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SUSTAINABLE USE OF GROUNDWATER FOR IRRIGATION: A NUMERICAL ANALYSIS OF THE SUBSOIL WATER FLUXES[1]

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ABSTRACT

The food-producing regions of the world increasingly rely on irrigation from groundwater resources. Further increases of groundwater use can adversely affect the sustainability of irrigated agriculture and put food security at risk. Sustainability of irrigation at field scale with groundwater is obtained if groundwater recharge is in equilibrium with tubewell extractions and capillary rise. Traditional information on phreatic surface behaviour does not explain the processes causing a phreatic surface to decline or incline. In this study, the physically based numerical model Soil–Water–Atmosphere–Plant (SWAP) was applied to compute soil moisture content and vertical soil water fluxes in the unsaturated zone for the cotton–wheat and rice–wheat cropping system of Punjab, Pakistan. SWAP has been calibrated and verified with *in situ* measurements of soil moisture content and evapotranspiration fluxes measured by means of the Bowen ratio surface energy balance technique. Accurate data of the soil hydraulic properties are critical for the calibration of the soil moisture distribution. With knowledge of the van Genuchten–Mualem parameters available, SWAP could be applied to assess recharge and capillary rise for most field conditions, including basin irrigation. The results under Pakistani conditions show that deep percolation cannot always be estimated from root zone water balances. An annual recharge of 23.3 cm was computed for the cotton–wheat area. Sustainability of irrigation with groundwater is obtained if a reduction in irrigation with groundwater by 36% is obtained. An annual recharge of 38.9 cm is estimated in rice–wheat systems, and a reduction of 62% in groundwater extraction is required to reach sustainability of groundwater use at field scale. Such information cannot be obtained from classical phreatic surface fluctuation data, and unsaturated zone modelling therefore provides additional insights for groundwater policy making. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: groundwater; irrigation; aquifer over-exploitation; recharge; net groundwater use; field scale modelling; Pakistan

RÉSUMÉ

Les régions de production alimentaire de la planète se servent de plus en plus de l'eau souterraine pour l'irrigation. Ultérieurs accroissements de l'utilisation des eaux souterraines peuvent avoir des répercussions négatives sur l'irrigation agricole soutenable et sur la sécurité alimentaire. Une irrigation soutenable au niveau de la parcelle cultivée en utilisant l'eau souterraine est obtenue si le taux de recharge de cette dernière est en équilibre avec le taux d'extraction des puits et la remontée capillaire. L'information traditionellement

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[1] Utilisation soutenable de l'eau souterraine pour l'irrigation: une analyse numérique des flux d'humidité du sous-sol.

disponible concernant l'évolution du niveau phréatique ne permet pas d'expliquer les procès qui causeraient son abaissement ou son accroissement. Cette étude présente les resultats obtenus grâce à l'utilisation d'un modèle numérique appelé Soil–Water–Atmosphere–Plant (SWAP), qui se base sur des principes physiques, avec lequel ont été calculés les taux d'humidité du sol et les flux verticaux d'humidité dans la zone non-saturée du sol pour ce qui concèrne le système de cultivation coton–blé et riz–blé du Pounjab, au Pakistan. SWAP a été calibré et verifié grâce à des mesures *in situ* du taux d'humidité du sol et des flux d'évapotranspiration quantifiés en appliquant le rapport de Bowen, basé sur le concept du bilan énergétique au niveau du sol. Disposer de données prises concernant les propriétés hydrauliques du sol est essentiel pour calibrer la distribution de l'humidité du sol. Grâce à la connaissance des paramètres de van Genuchten–Mualem disponibles, SWAP a pu être utilisé pour évaluer le taux de recharge et la remontée capillaire en fonction de différentes conditions du terrain, irrigation de bassin incluse. Les résultats sous les conditions Pakistanes montrent que la percolation profonde ne peut pas toujours être estimée par les équilibres hydrologiques de la zone radicale. Une recharge annuelle de 23,3 cm a été estimée pour la zone coton–blé. L'utilisation soutenable de l'eau souterraine pour l'irrigation serait obtenue si on en réduisait l'extraction de 36%. Pour ce qui concerne la zone riz–blé, une recharge annuelle de 38,9 cm a été estimée, et une réduction de 62% de l'extraction de l'eau souterraine serait nécessaire pour une utilisation soutenable de l'eau souterraine à l'échelle de la parcelle cultivée. Ces informations ne peuvent pas être obtenues sur la base des données ordinaires concernant les fluctuations du niveau phréatique; la modélisation représente donc un appui essentiel en matière de prise de décision concernant la gestion de l'eau souterraine.

