Modeling Approaches to Quantify the Water Balance in Groundwater-Dominant Irrigation Systems - An Example of Rechna Doab Pakistan

S. Khan[1], M. Kaleem Ullah[2], E. Christen[3] and H. M. Nafees Ahmad[4]

Abstract

Irrigated agriculture in alluvial basins is characterized by high seepage losses from rivers, channels and irrigated fields to the aquifer systems. Water accounting at the farm or management unit level tends to underestimate the productive use of water since losses from the supply system can be reused for irrigation through downstream groundwater pumping. In areas having less canal water supplies, pumping can mobilize poor quality groundwater and can cause overall loss of good quality ('blue") water supplies. Increased groundwater pumping also causes enhanced seepage losses from irrigation channels and watercourses. This situation demands understanding of spatial and temporal variation of surface and groundwater interactions and salt movements under variable scenarios of surface water availability.

This paper describes details of hydrological studies carried out during the past couple of years in Rechna '*Doab*' (land between two rivers) in Pakistan. The gross area of Rechna Doab is 2.97 million ha, with a longitudinal extent of 403 km and maximum width of 113 km, comprises of 2.3 million ha of prime cultivated land. It is one of the oldest, agriculturally richest and most intensively populated irrigated areas of Punjab. The area falls in the rice-wheat and sugar-cane wheat agro climatic zones of the Punjab province, with rice, cotton and fodder crops dominating in summer (Kharif), wheat and fodder in winter (Rabi). In some parts sugar cane is also cultivated as an annual crop.

A top down nodal network approach was developed to determine irrigation water balance for the individual administrative units within Rechna Doab. The spatial groundwater recharge estimates obtained from the nodal network framework were used as sanity checks for the water balance estimates for a more distributed bottom up approach. The bottom up approach utilized a distributed dynamic model, which could simulate surface and groundwater interactions at the desired level of interest. The distributed nature of the surface-groundwater interaction model enabled performance assessment of individual administrative units by taking into account downstream beneficial use and quality variation of lost surface water resource. This water and salt balance approach has highlighted

---

[1] Senior Research Scientist, CSIRO Land and Water PMB 3, Griffith, NSW 2680, Australia
[2] Junior Civil Engineer, International Water Management Institute (IWMI), Lahore, Pakistan
[3] Irrgation and Drainage Engineer (Research), CSIRO, Land and Water, Griffith, NSW, Australia
[4] Research Officer, Pakistan Council of Research in Water Resources (PCRWR)

the need for integrated management of surface and groundwater from the administration unit to the hydrological basin level.

INTRODUCTION

In groundwater dominant irrigation systems crop water demands are conjunctively met by surface and groundwater. While it is important to ensure efficient use of surface water supplies (e.g. more grains per drop of water) by improved transmission and irrigation methods, this may cause reduced recharge to aquifers and hence lower availability of water to farmers relying on groundwater for agriculture. This problem demands a system's approach to determine water balance at different scales as deep percolation losses from one administrative or hydrologic unit may be reused in another unit (Rushton, 1999; Seckler, 1996). The water lost through deep percolation from one hydrological unit goes through geochemical changes before it becomes available as groundwater in another hydrological unit. This aspect may necessitate consideration of water quality implications in upscaling efforts in groundwater dominant systems.

Often, water rights are associated with administrative units irrespective of the hydrological interactions and boundaries of the system. This necessitates determination of water use efficiency at each of the administrative units and how it contributes to the overall system's efficiency. The quantitative assessment of water productivity or water use efficiency requires a range of methodologies which can capture system water and salt dynamics at both the hydrological and administrative scales. This paper describes two approaches for understanding the role of both surface water and groundwater in meeting crop water demand at administrative and hydrological unit levels in Rechna Doab, Pakistan.

DESCRIPTION OF STUDY AREA

The Rechna '*Doab*' (land between two rivers) is the interfluvial sedimentary basin of the Chenab and Ravi Rivers in Pakistan (Fig-1). It 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 2.3 million ha of prime cultivated land. It is one of the oldest, agriculturally richest and most intensively populated irrigated areas of Punjab, Pakistan. The flows of the Chenab and Ravi rivers bounding the Rechna Doab are regulated through six major headworks. Four of these headworks, Marala, Khanki, Qadirabad and Trimmu are on the Chenab River while Balloki and Sidhnai Headworks are on the Ravi River. These headworks enable diversions to the main and link canals servicing the irrigation areas. The Chenab and the Ravi River meet about 64.4 km further downstream of the Trimmu Headworks at the lower tip of the Rechna Doab area. Two main canals and five link canals take supplies from the Chenab River. The Upper Chenab Canal (UCC) and Lower Chenab Canals (LCC) are the main supply canals, off taking at the Marala and Khanki Headworks, respectively. The five link canals Marala-Ravi (MR), BRBD (Bambanwala-Ravi-Bedian-Depalpur), Qadirabad-Balloki (QB), Trimmu-Sidhnai (TS), and Haveli mainly transfer water from the Chenab River to the Ravi River. Some of these link canals were constructed after the Indus Basin Treaty in 1960s, which gave India exclusive rights on the Ravi River greatly restricting flows into the Pakistani part of this river.

