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# Development of a conjunctive use model to evaluate alternative management options for surface and groundwater resources

Asaf Sarwar · Helmut Eggers

**Abstract** A conjunctive use model has been developed to evaluate alternative management options for surface and groundwater resources. A simple water balance approach was used to estimate net recharge to the aquifer. The groundwater model FEFLOW takes net recharge as an input for the water balance calculation and simulates flow in the groundwater under all boundary stresses. The developed model was applied to an irrigated area in the Indus Basin, Pakistan, to predict groundwater levels up to 2010 in response to the possible need for intervention in irrigation and/or agricultural practices. A geographical information system (GIS) was used to assemble various types of spatial data. The study revealed that an increase in pumpage from the present rate would further strain the scarce water resources. Lining of watercourses and adjustment in cropping pattern could be adopted as alternatives for better management of surface and groundwater resources.

**Resumé** Un modèle à utilisation conjonctive a été développé pour évaluer des options alternatives de gestion des ressources en eau de surface et eaux souterraines. Une approche par bilan hydrique a été utilisée pour estimer la recharge nette des aquifères. Le modèle FEFLOW utilise la recharge nette lors du bilan hydrique et simule l'écoulement des eaux souterraines suivant les conditions précisées aux limites. Le modèle développé a été appliqué dans la zone irriguée du bassin de l'Indus au Pakistan, pour prédire les niveaux d'eau jusqu'en 2010 en réponse au besoin des pratiques agricoles et de l'irrigation. Un

système d'informations géographiques (GIS) a été utilisé pour assembler divers types de données spatiales. L'étude a révélé qu'un taux d'exploitation par pompage croissant vis-à-vis du taux actuel, mettrait en danger les fragiles ressources. Le revêtement des cours d'eau et l'ajustement des aires cultivées présentent des alternatives à une meilleure gestion des ressources de surface et souterraines.

**Resumen** Se ha desarrollado un modelo de uso conjuntivo para evaluar opciones de alternativas de gestión de recursos de agua subterránea y superficial. Se usó un enfoque simple de balance hídrico para estimar la recarga neta al acuífero. El modelo de agua subterránea FEFLOW toma la recarga neta como una entrada en los cálculos de balance hídrico y simula el flujo en agua subterránea bajo distintos límites de presión. El modelo desarrollado se aplicó en un área de riego en la cuenca Indo, Paquistán, para predecir niveles de agua subterránea hasta el año 2010 en respuesta a la posible necesidad de intervenir prácticas agrícolas y/o de riego. Se usó un Sistema de Información Geográfico (SIG) para reunir varios tipos de datos espaciales. El estudio revela que un incremento del bombeo por encima de la tasa actual presionaría aún más los escasos recursos hídricos. El alineamiento de cursos de agua y los ajustes en patrones de cultivos pueden adoptarse como alternativas para una mejor gestión de los recursos de agua subterránea y superficial.

**Keywords** Groundwater management · Geographic Information System (GIS) · Water balance model · FEFLOW groundwater model · Indus Basin · Groundwater development · Groundwater/surface water relations · Over-abstraction

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## Introduction

A significant percentage of irrigated area in the Indus Basin in Pakistan is either totally dependent on groundwater or is irrigated in combination with surface water supplies. In a number of canal command areas where surface water supplies are inadequate, irrigation with groundwater of marginal quality is resulting in depletion of groundwater resources besides the problem of secondary salinization. The excessive continued exploitation of this resource at a rate greater than natural replenishment

has caused groundwater levels to decline. The situation has reached the point where all the developed water resources are inadequate to meet irrigation demand and other water requirements and there is no prospect of augmenting the water availability in the near future.

The most serious groundwater challenge facing the country presently is not the development of groundwater but its sustainable management. The shortfall in water availability, which was of the order of 49.71 billion  $m^3$  in the year 2000 would increase to 133 billion  $m^3$  in year 2013 (PWP 2000). As problems of groundwater depletion and its deleterious consequences have surfaced in different parts of the country, a number of measures have also been suggested by the scientific community to reverse the situation which include: adjustment in cropping pattern, i. e., replacement of water-intensive, low-yield crops such as sugarcane and rice with less water-intensive, higher yield crops such as sugar beet, wheat, maize, cotton etc; lining of irrigation canals and the farmer's watercourses; control of groundwater pumping, etc. (Sarwar and Eggers 2001; Jiskani 2001). The Government of Pakistan has been taking extensive measures to conserve large losses in the irrigation system through improvement of the farmer's watercourses, rehabilitation of irrigation canals and lining of distributaries, etc. (Anonymous 2000). However, at the same time, the installations of private tubewells are also being carried out to supplement surface water supplies and presently more than 0.6 million tubewells are operating in the country. Groundwater provides almost 40–50% of the water required to meet the crop water demand and is no longer a supplement to canal water, but is an integral part of the irrigated agriculture of Pakistan (Bhutta and Vander Velde 1992). Conjunctive use management of surface and groundwater resources is therefore indispensable for irrigated agriculture of Pakistan.

In order to study the impact of multiple activities carried out simultaneously, there is a need to develop a model

which can quantify the response of the groundwater system to changes in surface water management options (irrigation and or agriculture) and or groundwater pumping so that proper measures could be adopted for the sustainable management of surface and groundwater resources.

This report presents a conjunctive model which can be used to evaluate the impact of different surface and groundwater management options on the changes in groundwater levels. A geographical information system (GIS) was used to develop and handle large amounts of spatial data required for modelling purposes. After developing the databases and model base, numerous scenarios of near future situations were generated by applying the model to an irrigated area in the Indus Basin to predict changes in groundwater levels up to 2010.

### Conceptual framework of conjunctive use modelling

The conceptual framework of conjunctive use modelling is presented in Fig. 1. The surface hydrological processes were modeled using a simple water balance (WB) approach. The main inputs to the water balance model include rainfall, irrigation deliveries, tubewell pumpage, area under different crops, crop coefficient values and growth period of various crops and evapotranspiration (ET). Evapotranspiration was estimated from various climatic parameters using CROPWAT4W software developed by FAO (Smith et al. 1990). Databases were prepared for these parameters to estimate various components contributing to net recharge. Net recharge was estimated as an output from the water balance model. The groundwater model takes the net recharge from the WB model as an input and simulates the water movement in the groundwater aquifer under all other applied stresses. The GIS was used first to work on the base map and finally for analysis of simulation results. The model