MOTS CLÉS: irrigation; eaux souterraines; surexploitation de l'aquifère; recharge des eaux souterraines; utilisation nette de l'eau souterraine; modélisation au niveau de la parcelle cultivée; le Pakistan

INTRODUCTION

Groundwater plays a vital role in sustaining agricultural productivity in many irrigated areas in the world. In most of these regions, the level of aquifer exploitation has reached its maximum potential or has already exceeded it. Further increase in groundwater use will cause lowering of the phreatic surface below which extraction will no longer be economically viable and will harm the environment. Furthermore, if the present groundwater extraction patterns continue, it will soon result in saltwater intrusion. Irrigation with saline groundwater will increase the risk of secondary salinity and sodicity by importing salts from the deep aquifer to the root zone. But also the opposite with a fast rising phreatic surface is being witnessed. The immediate effect is that the required increased food production to feed the unprecedented growing population cannot be met in arid and semi-arid zones. To avoid these undesirable scenarios, it is recognized that groundwater withdrawals should balance with the rate of replenishment (De Vries, 1984).

Groundwater conditions are classically described by means of phreatic surface fluctuations. This provides direct information on the rate of changes. There is, however, one major drawback in studying phreatic surface data; how can a rise or fall of the phreatic surface be arrested? To answer this question, the cycle between tubewell extractions and recharge needs to be known. Also the groundwater contribution to crop evapotranspiration through capillary rise needs to be quantified, because this can be paramount in areas with a shallow phreatic surface and areas prone to waterlogging. This paper deals with a methodology that describes the subsoil water fluxes and addresses the need for greater information in managing this type of irrigation configuration. In particular the fluxes at the interface between the unsaturated and saturated zones need to be quantified. The difference between groundwater removal through tubewell and capillary rise vs. recharge is not straightforward to determine, not even on a field scale. To understand these complex transient recharge and groundwater use processes, a complete understanding of soil water fluxes in the unsaturated zone is essential (e.g. Hendrickx and Walker, 1997).

The Indus basin irrigation system of Pakistan is one of the largest contiguous surface irrigation systems in the world. A fixed quantity of canal water proportional to landholding is supplied on a weekly or 10-day rotation period, locally called *warabandi*. The losses from the earthen canal network and irrigated fields resulted in a rise of the phreatic surface in several places. The problem of a rising phreatic surface sometimes resulted in waterlogging and salinization in the Indus plain (Smedema, 2000). The first symptoms of the problem appeared in the first half of the twentieth century, but the problem reached alarming proportions in the period between 1950 and 1960.

To combat this menace, the government of Pakistan took several measures and encouraged the farming community, through tax reduction and other subsidies, to install private tubewells to pump groundwater for irrigation. This additional and timely water supply from groundwater resulted in a rapid increase in cropped area and yield. As a result, in the non-saline groundwater area, the number of tubewells increased drastically and there was a considerable increase in the cultivated area. Now the situation has arrived where groundwater is at its maximum exploitable potential. Further unplanned increases in groundwater withdrawal may ruin aquifers. As not all irrigation water is consumed by the crop, a recharge from irrigated plots to the aquifer is expected. The question is: how much?

