.239	7.687	1.315	7.292	1.384
Total Outflows (Pumpage)	15.422		11.294		9.963	
Inflow - Outflow	-5.801	1.239	-3.607	1.315	-2.671	1.384
Groundwater Evaporation	0.382	0.098	0.383	0.098	0.383	0.098
Net Recharge (MAF)	-6.183	1.141	-3.99	1.217	-3.054	1.286
Net Recharge per Acre of CCA (feet)	-1.538	1.439	-0.993	1.535	-0.76	1.622



Water Supply and Crop Yield for Wheat



Water Supply and Crop Yield for Cotton

Figure 21. Relationship between Water Supply at Root Zone and Crop Yield.

e) Groundwater Balance

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

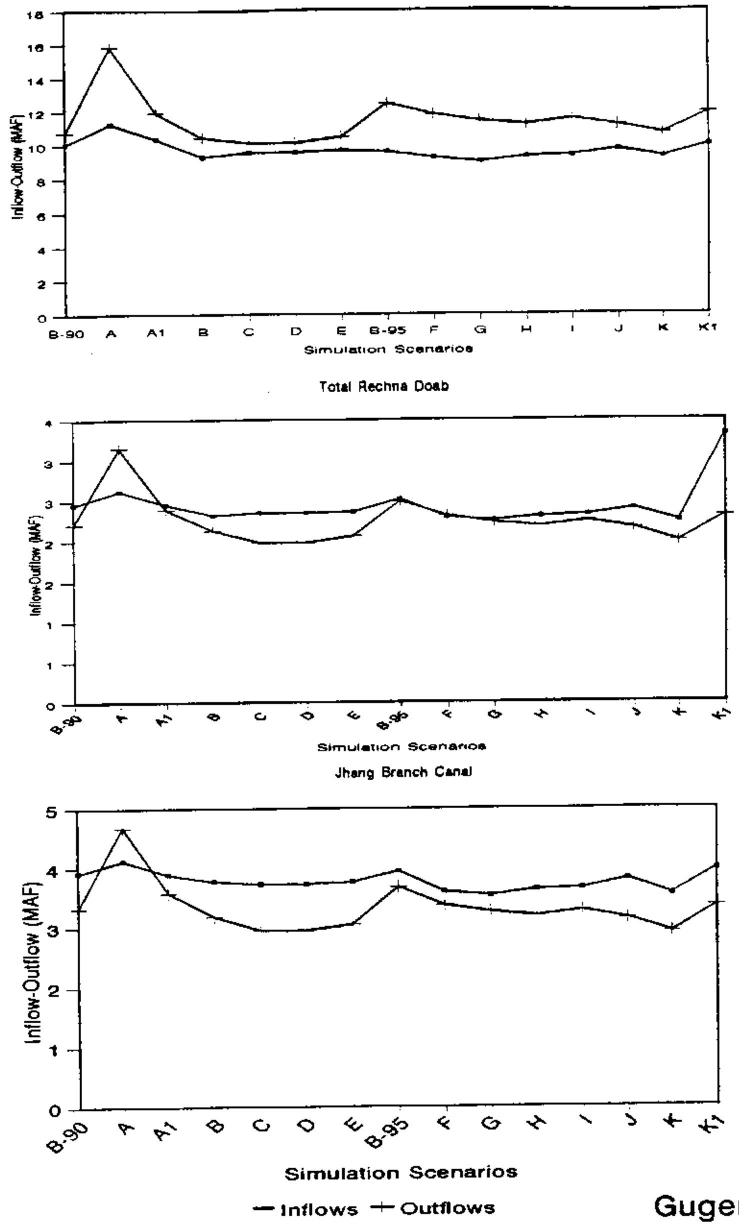
$$I \; O \pm \Delta S$$

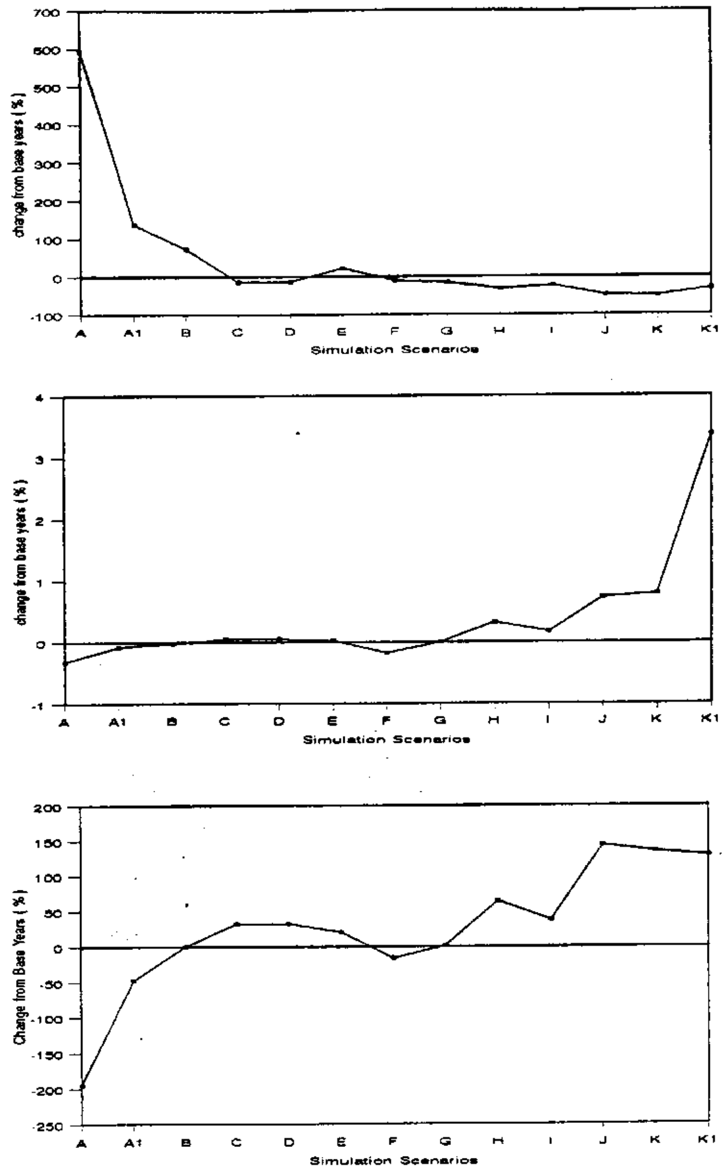
where I is equal to inflow, O is equal to outflow and ΔS is the net change in storage. If there is a net increase in storage , it is added to the right side of equation; if there is net decrease, it is subtracted. This equation is suitable for the analysis of the total surface, as well as groundwater, budget.

A comparison of *annual groundwater inflow-outflow* and *change in groundwater storage* for the scenarios A to K1 from the base years is shown in Figures 22 and 23. The positive change indicates that the recharge to the aquifer system is more than pumpage and a negative means that the outflow (pumpage) is more than recharge. The maximum change (increased pumpage) is expected under historical agricultural growth rates (Scenario A) because the surface water supplies are not sufficient to meet the crop water requirements, whereas the minimum is occuring under Scenario F where the contributions from public tubewells have been assumed to be zero by the year 2000 and the increase in cropped area is 0.5% per annum. The following discussion will be based on these two extreme situations and the Scenario J, for the entire Rechna Doab, as well as for the Jhang and Gugera Branch canals of the LCC system.

To study the impact of the simulation scenarios A-J on the behaviour of changes in groundwater storage, a pattern of groundwater inflows/outflows is illustrated in Figures 24-29 by seasons, and by areas of groundwater quality (details in Tables 17-20). The results show that groundwater outflow is more than the recharge to the aquifer in fresh areas of the Rechna Doab under all scenarios. The saline areas are receiving recharge from different seepage sources, but there is no groundwater pumpage, which may cause the water table to rise, or induce lateral flows to neighbouring areas.

A comparative behavior of groundwater inflow-outflow, based on Scenario J, is depicted in Figure 30. The total inflows in the Rechna Doab decrease by 10% from 9.635 MAF (1995) to 8.676 MAF (2000), whereas the total outflows (tubewell pumpage and evaporation from groundwater) have decreased by 16% from 12.447 MAF (1995) to 10.444 MAF (2000). The Upper Rechna Doab areas are showing groundwater extractions more than the recharge





Gugera Branch Canal

Figure 22. Comparison of Annual Groundwater Inflows-Outflows under IBMR Simulations A-K1.

Figure 23. Comparison of Change in Groundwater Storage underIBMR Simulations A-K1.

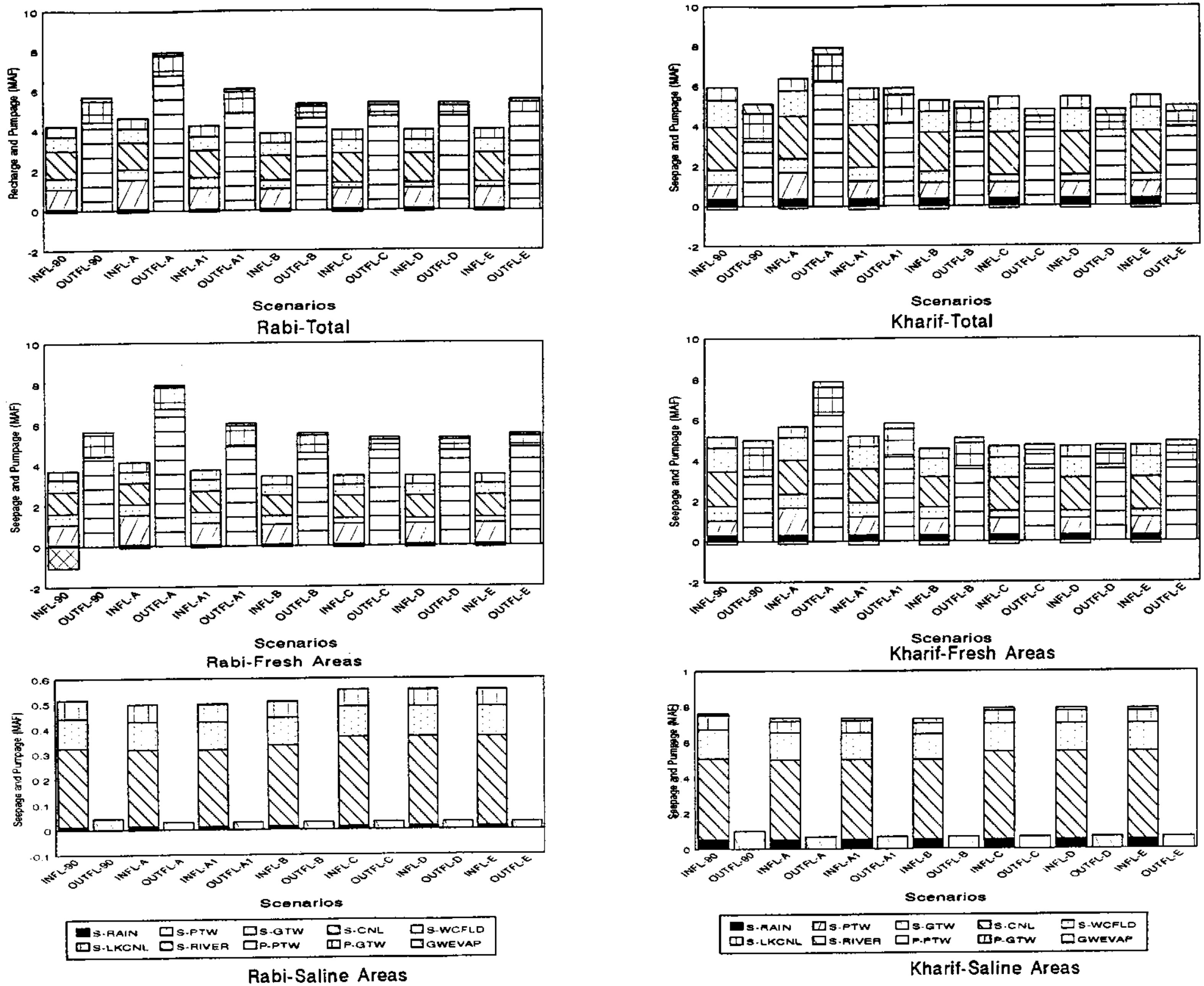


Figure 24. Groundwater Balance of Rechna Doab during Rabi and Kharif Season for the Period 1990-2000

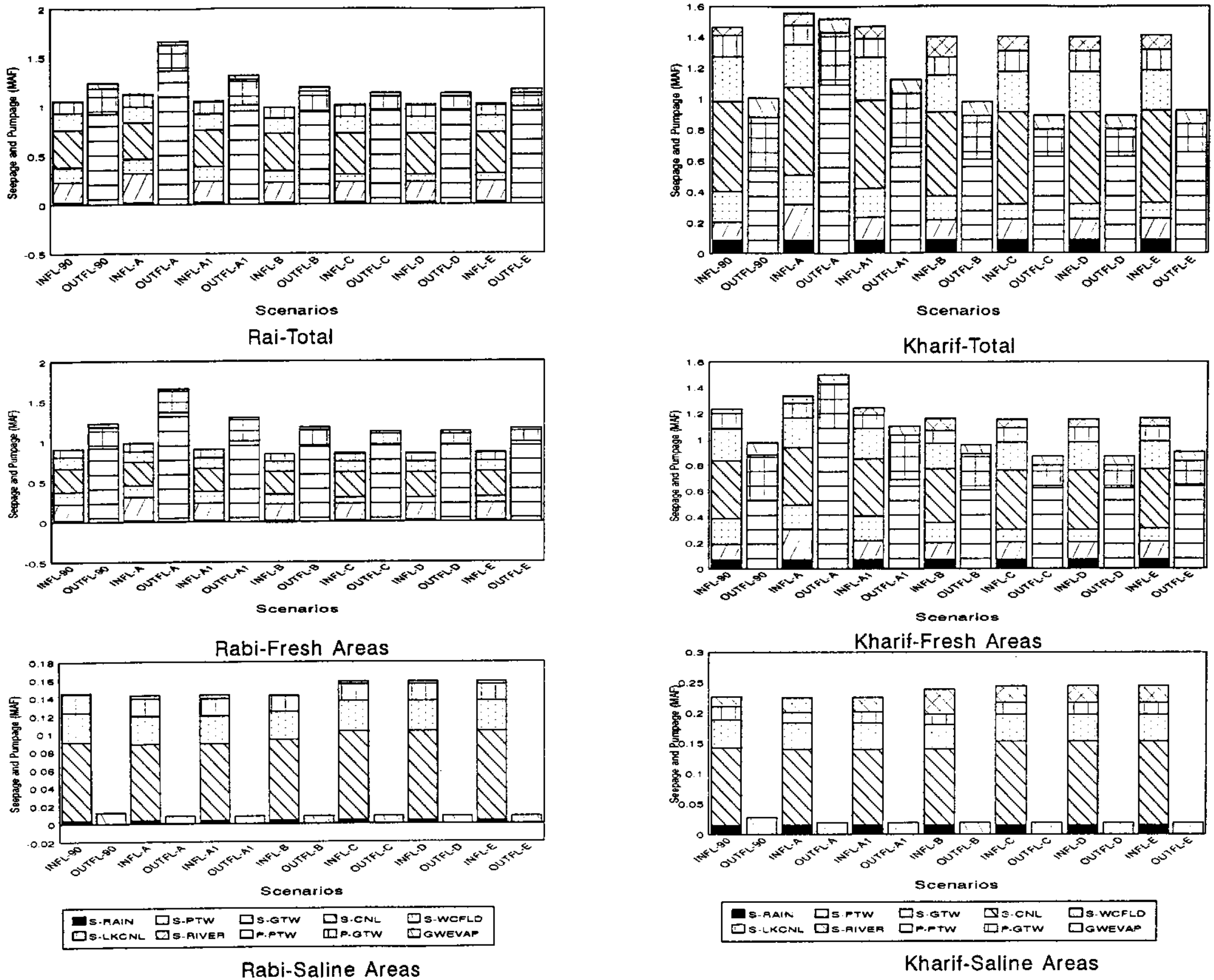


Figure 25. Groundwater Balance for the Jhang Canal during Rabi and Kharif for the Period 1990-2000.

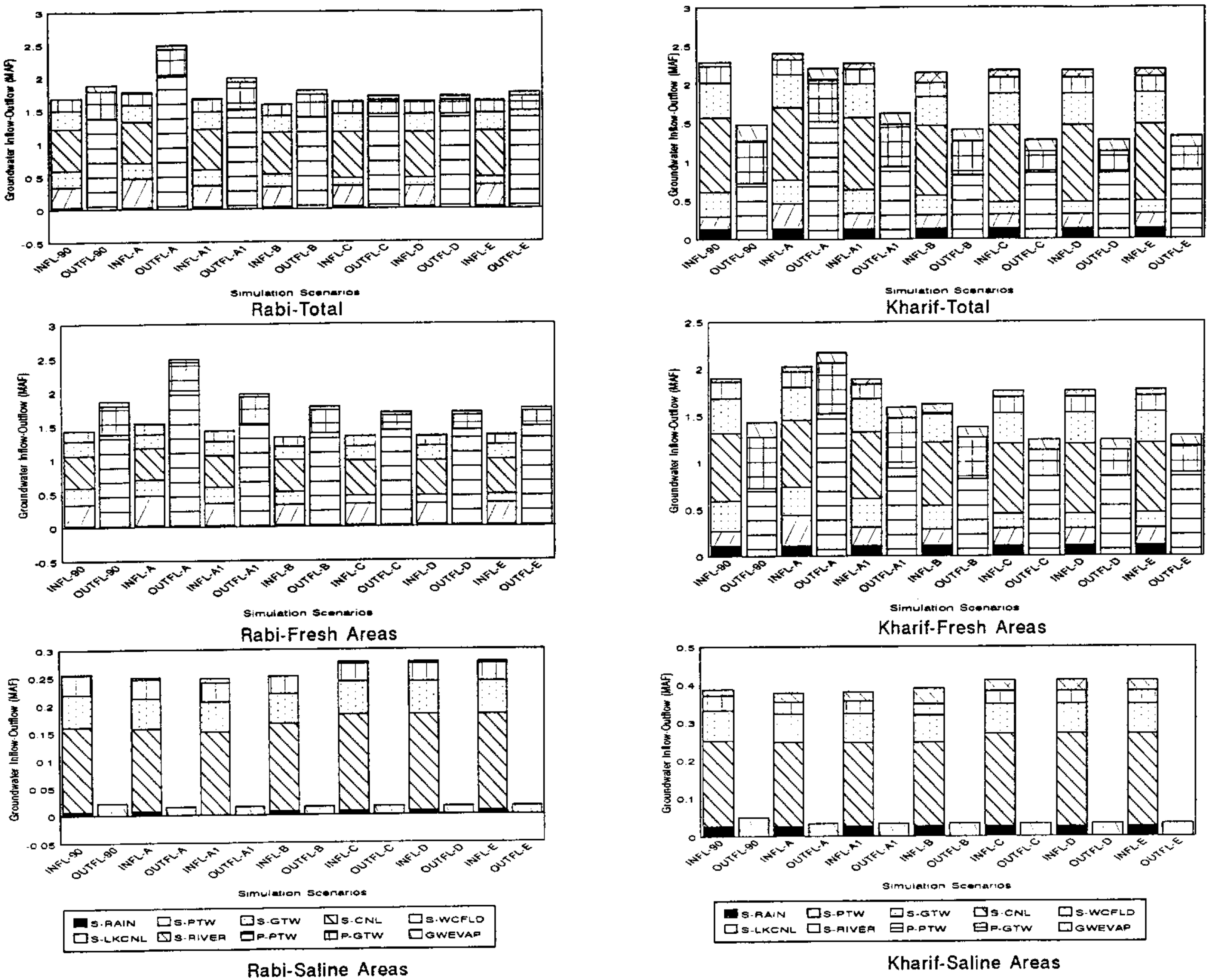


Figure 26. Groundwater Balance for the Gugera Canal during Rabi and Kharif for the Period 1990-2000.

