Role of Surface and Groundwater in Meeting Crop Water Demand in Intensive Agriculture Systems Using a Nodal Network Approach

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ABSTRACT

Over the years the cropping intensities and cropping patterns have changed for meeting the increased demand of food and fiber in the Indus Basin of Pakistan. Cumulative effect of rainfall, river irrigation and groundwater resulted in the high cropping intensities in the Basin. In the recent dry years rainfall and river supplies have failed to meet irrigation water requirements in some areas where there had been traditionally no surface water shortage for irrigation. Such conditions of drought in water scarce areas have increased pressure on groundwater, which has variable potential across the Indus Basin in terms of quality and quantity. Farmers are forced to increase their groundwater abstractions to fill the gap between crop demand and surface water supply.

The number of private tubewells has increased more than three-fold in the last 15 years. This increasing trend of tubewell installation in the basin, along with the uncontrolled groundwater abstraction has started showing aquifer stress in certain areas. In some parts, especially along the tail of canal systems, water levels are showing a steady rate of decline and hence - the mining of aquifer storage. Tubewell density is higher in areas having fresh groundwater as compared to saline groundwater zones. Even in fresh groundwater areas, uncontrolled groundwater abstraction may lead to the deterioration of groundwater quality. Under such aquifer stress conditions, there is a need to regulate and manage groundwater in agricultural context.

In this paper the contribution of groundwater in the irrigated agriculture of Rechna Doab, Punjab, Pakistan is explored using a nodal network approach and water balance. In the same paper, crop water demands, rainfall, and surface water are calculated to estimate the groundwater abstraction in different sections of canal commands of Rechna Doab to understand its usage patterns from 1997 to 2000. This work is also aimed at evaluating surface water availability and the assessment of spatial distribution of groundwater abstractions by considering the present crop water demand patterns.

INTRODUCTION

Water is the most vital resource for human existence from its drinking water requirements to the production of food and fiber. Since Pakistan lies in a sub-tropical continental lowland semi-arid region where the rainfall is untimely and not enough to support agriculture. To meet ever increasing

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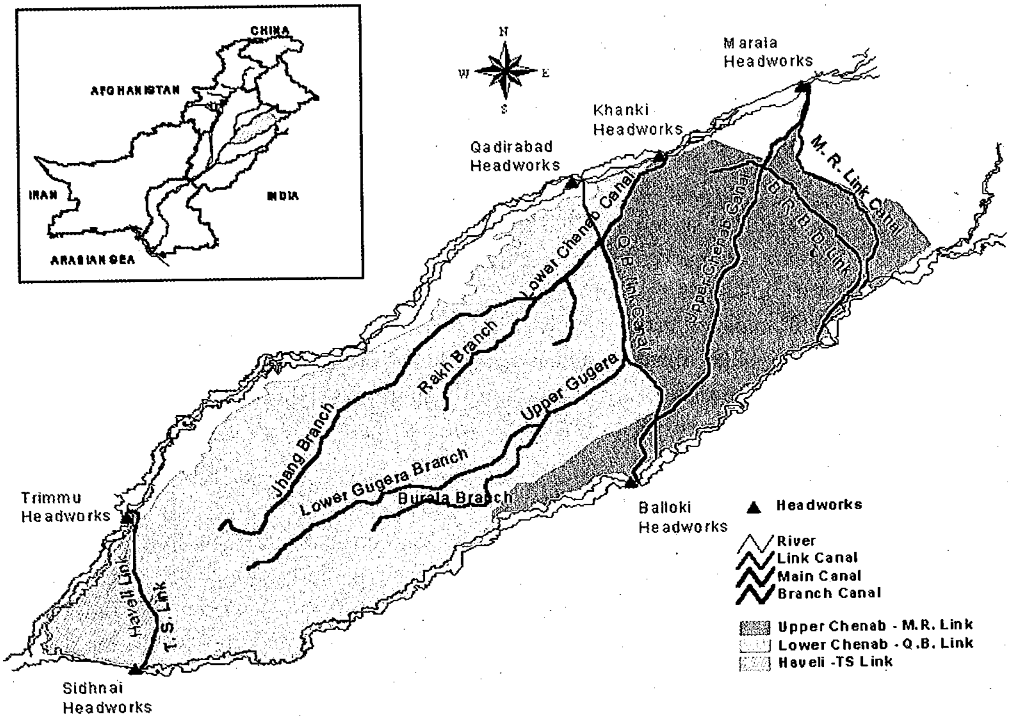
food and fiber requirements of a massive (>130 million) and growing population (growth rate ~ 3%) Pakistan has to rely on irrigation from surface and groundwater. In many parts of Pakistan the irrigation supplies do not meet the crop needs for better yield. The aggregate shortage of surface water is estimated to be about 40 percent of crop potential consumptive use (Ahmad, 1988).

During the recent dry years the surface water supplies have failed to meet irrigation water requirements in areas where there was traditionally no surface water shortage for irrigation. It has resulted in reduction in crop yields and dependence on import of agricultural commodities to feed masses. Since late 1970's the shortfall in surface water supplies has been fulfilled by groundwater, which has variable potential across the Indus Basin in terms of quality and quantity. Presently, farmers are increasing their groundwater abstraction to fill the gap between demands and supply as the surface water supplies are already fully committed and cannot cope with the crop water demand. Tubewell density is higher in areas that have fresh groundwater, and vise versa. Intensive groundwater pumping in certain areas has started showing stress on the aquifer in some parts especially in tail areas, water levels are already showing decline. Uncontrolled groundwater abstraction may lead to the mining of aquifer and/or deterioration of groundwater quality. As the rate of groundwater use is approaching its potential availability, there is need to define role of surface and groundwater in meeting the crop water demand.