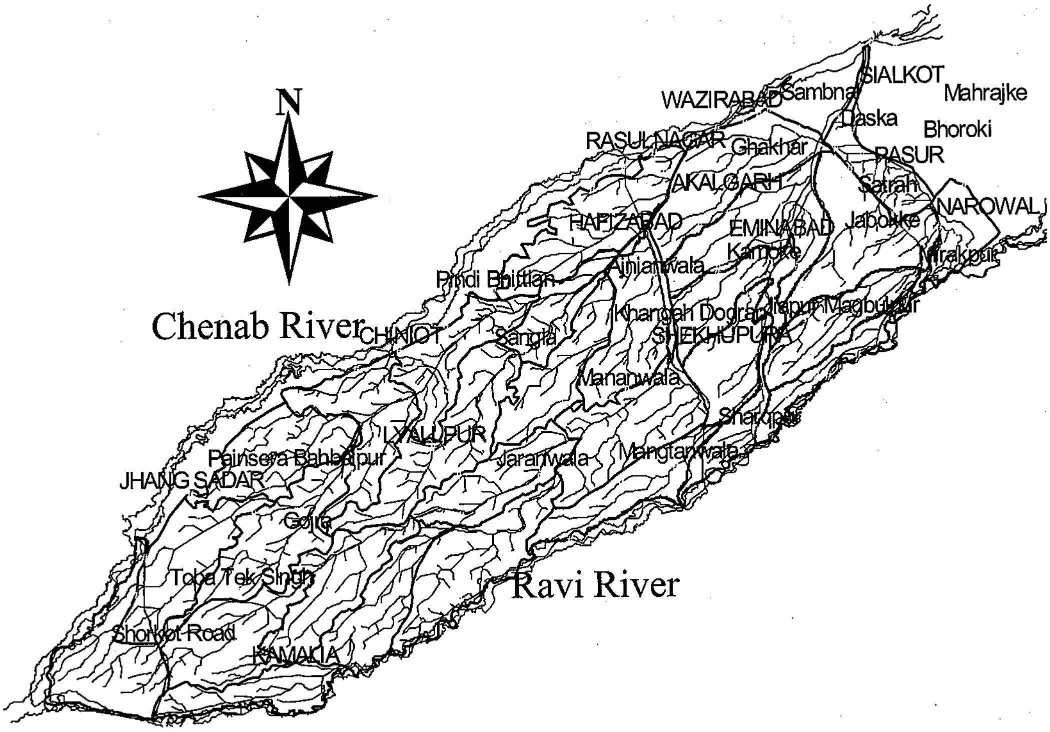

Figure 1: Rechna Doab Irrigation System

The study area falls in the rice-wheat and sugar cane-wheat agro-climatic zones of Punjab province, with rice, cotton and fodder crops dominating in summer season (Kharif), and wheat and fodder in winter season (Rabi). In some parts, sugar cane is also cultivated as an annual crop. At the time of construction the irrigation network was designed for supporting low cropping intensities; however, success of groundwater pumping to alleviate waterlogging and salinity problems in the late sixties helped increase the cropping intensities well over 150%, with the rapid development of public and private tubewells. The groundwater storage underlying the Rechna Doab has served as a vital irrigation resource to support these increased irrigation intensities.

The Rechna Doab is sub tropical, continental lowland often described as a semi arid region. The climate is characterized by large seasonal fluctuations of rainfall and temperature. Average annual precipitation varies from 290mm in the south (Shorkot) to 1046mm in the north (Sialkot) of the Doab. The highest rainfall occurs during the monsoon period in July and August and accounts for about 60 percent of annual rainfall. Due to the short time span of the monsoon, a large volume of rainfall is wasted, often causing floods. In the last three years the monthly effective rainfall (Fig. 2) available for crop production (Soil Conservation Service 1972) throughout the Rechna Doab has been very low. However, no substantial reductions in crop yields have been reported in the region. This illustrates increased dependence on groundwater resources to maintain the cropping patterns.

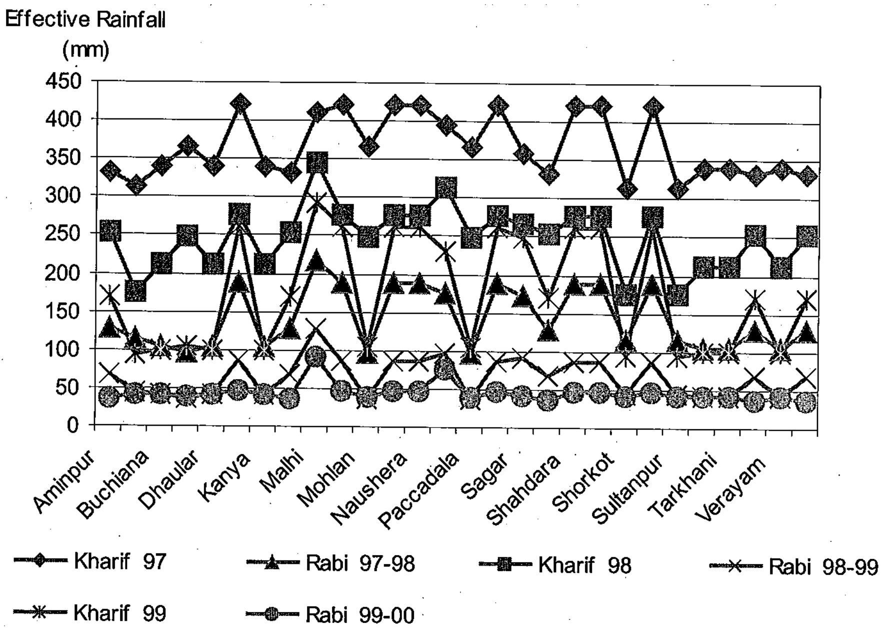

Figure 2: Effective Annual Rainfall in Rechna Doab from 1997-2000

WATER BALANCE ANALYSIS AT THE SYSTEM SCALE

Realizing the importance of surface-groundwater interactions the following two approaches were used to understand the role of groundwater to meet crop demand on both hydrological and administrative area bases:

- Top down approach using a nodal network model
- Bottom up approach using a surface-groundwater interaction model

The first approach subdivides the study area into a system of channel reaches and demand nodes linking the channel reaches, and therefore, follows the topography of the area. This approach recognizes the data limitations e.g. availability of groundwater pumping rates, and therefore, builds the desired complexity into the analysis only to answer specific questions.