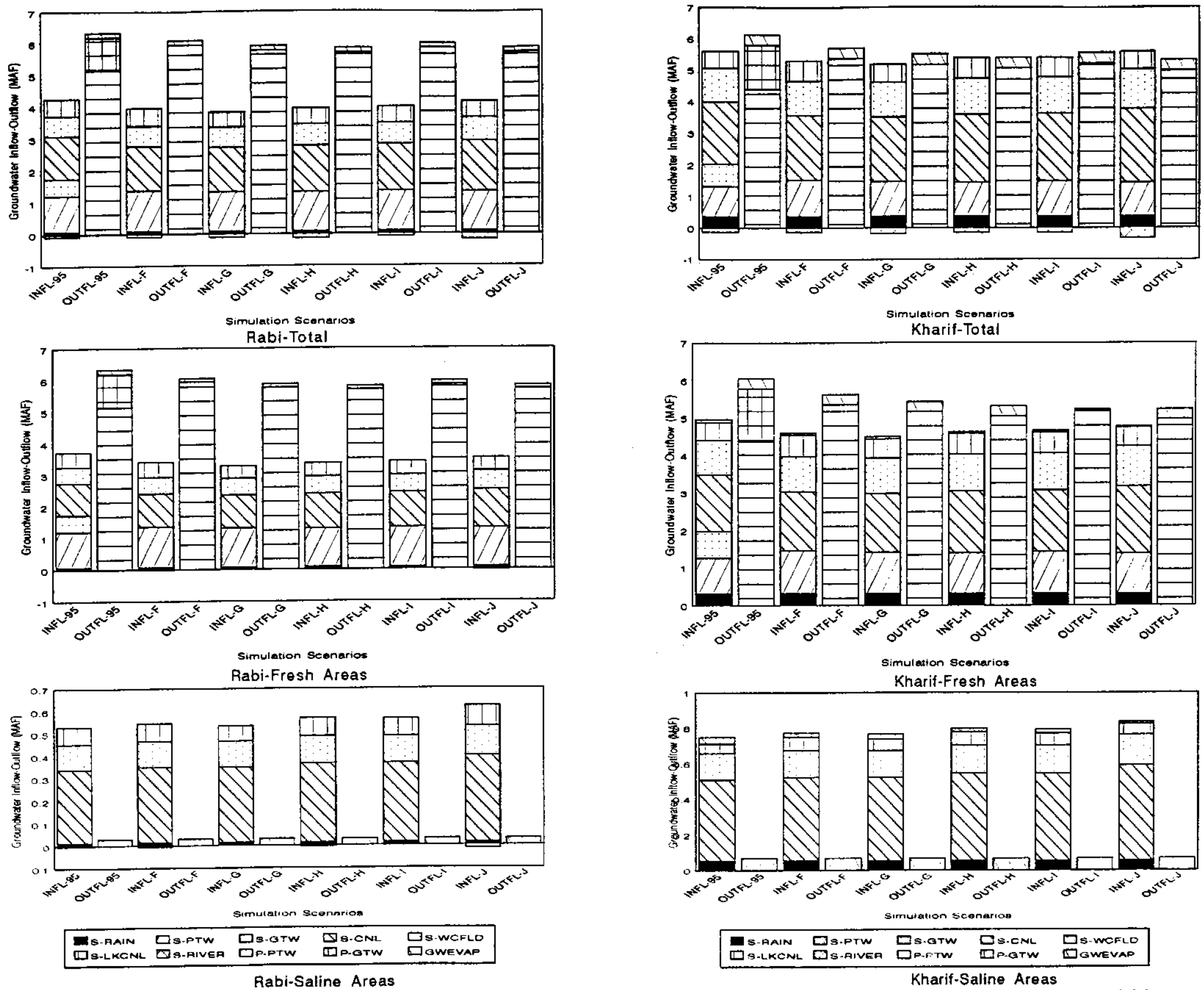


Figure 27. Groundwater Balance of Rechna Doab during Rabi and Kharif for the Period 1995-2000.

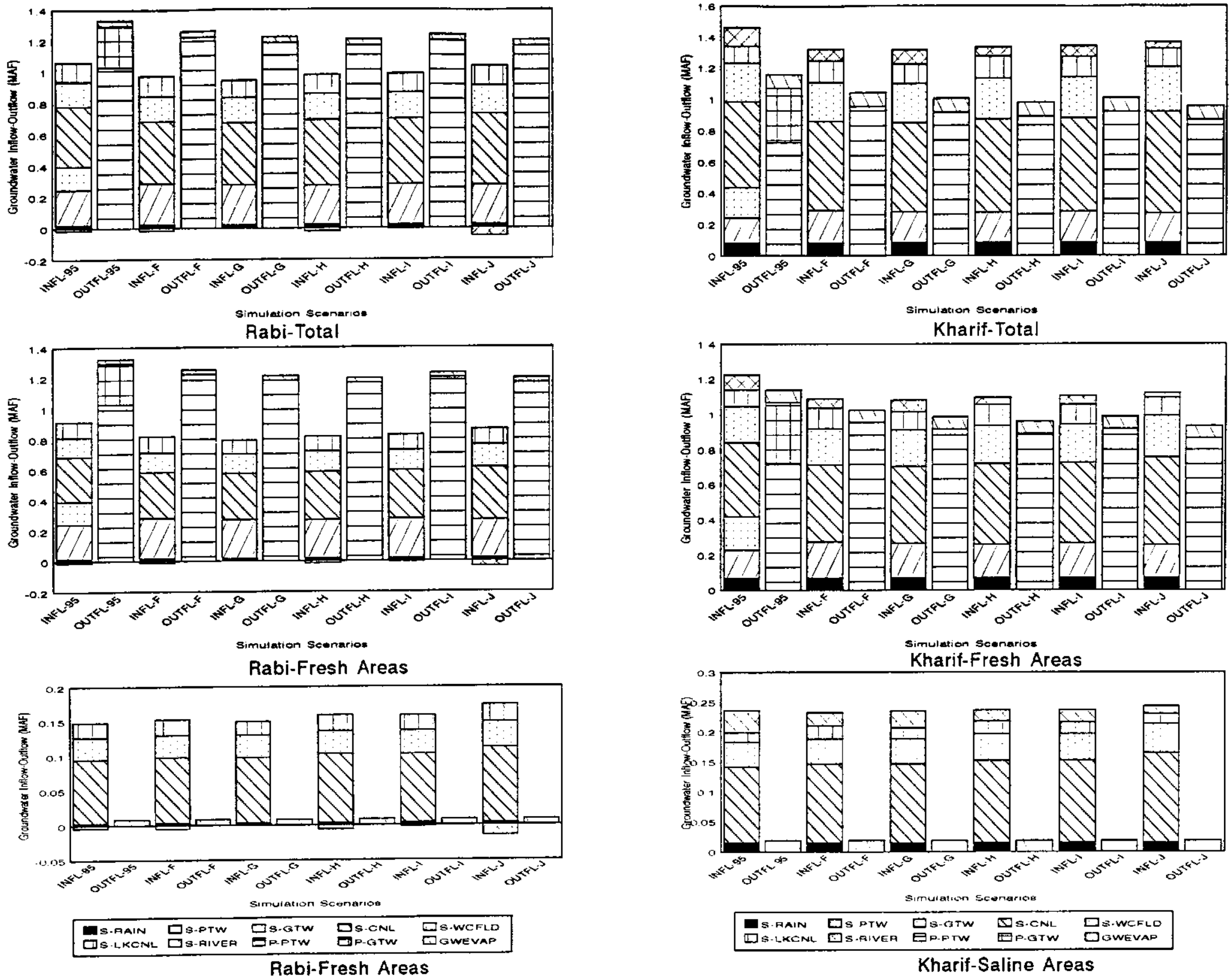


Figure 28. Groundwater Balance of Jhang Canal during Rabi and Kharif for the Period 1995-2000.

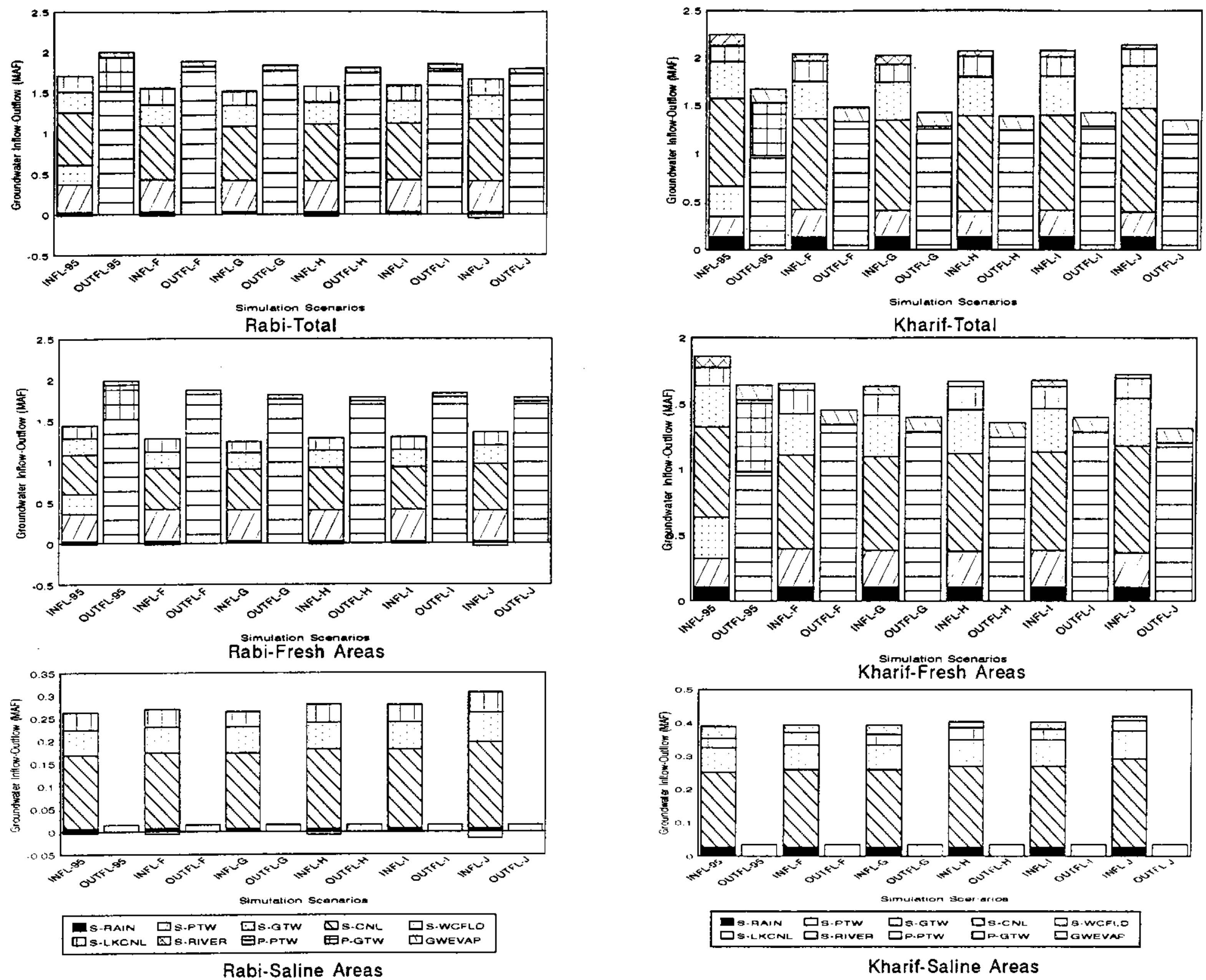


Figure 29. Groundwater Balance of Gugera Canal during Rabi and Kharif for the Period 1995-2000.

Table 18. Groundwater Balance for the Jhang Branch by Areas of Groundwater Quality (Scenario J).

(million acre feet)

Inflows and Outflows	Maximum (Scenario A)		Minimum (Scenario F)		Average (Scenario J)	
	Fresh	Saline	Fresh	Saline	Fresh	Saline
Seepage to Groundwater						
Rainfall	0.087	0.019	0.087	0.019	0.087	0.019
Private Tubewells	0.528		0.41		0.402	
Public Tubewells	0.335					
Irrigation Canals	0.731	0.21	0.74	0.226	0.772	0.242
Water Courses and Fields	0.368	0.074	0.335	0.074	0.385	0.085
Link Canals	0.208	0.037	0.226	0.044	0.203	0.042
Rivers	0.056	0.028	0.04	0.018	-0.078	0
Pumpage from Tubewells						
Private Tubewells	2.455		2.176		1.87	
Public Tubewells	0.605					
Total Inflows (Recharge)	2.313	0.368	1.838	0.381	1.771	0.388
Total Outflows (Pumpage)	3.06		2.176		1.87	
Inflow - Outflow	-0.747	0.368	-0.338	0.381	-0.099	0.388
Groundwater Evaporation	0.099	0.027	0.1	0.027	0.099	0.027
Net Recharge (MAF)	-0.846	0.341	-0.438	0.354	-0.198	0.361
Net Recharge per Acre of CCA (feet)	-0.894	1.536	-0.463	1.594	-0.209	1.626

Table 19. Groundwater Balance for the Gugera Branch by Areas of Groundwater Quality (Scenario J).

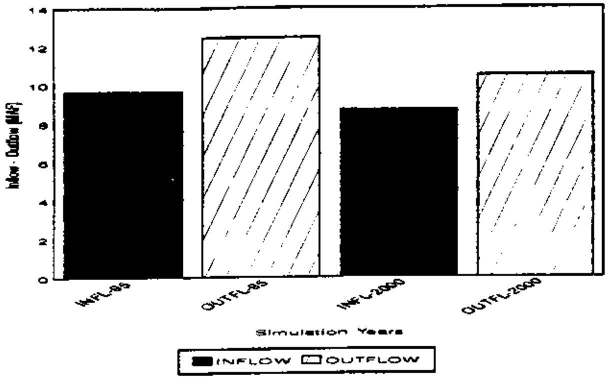
(million acre feet)

Inflows and Outflows	Maximum (Scenario A)		Minimum (Scenario F)		Average (Scenario J)	
	Fresh	Saline	Fresh	Saline	Fresh	Saline
Seepage to Groundwater						
Rainfall	0.134	0.033	0.134	0.033	0.134	0.033
Private Tubewells	0.763		0.682		0.579	
Public Tubewells	0.545					
Irrigation Canals	1.182	0.37	1.211	0.399	1.27	0.427
Watercourses and Fields	0.559	0.131	0.517	0.131	0.594	0.151
Link Canals	0.31	0.065	0.342	0.077	0.31	0.074
Rivers	0.056	0.028	0.04	0.018	-0.102	0
Pumpage from Tubewells						
Private Tubewells	3.54		3.162		2.688	
Public Tubewells	0.958					
Total Inflows (Recharge)	3.549	0.627	2.926	0.658	2.785	0.685
Total Outflows (Pumpage)	4.498		3.162		2.688	
Inflow - Outflow	-0.949	0.627	-0.236	0.658	0.097	0.685
Groundwater Evaporation	0.16	0.048	0.16	0.048	0.159	0.048
Net Recharge (MAF)	-1.109	0.579	-0.396	0.61	-0.062	0.637
Net Recharge per Acre of CCA (feet)	-0.752	1.477	-0.268	1.556	-0.042	1.625

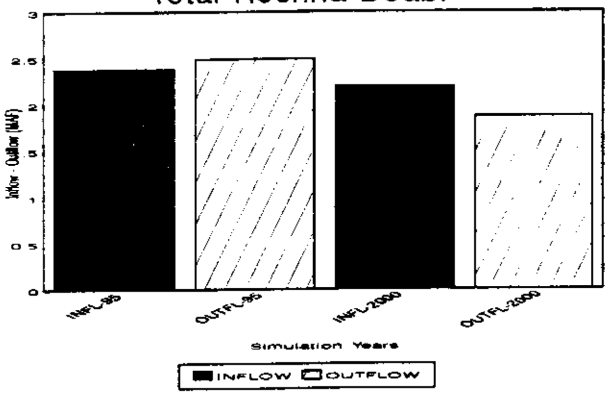
Table 20. Groundwater Balance for the Haveli Canal Command under Scenario J.