The Rechna '*Doab*' (*land between two rivers*) as shown in Figure 1 is selected for present study. It is the interfluvial sedimentary basin of the Chenab and Ravi rivers which lies between longitude 71' 48' to 75' 20' East and latitude 30' 31' to 32' 51' North. The gross area of Rechna Doab is 2.97 million ha, with a longitudinal extent of 403 km and maximum width of 113 km and comprises of 2.3 million hectares of prime cultivated land. The Rechna Doab is a sub-tropical, continental lowland best described as a semi-arid region. The climate is characterized by large seasonal fluctuation of rainfall and temperature. Average annual precipitation varies from 290mm in Shorkot (extreme south) to 1046mm in Sialkot (Extreme North) within the Doab. The highest rainfall occurs during the monsoon circulations in the month of July and August and accounts for about 60 percent of annual rainfall. It is one of the oldest, agriculturally richest and most intensively populated irrigated areas of Punjab, Pakistan. The area falls in the rice-wheat and sugar cane-wheat agro-climatic zones of the Punjab province, with rice, cotton and forage crops dominating in summer season *(Kharif)*, wheat and forage in winter season *(Rabi)*. In some parts sugarcane is also cultivated which is an annual crop.

In this paper spatio-temporal trends of surface water shortage and groundwater demand are estimated from 1997 to 2000 on monthly bases. For analysis purpose supply model of Rechna Doab is developed by dividing the area into a series of nodal networks consisting of channel segments, demand nodes and lumped production areas based on connectivity and on surface water flows. Major research contribution is to evaluate surface water availability and provide an assessment of groundwater abstractions by using Canal Water Availability Ratio (CWAR) concept.

Figure 1: Physical Layout of Canal Network in Rechna Doab



CONCEPTUALIZATION OF NODAL NETWORK APPROACH

In Rechna Doab, the canal irrigation system was introduced in 1892 with the construction of the Lower Chenab Canal (LCC). With the passage of time few other canals were constructed to irrigate the area of Doab. At present the flows of the Chenab and Ravi rivers are regulated at six major headworks (four on the Chenab River and remaining two on the Ravi river). These headworks ensure diversions to the main and link canals. All these head works were constructed in late 19th and early 20th century except Qadirabad headworks, which was constructed after Indus Basin Treaty with India in 1960. Rechna Doab comprises of two main canals and five link canals. The Upper and Lower Chenab Canals are the main canals, off taking at the Marala and Khanki Headworks, respectively. The five link canals are Marala-Ravi (MR), BRBD (Bambanwala-Ravi-Bedian-Depalpur), Qadirabad-Balloki (QB), Trimmu-Sidhnai (TS), and Haveli.

At the time of construction the canal network was designed for supporting low cropping intensities. However, the cropping intensities have been drastically increased (up to 150%), in the last two to three decades, with the rapid development of public and private tubewells. Nevertheless the quality of groundwater is not comparable with canal water. Presently, canal water availability is known and the contribution of groundwater to meet crop water demand is identified by water balance analysis.

For water balance analysis, depending on the direction of flow and connectivity of canals between Chenab and Ravi rivers the system has been divided into three sub-systems or sub nodal networks

(Figure 2). Nodes are the points where flows or command areas are known between different reaches of the channels.

- Upper Chenab and Marala Ravi Link canal (UCC-MR)
- Lower Chenab and QB Link canal (LCC-QB)
- Haveli and Trimu Sidhnai Link canal (H-TS)

Nodal Network Model of Upper Chenab and Marala Ravi Link Canal (UCC-MR)

Nodal network model of Upper Chenab and Marala Ravi Link canal consists of three canal systems as shown in Figure 2a. The first system is MR Link canal, an unlined channel of 101 km length and flows into Ravi upstream of Lahore. The second system is Upper Chenab canal, which was constructed under the triple canals project in Punjab, and by 1915, was completed. Upper Chenab canal also serves as link canal transferring water from Chenab to Ravi and is discharging above Balloki in Ravi River. At 40269 m from its head it is divided in three channels i.e. Nokhar branch, BRBD and Upper Chenab Main Line Lower. The third system is BRBD canal off taking from UCC and its length in Rechna Doab is 86128 m; this portion also irrigates some area in Rechna Doab.

Nodal Network Model of Lower Chenab and QB Link Canal (LCC-QB)

This is the biggest nodal network model in the Rechna Doab consisting of one link canal and one main canal from which number of branches are off taking as shown in Figure 2b. The LCC takes off from the Chenab River at the Khanki Headworks. It covers entire area between QB and TS Link Canals, some area above the QB Link Canal along the Chenab River and area below the TS Link Canal. The Lower Chenab canal at Sagar head regulator is divided into two branches: Main Line Lower and Gogera branch. The Main Line Lower is further divided into three branches Jhang branch, Mian Ali and Rakh branch. Similarly the Gogera Branch is divided into two branches: Burala and Lower Gogera. The QB Link Canal off-takes from the Qadirabad Headworks on the Chenab River. It was constructed and opened in the mid-1960s to transmit water to the Ravi River at Balloki Headworks. After 24 km from its head, LCC feeder takes off to add water into LCC-Jhang Branch.