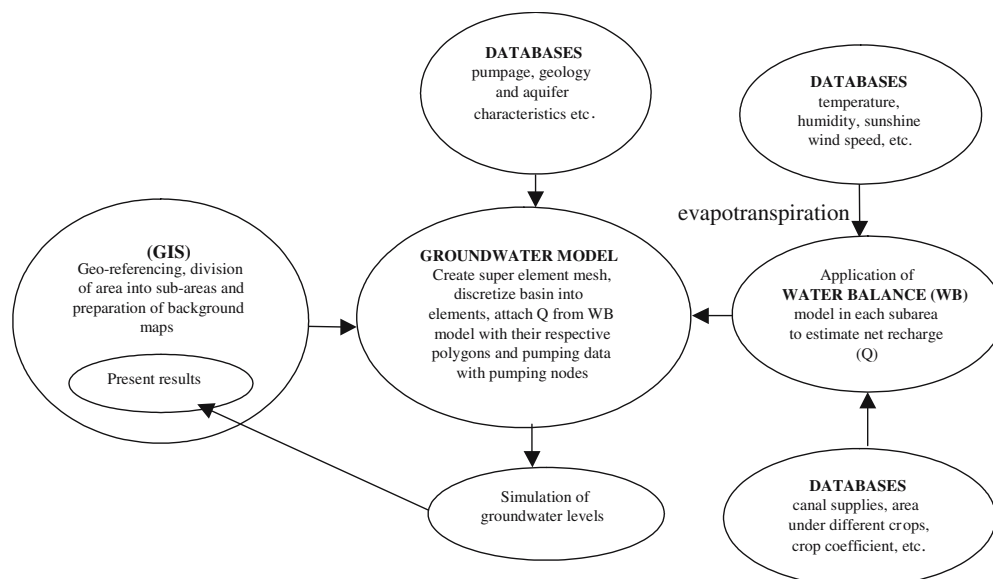


Fig. 1 Conceptual framework of conjunctive use modelling

operations were carried out from 1982 to 1995 on a monthly basis.

## Model application

### Description of study area

The developed model was applied to the most intensively irrigated area of the Indus Basin between the Ravi and Chenab rivers in Pakistan. The area comprises 381 km<sup>2</sup> and is located between latitude 31° 27' to 31° 47' N and longitude 73° 52' to 74° 6' E (Fig. 2). The climate of the area is semi-arid and monsoonal and is characterized by long and hot summers lasting from April through September (Kharif season) and cold winters usually considered as October through March (Rabi season). *Rabi* season starts on the 1st of October and ends on the 31st of March. The principal crops are barley, wheat, gram and oil seed. *Kharif* season starts on the 1st of April and ends on the 30th of September. Principal crops of this season are rice, cotton, groundnut, etc. Sugarcane covers both seasons. May and June are the hottest months with a mean daily maximum temperature of around 40°C. December and January are the coldest months with a mean daily minimum temperature of around 6°C. The annual rainfall for the last 66 years averaged 550 mm with 75% occurring during the monsoon from June to September. The topography of the area is almost plain with a slight inclination of about 0.025% from north to south. The soils of the study area are moderately coarse to medium texture, rich in plant nutrients adaptable to a wide variety of crops. With respect to agro-climatic conditions, the area falls in the rice-wheat zone. Rice occupies about 35% and wheat about 40% of the cultivable area. The large link canals, Qadirabad-Bulloki (4.1×10<sup>5</sup> L/s) and Upper Chenab (2.3×10<sup>5</sup> L/s), flow along the south-west and north-east boundaries of the study area. The growing season is sufficiently long for harvesting two crops, and in irrigated areas double cropping is widely practiced.

The surface water supply to the area is provided through the Upper Chenab canal system of the Indus Basin. The area covers 95% perennial canal command and farmers get water in proportion to their land according to the Warabandi system. The Warabandi refers to an irrigation water distribution method at the farm level, for which there are clear guidelines regarding the individual farmer's turn and duration of irrigation water available to him. Permanent Warabandi is administered in a rigid and fixed manner by the provincial Irrigation Department. The temporary Warabandi is generally established by the beneficiaries of watercourses with mutual understanding. Apart from the high-capacity public tubewells (75–140 L/s) for supplementing canal water supplies, a large number of private tubewells with an average capacity of about 25 L/s have also been developed by farmers. The public tubewells are owned by the government and private tubewells are owned by the farmer. In a supply-driven irrigation system, with an already rigid availability of surface supplies for meeting crop water requirements, tubewell pumpage becomes a demand-driven water supply available to farmers. These tubewells operate more during the Kharif season when crop water requirements are high. The variation in density of these wells within the area is quite marked and appears to be related to the scarcity of canal water (Sarwar 1999).

### Hydrogeology of the Indus Basin

The Indus Plain covers a gross area of about 20 million ha extending from the Himalayan Mountains to the Arabian Sea. The study area is a part of the abandoned flood plain. The basement is formed by the underlying metamorphic and igneous rocks of Precambrian age. The area is underlain by highly-stratified unconsolidated alluvial material composed of sand of various grades interbedded with discontinuous lenses of silt, clay and nodules of kanker—a calcium carbonate of secondary origin deposited by present and ancestral tributaries of the Indus River.