(million acre feet)

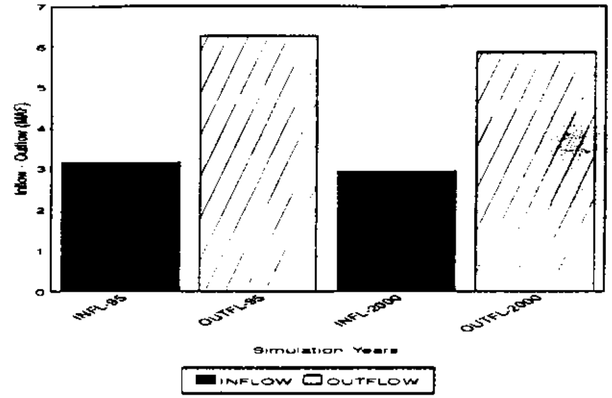
Inflows and Outflows	Maximum (Scenario A)	Minimum (Scenario F)	Average (Scenario J)
Seepage to Groundwater			
Rainfall	0.015	0.015	0.015
Private Tubewells			
Public Tubewells			
Irrigation Canals	0.169	0.182	0.195
Watercourses and Fields	0.06	0.06	0.069
Link Canals	0.03	0.035	0.034
Rivers	0.004	0.002	0
Pumpage from Tubewells			
Private Tubewells			
Public Tubewells			
Total Inflows (Recharge)	0.278	0.294	0.313
Total Outflows (Pumpage)			
Inflow - Outflow	0.278	0.294	0.313
Groundwater Evaporation	0.022	0.022	0.022
Net Recharge (MAF)	0.256	0.272	0.291
Net Recharge per acre of CCA (feet)	1.43	1.519	1.625



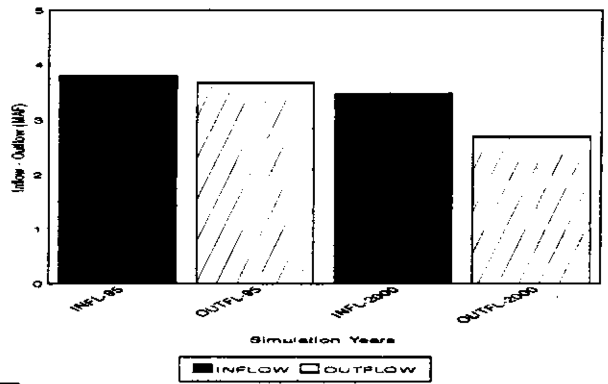
Total Rechna Doab.



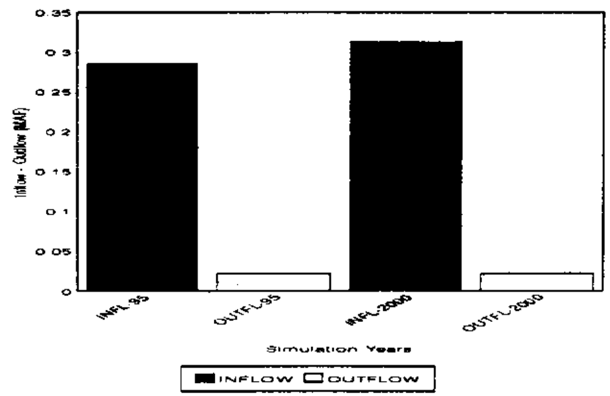
Jhang Branch of LCC.



Upper Rechna Doab.



Gugera Branch of LCC.



Haveli Canal.

Figure 30. Comparison of Groundwater Inflows-Outflows under IBMR Simulation J..

to the aquifer system. The results for the Jhang Canal command show that in fresh groundwater areas, the outflows are more than the recharge, thereby indicating a lowering of watertables; in saline areas, the recharge is more than the outflows, which is an indicator of rising water levels. The Gugera and the Haveli canals are also showing increases in subsurface water levels by the year 2000 because most of the saline groundwater areas are overlain by these canal commands.

f) Groundwater Development Potential

After having determined the inflows and the outflows to the aquifer system, it is now possible to estimate the remaining groundwater development potential in the canal commands of the Rechna Doab based on the simulation results of Scenario J. The groundwater development potential is the difference of useable net recharge and net pumpage, the negative (-) values being indicative of over-exploitation of the aquifer. Table 21 indicates over-exploitation of groundwater in the Upper Rechna Doab area by 1.311 MAF (which has decreased by 9% due to a decrease in tubewell pumpage). There is no change in groundwater development potential in the Jhang Branch of LCC, whereas the Gugera Branch is showing a decrease by 0.8% only because the proportionate fresh areas under the Gugera command are less than the Jhang command. There is a maximum increase of recharge (11%) in the Haveli Canal command as most of its area is saline and the pumped water cannot be used directly for irrigation purposes. However, this recharge from rainfall and canal supplies can be usefully exploited through skimming wells in a manner that would also keep the subsurface water levels within acceptable limits.

g) Summary

The cropped areas have increased the most under historic growth rates (ASP figures); the NCA projections, based on a country-wide generalization, have shown quite a different pattern of decrease in the areas of wheat and sugarcane. Hence, the middle course is the one assumed under the 0.5% per annum increase in Scenario J. Related to this increase in area, the yields have increased throughout the doab, however there is no noticeable difference amongst the major crops when comparing the Jhang and the Gugera Branch canals. The only significant difference in the yield growth rate is observed for cotton, which is about 3% higher in the Gugera Branch.

The 20% assumed increase in the surface supplies for Scenario J remains within the designed capacities of the canals; only a small adjustment to the flows in the Gugera Branch is required during the August-October period. The significant impact of this 20% increase has been in terms of the alleviation of shortages by 45% across the Rechna Doab, except in the Upper Rechna where there are non-perennial irrigation supplies. About 40% of this respite has been afforded in the saline groundwater quality areas where supplemental supplies from groundwater are restricted. There is a surplus of irrigation supplies

Table 21. Groundwater Development Potential by Year 2000 within the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Canal Command	Usable Net Recharge		Net Pumpage		Remaining Groundwater Development Potential (Actual)		Groundwater Potential (Adjusted)	
	1995	2000	1995	2000	1995	2000	1995	2000
Raya Canal	0.849	0.78	1.232	1.128	-0.383	-0.348		
Marala Ravi (Internal)	0.317	0.291	0.459	0.42	-0.142	-0.129		
Upper Chenab (Internal)	2.037	1.872	2.956	2.706	-0.919	-0.834		
Jhang Branch (LCC)	2.281	2.11	1.639	1.468	0.642	0.642	0.642	0.642
Gugera Branch (LCC)	3.63	3.364	2.365	2.109	1.265	1.255	1.265	1.255
Haveli Canal (Internal)	0.262	0.291			0.262	0.291	0.262	0.291
Total Rechna Doab	9.376	8.708	8.651	7.831	0.725	0.877	2.169	2.188

(0.27 MAF) in the Jhang Branch command by the year 2000; the net shortages have decreased in the saline groundwater areas by as much as 47% in comparison to the 26% decrease within corresponding areas in the Gugera Branch command.

The decrease in shortages in the fresh groundwater quality areas is much higher, and this is reflected in the pumpage related outflow figures for the groundwater balance (Figure 30). In the Upper Rechna Doab, where the groundwaters are fresh throughout, there are higher irrigation related extractions than recharge to the aquifer (over-exploitation by 1.31 MAF, although the extractions decrease by 9% to year 2000).

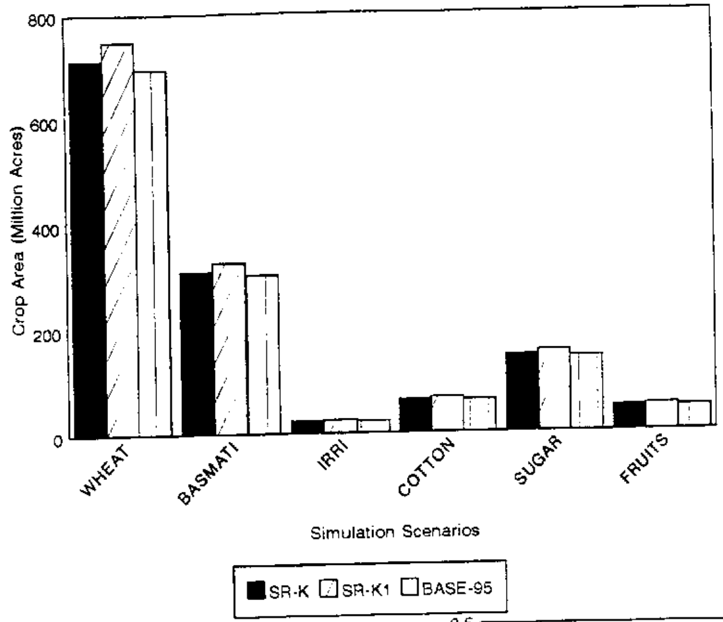
The increasing recharge to the aquifer in the saline groundwater areas (e.g. Gugera and Haveli canal command), is likely to cause a rise the the water levels, and it is perhaps in these areas that skimming wells could be most useful towards not only the lowering of the watertables but also in reducing the shortages further from the current 47% for the Jhang, 26% for Gugera and 84% for the Haveli Canal commands.

3) Simulation Period 1995-2010

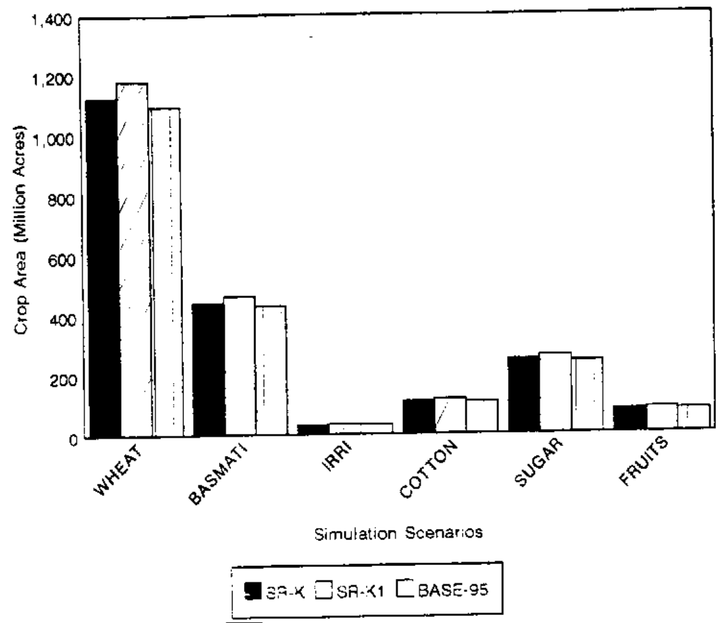
The period 1995-2010 has been selected to simulate the planned interventions in the agriculture sector leading to the 21st century. Based on different assumptions under scenarios K-K1 for canal water allocation, policy of groundwater usage, and increases in cropped area/production, the most suitable mix of resource management decision-making could be overseen and implemented in the context of the emergent threat of soil salinisation.

a) Cropped Area

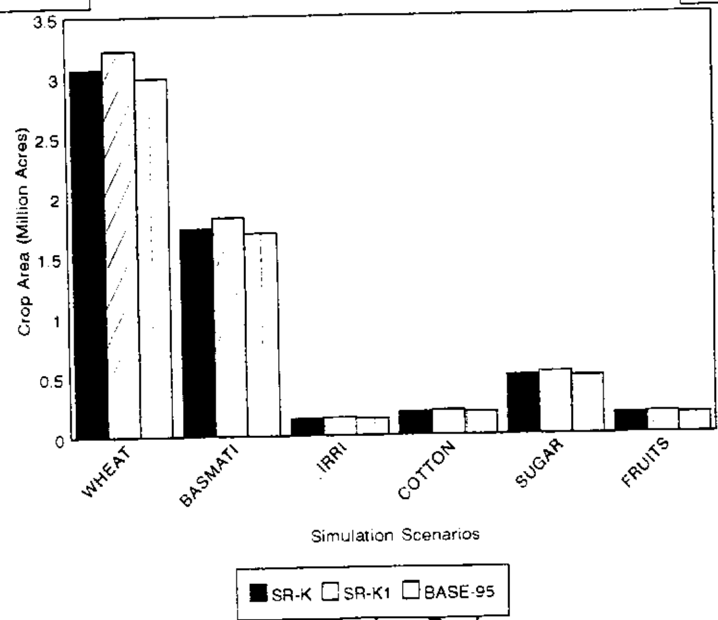
From the comparison of growth in cropped areas for scenarios K and K1 in Figure 31, it is clear that the maximum change is occuring under Scenario K1 from the base year 1995. The results for five major crops have been given in Table 22 for the total Rechna Doab, as well as the canal commands under LCC system and the Haveli Canal. A comparison of the simulated area and average crop yield of major crops with the actual data for 1994-95 is illustrated in Figure 32. The cumulative cropped area has increased for wheat (7%), basmati (7.5%), IRRI (8%), cotton (6.4%), and sugarcane (6.4%). In the LCC system, the increase in cropped area under the Jhang Branch command is 6.7% for wheat, 7.2% for basmati, 8.7% for IRRI, 6.3% for cotton and 6.2% for sugarcane; the corresponding increases for wheat (6.5%) and basmati (7.1%) in the Gugera Command are low, but high (9.4%) for IRRI.



Jhang Branch



Gugera Branch



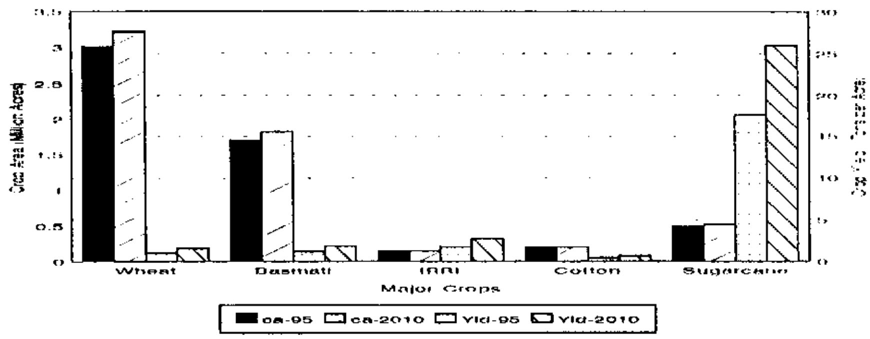
Total Rechna Doab

Figure 31. Simulated Cropped Area of Major Crops under IBMR Simulations K and K1..

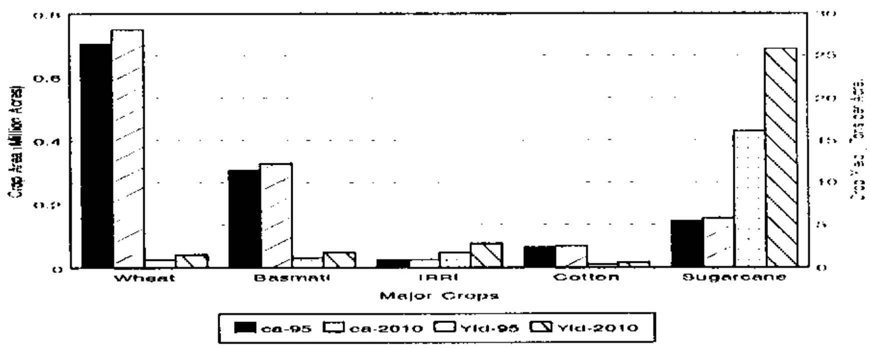
Table 22. Simulated Cropped Area by Year 2010 within the Rechna Doab, Punjab, Pakistan.

(million acres)

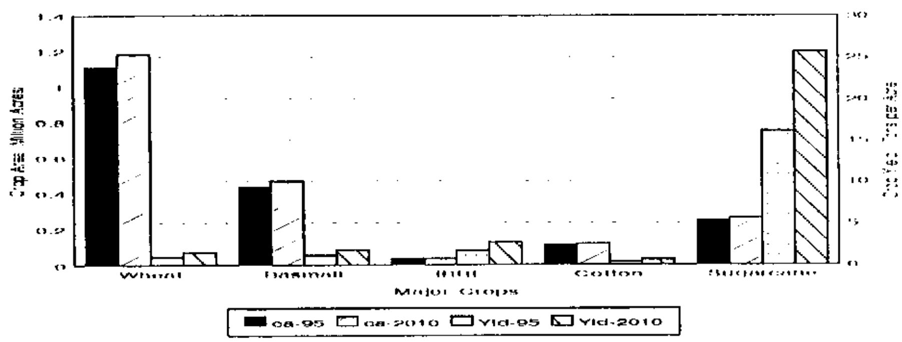
Major Crops	Rechna Doab		Jhang Canal		Gugera Canal		Haveli Canal	
	1995	2010	1995	2010	1995	2010	1995	2010
Wheat	3.008	3.218	0.702	0.749	1.108	1.18	0.100	0.106
Basmati Rice	1.69	1.817	0.304	0.326	0.433	0.464	0.019	0.021
IRRI Rice	0.136	0.149	0.023	0.025	0.031	0.035	0.001	0.001
Cotton	0.189	0.201	0.063	0.067	0.109	0.116	0.014	0.015
Sugarcane	0.487	0.518	0.145	0.154	0.245	0.261	0.029	0.031



Total Rechna Doab



Jhang Branch Canal



Gugera Branch Canal

Figure 32. Simulated Cropped Area and Average Yield under IBMR Simulation K1..

b) Production and Yield

The estimated crop production, based on the above simulations for a 3% increase in yield per annum, appears in Table 23. The increase is more than 50% from the base year 1994-95. For all the major crops, the increase in production has been higher than the corresponding increase in the yields. However, the increase in crop yields within the Haveli Canal command are higher because of the increase in canal diversions; the average yield increase for wheat is 74%, basmati 51.7%, IRRI 59.3%, cotton 66.2% and sugarcane 60.2%.

c) Canal Diversions

Under proportional allocation, water allocated by the IBMR to each canal is in strict proportion to the mean post-Tarbela seasonal canal diversions. Accordingly, the seasonal availability of water at each canal head by the year 2010 is shown in Table 24. The overall annual canal supplies at the canal heads in the Rechna Doab have increased by 24% from the base year (1994-95) canal diversions, and this increase is more in the rabi season (41%) than in kharif (13%). These canal diversions are within the designed capacity, as well as the Authorised Full Supply (AFS), at the canal head of each canal (Figure 33). The model has increased the canal supplies under this proposed allocation scenario to minimise the water shortages as far as possible within the resource constraints and the model objective function. This is one reason for higher increased diversions during the rabi season as compared with the kharif, especially in the saline areas (LCC System and Haveli canal) where the maximum shortages/stress is occuring. How this increase in canal supplies has been used to minimise the water shortages, especially during the rabi season, will be discussed in the following paragraphs.

d) Water Balance at the Root Zone

A comparison of crop water requirements and supplies from all sources, according to scenarios K and K1, is shown in Figures 34-36. The maximum reduction in water shortages is obtained via scenario K1, and <u>this scenario has been adopted as reference for the subsequent discussions</u>. From the comparison of water balance computations at the root zone, the annual water shortages have reduced from 1.162 MAF to 0.702 MAF (39.6%) across all canal commands of the Rechna Doab. The surplus waters have increased in the Jhang Branch Canal from 0.200 MAF (1995) to 0.397 MAF (2010); the shortages in the saline areas have also decreased by 41% (from 0.221 MAF (1995) to 0.131 MAF (2010)), resulting in a net surplus of 0.266 MAF by 2010. The shortages in the fresh groundwater areas of the Gugera Branch Canal have reduced by 61%, whereas in saline areas by 21%, resulting in an overall decrease of 31%. A summary of the water balance appears under Table 25.