Nodal Network Model of Haveli and Trimu Sidhnai Link Canal (H-TS)

This nodal network model consists of two canals (Haveli and TS Link) and one feeder (Koranga) canal. Haveli canal was formally opened in 1939 (Figure.2c). This canal off takes from Trimu Headworks on the Chenab River below confluence of the Chenab and Jhelum. The TS Link was the first canal under the Phase-1 of the Indus Basin settlement Plan and was aligned parallel to the Haveli canal. Both the canals were relocated and had a combine regulator. The feeder is off taking from LBDC system and entering in the Rechna Doab through an aqueduct at Sidhnai Barrage.

Figure 2a: Nodal Network Model of UCC-MR

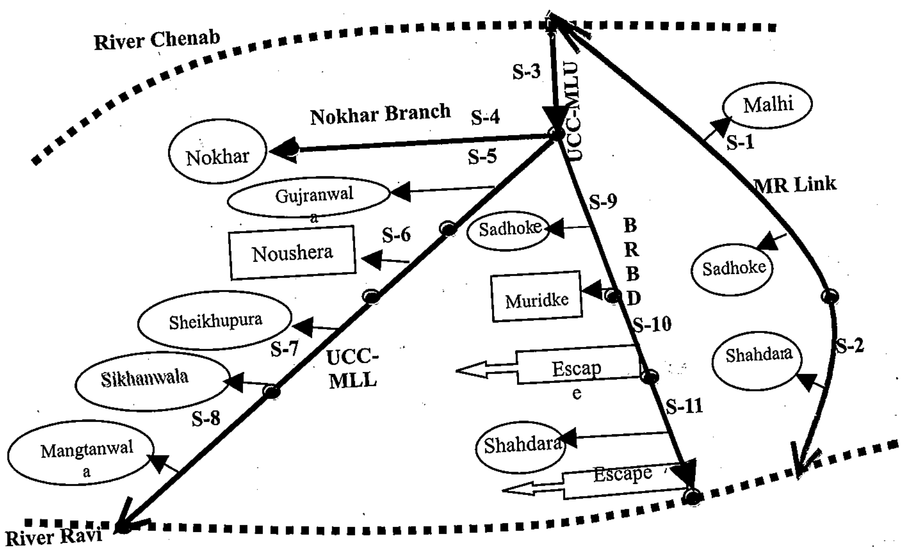


Figure 2b: Nodal Network Model of LCC-QB

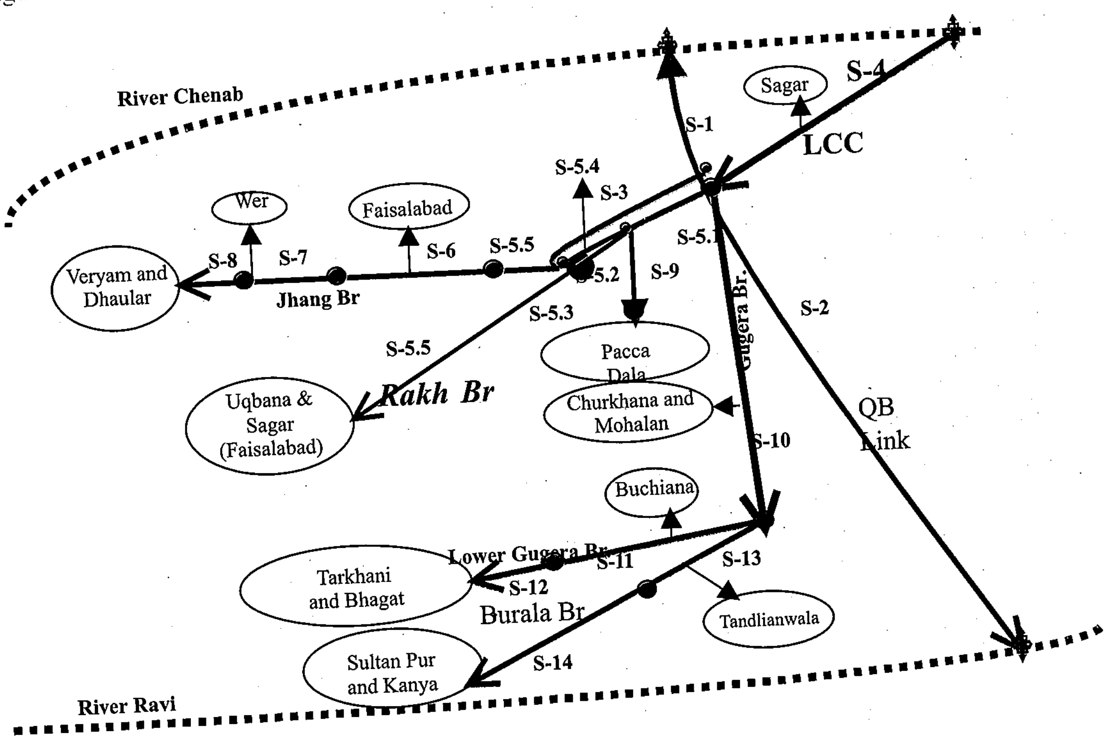
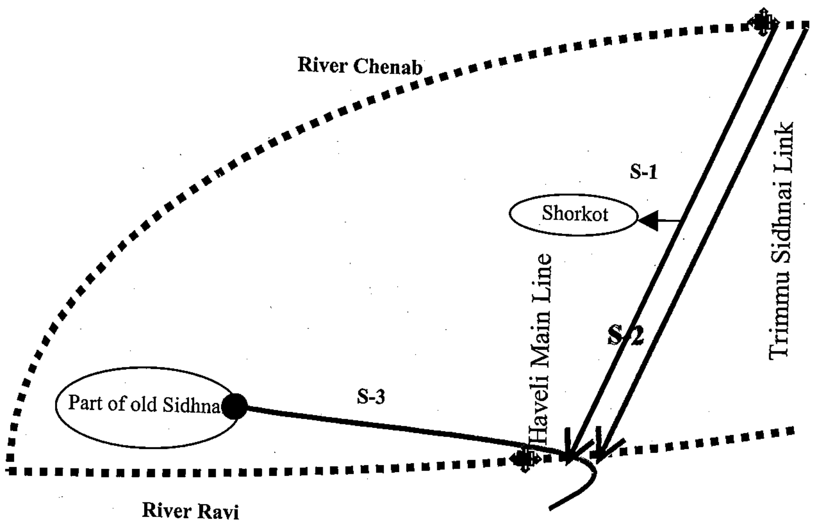