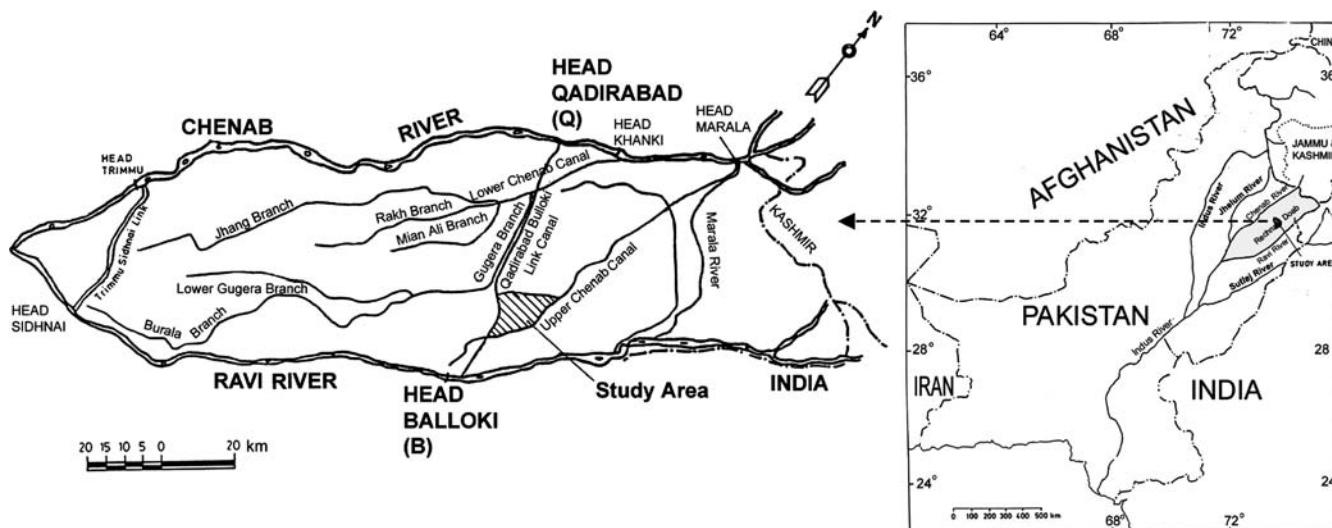


Fig. 2 Geographical location of the study area

A study of the drill cuttings and electric logs revealed an absence of thick horizons of pure clay within the alluvium. Except for local clay lenses, which are a few meters thick, the finer parts consist generally of sandy, gravely or silty clay with a considerable thickness of 180 m or more, as shown in Fig. 3. The material is highly porous and is capable of storing and transmitting water readily, as the horizontal permeability is greater than the vertical. Unconfined groundwater occurs extensively over the basin.

**Aquifer characteristics**

The aquifer characteristics were evaluated largely on the basis of numerous pumping tests carried out in the past by Water and Soil Investigation Division (WASID) of the Water and Power Development Authority (WAPDA) of Pakistan. Hydraulic conductivity and specific yield values of the aquifer were estimated from these pumping tests following a time drawdown method (Bennett et al. 1967). The hydraulic conductivities around the study area determined by the above tests vary from 47 to 120 m/day and the specific yield ranges from 0.01 to 0.13. The quality of groundwater in most of the area is good, ranging in salinity from 500–1,000  $\mu\text{S}/\text{cm}$ . The shallow and underlying deep-water quality is found to be generally similar but shallow water is somewhat less hazardous for most of the crops when compared with deep water. General movement of groundwater is from the north-east to south-west.

**Drainage**

The general slope of the study area is from north to south averaging about 0.25 m/km. A number of the drains such as Sheikhpura, Ghazi, Bhikki and Chichokimallian, or a part of them, traverse through the area. The catchment areas for these drains, which facilitate the disposal of residual runoff, vary from 40 to 250  $\text{km}^2$ . A depth of 4.0 m below the ground surface was regarded as critical. When water table depth was equal to or greater than 4.0 m, seepage to drain was assumed to be zero. The general survey indicated that these drains were not operating satisfactorily. However, it is not on record that standing crops were destroyed or even damaged in any area due to flooding and stagnation of rainwater. The study area was also not subjected to flood spills from any nearby natural drain or stream during the period of simulation. The water table in the area is quite deep and these drains now only serve the purpose of removal of runoff during the monsoon season.

**Estimation of net groundwater recharge (Q)**

The net recharge is defined as the algebraic sum of rainfall, evapotranspiration (ET), surface runoff, canal losses from irrigation channels traversing the area (from those running along or close to the boundary), seepage from farmer’s irrigation channels (watercourses), irrigation losses, seepage to drains, evaporation from bare soil, abstraction by pumped wells and artificial recharge (if

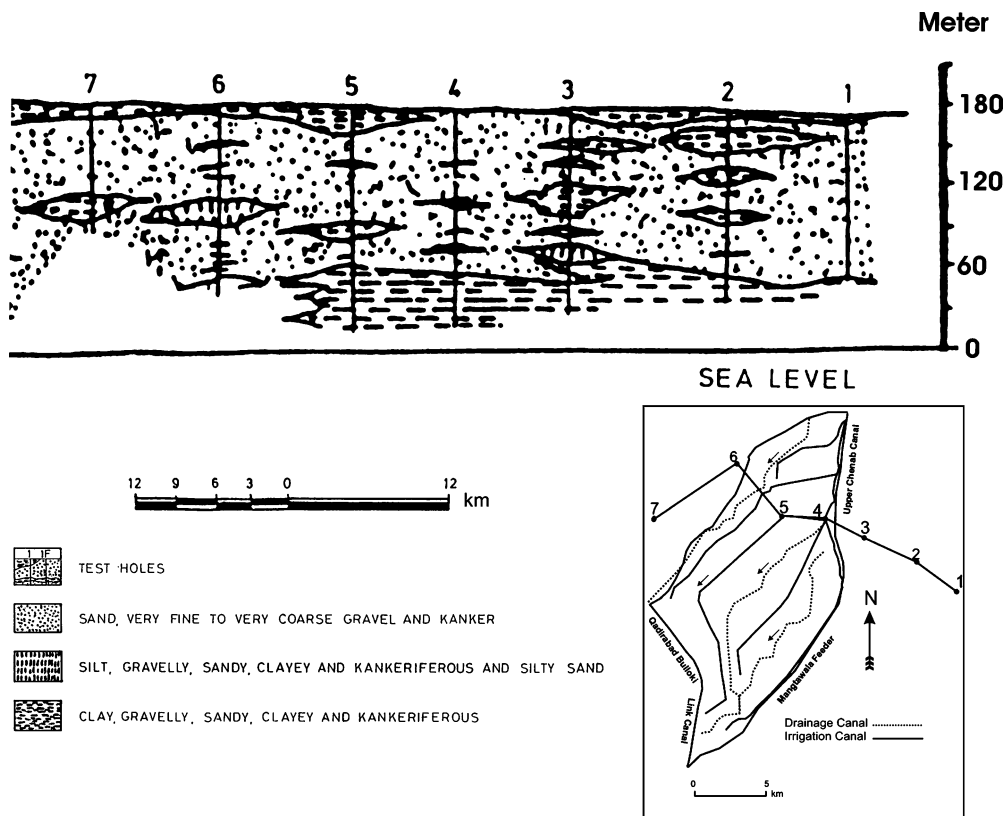


Fig. 3 Depth of test holes and geological cross-section of the aquifer



any; Boonstra and Ridder 1990). Various recharge and discharge components of a typical irrigated agriculture in an Indus irrigation system contributing to net recharge are shown in Fig. 4. The surface water to the area is supplied through irrigation distribution networks. The groundwater is pumped through high-capacity public tubewells as well as from shallow private wells to meet water requirements of crops. In addition to rainfall, some water returns to the aquifer via seepage from canals and watercourses and deep percolation losses from irrigated fields supplied by groundwater. Large link canals carrying water from adjacent areas are also sources of recharge to the aquifer.