The second approach subdivides the area into a number of connected square grid cells in four layers which can dynamically simulate the surface-groundwater interactions under varying depths and quality of groundwater abstractions represented by model layers. The second approach assumes better knowledge of the system and can integrate water and salt balances from individual cells up to the hydrologic or administrative unit level.

Top Down Approach

The study area was divided into three nodal networks reflecting the direction of surface water flow and connectivities of canals between the Chenab and Ravi rivers as given below (Fig-1):

- Upper Chenab Canal and Marala Ravi Link Canal (UCC-MR) Fig-3
- Lower Chenab Canal and QB Link Canal (LCC-QB)
- Haveli and Trimu Sidhnai Link Canal (Haveli-TS)

A lumped monthly water balance was determined for each of the demand nodes using monthly canal supplies, irrigation system loss estimates and net crop water requirement. This approach helped determine groundwater requirements by finding the difference between monthly water supplies and crop demand volumes in Mm^3 using Equation1:

$$VGW = VNCWR - (VCH - VL) \tag{1}$$

where

$$VL = VMCL - VDL - VWCL - VFL \tag{2}$$

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

VCH = Volume water at head of network reach from canal flow data

VL = Volume of all water losses

VGW = Volume of groundwater required to meet crop water demand

VMCL = Main canal seepage and evaporation losses

VDL = Distributary seepage and evaporation losses

VWCL = Water course seepage and evaporation losses

VFL = Field seepage and evaporation losses

VNCWR = Volume of net crop water requirement

ETo=Potential crop water determined using Penman Monteith equation (FAO, 1998)

Kc= Crop Factors for individual crops grown in the demand area

Effective Rainfall = Rainfall available to crop after losses determined using Soil Conservation Service (1972)

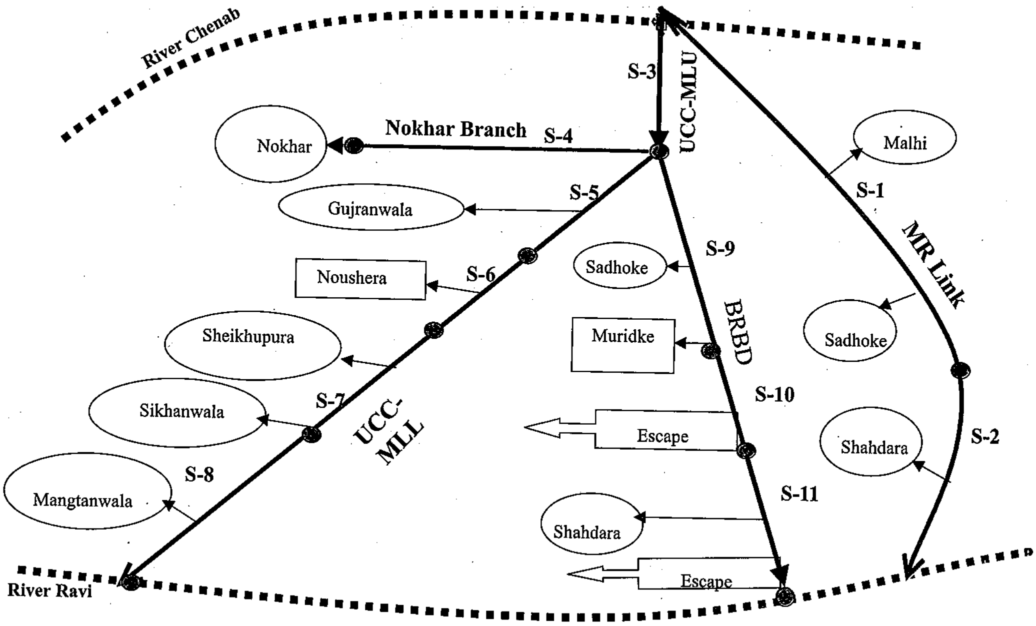

Figure 3: Upper Chenab Canal and Marala Ravi Link Canal Nodal Network

To visualize the role of surface water in meeting crop demand, monthly canal water availability ratios (CWAR) were determined for each of the demand nodes using Equation-4.

$$CWAR=(VCH-VL)/VGW \tag{4}$$

To illustrate the usefulness of this technique results at two demand nodes are presented in this paper.

WATER BALANCE FOR A NODE LOCATED IN THE UPPER PART OF THE SYSTEM

Figure-4 shows the CWAR and groundwater demand at the Nokhar demand node for 1997-2000 for the UCC-BRBD Nodal Network (Fig-3). Although the Nokhar demand area is non perennial (supplies only in summer) and is located at the upper end of the irrigation system, results show that, both during summer and winter, the canal water supplies are not enough to meet crop demand and substantial groundwater pumping is necessary throughout the year.