Figure 2c: Nodal Network Model of H-TS



METHODOLOGY FOR COMPUTATION OF WATER BALANCE ALONG THE NODAL NETWORKS

The following methodology was used for developing spreadsheet model of the monthly water balance for each production area of all three individual nodal network models:

- Crop water demand of each production area
- Surface water availability to the crops
- Canal water availability ratio
- Estimation of groundwater demand

Crop water demand of each production area

Many factors influence water demand by plants and it may differ with locality and fluctuate from year to year. Based on these factors the process of crop water requirement is divided into 5 sections: 1) Computation of Reference Evapotranspiration 2) Selection of Crop Coefficients 3) Potential water demand of different crops 4) Net water demand of different crops 5) Estimation of crop water demand of production area.

- Reference evapotranspiration was computed by FAO CROPWAT model based on Penman-Monteith equation. The key climatic parameters used for the estimation of reference evapotranspiration are temperature, humidity, wind speed and sunshine hours. Data on all-climatic parameters were available for climatic stations within the Rechna Doab on long-term basis (20 to 30 years from 1960-1995). The data for different climatic factors was pre-processed to meet the model requirement.
- The Rechna Doab lies in rice wheat and sugarcane wheat agro-climatic zone. These agro-climatic zones exhibit different cropping patterns and crop-periods within the zone. For the selection of Kc value, Rechna Doab is divided into five different zones and for each zone the periods of planting and harvesting, crop duration and crop growth stages for different groups of areas were determined on the basis of primary and secondary information (WAPDA 1979, IIMI 1996, GOP 1997, PARC 1982, PPSGDP 1998, FAO, 1977 and FAO

1998) about cropping practices in the Doab. For most of the crops, the planting and harvesting period is extended over a couple of weeks.

- Potential water demand of different crops was computed by multiplying reference evapotranspiration of that production area with crop co-efficient selected for different crops in respective production area.
- The net water demand for a given crop is the depth of irrigation water, exclusive of effective rainfall from crop water requirement. It is the quantity of irrigation water required to keep the soil moisture at readily available water (RAW) level in the crop root zone. To compute the net water demand of different crops, the effective precipitation was estimated by using relationship developed by U.S. Bureau of Reclamation. The effective precipitation for climatic stations within and close to the Rechna Doab was estimated and delineated for each production area associated with each segment of nodal network model. The net demand of water for different crops was water determined by subtracting effective rainfall from the water demand.
- Water demand of production areas was estimated by multiplying net crop demand of different crops with the area under each of these crops and summed for each production area of nodal network models.

Canal Water Availability for Crops

Canal water available to crops for irrigation of production areas of various segments of nodal network model was estimated by subtracting losses (seepage and evaporation) from available flows. These flows were measured at different locations in the irrigation network. For the estimation of canal water available to crops losses were considered at main canal or branch canal, distributary, watercourse and field level. The description of each type of losses is discussed below:

Main Canal or Branch Canal Losses: For main canal, seepage and evaporation losses are calculated separately by method given below:

- Seepage Losses: Patten et al. 1963 attempted to statistically correlate canal seepage with the canal discharge. Similar to Patten's original relationships the following relationship has been used (PPSGDPC, 1998):

  $S = 0.052Q^{0.658}$

  Where s is seepage loss in cfs/mile and Q is canal discharge in cusecs. For present study, main and branch canal seepage losses are estimated by this method.

- Free Surface Evaporation Losses: For different segments of nodal network models the evaporation value of nearby station is used. These losses were calculated by multiplying free surface evaporation with area of channel.

Distributary losses: Distributary losses were assumed 6 percent by considering the work of Khunger (1946) in Punjab (Ahmad, 88). Percolation and evaporation losses were considered 95 percent and 5 percent respectively.

Watercourse losses: These losses were calculated by using Maasland (1968) approach (Ahmad, 88), which was developed during recent years; he worked out 10% losses employing different assumptions, half of these losses consist of percolation and the rest are evaporation.

Field Losses: For present study Maasland assumption of 20 percent loss of water delivered to the field is used. 25% of which is lost as evaporation and remaining is recharged to groundwater.