The water balance of an irrigated area can be carried out, based on the balance between the quantity of water entering into the area and amount stored or leaving the same area during a certain period of time. In its simplest form, the general mass conservation equation for any hydrologic system can be written as:

$$I - O = \pm \Delta S_t \tag{1}$$

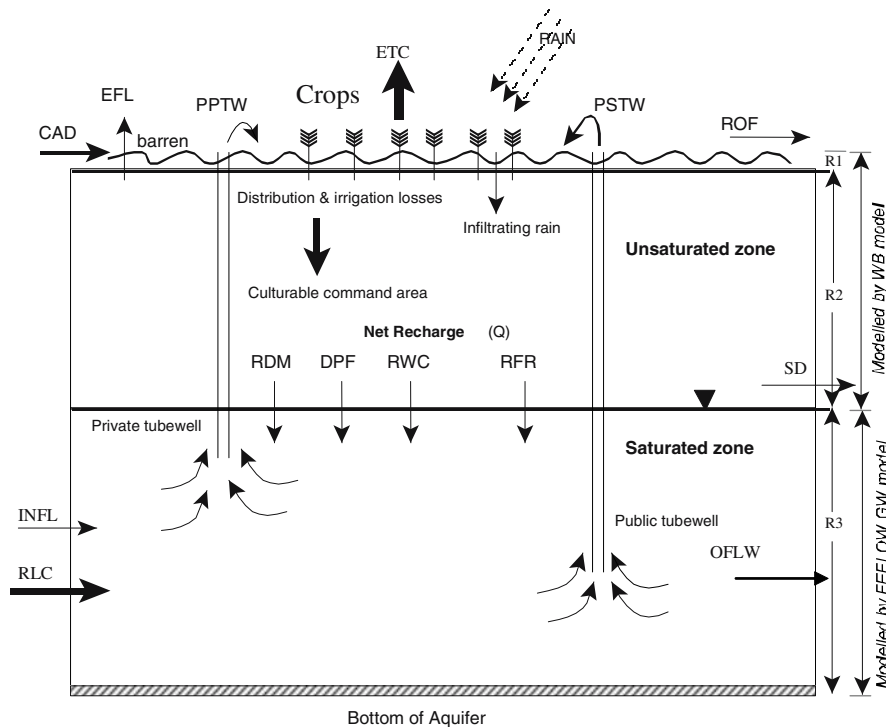
where  $I$  = total inflow,  $O$  = total outflow and  $\Delta S_t$  = change in groundwater storage during a particular time  $t$ .

The net recharge of an irrigated area can be expressed as:

$$Q = RFR + DPF + RDM + RWC + RLC + INFL - OFLW - ROF - ETC - EFL - PSTW - PPTW - SD \tag{2}$$

where  $Q$  = net recharge to the aquifer,  $RLC$  = recharge from link canals,  $INFL$  = inflow from adjacent area,  $OFLW$  = outflow to adjacent area,  $RFR$  = recharge from rainfall,  $DPF$  = deep percolation from irrigated field (here, irrigation includes canal supplies and pumpage through private and public tubewells),  $RDM$  = recharge from distributary and minor channels,  $RWC$  = recharge from watercourses,  $ETC$  = crop evapotranspiration,  $PPTW$  = pumpage by private tubewells,  $PSTW$  = pumpage by public tubewells,  $ROF$  = surface runoff,  $SD$  = seepage from the saturated zone to surface drains at the water table and  $EFL$  = evaporation from fallow/bare soil.

Generally speaking, three reservoirs occur in the flow domain: at the land surface itself, in the zone between the land surface and water table, and in the zone between the



Where R1= surface water reservoir, R2= sub-surface water reservoir, R3= groundwater reservoir, Q= net recharge to aquifer, EFL= evaporation from fallow land, PSTW= pumpage by public (SCARP) tubewells, ETC= crop evapotranspiration, CAD= canal deliveries, RAIN= rainfall, PPTW= pumpage by private tubewells, ROF= surface run-off, RFR= recharge from rainfall, DPF= deep percolation from irrigated fields, RDM=recharge through distributories and minor channels, RWC=recharge through watercourses, SD= seepage from saturated zone to surface drains, RLC= recharge from link canal, INFL= inflow from adjacent areas, OFLW is outflow to adjacent area, Finite Element subsurface FLOW system (FEFLOW GW) and Water Balance (WB).

**Fig. 4** Recharge and discharge components contributing to net recharge

water table and the impermeable base. Since flow in the saturated zone (groundwater reservoir) was simulated using a groundwater model, the net recharge to the groundwater reservoir was computed by integrating the water balance for the unsaturated zone with the water balance at the land surface. To minimize assumptions, both zones were coupled together. The recharge from large boundary link canals (RLC) in the study area was calculated by imposing constant head boundary conditions along these canals and inflow from adjacent areas (INFL) was computed using flow lines and hydraulic gradient between them. The pumpage through public tubewells were introduced as a point withdrawal in the groundwater modelling, hence pumpage through these tubewells was also not considered as a discharge component in the water balance computation. Equation (2), therefore, can be simplified as:

$$Q = \text{RFR} + \text{DPF} + \text{RDM} + \text{RWC} - \text{ROF} - \text{ETC} - \text{PPTW} - \text{EFL} - \text{SD} \quad (3)$$

Irrigation deliveries and pumpage through private tubewells were considered as lump parameters for each sub-area. Loss through canal systems and watercourses were estimated on the basis of the quantum of water supplied to each sub-area by introducing an empirical equation given by Fiering (1971). Lowdermilk et al. (1978) conducted various experiments using the inflow–outflow method and expressed the losses from canal and watercourses as a certain percentage of water delivered at the head. They found, on the basis of a series of calculations, that 6% of the total canal loss is evaporated from canal surfaces and a further 6% was evaporated/transpired by canal bank vegetation. These losses were kept within certain limits as reported by Lowdermilk et al. (1978) and the Water and Power Development Authority (WAPDA 1982). Stamm's (1967) method was used to compute effective rainfall. The detail of the computation of various recharge and discharge components is presented in Sarwar (1999); however, a brief description is presented below.

### **Recharge from distributaries and minor channels (RDM)**

Various studies revealed that loss from a canal system depends on the quantum of water supplied to the system, the nature of the soils through which the system passes and length of the system. WAPDA (1982) has taken 30% of the canal water as seepage losses and 75% of the lost water was assumed to recharge the groundwater reservoir. The same criterion as reported by WAPDA (1982) was adopted to estimate the recharge to groundwater from canal seepage.

### **Recharge from farmer's watercourses (RWC)**

WAPDA (1982) has estimated the losses through watercourses to be in the range of 10 to 20% of the watercourse head discharge. Since existing public and private tubewells deliver pumped water at the head of watercourses, seepage through watercourses were computed by the same method as for canal seepage, except that canal deliveries (CAD) includes both tubewell and canal supplies reaching the head of watercourses.