The groundwater pumpage is only from private tubewells because the contribution from public tubewells has been assumed to be zero. Consequently, the private tubewell pumpage

Table 23. Comparison of Crop Production and Average Yield for the Years 1995 & 2010 within Rechna Doab, Punjab, Pakistan.

Major Crops	Production (million tons)		Average Yield (tons per acre)	
	1995	2010	1995	2010
Total Rechna Doab				
Wheat	3.005	4.915	0.999	1.527
Basmati	1.964	3.287	1.162	1.809
IRRI	0.241	0.404	1.745	2.73
Cotton	0.075	0.124	0.396	0.617
Sugarcane	8.58	13.434	17.632	25.984
Jhang Branch				
Wheat	0.702	1.134	1	1.514
Basmati	0.354	0.59	1.163	1.81
IRRI	0.041	0.069	1.744	2.76
Cotton	0.025	0.041	0.397	0.612
Sugarcane	2.559	3.969	17.634	25.772
Gugera Branch				
Wheat	1.106	1.782	0.998	1.51
Basmati	0.503	0.839	1.162	1.808
IRRI	0.057	0.095	1.754	2.714
Cotton	0.043	0.071	0.394	0.612
Sugarcane	4.327	6.696	17.631	25.655
Haveli Canal				
Wheat	0.1	0.159	0.861	1.5
Basmati	0.023	0.037	1.161	1.762
IRRI	0.002	0.003	1.743	2.777
Cotton	0.005	0.009	0.361	0.6
Sugarcane	0.514	0.79	15.906	25.484

Table 24. Simulated Canal Diversions at Canal Head by Year 2010 within Rechna Doab, Punjab, Pakistan.

(million acre feet)

Canal Command	Rabi	Change (%)	Kharif	Change (%)	Annual	Change (%)
Raya (BRBD-Internal)	0.089	39	0.404	12	0.493	16
Marala Ravi (Internal)	0.011	38	0.349	40	0.36	39
Upper Chenab (Internal)	0.396	40	0.961	12	1.357	19
Jhang Branch (LCC)	2.069	40	2.141	12	4.21	24
Gugera Branch (LCC)	2.323	40	2.403	12	4.726	24
Haveli Canal (Internal)	0.375	61	0.389	12	0.764	31
Total Rechna Canals	5.263	41	6.648	13	11.911	24

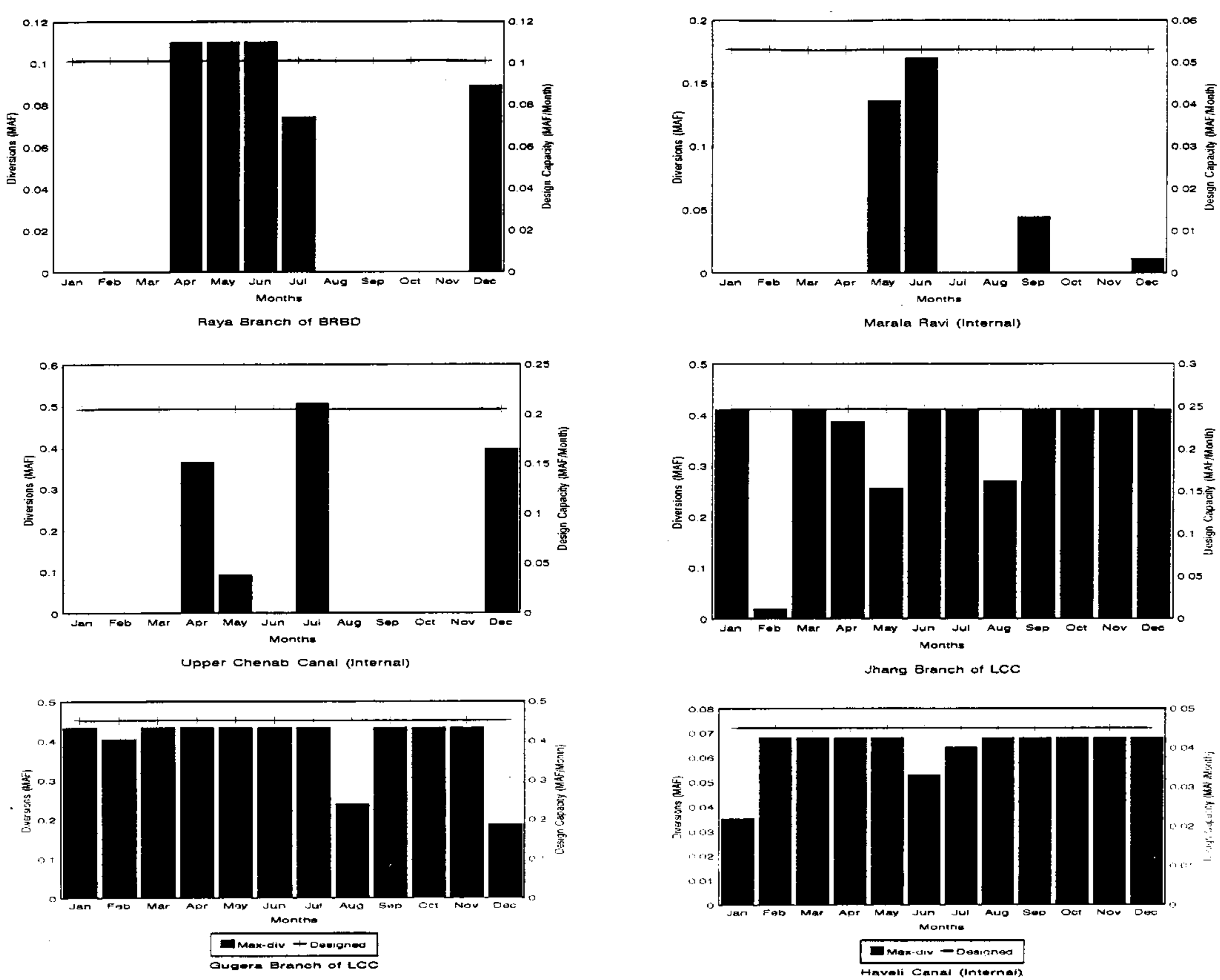


Figure 33. Comparison of Maximum Canal Diversions and Design Capacity at Canal Head, under IBMR Simulation K1.

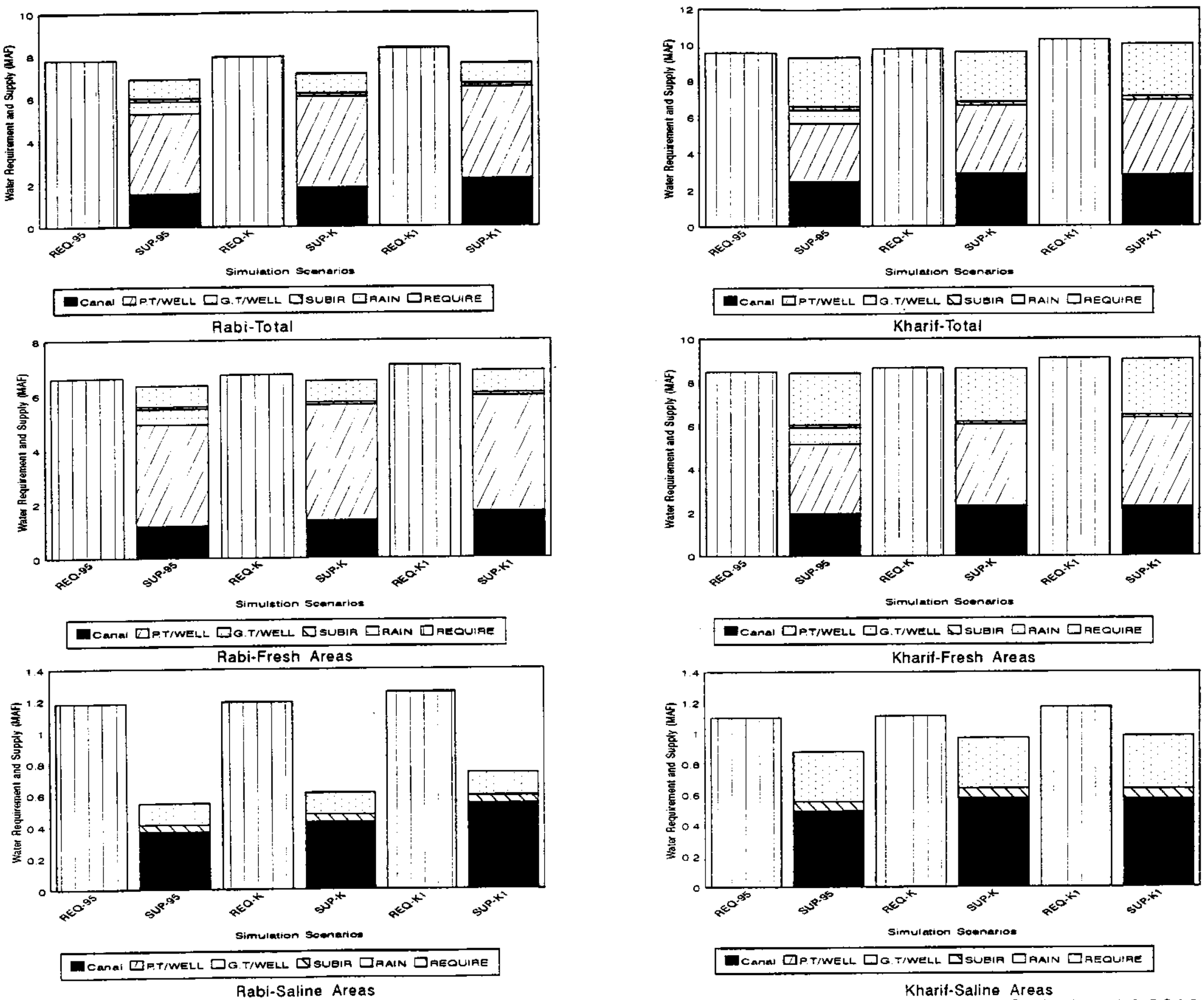
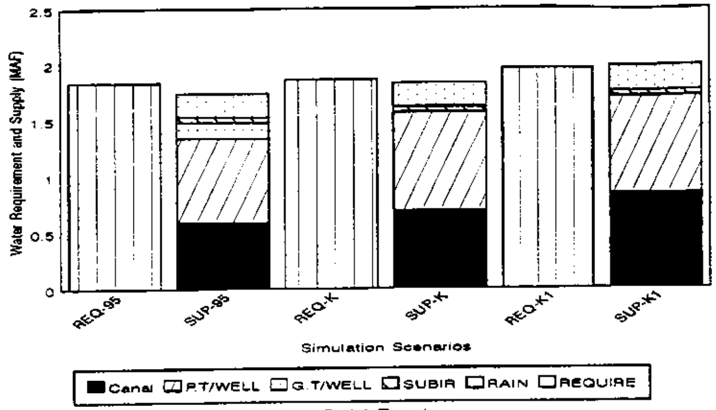
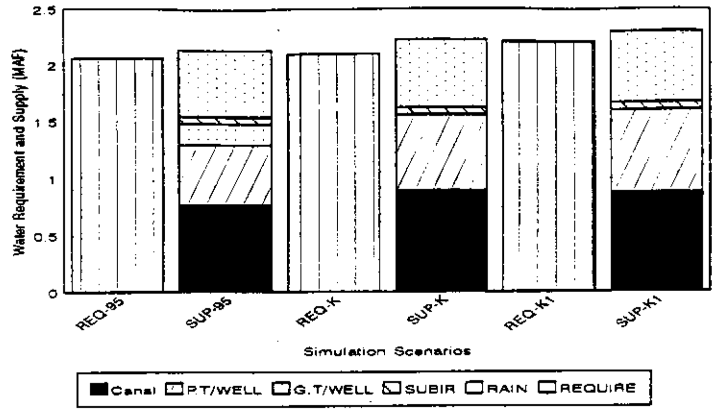


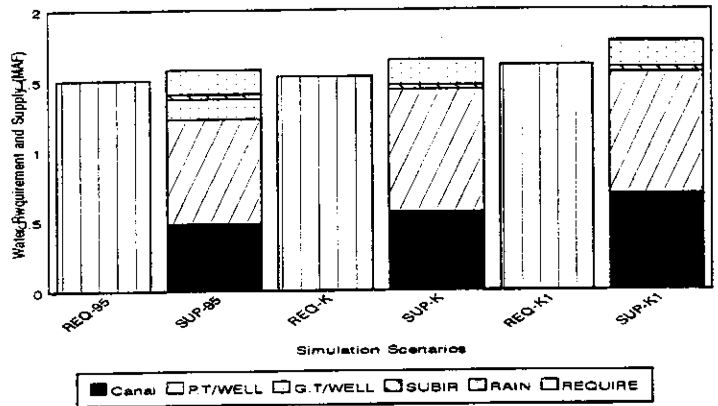
Figure 34. Water Balance during Rabi and Kharif seasons of Rechna Doab for the Period 1995-2010.



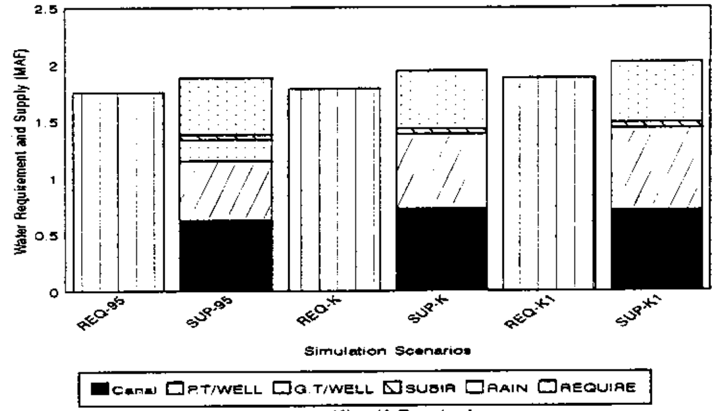
Rabi-Total



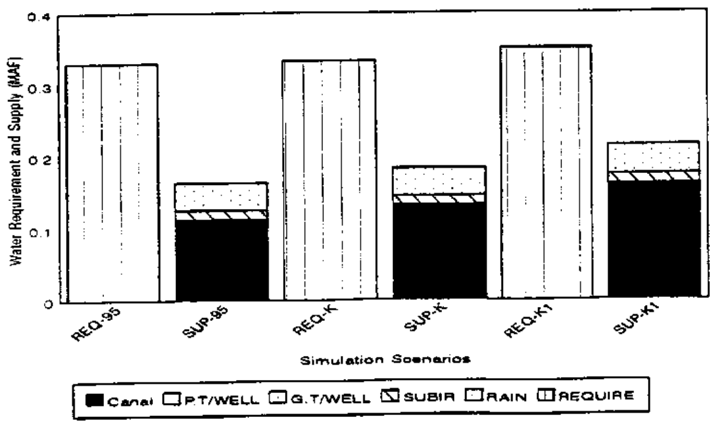
Kharif-Total



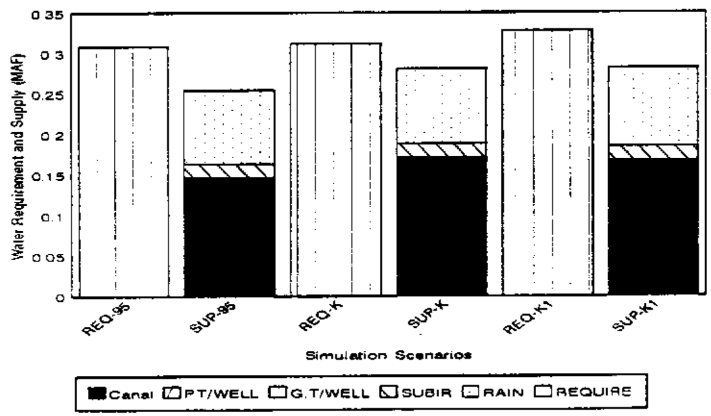
Rabi-Fresh Areas



Kharif-Fresh Areas



Rabi-Saline Areas



Kharif-Saline Areas

Figure 35. Water Balance during Rabi and Kharif seasons of Jhang Canal for the Period 1995-2010.

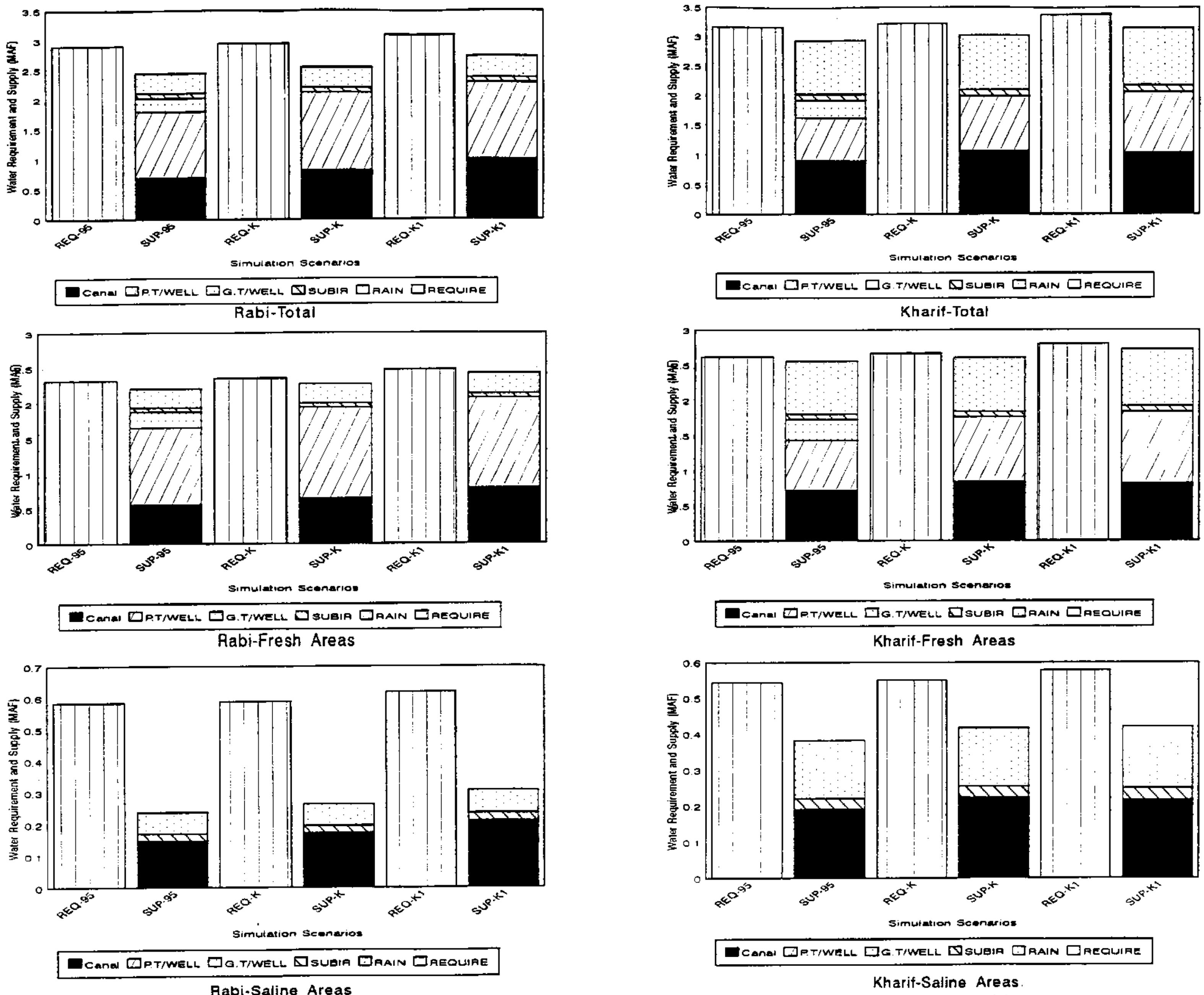


Figure 36. Water Balance during Rabi and Kharif seasons of Gugera Canal for the Period 1995-2010.