The unsaturated zone, through which most important processes such as evapotranspiration and recharge take place, is heterogeneous and complex. A transient soil moisture transport model can provide a proper indication of how moisture in the unsaturated zone and the saturated phreatic aquifer interact. Investigation of the processes of recharge and net groundwater use with physically based models has two great advantages over other approaches. First, models can be used to understand processes that are difficult to measure *in situ*. Second, models can be used to forecast hydrologic processes under changing boundary conditions, such as changes in groundwater extraction and artificial recharge (Allison *et al*., 1994). This is highly useful for the modelling of different groundwater application scenarios.

The rate and volume of recharge and groundwater use largely depend upon irrigation and agronomic practices, and the physical characteristics of the soil, such as infiltration rate, water retention capacity and unsaturated hydraulic conductivity. Under gravity irrigation net groundwater use can be significantly less than expected, because a large fraction of irrigation water returns to the aquifer. Hence, management and policy making of groundwater issues are feasible, provided that the flow to and from the irrigated fields is understood. The main objectives of this research work are:

- To calibrate a numerical model that predicts the soil water fluxes at the interface between the unsaturated and saturated zones
- To understand soil moisture dynamics in the unsaturated zone of crops irrigated with groundwater in the Rechna Doab, Pakistan
- To estimate groundwater over-exploitation in areas with a deep and shallow phreatic surface

DEFINITIONS

To understand and quantify the recharge mechanisms and groundwater contribution to irrigated agriculture in phreatic aquifer systems, different soil water fluxes in a one-dimensional vertical soil column are presented in Figure 1. The water balance of the unsaturated zone reads as:

$$\frac{\Delta W_{\mathrm{u}}}{\Delta t} = I_{\mathrm{cw}} + I_{\mathrm{tw}} + P_{\mathrm{n}} - ET_{\mathrm{a}} + q^{\uparrow} - q^{\downarrow} \qquad (1)$$

where ΔW_{u} is the change in the unsaturated zone storage over a period of time Δt, I_{cw} is irrigation with canal water, I_{tw} is irrigation with groundwater (tubewell water), P_{n} is the net precipitation (gross precipitation P minus interception losses P_{i} and surface runoff), ET_{a} is the actual evapotranspiration, and q is the lower boundary flux of the unsaturated zone. Recharge $q^{\downarrow}_{(h_{\mathrm{m}}=0)}$ is the percolation or soil water flux that reaches the phreatic surface, i.e. the location where matric head is zero ($h_{\mathrm{m}} = 0$). Similarly, we have defined the capillary rise as $q^{\uparrow}_{(h_{\mathrm{m}}=0)}$, hence it is the upward flux between the saturated and unsaturated zone. The capillary flux does not necessarily convey moisture to the root zone. That depends on the distance between the phreatic water surface and the root zone, among many other factors. Groundwater use I_{gw} is the amount of groundwater being extracted from the saturated zone by means of pumping I_{tw} and applied on the soil surface for irrigation or

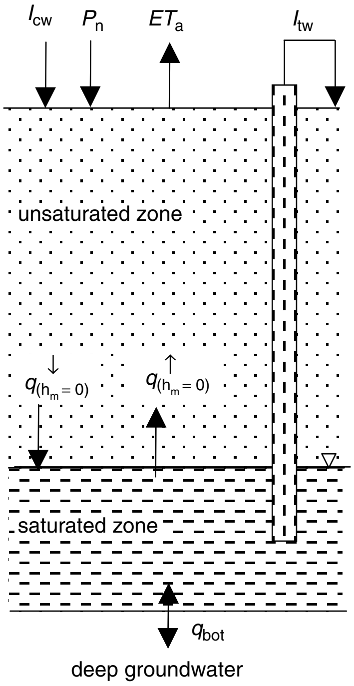

Figure 1. Schematization of different soil water fluxes in phreatic aquifer (I_{cw} is canal water irrigation, P_n is net precipitation, ET_a is actual evapotranspiration, I_{tw} is tubewell irrigation, $q^{\downarrow}_{(h_m=0)}$ recharge, $q^{\uparrow}_{(h_m=0)}$ capillary rise, q_{bot} bottom flux)

capillary rise from the phreatic surface ($I_{gw} = I_{tw} + q^{\uparrow}_{(h_m=0)}$). Net groundwater use is the part of groundwater use I_{gw}, which is not replenished by recharge ($I_{ngw} = I_{tw} + q^{\uparrow}_{(h_m=0)} - q^{\downarrow}_{(h_m=0)}$).