### **Recharge from rainfall (RFR)**

The contribution of rainfall to groundwater recharge was considered in the surface water balances at the field level. Stamm's (1967) method was used to calculate the effective rainfall for the cropped area. To account for interception, evaporation and surface runoff, he has given percentage values to increments of monthly rainfall ranging from greater than 90% for the first 25 mm to 10% for the precipitation increment above 150 mm.

### **Estimation of crop evapotranspiration (ETC)**

Evapotranspiration is the combined effect of the evaporation of water from moist soil and the transpiration of water by cultivated crops. Accurate estimation of the evapotranspiration (ETC) is important in groundwater modelling of irrigated areas, particularly in estimating the net recharge. Because of the difficulty and time-consuming procedure involved in obtaining direct measurements of water use by crops or natural vegetations, a large number of methods have been developed to calculate these values. An excellent review of various methods for estimation of reference evapotranspiration (ETR) is given in Doorenbos and Pruitt (1977). All methods for computing crop ETC involve the following equation:

$$\text{ETC} = \text{Kc} \times \text{ETR} \quad (4)$$

where ETC = evapotranspiration of a specific crop (L/T, e.g. mm/day, mm/month, inches/month, etc.), ETR = potential or reference evapotranspiration (L/T) and Kc = crop coefficient (dimensionless). After combining the derivation for the aerodynamic and radiation terms, the Penman-Monteith combination formula (Allen et al. 1998) can be written as:

$$\text{ETR} = \frac{\{0.408\Delta(R_n - G) + \gamma[900/(T_a + 273)]U_2(e_a - e_d)\}}{[\Delta + \gamma(1 + 0.34U_2)]} \quad (5)$$

where ETR = reference crop evapotranspiration (mm/day),  $R_n$  = net radiation at crop surface ( $\text{MJ m}^{-2}\text{day}^{-1}$ ),  $G$  = soil heat flux ( $\text{MJ m}^{-2}\text{day}^{-1}$ ),  $T_a$  = average air temperature ( $^{\circ}\text{C}$ ),

$U_2$  = wind speed at 2 m height (m/s),  $e_a$  = saturation vapour pressure (kPa),  $e_{day}$  = actual vapour pressure (kPa),  $\Delta$  = slope of saturation vapour pressure–temperature curve at air temperature (kPa °C<sup>-1</sup>),  $\gamma$  = psychrometric constant (kPa °C<sup>-1</sup>). The computer software CROPWAT4W was used to estimate reference crop evapotranspiration (Smith et al. 1990). The method requires maximum and minimum air temperature, relative humidity, wind speed and bright sunshine. The crop coefficient values for various crops for local climatic conditions were obtained from On-Farm Water Management (OFWM 1986) and the Pakistan Agricultural Research Council (PARC 1982).

### **Evaporation from fallow land and land that has never been cultivated (EFL)**

Correlation of evaporation rate and water table depth has been derived by various investigators (WAPDA 1982; Boonstra and Ridder 1990). Equation (6), as proposed by WAPDA (1982), was adopted to compute evaporation from fallow and areas that have never been cultivated:

$$EFL = EPF \times FSE(1 - XR) \times CCA \quad (6)$$

where EFL = evaporation from fallow land (L<sup>3</sup>/T), EPF = equivalent evaporation factor in terms of ratio of evaporation as related to depth of water table below land surface, FSE = free surface evaporation i.e., pan evaporation (L/T), XR = the ratio of cropped to culturable area and CCA = the culturable command area (L<sup>2</sup>). The CCA was calculated from the geo-referenced topographic sheet (GT-sheet) and the satellite image of the study area and to compute EPF for various water table depths, the following equation proposed by Ahmad (1995) was used:

$$EPF = [(0.17/(0.20 + WTD))] + 0.009 \quad (7)$$

where WTD = water table depth (m).

### **Groundwater pumpage by private tubewells (PPTW)**

Pumpage through private tubewells was taken as a discharge component in the water balance model. Multi-Dimensional Consultants (MDC 1995) observed that the average annual utilization varied from 10 to 16%. The month-wise pattern of the operation of private tubewells was taken from Associated Consulting Engineers (ACE 1990). The monthly pumpage by private tubewells was computed using:

$$PPTW = 0.000036 \times NPTW \times UTF \times AD \times TOH \quad (8)$$

where PPTW = pumpage of groundwater by private tubewells (ha-cm)<sup>1</sup>, NPTW = number of private tubewells, UTF = the utilization factor for each month, TOH = total operational hours in a year (h), AD = the actual discharge of private tubewell (m<sup>3</sup>/s), 0.000036 = conversion factor.

<sup>1</sup> The ha-cm is a volumetric unit (if one cm depth of water is on one hectare of land, then it is considered as 1 ha-cm).

To determine the utilization factor, a number of farmers were asked about the number of hours their tubewell operated daily or weekly. MDC (1995) observed through a field survey that the average annual utilization factor varied from 10 to 16%. The monthly utilization factor is presented in detail in Sarwar (1999).

### **Seepage to surface drains (SD)**

At the start of simulation in 1982, in certain areas, the water table was shallow (<2.5 m below surface) and there was a possibility of seepage into the nearby drains, hence the seepage to surface drains was introduced as an outflow component. Due to heavy pumping, however, groundwater levels have fallen to more than 2.5 m from the surface since 1984. Therefore, the seepage from groundwater to drains was found to be insignificant. Fiering's (1971) approach was used to compute groundwater seepage to surface drains, when the water table stood higher than the bed level of the drain. The maximum seepage was adjusted in the model to obtain a reasonable match between the observed and computed water-table elevation.

### **Deep percolation from irrigated fields (DPF)**

In the model, surface water balance was considered at the field level and any differences between recharge and discharge components were computed. The value thus obtained could be positive or negative; these are positive when supplies are more than crop water requirements and evaporation losses, and negative otherwise. In the case of a negative value, crop water requirements were assumed to be met from groundwater and for positive values, the percolated water is recharged to the aquifer. This leads to the following relation:

$$DPF = CADF + PUMPF + RAIN - ETC \quad (9)$$

where DPF = deep percolation from fields (L/T), CADF = canal deliveries reaching the fields (L/T), PUMPF = pump deliveries reaching the fields (L/T), RAIN = rainfall remaining in the field after runoff and interception (L/T) and ETC = crop evapotranspiration (L/T). Most of the farmers in the area have their own private tubewells to supplement the crops' water requirements. In a supply-driven irrigation system with an already fixed availability of canal supplies, tubewell pumpage becomes a demand-driven water supply available to farmers who can pump the water as per requirements. As a result, there is a higher cropping intensity (150%) in the area because the farmer has access to groundwater as and when required. Hence, ETC was considered to be the maximum evapotranspiration.