Canal Water Availability Ratio (CWAR)

This is simply the ratio of available canal water for crops to meet crop water demand of production area. If this ratio is less than 1 then there will be shortage of canal water supply and groundwater contribution is required to meet crop demand. Otherwise, if it is greater than 1 then surface water supply is more than crop water demand resulted in over irrigation of that production area. To visualize the role of surface water in meeting crop demand, monthly canal water availability ratios (CWAR) are determined for each of the production area using Equation-1.

$$CWAR=(VCH-VL)/ VNCWR \quad (1)$$

Where

$$VL = VMCL - VDL - VWCL - VFL \quad (2)$$

$$VNCWR = \Sigma(ETo \times Kc)\text{-Effective Rainfall} \quad (3)$$

VCH = Volume Water at Head of Canal

VL = Volume all Water Losses

VMCL = Main canal Losses (seepage and evaporation)

VDL = Distributary Losses (seepage and evaporation)

VWCL = Water Course Losses (seepage and evaporation)

VFL = Field Losses (seepage and evaporation)

VNCWR = Volume of net crop water demand for production area

Estimation of Groundwater Demand

Canal water supplies and groundwater are the only resources to fulfill net crop demand in each production area. On the bases of estimation of monthly canal water supplies available to crops and net crop water demand, groundwater contribution can be calculated by finding the gap between demand and supply. The simple equation 4 was established for the estimation of groundwater for each production area, which is given below:

$$VRGW=VNCWR -(VCH - VL) \quad (4)$$

Where

VGW = Volume of Required Groundwater Contribution

RESULTS AND DISCUSSIONS

The water balance analysis was carried out for the all production areas of three nodal network models of Rechna Doab. This analysis will help in understanding surface and groundwater interaction along the supply network. In this paper, to illustrate the usefulness of this technique, results of three production areas are discussed from each nodal network model. The general features of these production areas are given in Table 1:

Table 1: Salient Features of Selected Production Areas

Name of Production Area	Nodal Network Model	Off-taking Segment Number	GCA (Hectares)	CCA	No. of Channels	No. of Outlets
Muridke	UCC-MR	IX	74548	73813	10	314
Veryam and Dhular	LCC-QB	VIII	206051	160936	51	761
Shorkot	Haveli-TS	II	78805	74936	15	325

The results of different components of water balance analysis of these production areas for period 1997-00 are presented one by one in the following section:

Crop water demand of selected Production Areas

Reference Evapotranspiration

Monthly reference evapotranspiration for the climatic stations within and close to Rechna Doab are computed by using model indicated in previous section. The computed values of reference evapotranspiration for each climatic stations are delineated at different production areas of segments of nodal network models. The temporal variation of ET_o in selected production areas is shown in the Figure 3.

Figure 3: Variation of Reference Evaporation Over the Year for the Selected Production Areas

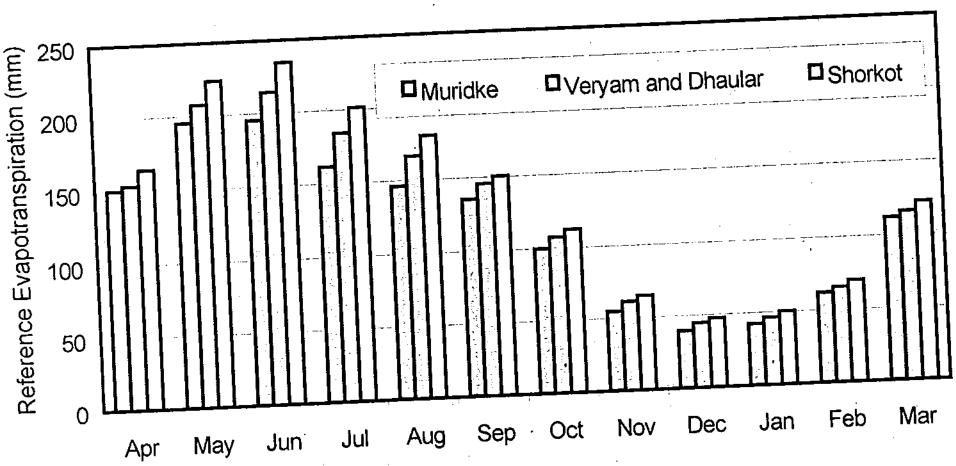


Figure 3 shows that ET_o increases from north to south- Muridke located in Upper Rechna (extreme North), has minimum ET_o value of 1396 mm/year whereas Shorkot which is located in Lower Rechna (extreme South) has maximum value of 1622 mm/year. Temporally, minimum and maximum ET_o values are found in December and June respectively. The main factors influencing this spatio-temporal variation are temperature, humidity, wind speed and altitude.

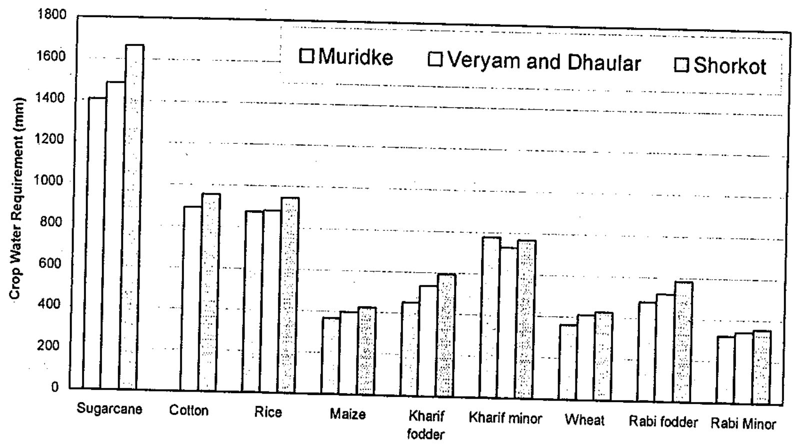
Selection of Crop Coefficient

The reference evapotranspiration generally increases from North to South in Rechna Doab. This variation of reference evapotranspiration along with different landforms resulted in diversified agriculture with respect to crop calendar and period. In Rechna Doab the cropping seasons vary for individual crops but are generally defined as "Rabi" and "Kharif". Rabi crops (wheat and fodder) are sown after the rainy season in October and November, and harvested in spring in April and May. Kharif crops including cotton, rice, maize, sorghum and fodder are sown between April and June and harvested in October and November. The crop duration of major seasonal crops varies from 3 to 6 months. Sugarcane is a perennial crop. The Kc values developed for seven individuals (Sugarcane, Cotton, Rice, Maize, Kharif fodder, Wheat and Rabi fodder) and two groups of minor crops (kharif and Rabi). For the selection of crop period, longer period and high starting value is considered to accommodate preparation of land.