Water supply to the cropped area can be from three different sources, i.e. I_{cw}, I_{tw} and P_n. For sustainable groundwater management it is important to estimate the reliance of agriculture on groundwater resources. The groundwater resource ratio ξ can be estimated by the ratio of irrigation with groundwater I_{tw} to the total inflow from all sources ($\xi = I_{tw}/(I_{cw} + I_{tw} + P_n)$).

MATERIALS AND METHODS

Description of SWAP model

Water flow in the unsaturated zone is predominantly vertical, and can generally be simulated as one-dimensional flow (Romano *et al.*, 1998). Earlier versions of the one-dimensional physically based Soil–Water–Atmosphere–Plant (SWAP) model were developed by Feddes *et al.* (1978), Belmans *et al.* (1983) and Kabat *et al.* (1992). It has been tested for a number of hydrological studies under a wide range of climate and agricultural systems (e.g. Feddes *et al.*, 1988). SWAP has previously been applied and validated for the irrigation conditions in Pakistan, Iran and India (Bastiaanssen *et al.*, 1996; Van Dam and Feddes, 1996; Smets *et al.*, 1997; Beekma *et al.*, 1997, Sarwar *et al.*, 2000; Droogers *et al.*, 2001). In the present study, particular emphasis is given to changes of the vertical soil water fluxes with depth.

The SWAP model is based on Richard's equation, which combines Darcy's law and the continuity equation, for moisture transfer and the advection–dispersion equation for solute transfer (Van Dam *et al.*, 1997; Van Dam and Feddes, 2000). SWAP predicts the dynamic interaction between soil, water, atmosphere and plant on a daily time step. In order to solve these equations, the program uses a finite difference scheme with explicit linearization. In order to apply this finite difference scheme, the soil profile is divided into thin layers and soil horizons of similar hydraulic properties. SWAP may simulate up to three rotating crops in a year and contains three crop growth routines. In this study, a simple crop development model available in SWAP is used which only requires information about the leaf area index (or soil cover fraction), crop height and rooting depth as a function of crop development stage.

Study area

This research work was carried out in the Rechna Doab area of the Indus basin irrigation system. For a detailed analysis and understanding of the different components at a field level, two sites, Pindi Bhattian and Faisalabad, were selected.

Pindi Bhattian. The site at Pindi Bhattian is the experimental field of 0.42 ha (72 m long and 58 m wide) of the Soil Salinity Research Institute (SSRI), which is located on the north-western border of Rechna Doab (coordinates: 73°20′50.2″ E. 31°52′34.2″ N.). The site is flat and situated at an altitude of 212 m above sea level. The average precipitation is approximately 500 mm yr^{-1}. Two-thirds of the precipitation occurs during the monsoon period from July to September. The rice and wheat were sown in the summer season (*kharif*) and winter season (*rabi*), respectively. A double crop is practised. The phreatic surface is approximately 2 m below from the soil surface. A surface irrigation system with borders is employed and conjunctive use of canal and groundwater resources is applied.

Faisalabad. The second site is the experimental field of 0.21 ha (51 m long and 42 m wide) at the Cotton Research Institute of the Ayub Agricultural Research Institute (AARI), Faisalabad, which is situated in the centre of Rechna Doab (coordinates: 73°2′49.8″ E. 31°23′26.2″ N.). The flat area lies at an altitude of 130 m above sea level. The climate is drier than in Pindi Bhattian with an average annual precipitation of 360 mm, with a large fraction falling in the monsoon. Cotton was sown in *kharif* and wheat in *rabi* at this experimental site. The phreatic surface is fairly deep, approximately 10 m below the surface. There is conjunctive use of canal and groundwater resources.