Various components were then used to compute the net recharge on a monthly basis using the following relation:

$$Q = DPF + RWC + RDM + RFL - ETF - SD \quad (10)$$

where  $Q$  = net recharge (L/T), DPF = deep percolation from irrigated fields (L/T), RDM = recharge from distributaries and minor channels (L/T), RWC = recharge from watercourses (L/T), RFL = recharge to groundwater from fallow land (L/T), ETF = evaporation from fallow and never cultivated areas (L/T) and SD = seepage to surface drains from groundwater (L/T).

**Division of study area into sub-areas**

To compute water balance from each sub-area, the study area was divided into six sub areas. The sub-areas were bounded by drainage divides and divided so that irrigation could easily be accounted for (Fig. 5). The GIS software ArcView 3.1 (ESRI 1996) was used for the division of the total area into surface sub-areas (using polygons in GIS). The water-balance model representing the surface processes was applied independently to each sub-area. This allowed spatial modelling of hydrological processes, as different input data and parameter values can be used for different sub-

areas. However, as surface parameters did not differ significantly, similar parameters were used within each sub-area. This approach improves the modelling of spatial variation of recharge resulting from irrigation deliveries and pumpage by public and private tubewells without complicating the calibration procedure.

**Modelling of groundwater flow**

The groundwater basin was discretized into 2,319 two-dimensional triangular elements with 1,244 nodes with finer discretization around the discharge wells where higher drawdowns were expected (Fig. 6). As there were a large number of Salinity Control and Reclamation Project (SCARP) tubewells in the study area, locating a node on each tubewell resulted in a mesh fine enough to represent the spatial variability within the area. Nodes were also located wherever observation wells were available to calibrate the model against the water level recorded in the wells. The operations of both models were carried out on a monthly basis, as reliable data on irrigation deliveries and groundwater pumpage were available only at 1-month time intervals. Furthermore, the advantage of using the same time step for both

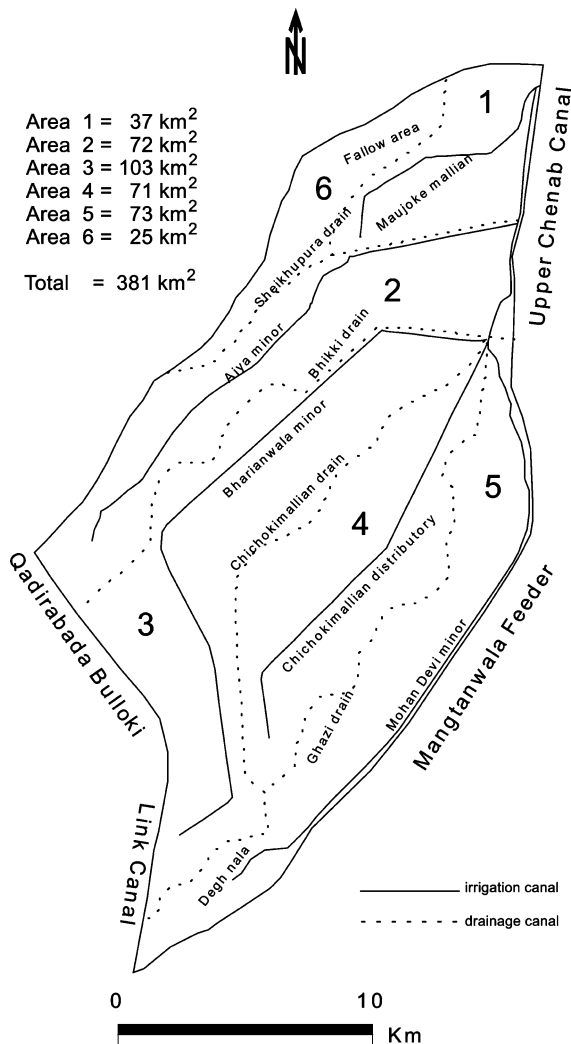


Fig. 5 Division of study area into surface sub areas

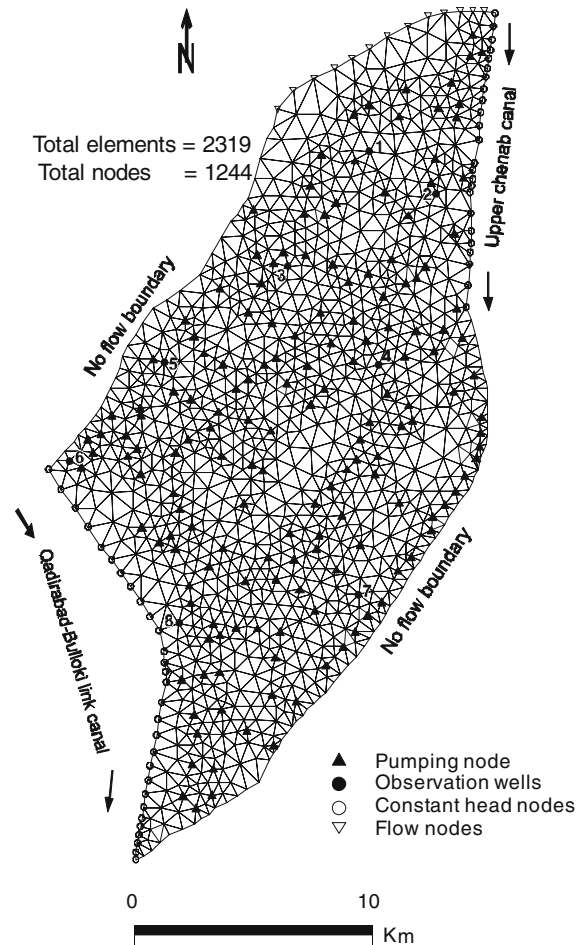


Fig. 6 Finite element mesh for simulating groundwater flow



models was that it removes any inconsistency between surface- and groundwater models which might become apparent when different time steps are simulated in each model (Yan and Smith 1994). Prescribed-head-boundary conditions were assigned along the link canals based on the historical water level record in the canals.

### **Initial, boundary and constraint conditions**

For reasons of data availability, 1982 was chosen as the initial year to simulate the groundwater flow. Prescribed-head-boundary conditions were assigned along the link canals based on the historical water level record. Boundary constraints have also been imposed on these canals to keep the seepage rate within a certain range. The north-west and south-east boundaries coincide with groundwater flow lines and were assumed to be no-flow boundaries, whereas the north boundary was assumed to be a flow boundary. Nodal flow rates for this boundary were assumed to be constant throughout the period of simulation.