Potential Water Demand of different Crops

Monthly water demand of all individual and group of minor crops is estimated for three production areas. Total water demand is presented in Figure 4, which indicates water demand for most of crops increase from North to South e.g. for sugarcane it varies from 1407 and 1667 mm/year for Muridke and Shorkot production area. It is mainly due to the differences in reference evapotranspiration (Figure 3).

Figure 4: Variation in Water Demand of different Crops in Selected Production Areas.



Net Water Demand of Different Crops

Monthly effective precipitation is calculated by USBR method to estimate the net water demand of different crops. The effective precipitation for the period April 1997 to March 2000 is presented in Figure 5. The effective rainfall shows decreasing trend in the last three years due to semi drought conditions in the area. Figure 5 shows that effective precipitation is highest in kharif 1997 and for Kharif 1999 the effective precipitation is almost equal to Rabi 1997-98 in most of areas. Similar to reference evapotranspiration rainfall is also higher in northern part as compared to southern part. For the past three years impact of lower effective rainfall is observed for all crops in area, which ultimately resulted in increased net demand of water. For example, water demand for sugarcane in Shorkot in last three years is shown in Figure 6. It has increased from 1238 mm/year in 1997-98 to

1531 mm/year in 1999-00. This increase of 297 mm is due to less rainfall during this period. Similar effect is also observed for all the selected crops in production area.

Figure 5: Temporal Variation of Effective Rainfall in Selected Production Areas

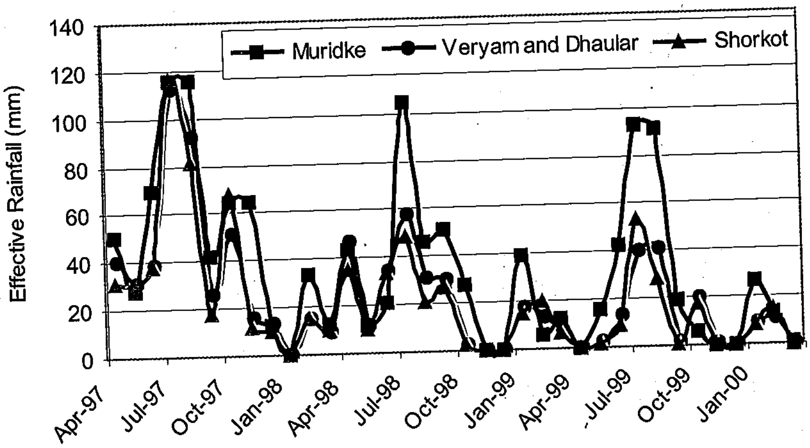
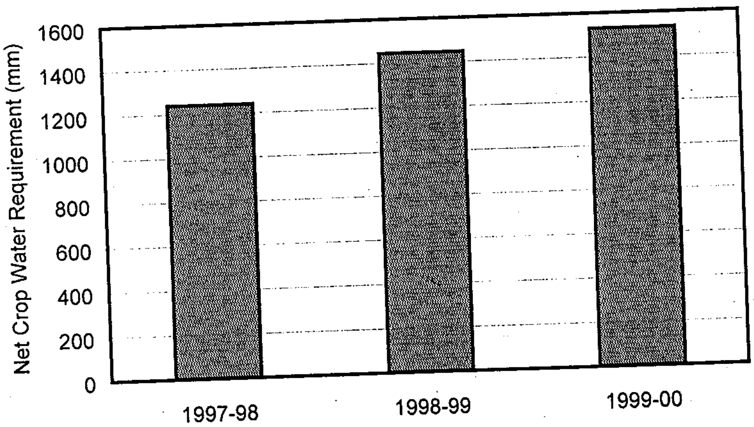


Figure 6: Annual Net Crop Water Demand for Sugarcane in Shorkot



Water Demand of Production Areas

For the estimation of net water demand of production area, spatial data for land use under different crops in each area was not available due to smaller land-holdings and mixed cropping patterns. The reported annual cropping intensities by Irrigation Department during 1997-2000 vary from 30 percent to 150 percent in upper and lower Rechna Doab respectively. This huge difference is due to the reason that upper Rechna Doab has fresh groundwater aquifer. The irrigation Department is supplying water only to a limited area in Kharif season. In the rest of the year the farmers have to depend on groundwater. To overcome this limitation, crop data on the intensity and pattern during Rabi and Kharif at canal command level was taken from the IWMI-Pakistan survey of 443 farms in the Lower Rechna Doab in 1997, and from another survey of about 400 farms in the Upper Rechna

Doab. The intensities of different crops are depicted from these sample surveys in selected production areas are given in the Table 2.