Table 25. Comparison of Annual Net Water Requirements and Supplies at the Root Zone for IBMR Scenario K1.

(million acre feet)

Description	Fresh 1995	Fresh 2010	Saline 1995	Saline 2010	Total 1995	Total 2010
Rechna Doab						
Net Requirements	11.716	12.57	1.714	1.818	13.43	14.388
Water Supplies						
Canal	3.164	4.61	0.859	1.284	4.023	5.894
Tubewell Pumpage	8.245	7.792			8.245	7.792
Total Supplies	11.409	12.402	0.859	1.284	12.268	13.686
Shortage	0.307	0.168	0.855	0.534	1.162	0.702
Surplus						
Total Water Stress			0.174	0.097	0.174	0.097
Upper Rechna Canal Commands						
Net Requirements	5.426	5.847			5.426	5.847
Water Supplies						
Canal	0.784	1.125			0.784	1.125
Tubewell Pumpage	4.309	4.225			4.309	4.225
Total Supplies	5.093	5.35			5.093	5.35
Shortage	0.333	0.497			0.333	0.497
Surplus						
Total Water Stress						
Jhang Canal Command						
Net Requirements	2.506	2.68	0.48	0.509	2.986	3.189
Water Supplies						
Canal	1.104	1.614	0.259	0.378	1.363	1.992
Tubewell Pumpage	1.602	1.463			1.602	1.463
Total Supplies	2.706	3.077	0.259	0.378	2.965	3.455
Shortage			0.221	0.131	0.221	0.131
Surplus	0.2	0.397			0.2	0.397
Total Water Stress			0.049	0.027	0.049	0.027
Gugera Canal Command						
Net Requirements	3.785	4.043	0.847	0.899	4.632	4.942
Water Supplies						
Canal	1.276	1.871	0.339	0.497	1.615	2.368
Tubewell Pumpage	2.334	2.104			2.334	2.104
Total Supplies	3.61	3.975	0.339	0.497	3.949	4.472
Shortage	0.175	0.068	0.508	0.402	0.683	0.47
Surplus					------	--------
Total Water Stress			0.086	0.048	0.086	0.048
Haveli Canal Command						
Net Requirements			0.387	0.411	0.387	0.411
Water Supplies						
Canal			0.262	0.408	0.262	0.408
Tubewell Pumpage					-------	--------
Total Supplies			0.262	0.408	0.262	0.408
Shortage			0.125	0.003	0.125	0.003
Surplus					-------	--------
Total Water Stress			0.039	0.022	0.039	0.022

has increased by 13% from 6.919 MAF (1995) to 7.792 MAF (2010). The results have been depicted in Figure 37, where the annual water requirements have increased by 7% from 13.43 MAF (1995) to 14.39 MAF (2010), and the total water supplies (canal and groundwater) have increased by 12% from 12.268 MAF (1995) to 13.686 MAF (2010). The resulting decrease in net shortages has been 39.6% (from 1.162 MAF in 1995 to 0.702 MAF in 2010, with 45% in fresh groundwater areas and 38% in saline areas).

The Upper Rechna canals are showing an increase in shortages by 49% by the year 2010 due to the nonperennial nature of its canals; the source of water supply during the dry rabi season is the tubewell pumpage (85%) which has decreased by 2% only. The total water supplies are showing an increase of 6% against the increase in water requirements by 8%.

The surplus water (0.266 MAF by the year 2010) in the fresh groundwater areas of Jhang Canal command during the kharif season could be usefully deployed in the Gugera Branch command where the total water shortages have reduced by only 31% (from 0.683 MAF in 1995 to 0.470 MAF in 2010). This reduction has been less in the saline groundwater areas (21%) in comparison with the fresh areas (67%).

The Haveli Canal is showing a reduction in water shortages of 98% by the year 2010 because of the maximum allocation of canal water by the IBMR to the saline areas (from 0.262 MAF to 0.408 MAF).

For the above results, the increase in water supplies for crops like cotton, wheat and sugarcane is conducive to a corresponding increase in crop yields by 43%, 31% and 25%, respectively (Table 26).

e) Groundwater Balance

The pattern of groundwater inflows and outflows, based on the assumptions under Scenario K1, are shown in Figures 38-40 and in Tables 27-30. Figure 41 shows that the total annual inflows have decreased 9.5% from 9.635 MAF (1995) to 8.713 MAF (2010) due to improvements in irrigation system efficiencies (Annexure-b) and reductions in system losses; the total outflows (tubewell pumpage and evaporation from groundwater) have also decreased by 10.7% from 12.447 MAF (1995) to 11.118 MAF (2010), which is indicative of rising subsurface water levels.

The results for the Jhang Branch command show that the total inflows have decreased by 9% from 2.382 MAF (1995) to 2.164 MAF (2010); these total inflows are more than the total outflows which have decreased 14.6% from 2.490 MAF to 2.127 MAF, indicating an overall trend of rising watertables. The Gugera and the Haveli canals are also showing a rise in their respective watertable regimes by the year 2010 as most of the saline areas lie under these canal commands where pumpage is minimal. Even in the fresh groundwater areas of the Gugera Branch, the tubewell pumpage has decreased.

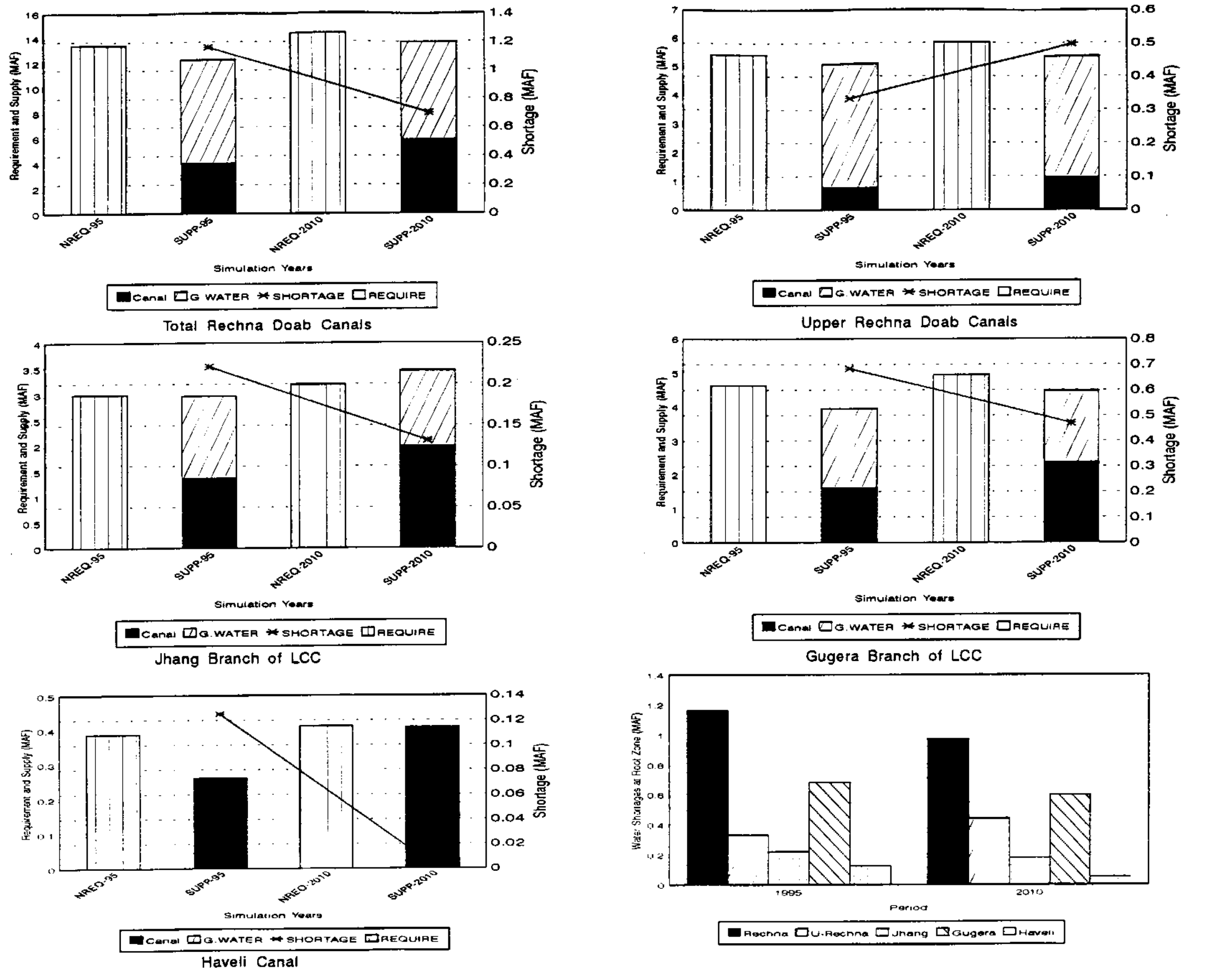


Figure 37. Simulated Water Balance at the Root Zone by Year 2010 under IBMR Simulation K1.

Table 26. Water Supply and Crop Yield Relationship for Scenario K1 due to Water Stress within the Rechna Doab, Punjab, Pakistan.

Crop	1995		2010	
	Water Supply (%)	Crop Yield (%)	Water Supply (%)	Crop Yield (%)
Cotton	40	70	100	100
Rabi Fodder	30	65	30	65
Maize	40	70	40	70
Kharif Fodder	74	82	100	100
Sugarcane	60	68	82	85
Wheat	50	70	86	92
Fruits	70	78	70	78

Table 27. Groundwater Balance for Rechna Doab by Areas of Groundwater Quality for Scenario K1.

(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.388	0.067	0.388	0.067
Private Tubewells	2.072		2.277	
Public Tubewells	1.243			
Irrigation Canals	2.524	0.781	2.762	0.89
Watercourses and Fields	1.437	0.263	1.732	0.318
Link Canals	0.93	0.132	0.655	0.069
Rivers	-0.221	0.019	-0.473	0.028
Pumpage from Tubewells				
Private Tubewells	9.509		10.638	
Public Tubewells	2.458			
Total Inflows (Recharge)	8.373	1.262	7.341	1.372
Total Outflows (Pumpage)	11.967		10.638	
Inflow - Outflow	-3.594	1.262	-3.297	1.372
Groundwater Evaporation	0.382	0.098	0.382	0.098
Net Recharge (MAF)	-3.976	1.164	-3.679	1.274
Net Recharge per Acre of CCA (feet)	-0.989	1.468	-0.915	1.606

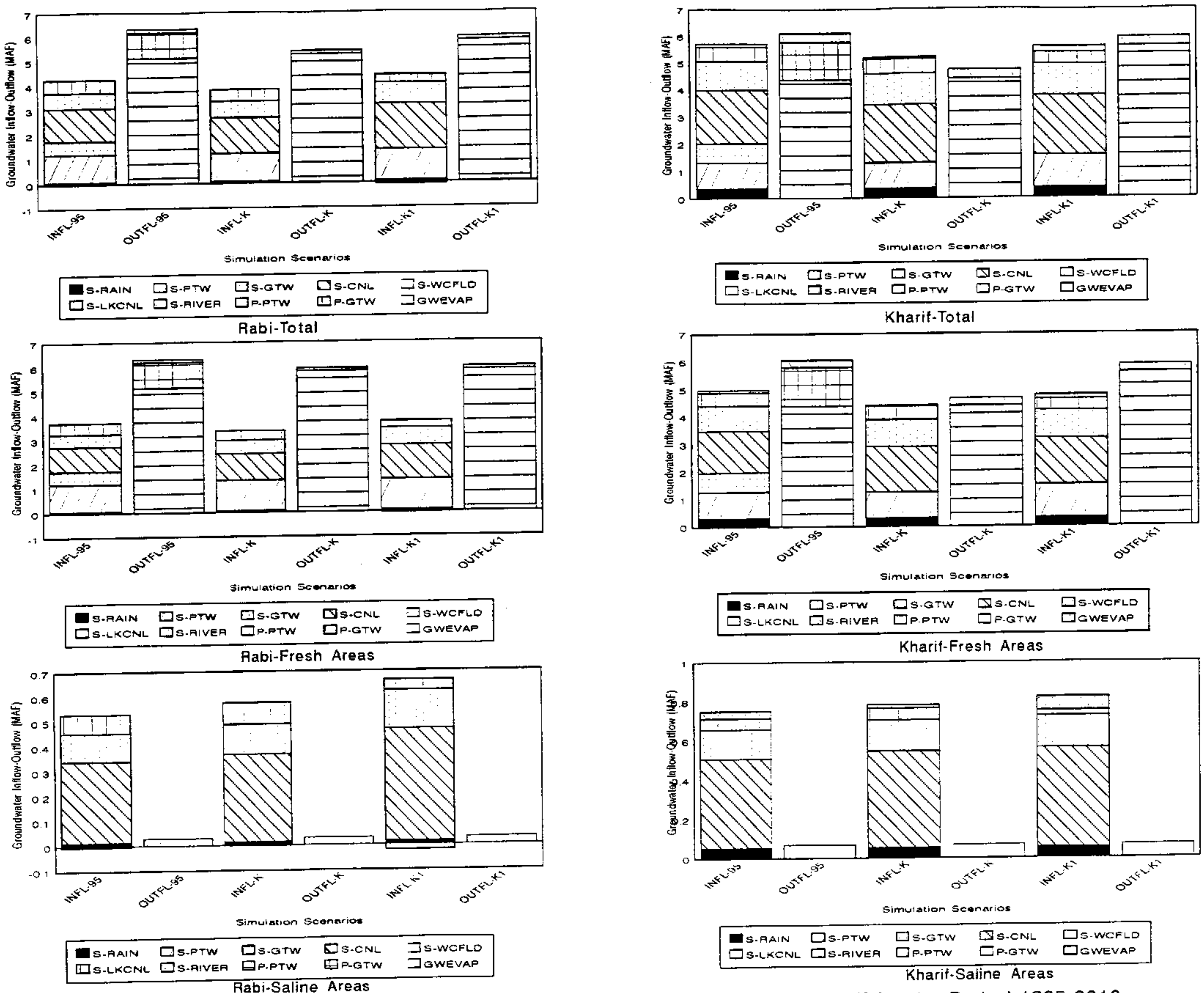


Figure 38. Groundwater Balance of Rechna Doab during Rabi and Kharif for the Period 1995-2010.

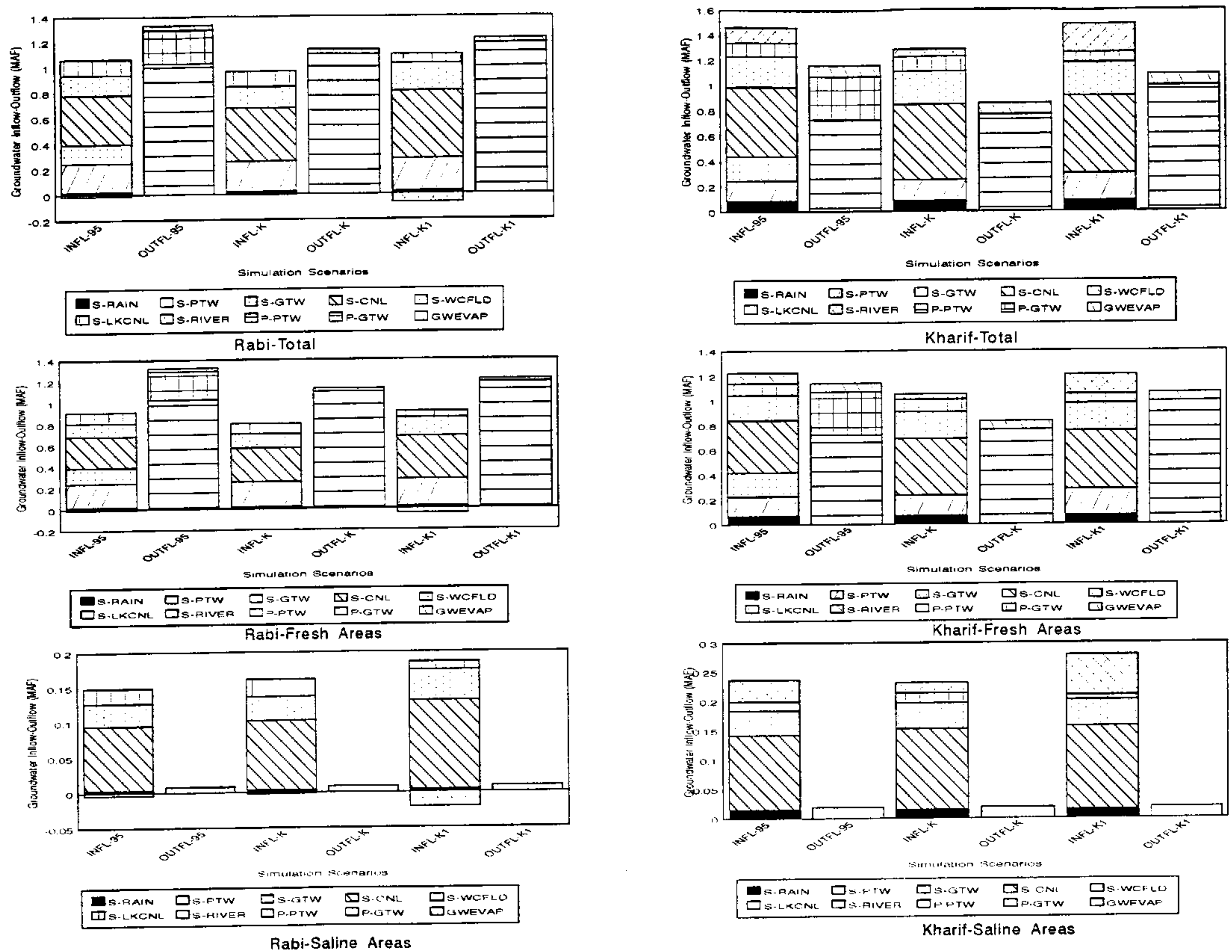


Figure 39. Groundwater Balance of Jhang Canal during Rabi and Kharif for the Period 1995-2010.