### **Handling of time variant data in groundwater modelling**

The time-variant data in the modelling of groundwater include monthly pumping through public tubewells applied at the pumping well node and monthly net recharge to groundwater applied to each sub-area. To simulate outflow through pumping wells, databases were prepared on a monthly basis for all 165 tubewells by assigning different identification numbers (IDs) to each tubewell. These IDs were then attached to the respective pumping nodes of the finite-mesh using a background map prepared via GIS. The second important time-variant data were the dynamic net recharge for each sub-area from water balance model. To handle data more efficiently and repeatedly for the purpose of calibration and forecasting, data were organized in the form of polygons (sub-areas) with associated time curves. These monthly time curves were also assigned identification numbers (different IDs) and attached to the respective polygonal maps prepared via GIS using the JOIN operation of the FEFLOW groundwater model. This operation assigned the values from power functions to the respective elements inside each polygon. During the process of calibration, verification and forecasting analysis, the water-balance model was run for each sub-area and new databases were generated. The same procedure as explained above was followed for each sub-area to attach the data to the respective polygons.

### **Model calibration and verification**

A transient calibration of the model was done using a trial and error procedure (Anderson and Woessner 1992). Simulated and measured values of water levels were compared and aquifer parameters were adjusted to improve the fit. Water-level measurements throughout

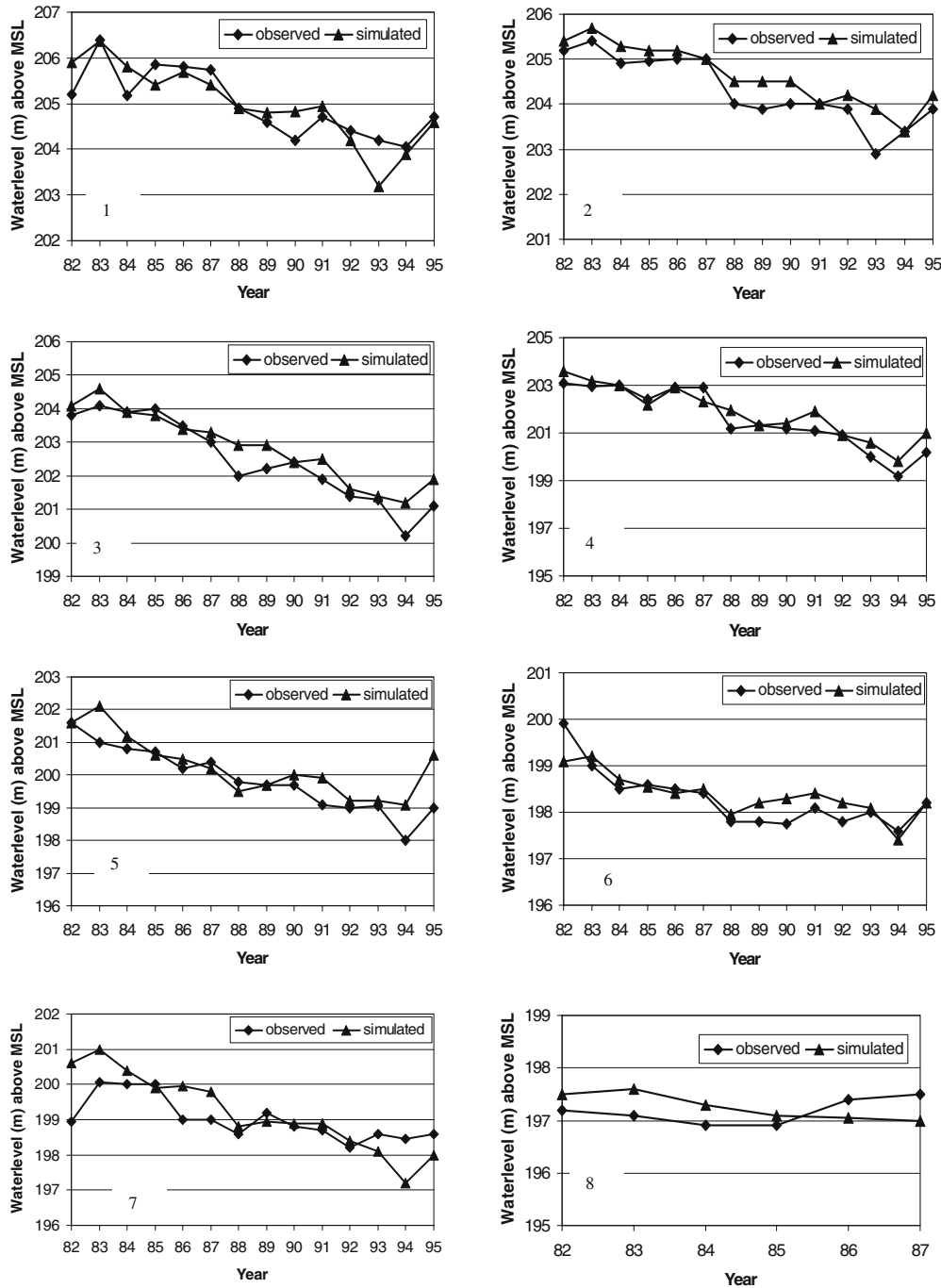
Pakistan are carried out twice per year, once before the monsoon at the beginning of June and then after the monsoon in October to study the effect of monsoon rainfall on water-table depth. Due to non-availability of sufficient data measured in the month of October, the water levels measured at the beginning of June were used for model calibration and verification purposes. Eight observation wells were used as 'fitting' wells after consideration of their data availability and distribution in the region. The FEFLOW datatool package (WASY 1998) was used to extract simulated values at locations for which observed values were available for calibration purpose. The calibration of the model was done using water-level data from 1982 to 1990 and another set of data, available from 1991 to 1995, was then used to verify the model. The water table elevations simulated by the model were compared with observed levels at eight locations as shown in Fig. 7. The scatter plots and regression analyses of the calibration and verification periods indicate that the agreement between simulated and measured water levels was reasonably good as shown in Fig. 8a,b.

The error parameters, mean error (ME) and root mean square error (RMSE) from 1982 to 1995 were used for evaluating the calibration and verification quality at all locations (Table 1). An examination of the spatial distribution of these errors showed that comparatively large errors were confined to an area near the eastern and north-western boundaries of the study area, where no-flow boundary conditions were imposed. This is due to the fact that large numbers of tubewells were also located near these boundaries, therefore, the possibility of occasional partial inflow from the outside could not be ignored due to the drawdown effect; however, this situation was found to be very rare during the long period of simulation. The RMSE was found to vary from 0.17 to 0.41. The model was considered to have been calibrated satisfactorily.