Field data collection

Field data on various agronomic aspects required for SWAP simple crop growth model and water balance components were collected for two growing seasons, *kharif* 2000 and *rabi* 2001. Bowen ratio towers for measuring the actual evapotranspiration rates (ET_a) were installed and operated between June 21 (2000) and March 21 (2001) in parallel at both experimental plots. Air temperature and humidity were measured at different heights: above the canopy, and at 2 and 4 m from the ground surface. Wind speed was measured at 4 m height above natural ground level along with precipitation (P) and incoming solar radiation. For missing days, climatic data from the nearest meteorological stations were collected. The irrigation applications (I_{cw}, I_{tw}) were monitored using cut-throat flumes and a current meter. Daily fluctuations in the phreatic surface were recorded manually at both sites in a piezometer with sounding device and an automatic water level recorder (*Diver*). The latter recorder measures absolute pressure (water pressure + atmospheric pressure) expressed in centimeters of water column. To obtain accurate changes in water level, one needs to compensate for atmospheric pressure. Soil moisture changes in the root zone at 35, 70 and 100 cm depth were monitored in the field using a *theta probe* based on the frequency domain technique. The theta probe measures the volumetric moisture contents through the variability of the dielectric constant. The frequently measured parameters for input and calibration of the SWAP model are summarized in Table I.

The crop growth in SWAP is forced by a prescription of the development of leaf area index (LAI), crop height and rooting depth. The crop height needs to be specified for the calculation of the crops' aerodynamic resistance. LAI is necessary for the computation of potential transpiration from crop reference evapotranspiration. The root depth determines from which depth water is withdrawn from the soil into the plant. There are more sophisticated model options related to carbon assimilation and the simulation of crop growth, but

Table I. Field data collection for SWAP model

Parameter	Collection method/instrument	Frequency
Air temperature	Thermocouple	5 min
Relative humidity	Thermocouple	5 min
Shortwave radiation	Pyranometer	5 min
Precipitation	Tipping bucket	30 min
Wind speed	Anemometer	5 min
Phreatic surface	Piezometric level (using sounding device and *Diver*)	Daily
Soil moisture content	Frequency domain technique	Weekly
Irrigation	Cut-throat flume and current meter	Per event
Agronomic data	Field surveys	Continuous

these options were not explored. The interception P_i is a function of the gross precipitation P, LAI and the maximum storage of a thin water layer on the canopy.

The extensive field data collection program implies that all terms except q could be measured. As the moisture profiles and ΔW_u are applicable to the first 1 m of soil only, it follows from the formulation in Equation (1) that q applies to the flux through the soil profile at 1 m depth. This may not be regarded as the deep percolation flux. As the subsoil water fluxes cannot be measured, a transient moisture flow model such as SWAP is required. The input parameter for SWAP consists of P, I_{tw} and I_{cw} and they are taken directly from the field data collection program. In addition, potential evapotranspiration ET_p needs to be specified. The SWAP outputs consist of ET_a, soil moisture storage in simulated profile ΔW and the flux at any depth $q(z)$. The data of ET_a and ΔW can be used for calibration of the model. The data series of $q(z)$ cannot be verified with *in situ* measurements.

Input parameters

The upper boundary condition of SWAP consists of daily input of climatic data for the computation of ET_p and irrigation applications. Fixed irrigation depths were used as per actual measurement in the field. Following the experiences of Sarwar *et al.* (2000), potential evapotranspiration ET_p was calculated using the Priestley and Taylor (1972) equation. During certain days of the hot season prior to the monsoon, the actual evapotranspiration ET_a measurement from the Bowen ratio system was higher than the predicted ET_p from the Priestley and Taylor equation. The ET_a resulting from the Bowen ratio surface energy balance method enabled us to adjust the value of empirical coefficient α for local advective conditions. The value of $\alpha = 1.4$, for both *kharif* and *rabi*, was found to be more realistic for the environmental conditions of Pakistan than the standard $\alpha = 1.26$ (see also Choudhury *et al.*, 1994). For the calculation of net radiation R_n, a surface albedo r_0 of 0.14, 0.15, 0.18 and 0.21 was used for rice, cotton, wheat and fallow land respectively.