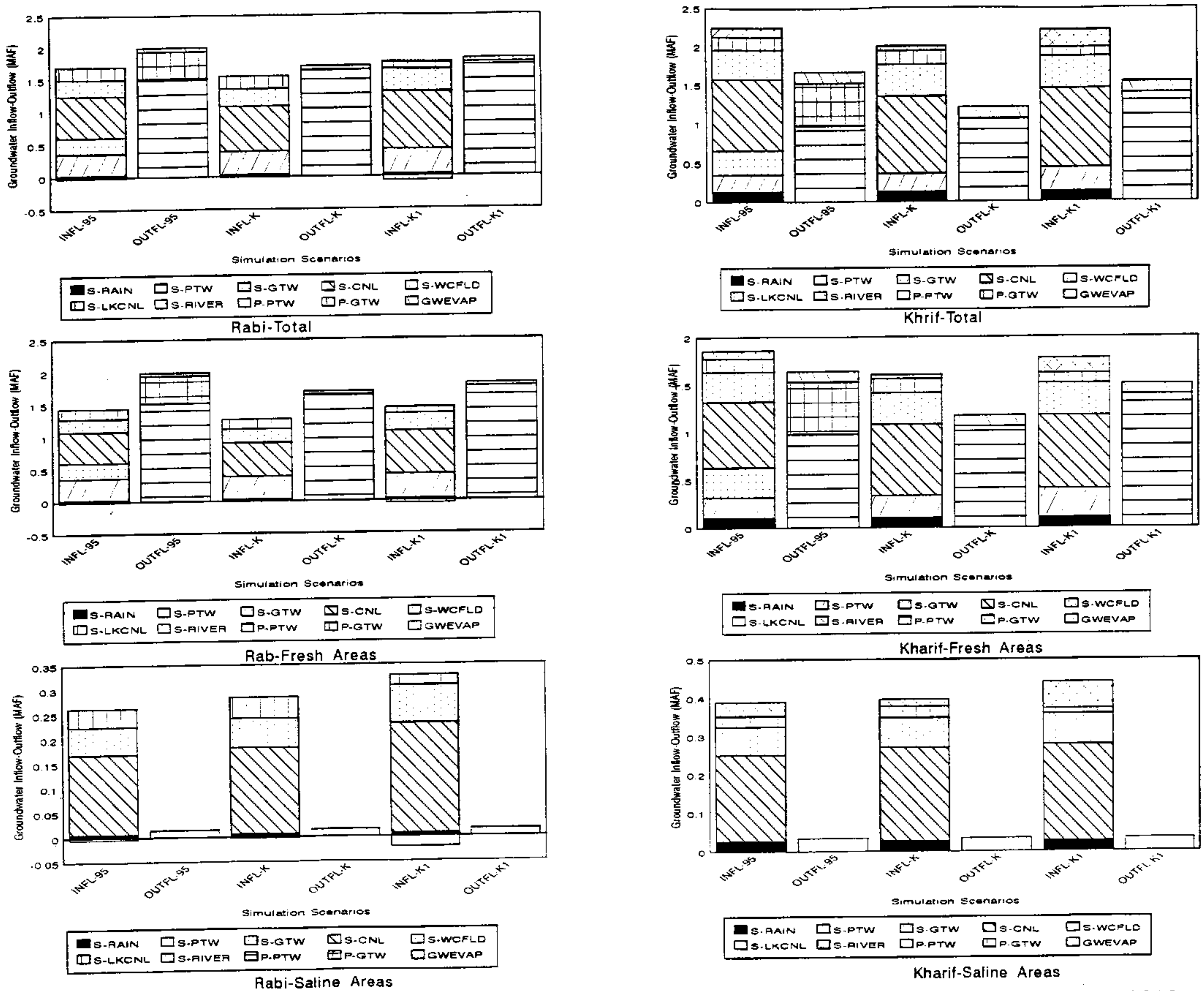


Figure 40. Groundwater Balance of Gugera Canal during Rabi and Kharif for the Period 1995-2010.

Table 28. Groundwater Balance for Jhang Branch by Areas of Groundwater Quality (Scenario K1).

(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.087	0.019	0.087	0.019
Private Tubewells	0.383		0.43	
Public Tubewells	0.342			
Irrigation Canals	0.714	0.219	0.796	0.249
Watercourses and Fields	0.33	0.074	0.398	0.089
Link Canals	0.197	0.037	0.129	0.019
Rivers	-0.025	0.005	-0.06	0.008
Pumpage from Tubewells				
Private Tubewells	1.752		2.001	
Public Tubewells	0.612			
Total Inflows (Recharge)	2.028	0.354	1.78	0.384
Total Outflows (Pumpage)	2.364		2.001	
Inflow - Outflow	-0.336	0.354	-0.221	0.384
Groundwater Evaporation	0.099	0.027	0.099	0.027
Net Recharge (MAF)	-0.435	0.327	-0.32	0.357
Net Recharge per Acre of CCA (feet)	-0.46	1.473	-0.338	1.608

Table 29. Groundwater Balance for the Gugera Branch by Areas of Groundwater Quality (Scenario K1).

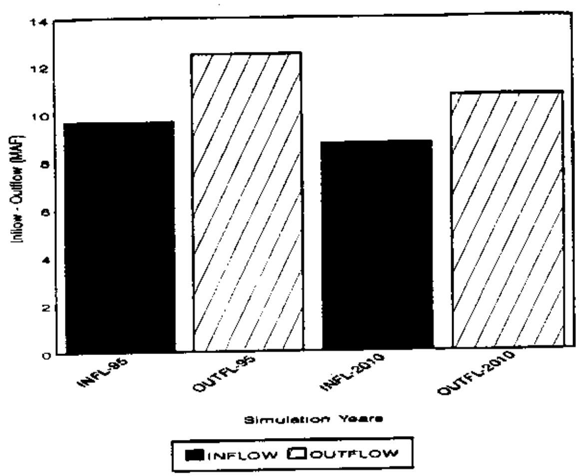
(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.134	0.033	0.134	0.033
Private Tubewells	0.548		0.62	
Public Tubewells	0.556			
Irrigation Canals	1.169	0.386	1.31	0.44
Watercourses and Fields	0.51	0.13	0.615	0.157
Link Canals	0.297	0.065	0.188	0.034
Rivers	-0.027	0.009	-0.069	0.014
Pumpage from Tubewells				
Private Tubewells	2.499		2.879	
Public Tubewells	0.97			
Total Inflows (Recharge)	3.187	0.623	2.798	0.678
Total Outflows (Pumpage)	3.469		2.879	
Inflow - Outflow	-0.282	0.623	-0.081	0.678
Groundwater Evaporation	0.159	0.048	0.159	0.048
Net Recharge (MAF)	-0.441	0.575	-0.24	0.63
Net Recharge per Acre of CCA (feet)	-0.299	1.467	-0.163	1.607

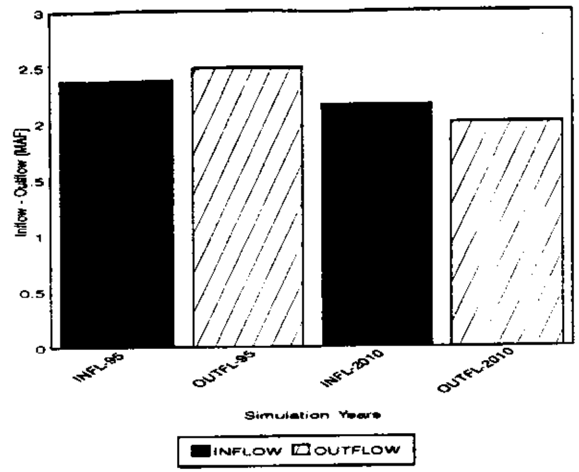
Table 30. Groundwater Balance for the Haveli Canal Command for Scenario K1.

(million acre feet)

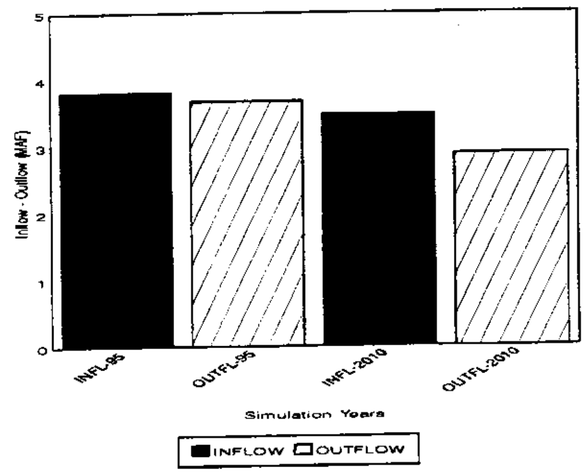
Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall		0.015		0.015
Private Tubewells				
Public Tubewells				
Irrigation Canals		0.176		0.201
Watercourses and Fields		0.059		0.072
Link Canals		0.03		0.016
Rivers		0.004		0.006
Pumpage from Tubewells				
Private Tubewells				
Public Tubewells				
Total Inflows (Recharge)		0.284		0.31
Total Outflows (Pumpage)				
Inflow - Outflow		0.284		0.31
Groundwater Evaporation		0.022		0.022
Net Recharge (MAF)		0.262		0.288
Net Recharge per Acre of CCA (feet)		1.464		1.609



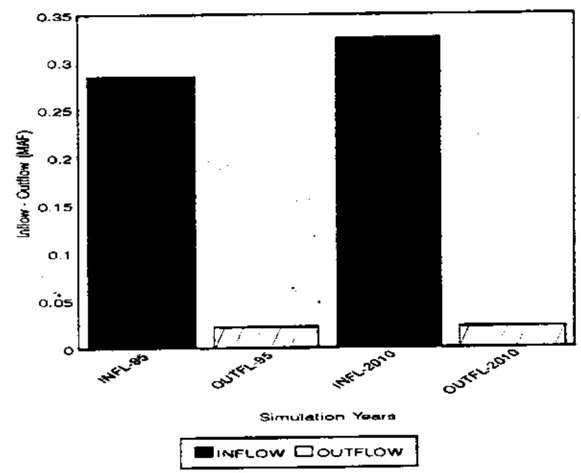
Total Rechna Doab.



Jhang Branch of LCC.



Gugera Branch of LCC.



Haveli Canal.

Figure 41. Comparison of Groundwater Inflows-Outflows under IBMR Simulation K1..

f) Groundwater Development Potential

After having determined the incoming recharge to the aquifer system and outgoing extractions from the aquifer, it is now possible to estimate the remaining groundater development potential in the Rechna Doab by the year 2010 on the basis of Scenario K1. Table 31 indicates that the over-exploitation of groundwater in the Upper Rechna Doab has increased by 7% from 1.444 MAF (1995) to 1.548 MAF (2010) due to a reduction in net recharge by 6.8% caused by improvements in conveyance and application efficiencies (Annexure-B). Similarly, there is a decrease in net recharge in the command area of the LCC System by 8% (from 5.911 MAF to 5.413 MAF) and the net groundwater pumpage by 4% (from 4.004 MAF to 3.830 MAF). This has caused a decrease in the groundwater potential under Jhang Branch command by 19% (from 0.642 MAF in 1995 to 0.518 MAF in 2010) and in the Gugera Branch command by 15% (from 1.265 MAF in 1995 to 1.065 MAF in 2010).

The area under the Haveli Canal is saline, and there is no groundwater outflow through irrigation related pumpage. Hence, the recharge has increased by 10% from 0.262 MAF (1995) to 0.288 MAF (2010).

g) Summary

The maximum growth in the cropped area is being achieved under Scenario K1 (Table 22). The increase in area for wheat and the basmati rice crop is low in the Gugera Branch command, but exceeds the IRRI cultivation in the Jhang Branch command. The resultant increase in crop production is more than 50% by the year 2010. Although the yield growth rates are lower than the ones for production throughout the Rechna Doab, amongst the canal commands they are substantially higher for the Haveli due to increased canal diversions effected by the proportional allocations within the IBMR. These allocations are higher in the rabi (41%) than kharif (13%). As a result, the annual water shortages have reduced by nearly 40% across all canal commands of the Rechna Doab. Specifically, for the Jhang Branch, the irrigation surplus has increased by 0.266 MAF; its decrease in shortages within the saline groundwater areas has been more than the corresponding decrease in the Gugera command (Table 25).

The surplus of irrigation supplies in the Jhang Branch, coupled with the 61% reduction in shortages within the fresh groundwater quality areas of the Gugera Branch, have meant that the pumpage from the private tubewells has been the key to increasing total water supplies by 12% (the requirement being 14.39 MAF vs a supply of 13.686 MAF).

Due to improvements in system efficiencies and a reduction of system losses, there has been a decrease in inflows by 9.5% between 1995-2010. This has been accompanied by a 10.7% decrease in outflows for the same period. The decrease in outflows is even higher within

Table 31. Groundwater Development Potential by Year 2010 within the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Canal Command	Useable Net Recharge		Net Pumpage		Remaining Development Potential (Actual)		Groundwater Development Potential (Adjusted)	
	1995	2010	1995	2010	1995	2010	1995	2010
Raya Canal	0.849	0.791	1.232	1.202	-0.383	-0.411		
Marala Ravi	0.317	0.295	0.459	0.448	-0.142	-0.153		
Upper Chenab	2.037	1.898	2.956	2.882	-0.919	-0.984		
Jhang Branch	2.281	2.089	1.639	1.571	0.642	0.518	0.642	0.518
Gugera Branch	3.63	3.324	2.365	2.259	1.265	1.065	1.265	1.065
Haveli Canal	0.262	0.288			0.262	0.288	0.262	0.288
Total Rechna Doab	9.376	8.685	8.651	8.362	0.725	0.323	2.169	1.871

the Jhang Branch; seen in the context of the propotionately higher saline groundwater areas in the Gugera and Haveli canal commands, the overall situation for increasing watertables seems unavoidable. The reduction in system losses actually works to the disadvantage of the regime in the Upper Rechna where a 6.8% decrease in net recharge to the aquifer has occurred. Coupled with the water shortages in this area, the IBMR simulation shows an increase in over-exploitation by as much as 7%. Elsewhere, the decreasing recharge across the LCC command has reduced the groundwater potential between 15-19 percent.

II. ADJUSTMENTS TO THE SELECTED SIMULATIONS

In Volume Seven, the discourse in Section III.A describes aspects of the area intensive strategy for production enhancement of major crops that could be effected through selective assimilation of the fallow lands into cultivation across the irrigation subdivisions of the LCC system. These marginal improvements to major crop intensities (at the irrigation subdivision level) do not interfere with the existing farming preferences for the minor crops or the reliance on the culturable waste, which in itself is the most significant limitation to higher land use after irrigation supplies. The primer for these marginal improvements comes from IIMI's own samples of farm level cultivation intensities prevailing across the subdivisions of the LCC and the Haveli system (Table 4, Volume Seven). For this data, of particular significance is the wide variation in the intensities of the culturable waste and fallowing during the kharif season. The available margin in fallowing is relatively less during the rabi season due to the higher intensities of the wheat crop.

When compared in the context of the seasonal fallowing, there is much scope for expansion of the cultivated area devoted to the major crops. Figure H3, Volume Four, has already shown that much of the fallowing is necessitated by the scarcity of surface water supplies. Hence, assuming the surface supplies are better managed (as already simulated for Scenarios J and K1 above), there is room for expansion of the existing cropping intensities of these major crops.

For the area intensive strategy adopted in Volume Seven, Tables 5(a)-(d) therein list the marginal improvements to the existing cropping intensities for each of the four major crops of wheat, cotton, rice and sugarcane out of the existing share of the fallow lands in their respective growing seasons. For the wheat crop, as much as 50% of the fallow land intensity has been consumed towards bolstering the cropping intensity. Since wheat is universally grown across the Rechna Doab, this implied increase was consistent across all the irrigation subdivisions (Haveli and Sagar subdivisions were omitted because figures on their commanded area were not available). A similar increase in the intensity of the cotton crop has also been implied; however, subdivisons like Aminpur, Kot Khuda Yar, Sangla, Chuharkana, Kanya, Mohlan, Pacca Dala, Uqbana and Wer have been omitted due to either already low values of areas under its cultivation or inadequate sample data on farmers

reporting its cultivation during the IIMI questionnaire-based field surveys. For the higher consumptive use crops like rice and sugarcane, the increase in their respective cropping intensities (out of the kharif and rabi fallow, respectively) is 10% and 25%. Again, subdivisional level exclusions have been made where necessary (Tables 5(c) and 5(d)).

For the proposed production levels above (originally derived at the subdivision level), the quantum increases in the cultivated areas and production at the irrigation Circle level are summarised in Table 15 of Volume Seven. Larger cultivation extents have been devoted to the wheat, cotton and sugarcane crops in the LCC (East) Circle vs rice in the LCC (West). The lesser areal increase for rice in the LCC (East) is primarily due to the already high cropping intensities prevailing in this area. The values of the cumulative area and production for the area intensive strategy appear under Tables 16 of Volume Seven. The cumulative area under rice in the LCC (West) Circle remains low due to an absence of corresponding figures for the Aminpur and Wer subdivisions.

For the area intensive strategy to be implementable at the sector or canal command level, the increase in respective cropped areas (realized from existing fallow practices) needs to be compared in the context of the available water supplies simulated by the IBMR. Since the preceding discussion in Section I has already narrowed the choices from amongst the thirteen simulation scenarios originally applied for surface and groundwater balance, the modifications are easy to implement for the area intensive strategy. Based on the proposed cumulative area for the major crops across both the LCC East and West Circles (Table 16, Volume Seven), the IBMR simulations J and K1 have been modified to reflect the rate of areal increase to the years 2000 and 2010, respectively. The comparative figures for these adjustments are given in Table 32 for Scenario J and K1.