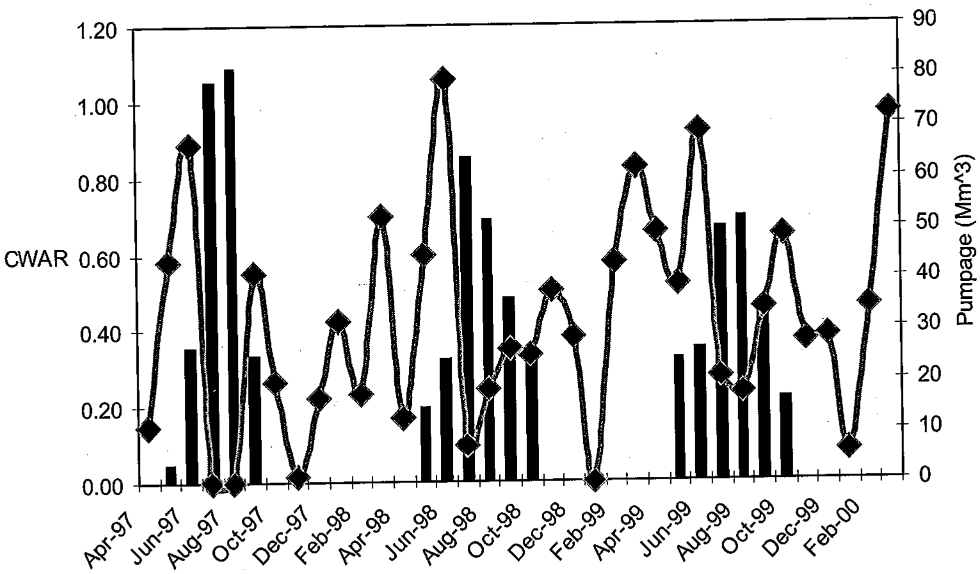

Figure 4: Canal Water Availability Ration (CWAR; solid bars) and pumping volume (line) in the upper end of the UCC-MR Nodal Network

WATER BALANCE FOR A NODE LOCATED IN THE LOWER PART OF THE SYSTEM

Fig-5 shows the CWAR and groundwater demand at the Mangtanwala demand node for 1997-2000 located at the lower end of UCC-BRBD Nodal Network (Fig-3). Water balance shows that the surface water supplies are not enough to meet the crop water demand in both the winter and summer seasons. Similar results were obtained for the other demand areas in the Rechna Doab system, and therefore, indicating strong dependence of irrigated agriculture on groundwater.

This analysis helped to establish lumped spatial distribution of crop water demand, surface water availability, system losses and groundwater demand along with the irrigation supply system. This methodology can provide a better understanding of surface and groundwater use efficiency on a nodal area basis but failed to quantify contribution of losses from one part of the system to the groundwater gains in the other part.

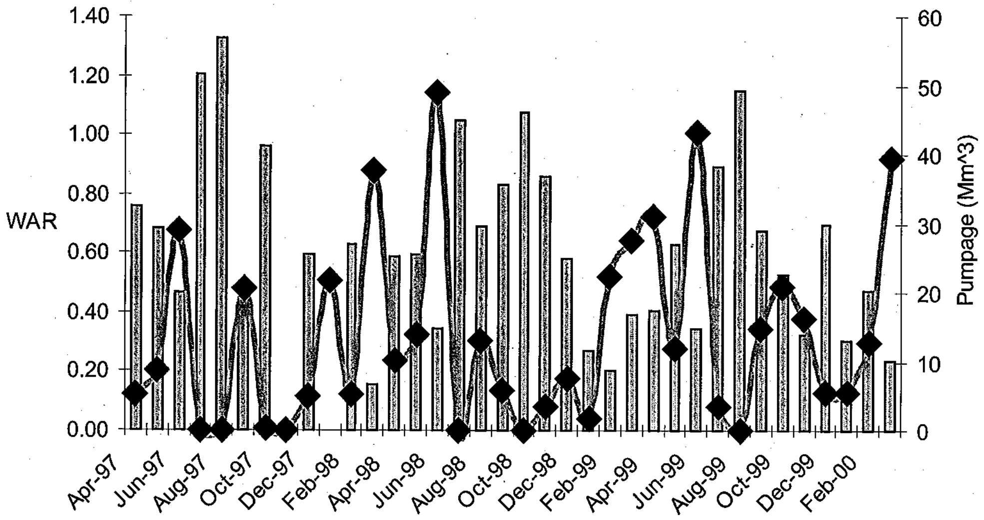

Figure 5: Canal Water Availability Ration (CWAR; solid bars) and pumping volume (line) in the lower end of the UCC-MR Nodal Network

Example of a Bottom Up Approach

In bottom up approaches the biophysical processes are scaled up to the desired level of interest using biophysical parameters and process simulation at a more detailed level. In the case of Rechna Doab the system was described using a surface-groundwater interaction model by dividing the study area into 4x106x132, 2.5 km finite difference cells in four aquifer layers using MODFLOW and MT3D (Harbaugh and Macdonald, 1996; Zheng, 1996; Khan, 2001). This arrangement required aquifer lithology, surface water interaction parameters, and water quality, recharge and discharge parameters descriptions on a 2.5 km grid. This finer level of system description helped incorporate biophysical constraints to groundwater movement such as heterogeneity of alluvial aquifer properties and spatial variation in aquifer thickness.

Bennett et al. (1967) provided a detailed hydrologic description of the aquifer systems in the Rechna Doab. The Rechna Doab aquifer system has a major discontinuity due to a bedrock outcrop near Chiniot (Fig. 6) which divides it into two semi dependent basins. The spatial variation in the thickness of Rechna Doab alluvium is shown in Fig-7. The alluvial sediments mainly consist of gray and grayish-brown fine to medium sand, silty sand, silt and clay (Khan, 1978). The composite hydraulic conductivities of the alluvium range from 25 m/day to 150 m/day. The shallow groundwater quality (Fig. 8) in the upper part of the Doab has low salinity (EC less than 1000 μS/cm) whereas the lower part of the Doab has higher groundwater salinity (EC ranging from 5000-25000 μS/cm).

Using the geometrical description of the surface water network (rivers and channels) the surface-groundwater interaction parameters were defined in the model. The groundwater parameters such as hydraulic properties, recharge, water quality, evapotranspiration from the phreatic surface and groundwater pumping were described on a cell by cell basis for each of the corresponding layers in the model. The evapotranspiration from the phreatic surface depends on soil type, depth to watertable and land use. It consists of capillary upflow caused by plant roots or suction caused at the soil surface due to evaporation. This model used water balance estimates from the nodal network approach as sanity checks for water budget outputs. The combined description of surface and groundwater systems at a finer scale helped dynamically simulate system response to changing surface-water availability and rainfall scenarios on a seasonal basis.