### **Future Simulations**

To study the groundwater behaviour as a result of different stresses on the aquifer, the verified model was used to evaluate different options for the aquifer system under consideration. For this purpose various scenarios were developed as presented below. In developing the various scenarios, the following points were taken into consideration:

- The concept of the second SCARP Transition Project (SSTP) was based on the Government's policy of transferring the responsibility of development and management of groundwater from the public to the private sector. This involves the termination of SCARP tubewells and installation of private tubewells (PTWs)/ community tubewells (CTWs).
- Under the On-Farm Water Management (OFWM) programme, watercourses are being lined, each up to 15% of its entire length of about 5 km. The improvement of watercourses will increase the surface water availability at the field level to a certain extent.



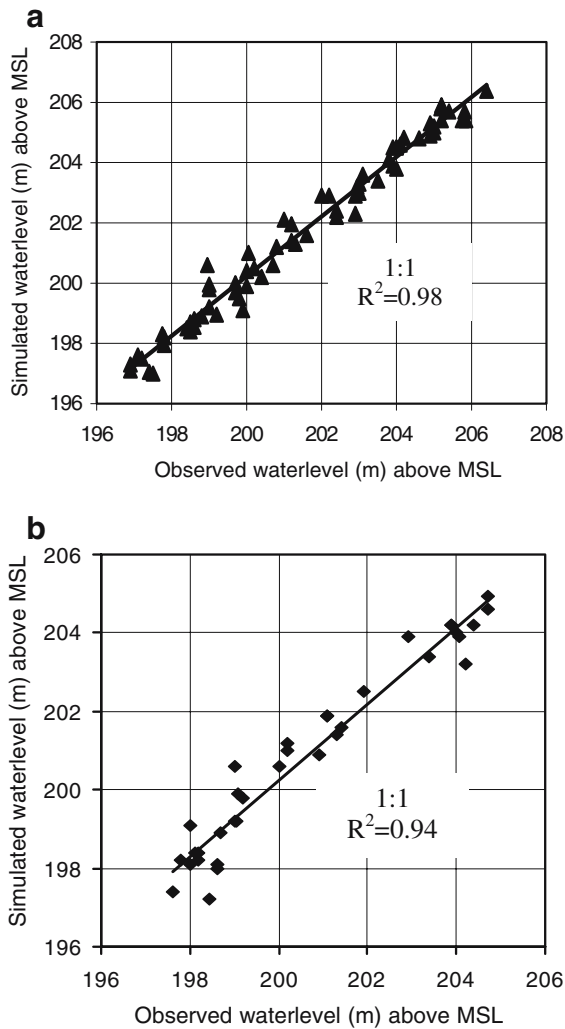
**Fig. 7** Comparison of simulated and observed groundwater levels at eight locations (see Fig. 6), for the calibration and verification period (1982–1995)

The consequence of such a surface-water management effort needs to be quantified.

- The cropping intensity, which is defined as the ratio of the total cropped area to the actual cultivated area in each year, continuously increased over time due to the availability of increased water supply by the increased number of private tubewells. This trend is likely to be continued into the future as well and may result in increased groundwater abstraction. At present, surface water supplies fulfil the requirements that satisfy a

cropping intensity of about 75%, under the existing cropping pattern. It is likely that the present trend of installation of private tubewells by the farmers through their own resources may increase the use of groundwater to attain a cropping intensity of 150% for the same cultivable area, by allowing two seasons per year (Kharif and Rabi).

- Due to a shortage of surface-water supply and a depletion of groundwater resources in many areas, there is the chance that there may be a replacement of



**Fig. 8** **a** Simulated and observed groundwater level for the calibration period (1982–1990), and **b** simulated and observed groundwater level for the verification period (1991–1995), where  $R^2$  is the regression coefficient

high-water requirement crops with crops with a low-water requirement. The effects of such changes also need to be studied.

The above-mentioned points were taken into consideration to develop various scenarios as presented in Table 2 and simulations were extended from June 1995 (the last step of the verification period) to the year 2010.

The results indicate that if the present conditions of irrigation and agriculture continue, the mean water table will decline to 4.17 m below the soil surface by 2010 with a net change of  $-0.14$  m. The linear increase in cropping intensity from its value in 1995 to about 150% in 2005, remaining constant until 2010, causes a significant fall of 2.54 m in the water table. This is because canal deliveries are fixed and the required irrigation water has to be drawn from groundwater storage. The combined impact of the increase in cropping intensity and 25% reduction in seepage losses due to lining of watercourses will cause a decline in the water table of 2.10 m. This is due to the fact that the reduction in watercourse losses will cause an increase in surface water availability to some extent and consequently a lesser amount of irrigation water needs to be drawn from groundwater storage to fulfil the crop water requirements. Under the scenario that if the cropping intensity and farmer’s watercourse losses will be the same as in 1995 and pumpage is increased by 30% of that in 1995, the water table will decline to 4.42 m below the ground surface, causing a net change of  $-0.39$  m; similarly a 60% increase in pumpage causes a net change of  $-0.83$  m. With a 10% reduction in rice cultivation and a 20% increase in maize cultivation, the water table was raised by 0.24 m. The reason of this is that the irrigation requirement of maize is much less compared to rice and, therefore, double cultivation of maize is possible with the same amount of water.

**Table 1** Goodness-of-fit statistics for comparison between simulated and observed levels

Sites	1	2	3	4	5	6	7	8
ME	0.02	0.18	-0.21	-0.06	0.05	0.09	0.18	0.14
RMSE	0.22	0.23	0.31	0.25	0.41	0.17	0.39	0.20

ME mean error

RMSE root mean square error

**Table 2** Details of developed scenarios and simulated results (mean WTD in 1995 is 4.03 m)

Scenario	Description	Mean WTD in 2,010 (m)	Net change (m)
1	Present conditions continue, i.e. cropping intensity (CI 130%) till 2010	4.17	-0.14
2	Cropping intensity increased linearly to 150% by 2005 and then remained constant until 2010	6.57	-2.54
3	Cropping intensity increased linearly to 150% by 2005 with watercourse losses decreasing to 25% from 1995	6.13	-2.10
4	Pumpage increased to 30% from 1995 with all other conditions remaining constant	4.42	-0.39
5	Pumpage increased to 60% from 1995 with all other conditions remaining constant	4.86	-0.83
6	Reduction in rice cultivation by 10%, and a 20% increase in maize cultivation from 1995, with all other conditions remaining the same	3.79	+0.24

## Conclusions

The developed model is a useful tool for evaluating alternative options for the management of surface and groundwater resources. The use of GIS facilitates allow rapid and accurate assembly of large amounts of input and output data. Increase in pumpage from the present rate will further strain the scarce water resources. Lining of watercourses could be adopted as an alternative to a possible increase in surface water supplies. By increasing the area under maize cultivation and a corresponding decrease in rice, more area can be brought under cultivation without stressing the water resources.

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