Water stress in SWAP is described by the sink term and a matric potential-based root water uptake function as proposed by Feddes *et al.* (1978). Crops react differently to soil water limitations and their sensitivity to matric potential needs to be specified. In the present study, the *in situ* Bowen ratio provided us with a unique opportunity to calibrate the SWAP model against the measured ET_a. This was the first case of calibrating a hydrological model with measured ET_a in Pakistan. Initially the root water uptake sink-term values of Haryana state, India (Bastiaanssen *et al.*, 1996) were used in this study. Then these sink-term values (h_1 to h_4, see Table II) were adjusted to get good agreement of ET_a estimates from SWAP and with the Bowen ratio technique. The sink-term values describe the water uptake response of a certain crop at different pressure heads in the soil matrix, i.e. a potential-driven water uptake function. The crop parameters used in this study are summarized in Table II.

The SWAP model offers a broad range of bottom boundary conditions. The option of daily fluctuations of the phreatic surface (because they were measured) was chosen as the bottom boundary condition. The bottom flux q_{bot} through the saturated soil column is the residual and the result of all the errors in simulation

Table II. Crop input parameters used for the SWAP model

Input parameter	Faisalabad		Pindi Bhattian	
	Cotton	Wheat	Rice	Wheat
Length of crop cycle (days)	192	127	122	139
Maximum rooting depth (cm)	160	110	55	110
Limiting pressure heads (cm) for the root water uptake function of Feddes *et al.* (1978)	$h_1 = -10.0$ $h_2 = -30.0$ $h_3^{\mathrm{h}} = -300.0$ $h_3^{\mathrm{l}} = -1500.0$ $h_4 = -16\,000.0$	$h_1 = -10.0$ $h_2 = -30.0$ $h_3^{\mathrm{h}} = -400.0$ $h_3^{\mathrm{l}} = -1200.0$ $h_4 = -8500.0$	$h_1 = -0.1$ $h_2 = -30.0$ $h_3^{\mathrm{h}} = -100.0$ $h_3^{\mathrm{l}} = -200.0$ $h_4 = -16\,000.0$	$h_1 = -0.1$ $h_2 = -30.0$ $h_3^{\mathrm{h}} = -300.0$ $h_3^{\mathrm{l}} = -1500.0$ $h_4 = -16\,000.0$

h_1 relates to the air entry potential, the water uptake by roots is maximal between h_2 and h_3. h_4 relates to the potential at wilting point.

and measurements of P, I_{tw} and I_{cw}. As q_{bot} applies to the bottom of the 1D-column only, q_{bot} does not express percolation fluxes, but merely describes the regional connection between the fields investigated and their neighborhood. A positive bottom flux is related to an upward soil water flux.

Soil hydraulic properties

The finite difference scheme has a vertical grid with a total length of 1125 and 300 cm for Faisalabad and Pindi Bhattian, respectively. The schematized soil column at the sites represents the deep and shallow phreatic surface conditions. For both sites, the soil profile was divided into 40 numerical compartments and grouped into 4 soil horizons with different hydraulic properties. Soil hydraulic functions need to be specified for each layer. The soil hydraulic functions, expressing the relationship between soil moisture content (θ), soil matric head (h_{m}) and hydraulic conductivity (K), are described by the Van Genuchten–Mualem parameters (VGM) (Van Genuchten, 1987; Wösten and Van Genuchten, 1988). Beekma *et al.* (1993) have determined the VGM parameters residual moisture content (θ_{res}), saturated moisture content (θ_{sat}), saturated hydraulic conductivity (K_{sat}) and shape parameters α, n and λ by a series of field measurements and laboratory techniques in Rechna Doab. These values have been adjusted to match the *in situ* measurement of soil moisture content (Table III). By minimizing the difference between *in situ* and modelled soil moisture content and evaporative fluxes, the flux q at a depth of 1 m is quite well known.