The model was calibrated for a seven-year period from June 1993 to June 2000 at 190 piezometric locations throughout the Rechna Doab.

To illustrate the usefulness of this bottom up approach, model results for a 10-year simulation (June 1993 to June 2003) are presented here. These include a historic simulation period from June 1993 to June 2000 (calibration period) and a forecast period from October 2000 to June 2003 using year 2000 climate and an increased groundwater pumping regime due to recent dry weather conditions. Fig-9 shows simulated and observed piezometric levels at a representative location in the middle of the Doab. The cyclic nature of the simulated and observed hydrographs in the initial five years shows that groundwater in the aquifer is stored during the summer period due to excessive recharge from the rivers, channel network and field losses and is used during the winter period. During the last two years of the historic simulation period the watertables show a declining trend. The declining groundwater trend continues for the forecast simulation period due to increased groundwater pumping and lower surface water supplies (caused by lower than average rainfall). This situation demands careful groundwater management in the Doab as over exploitation of groundwater can make pumping operations expensive, and can also mobilize saline groundwater.

Figs-10 and 11 show the groundwater balance scaled up to the Doab level for the Rabi (winter) 1996 and Kharif (summer) 1996 periods respectively. This water balance helps visualise the relative magnitudes of groundwater pumping (WELLS), and evapotranspiration from watertable (ET) and groundwater recharge (RECHARGE), river and channel seepage and change in groundwater storage on the entire Doab basis. The positive storage terms indicate that during Rabi groundwater demand is partly met from aquifer storage component and negative storage terms show that during Kharif excessive groundwater recharge is stored in the aquifer.

Fig-12 shows the predicted June 2003 groundwater levels in the Rechna Doab. Due to strong dependence on groundwater lower parts of the Doab develop watertable depressions with depths greater than 15 meters, which can make groundwater pumping uneconomical for the farmers due to many fold increase in the capital and operating costs. These watertable depressions can also cause mobilization of saline groundwater from adjacent regions and from deeper groundwater. An example of degrading water quality with increased groundwater pumping under continued dry climate conditions for the lower part of the Doab (Haveli Division L-03/3) is given in Fig-13.

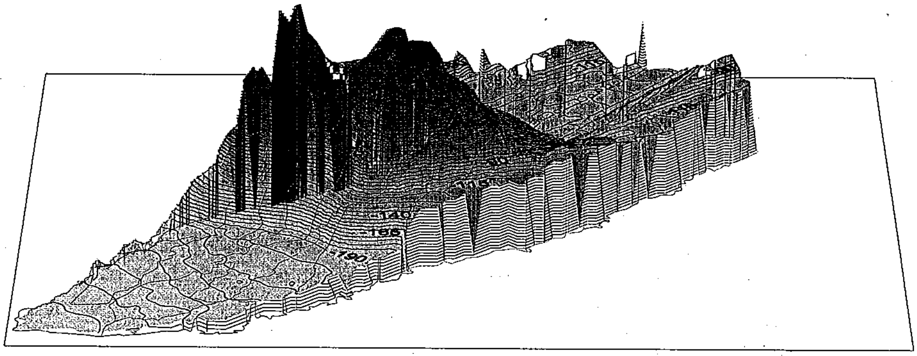

Figure 6: Shape of the Bedrock Surface Under the Rechna Doab [numbers indicate depth from mean sea level]

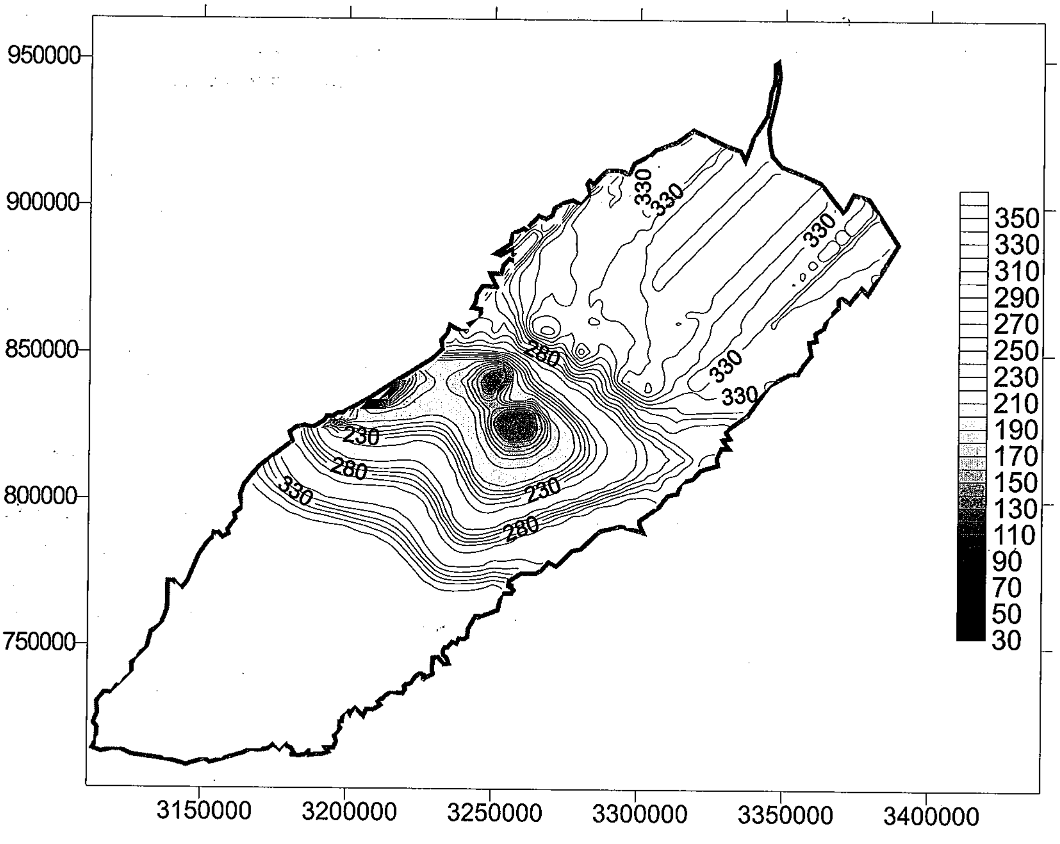

Figure 7: Thickness of Aquifers under the Rechna Doab in m, horizontal and vertical axis show UTM coordinates