III. RESULTS AND DISCUSSION

The increase in the area of the major crops has been the core strategic choice towards sustainable gains from irrigated agriculture within the Rechna Doab. While the benefits of this *extensive* strategy have already been compared in macro economic terms against marginal improvements in yield, the viability of its higher gross incomes would not be substantiated unless matched by a relaxation of the most critical constraint, i.e. irrigation supplies. The areal increase has not been haphazard; rather, it derives from the original calculations at the irrigation subdivision level where a fraction of the land currently being left fallow had been assigned to a potential increase in the intensity of the major crops. These 'recoveries' of the productive lands were subsequently aggregated across the two principal canals of the LCC system for sector level decision-making made possible by the IBMR.

Since specification of proposed or targeted growth rates in an irrigated area is not the sole input requirement for IBMR simulations, a sensitivity analysis was a must to establish the

Table 32. Simulated Areas for Major Crops after Adjustments as per Area Intensive Strategy for Years 2000 & 2010, Rechna Doab, Punjab, Pakistan.

(000 acres)

Crop	Simulation J			
	Gugera Canal (LCC(East))		Jhang Canal (LCC(West)	
	IBMR	IIMI	IBMR	IIMI
Wheat	1122.53	1142.17	712.32	715.73
Cotton	110.13	215.67	63.54	124.35
Basmati	441.17	206.55	310.47	136.93
IRRI	33.19	12.64	24.02	8.85
Sugarcane	247.85	382.55	146.62	225.09
	Simulation K1			
Wheat	1180	1123.09	749	711.98
Cotton	116	222.82	67	128.45
Basmati	464	203.93	326	135.92
IRRI	35	13.19	25	9.21
Sugarcane	261	373.33	154	219.49

Table 33. Production for the IBMR Simulation J (Adjusted) as per Area Intensive Strategy.

(000 metric ton)

Crop	Gugera (LCC(East))	Jhang (LCC(West))
Wheat	1140	720
Cotton	90	50
Basmati	250	170
IRRI	20	20
Sugarcane	6610	3900

larger domain of reference in terms of the surface and groundwater balance at the root zone and the recharge conditions for the aquifer. The discussion in Section I above has established that within the larger framework the most suitable and realistic targets in available irrigation supplies have been selected through IBMR simulations J and K1. Henceforth, it is the areal adjustments to these two simulations that would yield the overall situation with respect to:

- crop production;
- net crop water requirements and supplies at the root zone; and
- groundwater balance in both the fresh and saline areas.

A. Scenario J (Adjusted)

Crop Production: Table 33 provides the results of the *simulated* crop production for the major crops leading to the year 2000, as per areal growth rates specified in the extensive agriculture strategy. Herein, comparisons may be made against the cumulative production obtained in Table 16(b) of Volume Seven on the basis of proposed cropped area increases aggregated from the subdivision level to the Circle level. In Table 16(b), the production has been calculated as per proposed cropped area for each major crop at the subdivision level times the average value of the yield within the subdivision. The magnitude of the crop-specific production, at the canal command level, then, best represents the situation as per year 1995 if the area-intensive option was to be applied.

For the wheat crop, the IBMR provides slightly higher values of production in both of the canal Circles in the LCC system. The converse holds true for the production of the cotton crop that is slightly underestimated by the Model. This is largely because of the blight in recent years due to the virus attack (the specified yield increase, as an externality, is endogenously distributed amongst the crops by the Model). The Model's rice crop production estimate is 270,000 metric tons in the principal growing area of the Gugera command, which is significantly higher than the determination of 230,000 metric tons through the area intensive strategy. The difference is even large for the Jhang Branch command. For the sugarcane, the Model severely underestimates the production in the LCC (West) (Jhang Branch command). The explanation for this significant difference may be derived from Table 32, where the simulated area for sugarcane is much less than the growth rate specified for the LCC (West) under the area extensive strategy. When comparing the results of average yields under area adjustment strategy in Table 33(a) with the simulated yields in Table 13 under scenario J (3% growth rate for year 2000), there is no significant difference in the yields of major crops except sugarcane, which is a little higher under the area adjustment option for all canal commands of Rechna Doab.

Table 33(a). Crop Production and Average Yield under Crop Area Adjustment Strategy for the Year 2000 & 2010.

Crop	Rechna Doab			Gugera Canal			Jhang Canal			Haveli Canal		
	1995	2000	2010	1995	2000	2010	1995	2000	2010	1995	2000	2010
Production (million Tons)												
Wheat	3.01	3.32	4.69	1.11	1.26	1.71	0.70	0.79	1.09	0.10	0.12	0.15
Cotton	0.08	0.17	0.24	0.04	0.10	0.14	0.03	0.06	0.08	0.01	0.01	0.02
Rice	2.20	0.99	1.35	0.56	0.30	0.41	0.40	0.20	0.27	0.03	0.02	0.03
Sugarcane	8.58	14.20	19.33	4.33	7.29	9.86	2.56	4.29	5.82	0.51	0.88	1.18
Average Yield (Tons/Acre)												
Wheat	1.1	1.12	1.54	1	1.1	1.53	1	1.11	1.53	0.93	1.08	1.51
Cotton	0.4	0.46	0.62	0.39	0.46	0.62	0.4	0.46	0.62	0.36	0.46	0.62
Rice	2.21	1.39	1.88	1.21	1.38	1.87	1.21	1.38	1.87	1.25	1.35	1.85
Sugarcane	17.63	19.21	26.63	17.63	19.02	26.51	17.63	19.08	26.57	15.9	19.02	26.24
Percentage Increase in Production												
Wheat		10	56		14	53		13	55		18	54
Cotton		128	264		130	218		128	216		160	260
Rice												
Sugarcane		65	125		68	128		68	127		170	130

Water Balance at the Root Zone: A comparison of Table 15 with Table 34 shows that for the entire Rechna Doab, the shortages are lower in the saline zones for the year 2000 under the non-adjusted strategy (assuming 0.5% growth rate in area). The overall supplies are also higher due to the higher net requirements by the year 2000 (10.8 MAF for the adjusted vs 13.43 MAF non-adjusted situations). This situation is common to all the canal commands, except Haveli Canal where the net requirements are higher for the adjusted option due to higher supplies (0.433 MAF in the adjusted option vs 0.391 MAF in the non-adjusted option). The surface supplies have not increased in the Upper Rechna and the tubewell pumpage in this fresh groundwater quality area has also reduced substantially (3.982 MAF to 1.767 MAF). In the context of the net irrigation requirements for this area, however, the shortages have slightly reduced (from 0.47 MAF to 0.445 MAF).

Groundwater Balance: Tables 35-38 give the summary of the groundwater balance across the Rechna Doab, as well as the Jhang, Gugera and Haveli Canal commands. The results show that recharge in the fresh groundwater areas of the doab has decreased by 22% from 8.37 MAF to 6.55 MAF. The total pumpage has also decreased by 51% (11.96 MAF to 5.8 MAF), thereby indicating a trend of rising water tables. Quite the opposite situation for the net annual recharge prevails in the saline areas where it has increased by 11%. The recharge and pumpage situation in the fresh areas is consistent across the canal commands; for the Jhang Branch, both decrease by 18% and 43%, respectively. This is about the same as for the Gugera Branch command. However, the pumpage in year 2000 remains higher in the Gugera command (2.05 MAF to Jhang's 1.34 MAF). The percentage difference in the increase in recharge within Gugera's saline zone is equal to that for the Jhang (and also that of the Haveli Canal); however, its volume of 0.636 MAF by year 2000 is much greater than the 0.36 for the Jhang canal command.

B. Scenario K1 (Adjusted)

Crop Production: The production figures estimated for the major crops within the area adjusted simulation, K1 appears in Table 39. A comparison with the results in Table 16(b), Volume Seven shows that the IBMR estimations are higher than the derived figures for the extensive option in all cases, except sugarcane, for which its cumulative production in the LCC (West) (Jhang Canal command) is 18% less by the year 2010. These simulated higher values under the extensive option are because of the assumed 3% growth rate in crop yield upto year 2010 taking the base year of 1994-95. While comparing the figures of average crop yield in Table 33(a) with the simulated crop yield (without adjustments) for the year 2010 (Table 23), it is evident that the average yield of the major crops under the area adjustment strategy are very close under both administrative circles of the LCC system. Therefore, the crop yield under any option can be projected for the year 2010.

Table 34. Annual Net Crop Water Requirements and Supplies at the Root Zone after Crop Area Adjustments to Simulations J & K1 within the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Description	Fresh		Saline		Total	
	2000	2010	2000	2010	2000	2010
Rechna Doab						
Net Requirements	8.80	9.261	1.916	1.904	10.796	11.165
Water Supplies						
Canal	4.478	4.160	1.218	1.284	5.696	5.894
Tubewell Pumpage	4.225	4.450			4.225	4.450
Total Supplies	8.703	9.060	1.218	1.284	9.921	10.344
Shortage	0.177	0.201	0.698	0.620	0.875	0.821
Surplus						
Total Water Stress			0.154	0.112	0.154	0.112
Upper Rechna Canal Commands						
Net Requirements	3.323	3.585			3.323	3.585
Water Supplies						
Canal	1.111	1.125			1.111	1.125
Tubewell Pumpage	1.767	1.963			1.767	1.963
Total Supplies	2.878	3.088			2.878	3.088
Shortage	0.445	0.497			0.445	0.497
Surplus						
Total Water Stress						
Jhang Canal Command						
Net Requirements	2.160	2.213	0.563	0.533	2.696	2.746
Water Supplies						
Canal	1.559	1.614	0.366	0.378	1.925	1.992
Tubewell Pumpage	0.966	0.984			0.966	0.984
Total Supplies	2.525	2.598	0.366	0.378	2.891	2.976
Shortage			0.170	0.155	0.170	0.155
Surplus	0.365	0.385			0.365	0.385
Total Water Stress			0.043	0.031	0.043	0.031
Gugera Canal Command						
Net Requirements	3.398	3.464	0.947	0.941	4.345	4.405
Water Supplies						
Canal	1.808	1.871	0.481	0.497	2.289	2.368
Tubewell Pumpage	1.492	1.503			1.492	1.503
Total Supplies	3.30	3.374	0.481	0.497	3.781	3.871
Shortage	0.098	0.090	0.466	0.444	0.564	0.534
Surplus						
Total Water Stress			0.076	0.055	0.076	0.055
Haveli Canal Command						
Net Requirements			0.433	0.430	0.433	0.430
Water Supplies						
Canal			0.372	0.408	0.372	0.408
Tubewell Pumpage						
Total Supplies			0.372	0.408	0.372	0.408
Shortage			0.061	0.022	0.061	0.022
Surplus						
Total Water Stress			0.035	0.025	0.035	0.025

Water Balance at the Root Zone: A comparison of Table 25 with Table 34 shows that the net irrigation requirements to year 2010 at the doab level are less for the adjusted option in the fresh groundwater command areas (9.261 MAF vs 12.57 MAF); however, they are higher in the saline areas (1.904 MAF vs 1.818 MAF). Overall, the net irrigation requirements across the entire doab, and for all canals in the LCC system, are higher for the non-adjusted option; the exception being the Haveli Canal command where the requirements have increased (0.430 MAF vs 0.411 MAF) due to an increase in the surface supplies. The tubewell pumpage in the fresh groundwater regime of Upper Rechna has decreased substantially (4.22 MAF to 1.963 MAF); however, the shortages remain the same due to lower net irrigation requirements in the adjusted option.

Groundwater Balance: Tables 40-43 show the results of the simulation for the groundwater balance leading to the year 2010. Based on the trends previously shown for the simulation J (adjusted), the situation for the results in K1 (adjusted) is not too different. The total recharge across the fresh groundwater quality areas has decreased by 22%, which is slightly less than the percentage decrease in the simulation for the year 2000. This is accompanied by a pumpage decrease of 49% (11.96 to 6.08 MAF), but the volume of pumpage remains higher as compared to simulation J (the same holds true at the LCC command level). The recharge to the saline areas (Table 35) within either of the major canal commands of the LCC and the Haveli Canal system is slightly less as compared with the corresponding figures for the year 2000.

Table 35. Groundwater Balance for Rechna Doab by Areas of Groundwater Quality as per IBMR Simulation J Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2000	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.388	0.067	0.387	0.067
Private Tubewells	2.072		1.231	
Public Tubewells	1.243			
Irrigation Canals	2.524	0.781	2.680	0.863
Watercourses and Fields	1.437	0.263	1.684	0.305
Link Canals	0.93	0.132	0.895	0.155
Rivers	-0.221	0.019	-0.515	-0.005
Pumpage from Tubewells				
Private Tubewells	9.509		5.722	
Public Tubewells	2.458			
Total Inflows (Recharge)	8.373	1.262	6.40	1.385
Total Outflows (Pumpage)	11.967		5.80	
Inflow - Outflow	-3.594	1.262	0.601	1.385
Groundwater Evaporation	0.382	0.098	0.382	0.097
Net Recharge (MAF)	-3.976	1.164	0.218	1.287

Table 36. Groundwater Balance for Jhang Branch by Areas of Groundwater Quality as per IBMR Simulation J Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2000	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.087	0.019	0.087	0.018
Private Tubewells	0.383		0.283	
Public Tubewells	0.342			
Irrigation Canals	0.714	0.219	0.772	0.241
Watercourses and Fields	0.33	0.074	0.385	0.085
Link Canals	0.197	0.037	0.202	0.043
Rivers	-0.025	0.005	-0.08	-0.001
Pumpage from Tubewells				
Private Tubewells	1.752		1.31	
Public Tubewells	0.612			
Total Inflows (Recharge)	2.028	0.354	1.659	0.387
Total Outflows (Pumpage)	2.364		1.329	
Inflow - Outflow	-0.336	0.354	0.330	0.387
Groundwater Evaporation	0.099	0.027	0.099	0.027
Net Recharge (MAF)	-0.435	0.327	0.230	0.360

Table 37. Groundwater Balance for the Gugera Branch by Areas of Groundwater Quality as per IBMR Simulation J Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2000	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.134	0.033	0.134	0.033
Private Tubewells	0.548		0.439	
Public Tubewells	0.556			
Irrigation Canals	1.169	0.386	1.270	0.426
Watercourses and Fields	0.51	0.13	0.594	0.150
Link Canals	0.297	0.065	0.310	0.076
Rivers	-0.027	0.009	-0.106	-0.002
Pumpage from Tubewells				
Private Tubewells	2.499		2.024	
Public Tubewells	0.97			
Total Inflows (Recharge)	3.187	0.623	2.658	0.685
Total Outflows (Pumpage)	3.469		2.054	
Inflow - Outflow	-0.282	0.623	0.603	0.685
Groundwater Evaporation	0.159	0.048	0.159	0.048
Net Recharge (MAF)	-0.441	0.575	0.444	0.636

Table 38. Groundwater Balance for the Haveli Canal Command by Areas of Groundwater Quality as per IBMR Simulation J Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2000	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall		0.015		0.015
Private Tubewells				
Public Tubewells				
Irrigation Canals		0.176		0.194
Watercourses and Fields		0.059		0.068
Link Canals		0.03		0.035
Rivers		0.004		-0.001
Pumpage from Tubewells				
Private Tubewells				
Public Tubewells				
Total Inflows (Recharge)		0.284		0.313
Total Outflows (Pumpage)				
Inflow - Outflow		0.284		0.313
Groundwater Evaporation		0.022		0.022
Net Recharge (MAF)		0.262		0.290

Table 39. Production for the IBMR Simulation K1 (Adjusted) as per Area Intensive Strategy.

(000 metric ton)

Crop	Jhang	Gugera
Basmati	220	330
IRRI	20	30
Cotton	70	120
Sugarcane	5,280	8,950
Wheat	990	1,550

Table 40. Groundwater Balance for Rechna Doab by Areas of Groundwater Quality as per IBMR Simulation K1 Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.388	0.067	0.387	0.067
Private Tubewells	2.072		1.308	
Public Tubewells	1.243			
Irrigation Canals	2.524	0.781	2.762	0.890
Watercourses and Fields	1.437	0.263	1.732	0.317
Link Canals	0.93	0.132	0.794	0.091
Rivers	-0.221	0.019	-0.432	-0.013
Pumpage from Tubewells				
Private Tubewells	9.509		6.085	
Public Tubewells	2.458			
Total Inflows (Recharge)	8.373	1.262	6.552	1.353
Total Outflows (Pumpage)	11.967		6.085	
Inflow - Outflow	-3.594	1.262	0.467	1.353
Groundwater Evaporation	0.382	0.098	0.382	0.097
Net Recharge (MAF)	-3.976	1.164	0.084	1.255

Table 41. Groundwater Balance for Jhang Branch by Areas of Groundwater Quality as per IBMR Simulation K1 Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.087	0.019	0.087	0.018
Private Tubewells	0.383		0.291	
Public Tubewells	0.342			
Irrigation Canals	0.714	0.219	0.796	0.249
Watercourses and Fields	0.33	0.074	0.397	0.088
Link Canals	0.197	0.037	0.159	0.025
Rivers	-0.025	0.005	-0.071	-0.003
Pumpage from Tubewells				
Private Tubewells	1.752		1.348	
Public Tubewells	0.612			
Total Inflows (Recharge)	2.028	0.354	1.660	0.378
Total Outflows (Pumpage)	2.364		1.348	
Inflow - Outflow	-0.336	0.354	0.312	0.378
Groundwater Evaporation	0.099	0.027	0.099	0.027
Net Recharge (MAF)	-0.435	0.327	0.212	0.351

Table 42. Groundwater Balance for the Gugera Branch by Areas of Groundwater Quality as per IBMR Simulation K1 Modified for Area Intensive Strategy.

(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall	0.134	0.033	0.134	0.033
Private Tubewells	0.548		0.446	
Public Tubewells	0.556			
Irrigation Canals	1.169	0.386	1.309	0.440
Watercourses and Fields	0.51	0.13	0.614	0.157
Link Canals	0.297	0.065	0.235	0.045
Rivers	-0.027	0.009	-0.096	-0.006
Pumpage from Tubewells				
Private Tubewells	2.499		2.061	
Public Tubewells	0.97			
Total Inflows (Recharge)	3.187	0.623	2.643	0.668
Total Outflows (Pumpage)	3.469		2.061	
Inflow - Outflow	-0.282	0.623	0.582	0.668
Groundwater Evaporation	0.159	0.048	0.159	0.048
Net Recharge (MAF)	-0.441	0.575	0.422	0.620

Table 43. Groundwater Balance for the Haveli Canal Command within the Rechna Doab, Punjab, Pakistan.