Table 2: Intensities of Different Crops in Selected Production Areas

	Sugar-cane	Cotton	Rice	Maize	Kharif Fodder	Kharif minor	Wheat	Rabi Fodder	Rabi minor
Muridke	0	0	75	0	10	2	57	21	2
Veryam and Dhaular	13	24	16	13	19	0	61	20	0
Shorkot	15	26	16	0	15	0	55	17	0

- Muridke has annual cropping intensity of 167 % with rice, wheat and rabi fodder are dominant crops.
- Veryam and Dhaular have annual cropping intensity of 166% with mixed cropping pattern in both seasons.
- Shorkot has annual cropping intensity of 126% with sugarcane, cotton, rice and fodder in Kharif and wheat with fodder in rabi.

The crop water demand for the production area is determined by using above-mentioned cropping intensities. The net monthly water demand for the existing cropping intensities for production areas is presented in Table 3. Water demand pattern for all three areas is more or less same - more demand in Kharif due to high evapotranspiration rate and less demand during Rabi due to low evapotranspiration rate.

Canal Water Availability to Crops

Canal water available to crops is calculated by subtracting all losses (main canal, distributary, water course, field losses with equation and assumptions discussed in methodology). This calculated volume of water on monthly basis for the selected production areas is given in the Table 4 and briefly discussed below.

- Muridke –a non-perennial system, the canal water was only supplied from May to October during the study period. The canal water available to crops had increasing trend in this period from 114 Mm^3 in 1997-98 to 139 Mm^3 in 1999-00. This excessive availability of canal water was to overcome the drought conditions during that period.

Table 3: Monthly Crop Water Demand (Mm^3) for Selected Production Areas

Month	Veryam and Dhaular	Shorkot	Muridke	Month	Veryam and Dhaular	Shorkot	Muridke
Apr-97	68	34	13	Oct-98	139	87	40
May-97	99	58	35	Nov-98	93	40	32
Jun-97	171	91	85	Dec-98	68	32	23
Jul-97	88	46	39	Jan-99	41	22	3
Aug-97	83	53	29	Feb-99	73	28	35
Sep-97	126	66	60	Mar-99	131	56	55
Oct-97	51	25	11	Apr-99	137	55	39
Nov-97	66	32	0	May-99	124	70	42
Dec-97	48	25	16	Jun-99	199	107	102
Jan-98	65	32	26	Jul-99	169	77	52
Feb-98	69	32	19	Aug-99	141	75	43
Mar-98	128	54	55	Sep-99	158	74	73
Apr-98	59	32	15	Oct-99	100	73	65
May-98	116	66	45	Nov-99	92	40	32
Jun-98	175	94	116	Dec-99	68	32	23
Jul-98	145	79	45	Jan-00	53	26	10
Aug-98	154	78	69	Feb-00	76	32	31
Sep-98	121	62	55	Mar-00	143	61	63

Table 4: Monthly Canal Water Available (Mm^3) to Crops in Selected Production Areas

Month	Muridke	Veryam and Dhaular	Shorkot	Month	Muridke	Veryam and Dhaular	Shorkot
Apr-97	0	52	26	Oct-98	15	58	32
May-97	9	57	42	Nov-98	0	59	22
Jun-97	28	61	43	Dec-98	0	50	24
Jul-97	32	59	46	Jan-99	0	0	3
Aug-97	24	57	34	Feb-99	0	37	11
Sep-97	13	45	34	Mar-99	0	56	30
Oct-97	9	55	26	Apr-99	0	59	32
Nov-97	0	64	26	May-99	4	58	45
Dec-97	0	55	18	Jun-99	27	55	38
Jan-98	0	8	6	Jul-99	35	55	46
Feb-98	0	53	22	Aug-99	27	58	47
Mar-98	0	59	32	Sep-99	33	53	46
Apr-98	0	60	37	Oct-99	13	57	16
May-98	13	53	41	Nov-99	0	34	24
Jun-98	30	51	40	Dec-99	0	51	38
Jul-98	33	55	45	Jan-00	0	26	9
Aug-98	18	57	45	Feb-00	0	51	14
Sep-98	29	55	44	Mar-00	0	61	15

- Veryam and Dhaular-a perennial system, the canal water was supplied throughout the year. The canal water available to crops decreased during the study period, as the amount of water available to crops was 625, 590 and 618 Mm^3 for the years 1997-98, 1998-99 and 1999-00 respectively. This was due to the fact that this system is located at tail of LCC-QB link nodal network model and upstream users consumed more water to combat drought conditions.

- Shorkot –a perennial system, the canal water was supplied during the whole period of study. The canal water available to crops increased from 354 Mm^3 in 1997-98 to 376 Mm^3 in 1998-99 and again decreases to 369 Mm^3 in 1999-00. This fluctuation in water available to crops was due to operation plan of irrigation canal for that area.

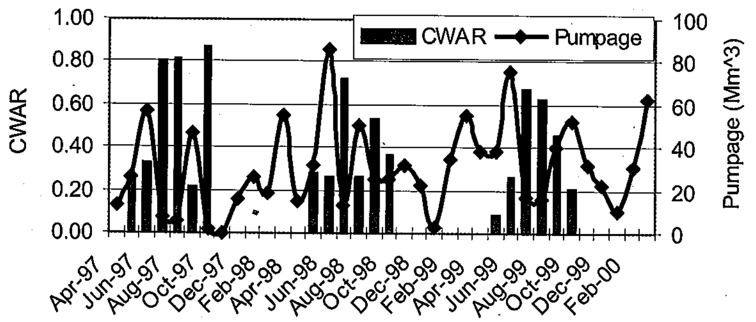
Canal Water Availability Ratio (CWAR) and Groundwater Requirement

Based on analysis presented in the previous section, Canal Water Availability Ratio and groundwater requirement to meet crop water demand was calculated for the production areas selected from three nodal network models. The variability of CWAR and groundwater requirement is presented below for each selected production unit.