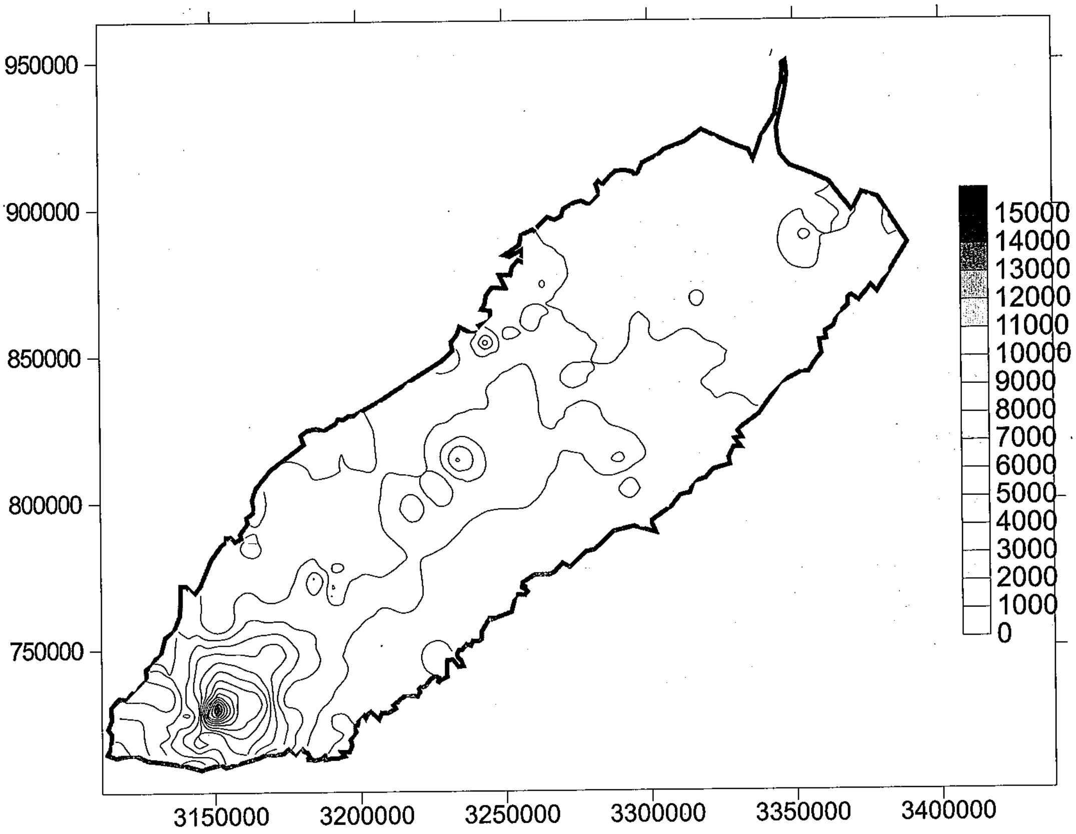

Figure 8: Groundwater Salinity under the Rechna Doab (µS/cm) horizontal and vertical axis show UTM coordinates

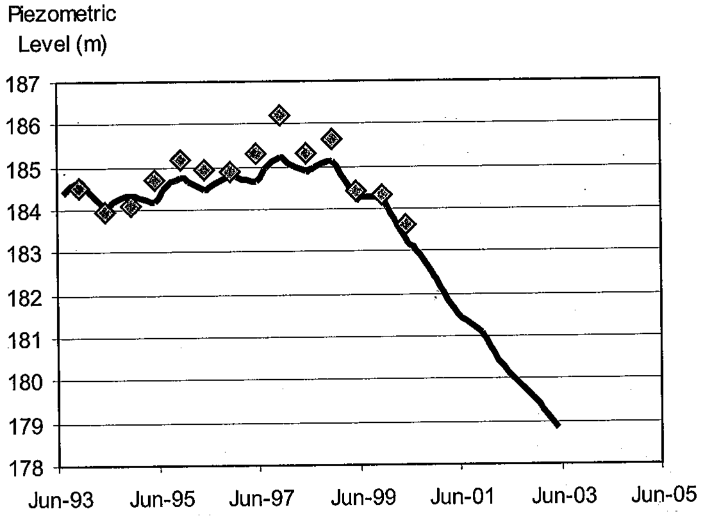

Figure 9: Observed (dots) and Predicted Groundwater Levels (line) at Piezometer L-28/11 located in the middle of Doab