(million acre feet)

Inflows and Outflows	1995		2010	
	Fresh	Saline	Fresh	Saline
Seepage to Groundwater				
Rainfall		0.015		0.015
Private Tubewells				
Public Tubewells				
Irrigation Canals		0.176		0.201
Watercourses and Fields		0.059		0.071
Link Canals		0.03		0.020
Rivers		0.004		-0.003
Pumpage from Tubewells				
Private Tubewells				
Public Tubewells				
Total Inflows (Recharge)		0.284		0.305
Total Outflows (Pumpage)				
Inflow - Outflow		0.284		0.305
Groundwater Evaporation		0.022		0.022
Net Recharge (MAF)		0.262		0.283

IV. CONCLUSIONS

On the basis of the results under irrigation system performance during the 1991-95 period and simulated results according to a set of defined scenarios for the years 2000 and 2010, it is concluded that;

1. Water shortages in the canal commands of upper Rechna Doab, are increasing under all scenarios in spite of increasing the canal supply by 24% by year 2010. These shortages are occurring because of non-perennial canal supplies. The increasing crop water requirements are met from pumpage of private tubewells, especially during the rabi season, which is resulting in over-exploitation of the groundwater aquifer and reducing the groundwater potential. This continuous over-exploitation may result in mining of the aquifer.

2. Under the LCC system, the Jhang Branch (LCC West) and the Gugera Branch (LCC East) are behaving in different ways.

   a) There is surplus water in the fresh areas of Jhang Branch, mostly during the kharif season, along with shortages in the saline areas during the rabi season, resulting in net annual surplus water during the kharif season.

   b) Gugera Branch Canal (LCC West) is showing shortages during both seasons, especially during rabi, and this shortage is occurring more in saline areas (70%) because most of the saline areas under the LCC are located in the Gugera Canal command.

   c) The net surplus from the Jhang Branch can be re-allocated to the saline areas of the Gugera command only during the late months of kharif season to overcome the shortages to some extent. But to overcome the shortages during the rabi season for both canal systems under LCC, there is a need for allocating additional water to the system, which can only be met from the addition of new water storage facilities in the Indus Basin.

   d) Using the concept of deficit irrigation, which is aimed at optimizing crop production under conditions of water deficit, the crops are to be stressed to varying degrees during the crop growing season. The stress is occurring in saline areas only, which has been reduced 44% by increasing the canal supplies upto 24%. The use of computers software is required as a practical tool for applying the principle of deficit irrigation.

e) As a consequence of proposed capital investment and management scenarios, the groundwater inflow-outflow balance has resulted in increased groundwater potential of the aquifer system that can be used to alleviate the water shortages in fresh groundwater areas of the LCC system in conjunction with canal water.

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

3. The Haveli Canal command, which is mostly underlain by saline groundwater, so the only source of irrigation is canal water and some rainfall. The water shortages have been eliminated upto 95% by allocating a maximum of canal supplies under the proportional allocation scenarios, but these increaed supplies have resulted in greater net groundwater inflows (recharge) to the aquifer, which will cause the watertable to rise. Different watertable control measures are required by providing adequate drainage facilities, including surface and subsurface drainage in the command area and interceptor drains along the major canal, as well as canal lining in highly salinized areas. Also, skimming well technology could be employed to skim the upper layer of fresh water recharge from the irrigation system, just to supplement the crop water supplies, as well as lower the watertable below the root zone.

4. The present emphasis on cultivation of four major crops -- wheat, rice, cotton and sugarcane -- results in, among other disadvantages, bunching up of the water requirements at peak demand periods which may exceed water availability or canal capacity. The benefits of using a larger crop mix and introduction of early and late varieties of the major crops can reduce peak period shortages and help to increase crop yields with available water supplies.

5. The warabandi system provides watercourse supplies by fixed turns for a fixed duration to every farmer. The critical needs of water may however be staggered in keeping with the crop varieties and dates of planting. The farmers often arrange mutual swapping of turns to meet what they perceive as the crop water demand. This practice can provide a much larger degree of flexibility in meeting the needs of demand sensitive irrigation scheduling if promoted on a scientific footing through demonstrations and farmer training.

6. Even if it becomes feasible to adopt a demand sensitive approach to operating the canal systems, much of the benefits of the change would be lost unless the supplies are equitably shared by all users. The farmers in the head reaches of the canal often draw more than twice their allocated share, leading to corresponding shortages in the share to the farmers in the tail reaches. Paradoxically, such inequity may lead to suppression of crop yields on almost the entire canal command. Crops yields in areas served by the tail reach of the canals suffer due to moisture stress, particularly during the peak demand periods when the canal supplies may be generally short of the requirement. Crops in the head reach may face yield reductions, on the other hand, due to leaching of nutrients caused by over-irrigation, particularly during low demand periods when any canal surplus must be also inequitably shared and absorbed on the farm lands due to a lack of adequate escape facilities.

7. To reduce the transient losses of privte tubewell water, the use of buried PVC or other portable pipe may be introduced to demonstrate the benefits of minimizing transit losses of the relatively small tubewell discharges. Similarly, incentives may be provided for field levelling to minimise the water losses at the farm level.

ANNEXURES

Annexure-A

MAIN FEATURES OF IBMR FOR RECHNA DOAB

IBMR Agroclimatic Zones: Punjab Sugarcane Wheat (PSW)
Punjab Rice Wheat (PRW)

Political Districts: Faisalabad, Jhang, T.T.Singh, Sheikhupura, Gujranwala, Hafizabad, Narrowal and Sialkot

Canal Command Characteristics:

Canal Command	CCA (MA)	Authorised Full Supply at Canal Head (Cusecs)	Authorised Full Supply at Canal Head (MAF/Month)	Designed Capacity at Canal Head (Cusecs) Irrigation	Designed Capacity at Canal Head (Cusecs) Transfer
Raya Branch(BRBD)	0.424	1725	0.104	1671	5140
Marala Ravi(Int.)	0.158	2000	0.120	871	22000
U.C.C.(Int.)	1.017	1100	0.066	3404	16500
Jhang Branch(LCC)	1.168)			4097	
Gugera Branch(LCC)	1.866)	12243	0.738	7498	
Haveli Canal(Int.)	0.179	5673	0.342	744	5250

Canal Command	Canal Efficiency (%)	Field Efficiency (%)	W.C. Command Eff. (%)
Raya Branch(BRBD)	80	90	45
Marala Ravi(Int.)	80	90	57
U.C.C.(Int.)	76	90	57
Jhang Branch(LCC)	70	90	55
Gugera Branch(LCC)	74	90	55
Haveli Canal(Int.)	77	85	67

Actual Canal Diversions and Apportioned Allocations at canal head (MAF)

	1989-90			1994-95			Apportioned Allocation		
	Rabi	Kharif	Annual	Rabi	Kharif	Annual	Rabi	Kharif	Annual
Raya Branch	0.036	0.394	0.430	0.064	0.361	0.425	0.354	0.559	0.913
M. R.(INT.)	0.049	0.205	0.255	0.008	0.250	0.258	0.098	1.238	1.336
U.C.C.(Int.)	0.563	1.682	2.245	0.282	0.859	1.141	0.930	1.454	2.384
Jhang Branch	1.478	2.034	3.513	1.477	1.913	3.390	1.238	1.946	3.183
Gugera Branch	1.672	2.323	3.995	1.658	2.147	3.805	1.389	2.184	3.573
Haveli (Int.)	0.261	0.354	0.616	0.233	0.348	0.581	0.494	0.902	1.396
Total canals	4.060	6.993	11.053	3.722	5.879	9.601	4.503	8.283	12.786

Actual Cropped Area of major crops in Thousand acres

	Wheat	Basmati	IRRI	Cotton	Sugarcane	Maize	Fruits
1990	2772	1437	137	274	372	235	156
1995	3008	1690	138	190	487	210	164

SUMMARY FO SIMULATED CANAL COMMAND SYSTEM HYDRAULIC CHARACTERISTICS

Water Supply	Raya Canal				MaralaRavi				Upper Chenab			
	1990	1995	2000	2010	1990	1995	2000	2010	1990	1995	2000	2010
Canal Head	0.430	0.425	0.511	0.439	0.255	0.258	0.310	0.360	2.245	1.141	1.370	1.357
WC Head	0.344	0.344	0.449	0.435	0.204	0.206	0.272	0.317	1.706	0.873	1.145	1.134
Root Zone	0.155	0.158	0.222	0.215	0.116	0.120	0.171	0.199	0.972	0.506	0.718	0.711
Cnl. Eff.	0.800	0.809	0.879	0.882	0.800	0.798	0.877	0.881	0.760	0.765	0.836	0.836
Irr. Eff.	0.360	0.372	0.434	0.436	0.455	0.465	0.552	0.553	0.433	0.443	0.524	0.524
WCC. Eff.	0.451	0.459	0.494	0.494	0.569	0.583	0.629	0.628	0.570	0.580	0.627	0.627
Water Supply	Jhang Branch				Gugera Branch				Haveli Canal			
	1990	1995	2000	2010	1990	1995	2000	2010	1990	1995	2000	2010
Canal Head	3.513	3.390	4.068	4.210	3.995	3.805	4.567	4.726	0.615	0.581	0.698	0.764
WC head	2.480	2.417	3.159	3.269	2.992	2.856	3.762	3.894	0.476	0.451	0.593	0.650
Root Zone	1.360	1.363	1.925	1,992	1.650	1.615	2.288	0.368	0.271	0.261	0.372	0.408
Cnl. Eff.	0.706	0.713	0.777	0.776	0.749	0.751	0.824	0.824	0.774	0.776	0.850	0.851
Irr. Eff.	0.387	0.402	0.473	0.437	0.413	0.424	0.501	0.501	0.441	0.449	0.533	0.534
WCC. Eff.	0.548	0.564	0.609	0.609	0.551	0.565	0.608	0.608	0.569	0.579	0.627	0.628
Water Supply	Upper Rachna				Total Rechna Doab							
	1990	1995	2000	2010	1990	1995	2000	2010				
Canal Head	2.930	1.824	2.191	2.210	11.053	9.601	11.522	11.860				
W.C. Head	2.254	1.423	1.866	1.886	8.202	7.149	9.381	9.699				
Root Zone	1.243	0.784	0.958	0.937	4.530	4.023	5.696	5.894				
Cnl. Eff.	0.769	0.780	0.852	0.853	0.742	0.745	0.814	0.818				
Irr. Eff.	0.424	0.430	0.437	0.424	0.410	0.419	0.494	0.497				
WCC. Eff.	0.551	0.551	0.513	0.497	0.552	0.563	0.607	0.608				

Note: The water supplies are in million acre feet (MAF)

Abbreviations:
- Cnl.Eff. Canal Conveyance efficiency
- Irr.Eff. Overall Canal Command Irrigation efficiency
- WCC.Eff. Watercourse Command efficiency

IIMI-PAKISTAN PUBLICATIONS
RESEARCH REPORTS

Report No.	Title	Author	Year
R-1	**Crop-Based Irrigation Operations Study in the North West Frontier Province of Pakistan** Volume I: Synthesis of Findings and Recommendations	Carlos Garces-R D.J. Bandaragoda Pierre Strosser	June 1994
	Volume II: Research Approach and Interpretation	Carlos Garces-R Ms. Zaigham Habib Pierre Strosser Tissa Bandaragoda Rana M. Afaq Saeed ur Rehman Abdul Hakim Khan	June 1994
	Volume III: Data Collection Procedures and Data Sets	Rana M. Afaq Pierre Strosser Saeed ur Rehman Abdul Hakim Khan Carlos Garces-R	June 1994
R-2	Salinity and Sodicity Research in Pakistan - Proceedings of a one-day Workshop	IIMI-Pakistan	Mar 1995
R-3	Farmers' Perceptions on Salinity and Sodicity: A case study into farmers' knowledge of salinity and sodicity, and their strategies and practices to deal with salinity and sodicity in their farming systems	Neeltje Kielen	May 1996
R-4	Modelling the Effects of Irrigation Management on Soil Salinity and Crop Transpiration at the Field Level (M.Sc Thesis - pulished as Research Report)	S.M.P. Smets	June 1996
R-5	Water Distribution at the Secondary Level in the Chishtian Sub-division	M. Amin K. Tareen Khalid Mahmood Anwar Iqbal Mushtaq Khan Marcel Kuper	July 1996
R-6	Farmers Ability to Cope with Salinity and Sodicity: Farmers' perceptions, strategies and practices for dealing with salinity and sodicity in their farming systems	Neeltje Kielen	Aug 1996
R-7	Salinity and Sodicity Effects on Soils and Crops in the Chishtian Sub-Division: Documentation of a Restitution Process	Neeltje Kielen Muhammad Aslam Rafique Khan Marcel Kuper	Sept 1996
R-8	Tertiary Sub-System Management: (Workshop proceedings)	Khalid Riaz Robina Wahaj	Sept 1996
R-9	Mobilizing Social Organization Volunteers: An Initial Methodological Step Towards Establishing Effective Water Users Organization	Mehmoodul Hassan Zafar Iqbal Mirza D.J. Bandaragoda	Oct 1996
R-10	Canal Water Distribution at the Secondary Level in the Punjab, Pakistan (M.Sc Thesis published as Research Report)	Steven Visser	Oct 1996
R-11	Development of Sediment Transport Technology in Pakistan: An Annotated Bibliography	M. Hasnain Khan	Oct 1996

Report No.	Title	Author	Year
R-12	Modeling of Sediment Transport in Irrigation Canals of Pakistan: Examples of Application (M.Sc Thesis published as Research Report)	Gilles Belaud	Oct 1996
R-13	Methodologies for Design, Operation and Maintenance of Irrigation Canals subject to Sediment Problems: Application to Pakistan (M.Sc Thesis published as Research Report)	Alexandre Vabre	Oct 1996
R-14	Government Interventions in Social Organization for Water Resource Management: Experience of a Command Water Management Project in the Punjab, Pakistan	Waheed uz Zaman D.J.Bandaragoda	Oct 1996
R-15	Applying Rapid Appraisal of Agricultural Knowledge Systems (RAAKS) for Building Inter-Agency Collaboration	Derk Kuiper Mushtaq A. Khan Jos van Oostrum M. Rafique Khan Nathalie Roovers Mehmood ul Hassan	Nov 1996
R-16	Hydraulic Characteristics of Chishtian Sub-division, Fordwah Canal Division	Anwar Iqbal	Nov 1996
R-17	Hydraulic Characteristics of Irrigation Channels in the Malik Sub-Division, Sadiqia Division, Fordwah Eastern Sadiqia Irrigation and Drainage Project	Khalid Mahmood	Nov 1996
R-18	**Proceedings of National Conference on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan**	M. Badruddin Gaylord V. Skogerboe M.S. Shafique (Editors for all volumes)	Nov 1996
R-18.1	Volume-I: Inauguration and Deliberations		
R-18.2	Volume-II: Papers on the Theme: Managing Canal Operations		
R-18.3	Volume-III: Papers on the Theme: Water Management Below the Mogha		
R-18.4	Volume-IV: Papers on the Theme: Environmental Management of Irrigated Lands		
R-18.5	Volume-V: Papers on the Theme: Institutional Development		
R-19	Detailed Soil Survey of Eight Sample Watercourse Command Areas in Chishtian and Hasilpur Tehsils	Soil Survey of Pakistan IIMI-Pakistan	Nov 1996
R-20	Unsteady Flow Simulation of the Designed Pehur High-Level Canal and Proposed Remodeling of Machai and Miara Branch Canals, North West Frontier Province, Pakistan	Zaigham Habib Kobkiat Pongput Gaylord V. Skogerboe	Dec 1996
R-21	**Salinity Management Alternatives for the Rechna Doab, Punjab, Pakistan**		
R-21.1	Volume One: Principal Findings and Implications for Sustainable Irrigated Agriculture	Gauhar Rehman Waqar A. Jehangir Abdul Rehman Muhammad Aslam Gaylord V. Skogerboe	May 1997
R-21.2	Volume Two: History of Irrigated Agriculture: A Select Appraisal	Gauhar Rehman Hassan Zia Munawwar Asghar Hussain	Jan 1997

Report No.	Title		Author	Year
R-21.3	Volume Three:	Development of Procedural and Analytical Liniks	Gauhar Rehman Muhammad Aslam Waqar A. Jehangir Abdul Rehman Asghar Hussain Nazim Ali Hassan Zia Munawwar	Jan 1997
R-21.4	Volume Four:	Field Data Collection and Processing	Gauhar Rehman Muhammad Aslam Waqar A. Jehangir Mobin Ud Din Ahmed Hassan Zia Munawwar Asghar Hussain Nazim Ali Faizan Ali Samia Ali	Jan 1997
R-21.5	Volume Five:	Predicting Future Tubewell Salinity Discharges	Muhammad Aslam	Jan 1997
R-21.6	Volume Six:	Resource Use and Productivity Potential in the Irrigated Agriculture	Waqar A. Jehangir Nazim Ali	Feb 1997
R-21.7	Volume Seven:	Initiative for Upscaling: Irrigation Subdivision as the Building Block	Gauhar Rehman Asghar Hussain Hassan Zia Munawwar	Apr 1997
R-21.8	Volume Eight:	Options for Sustainability: Sector-Level Allocations and Investments	Abdul Rehman Gauhar Rehman Hassan Zia Munawar	Apr 1997
R-22	Salinisation, Alkalinisation and Sodification on Irrigated Areas in Pakistan: Characterisation of the geochemical and physical processes and the impact of irrigation water on these processes by the use of a hydro-geochemical model (M.Sc Thesis published as Research Report)		Nicolas Condom	March 1997
R-23	Alternative Scenarios for Improved Operations at the Main Canal Level: A Study of Fordwah Branch, Chishtian Sub-Division Using A Mathematical Flow simulation Model(M.Sc Thesis published as Research Report)		Xavier Litrico	March 1997
R-24	Surface Irrigation Methods and Practices: Field Evaluation of the Irrigation Processes for Selected Basin Irrigation Systems during Rabi 1995-96 Season		Ineke Margot Kalwij	March 1997
R-25	Organizing Water Users for Distributary Management: Preliminary Results from a Pilot Study in the Hakra 4-R Distributary of the Eastern Sadiqia Canal System of Pakistan's Punjab Province		D.J. Bandaragoda Mehmood Ul Hassan Zafar Iqbal Mirza M. Asghar Cheema Waheed uz Zaman	April 1997