Muridke

Figure 7 shows the relationship between CWAR and groundwater requirement on monthly bases for 3 years. The CWAR ratio during the entire period of analysis is less than 1 as shown in Figure 7. This means that groundwater is required for each month to meet the crop water demand. As this area is non-perennial and water is available only from May to October, and even during these months CWAR is less than 0.5, which indicates that more contribution from, groundwater was required than canal water. From November to April no canal water was available, so farmers fulfilled their needs only from groundwater. Figure 7 also shows that the maximum 86 Mm^3 groundwater abstraction was required in June 1998 to meet demand of 116 Mm^3 (Table 3) and the contribution of canal water to crops was only 30 Mm^3 (Table 4). It also indicates that only in November 97, crop water demand was fulfilled by the excessive rainfall and no canal water as well as groundwater was required.

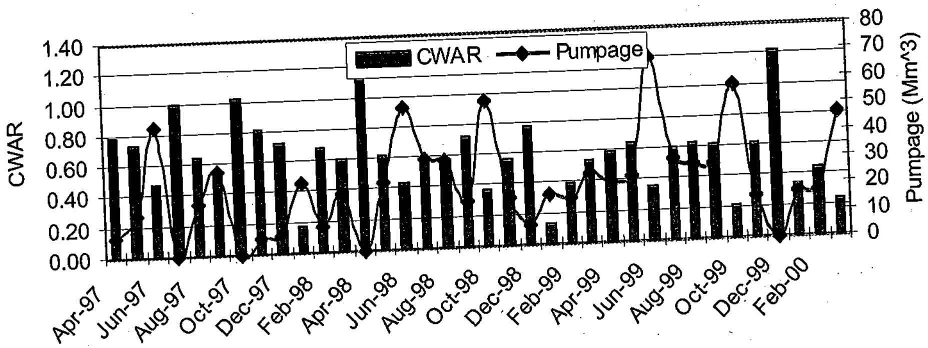
Figure 7: Water Balance in Muridke for the UCC-MR Nodal Network.



Veryam and Dhaular

The monthly relationship between CWAR and groundwater is presented in Figure 8. It indicates that October 1997, December 1997 and April 1998 were the only months that have CWAR more than 1, and in the remaining period contribution from groundwater was required. Overall CWAR is more in Rabi than in Kharif as shown in Figure 8. The monthly volume of water required to meet the crop demand varies from 41 Mm^3 in January 1999 to 199 Mm^3 in June 1999 (Table 3). In January 1999 there was no contribution from canal supplies and all demand was fulfilled by groundwater abstraction and in June 1999 canal supplies contributed 55 Mm^3 (Table 4) and for remaining amount of 144 Mm^3 the farmers had to depend on groundwater. In Kharif although more canal water was supplied but the demand was also more due to high evaporative requirement. This high demand increased the significance of groundwater contribution.

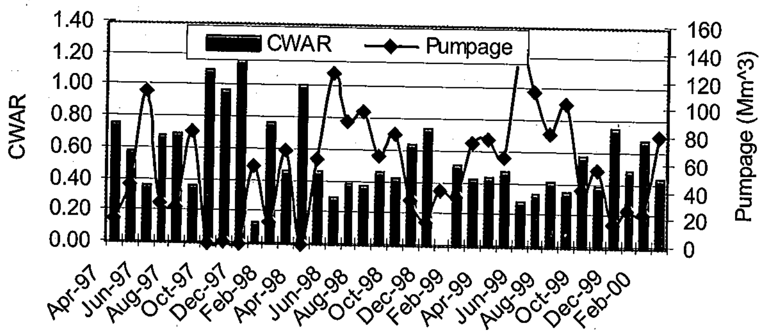
Figure 8: Water Balance in Veryam and Dhaular for the LCC-QB Nodal Network.



Shorkot

Figure 9 shows the variation of CWAR and required groundwater contribution during the study period from April 1997 to March 2000. There were only four months when canal water was sufficient to meet the crop water demand as shown in Figure 9. Except these four months, the farmers fulfilled their demand by supplementing irrigation through groundwater abstraction. Overall CWAR remained more than 0.5 for most of the time during the entire period of study and major contribution was from canal water in this production area. Figure 9 also indicates maximum required abstraction to meet crop demand was found 69 Mm^3 in June 99 against the crop water demand of 107 Mm^3 (Table 3) and the canal water available for crops during that month was only 38 Mm^3. Similarly, even in January 1999 crop water demand of 22 Mm^3 (Table 3) was estimated for which only 3 Mm^3 (Table 4) of canal water was available to crops and remaining demand of 19 Mm^3 (Figure 8) was assumed to be fulfilled by groundwater contribution.

Figure 9: Water Balance in Shorkot for the H-TS Nodal Network



CONCLUSIONS

Based on above analysis in three production areas of nodal network models following conclusions are drawn:

- Low rainfall in past few years has been substituted with groundwater for better production of food and fiber.
- Surface water supplies are not enough to meet net crop water demand in most areas.
- Temporal variability in surface supplies has increased reliance on groundwater. Therefore, groundwater serves as a capacitor of the agriculture system.
- In non-perennial areas having canal water supplies from May to October, crop water demand during the remaining months was fulfilled completely from groundwater
- This strong spatio-temporal groundwater demand variability necessitates development of groundwater management zones, based on dynamic analysis.

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