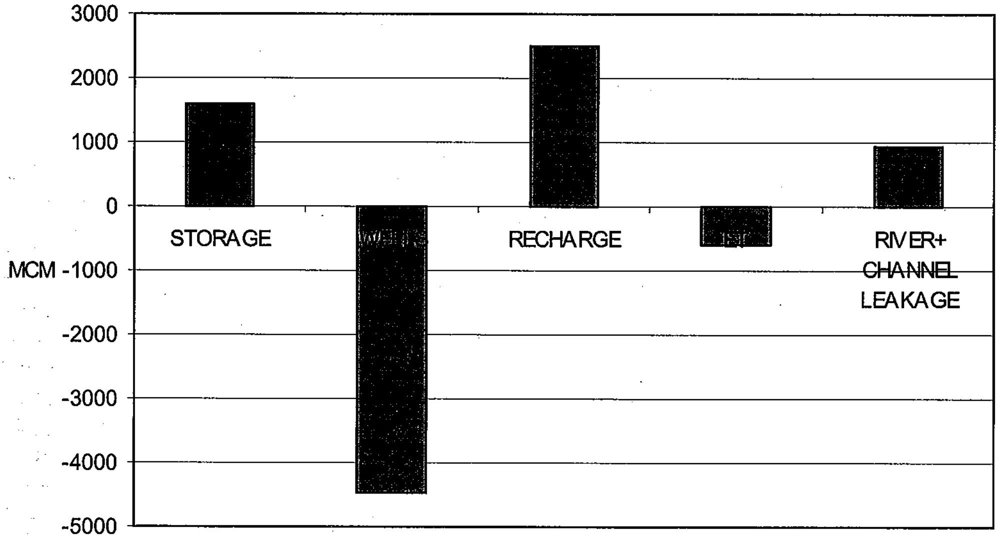

Figure 10: Rabi 1996 Groundwater Balance for Rechna Doab, (MCM=Million Cubic Meter)

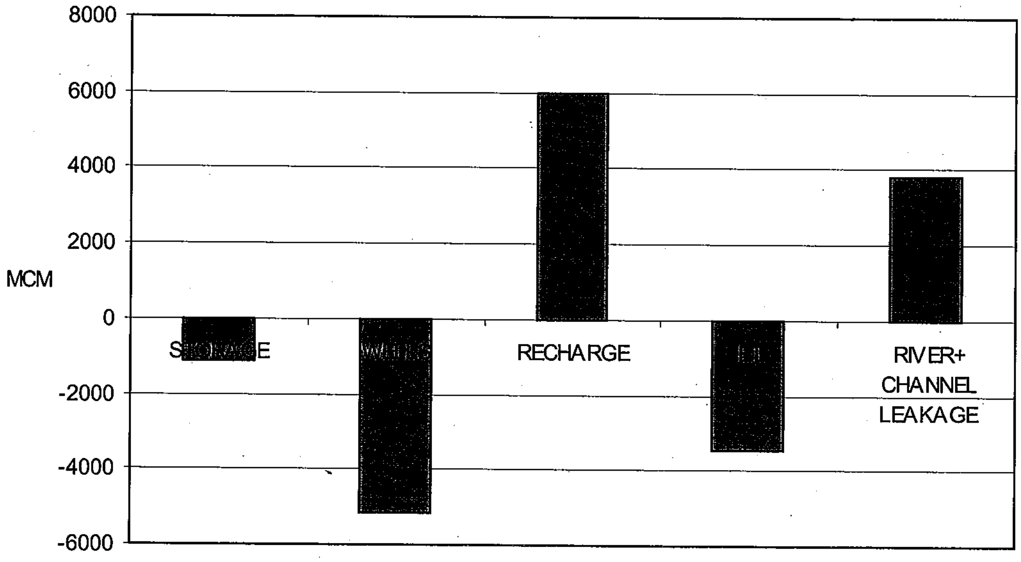

Figure 11: Kharif 1997 Groundwater Balance for Rechna Doab (MCM=Million Cubic Meter)