Table III. Calibrated Van Genuchten–Mualem (VGM) parameters used to describe soil hydraulic properties in the SWAP model

	Faisalabad				Pindi Bhattian			
	0–40 cm	40–85 cm	85–155 cm	More than 155 cm	0–10 cm	10–60 cm	60–150 cm	More than 150 cm
Soil type	Loam	Loam	Silt loam	Loamy sand	Sandy loam	Sandy clay loam	Loam	Silt loam
Parameters								
θ_{res} (cm^3 cm^{-3})	0.044	0.035	0.100	0.028	0.000	0.000	0.000	0.000
θ_{sat} (cm^3 cm^{-3})	0.340	0.354	0.250	0.400	0.424	0.380	0.440	0.400
K_{sat} (cm d^{-1})	145.000	180.000	180.000	180.000	20.000	35.000	45.000	45.000
α (cm^{-1})	0.018	0.018	0.012	0.011	0.064	0.0243	0.030	0.0124
λ	2.500	2.500	2.500	2.679	−1.382	1.850	1.700	2.750
n	1.260	1.260	1.130	2.680	1.399	1.250	1.200	1.200

RESULTS

Soil moisture content

The simulated moisture in the root zone is compared with measurement of soil moisture content at three different depths in top 100 cm of subsoil for both fields at Faisalabad and Pindi Bhattian (see Figure 2). The simulated soil moisture content agrees very well with the measured values at both sites throughout the simulation period. The model was able to reproduce temporal variation in the soil moisture content for heterogeneous soils under cotton–wheat and rice–wheat crop rotation. The effect of irrigation I_{rr} on soil moisture content is most evident at 35 cm depth, for both cases. The reason behind the less frequent measurements of soil moisture content in the *kharif* season for Pindi Bhattian is the ponding water in the rice field. Measurements were taken during the last few weeks when there was no standing water left. The high soil moisture content during the entire rice-growing season is clearly shown in Figure 2. The overall root mean square error after calibrating the Van Genuchten–Mualem parameters is found to be 0.022 and 0.027 $\text{cm}^3\ \text{cm}^{-3}$ for Faisalabad and Pindi Bhattian respectively.