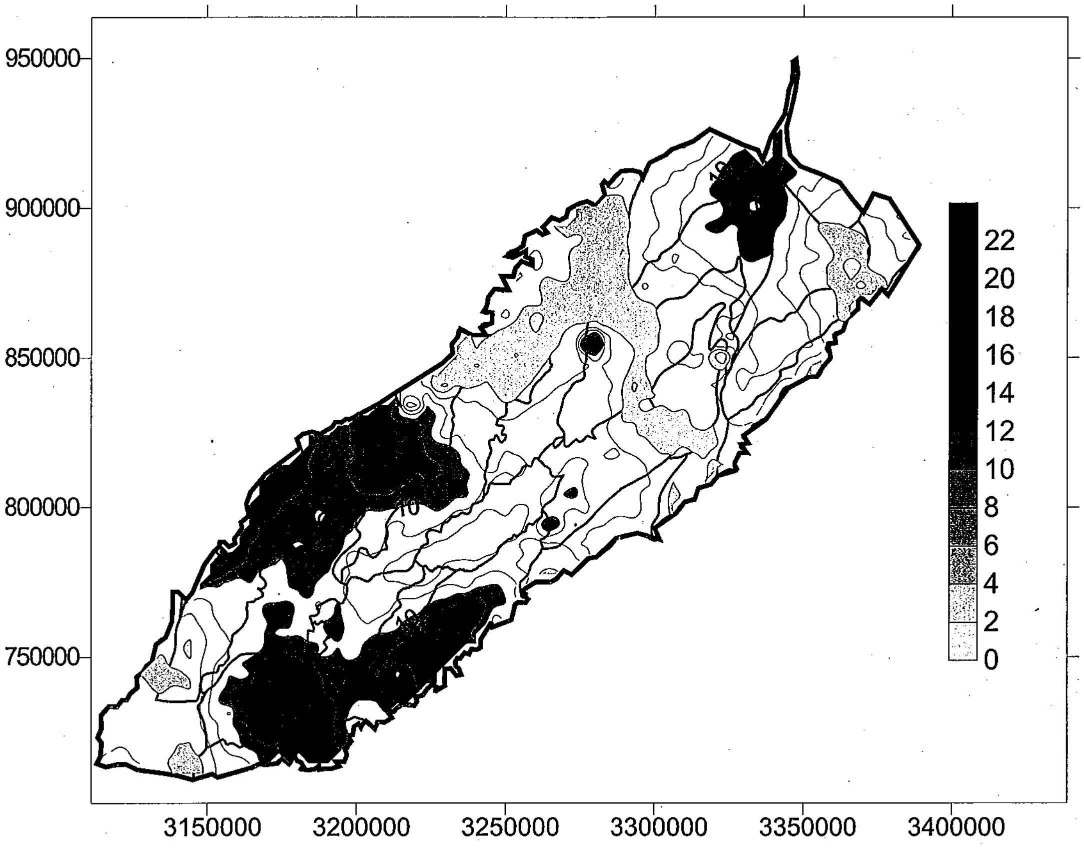

Figure 12: Predicted Depth to Watertable for June 2003 under the Rechna Doab in m below soil surface, horizontal and vertical axis show UTM coordinates

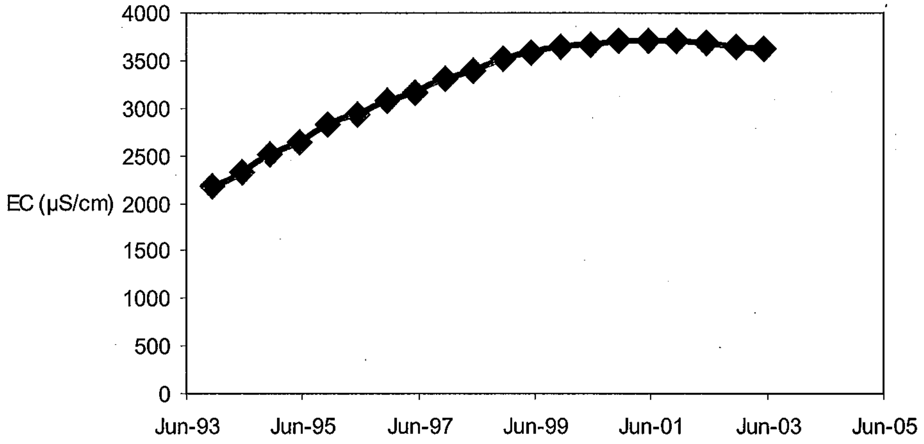

Figure 13: Predicted Salinity Trends in the Shallow Aquifer under the Haveli Division L-03/3

CONCLUSIONS

This paper has demonstrated two approaches for quantifying surface and groundwater balance in groundwater dominant systems. The top down approach is useful in situations where data on the distributed features of the system are scarce, while the bottom up approach is more suitable for data rich environments. The top down approaches can help get a handle on relative quantities of different hydrologic components distributed along the supply system. This type of methodology is recommended for rationalization of resource allocations along supply networks. However, this approach fails to quantify how losses from one demand node can become gains to other demand nodes in the system and how water quality transformations take place in this process.

The bottom up approaches offer integration of information from a lower level to any desired level of detail but demand huge data sets and intellectual investments. Their distributed nature can help represent system discontinuities and heterogeneity. These approaches can easily couple with water quality accounting methods and add the vital water quality dimension to the water balance debate.

The distributed nature of bottom up approaches facilitates lumping of water balance at the desired hydrologic or administrative units. The ability to link groundwater balance with water quality dynamics offers a tremendous tool for policy makers for defining rational productive use of surface water and groundwater without compromising the environmental conditions.

The water balance studies for Rechna Doab have shown that during Rabi crop water demand is partly met from mining of aquifer storage and while during Kharif excessive groundwater recharge is stored in the aquifer. Because of strong dependence on groundwater lower parts of the Doab, long term sustainability of this vital resource is threatened due to development of watertable depressions with depths greater than 15 meters, which can make groundwater pumping uneconomical for the farmers due to manifold increase in the capital and operating costs. These watertable depressions cause mobilization of saline groundwater from adjacent regions and from deeper groundwater.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Shamshad Gohar and Ahmed Nawaz of National Engineering Services of Pakistan (NESPAK) and Akhtar Hussain Shah of the Punjab Irrigation Department (PID) for the data sets used in this work. Project funding from Australian Centre for International Agricultural Research (ACIAR) is highly appreciated. Review comments from Dr Liz Humphreys helped improved the quality of manuscript.

REFERENCES

Bennett, G. D., A. Rehman, I. A. Sheikh, and S. Ali. 1967. Analysis of aquifer tests in the Punjab region of West Pakistan. US Geological Survey Water Supply Paper 1608-G, 56p.

FAO (Food and Agriculture Organisation). 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.

Harbaugh, A.W. and M. G. McDonald. 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model, USGS Open-File Report 96-485.

Khan, M. A. 1978. Hydrological data, Rechna Doab, Volume I. Lithology, mechanical analysis and water quality data of testholes/testwells. Publication Number 25, Project Planning Organization (NZ), Pakistan Water and Power Development Authority, Lahore.

Khan, S. (2001) Hydrological economic models for developing policies for irrigated agriculture. In: Donna Brennan editor. Water Policies Reform: Lessons from Asia and Australia. Proceedings of the International Workshop held in Bangkok, Thailand, 8-9 June 2001. Australian Centre for International Agricultural Research (ACIAR) Proceedings No. 106. 269-280.

Rushton, K.R., (1999) Groundwater aspects: losses are inevitable but re-use is possible? Agricultural Water Management 40,111-116

Seckler, D., (1996) The new era of water resources management: From 'dry' to 'wet' savings. Research Report No. 1, International Irrigation Management Institute, Colombo.

Soil Conservation Service (1972) National Engineering Handbook, Hydrology. Section 4.

Zheng, C., 1996, MT3D Version DoD_1.5, a modular three-dimensional transport model, The Hydrogeology Group, University of Alabama.