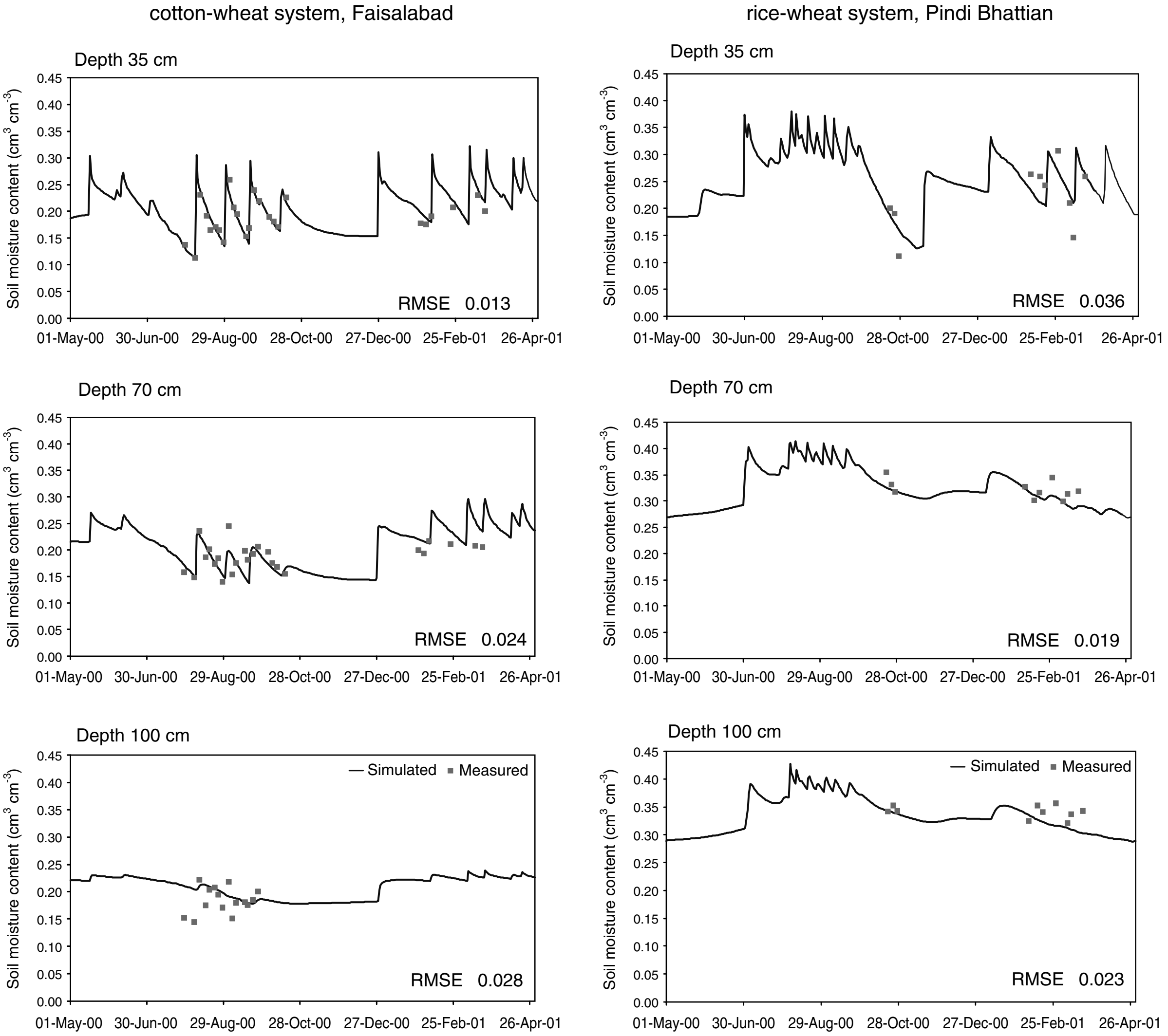

Figure 2. Comparison of measured and simulated soil moisture content at different depths for cotton–wheat system (Faisalabad) and rice–wheat system (Pindi Bhattian)

These calibration results reveal that estimates of some general crop and soil parameters, such as those specified in Tables II and III, are sufficient to simulate the water fluxes in the first 1 m of the soil profile.

Actual evapotranspiration

Actual evapotranspiration ET_a estimated with the SWAP model is compared with the measurement of ET_a from the Bowen ratio tower (Figure 3). The temporal variation in ET_a for both sites under different cropping rotations, soil types and irrigation systems could be simulated satisfactorily. A difference of 20.8 mm (2.9%) for accumulated evapotranspiration with an RMS error of 1.1 mm d^{-1} was observed for the wheat–cotton rotation from June 21 (2000) to April 21 (2001). Similarly for the rice–wheat rotation, a minor difference in the accumulated values of 10.7 mm (1.4%) with an RMS error of 0.9 mm d^{-1} was observed over the period from June 21 to April 21.

Seasonal and annual water balance

Daily values of precipitation P, irrigation I_{rr} from both canal and groundwater and potential evapotranspiration ET_p are specified as model input. The rest of the water balance terms are computed from SWAP, such as interception losses P_i, crop transpiration T, soil evaporation E, change in soil moisture storage ΔW at any depth and the Darcian flux at any depth. There was no noticeable surface runoff during the study period. The results of the complete water balance for the cotton–wheat area of Faisalabad and the rice–wheat area of Pindi Bhattian are presented in Tables IV and V respectively.

The total inflow, i.e. I_{rr} and P_n, in the cotton–wheat area of Faisalabad was 52.2 cm during the complete growing cycle of the cotton crop, and the actual evapotranspiration (sum of E and T) was at $ET_a = 64.8$ cm higher than the total water inflow to the field. This implies that 23.2 cm of water is depleted from the soil profile. In contrast, the amount of irrigation in the *rabi* season is higher than the actual evapotranspiration.

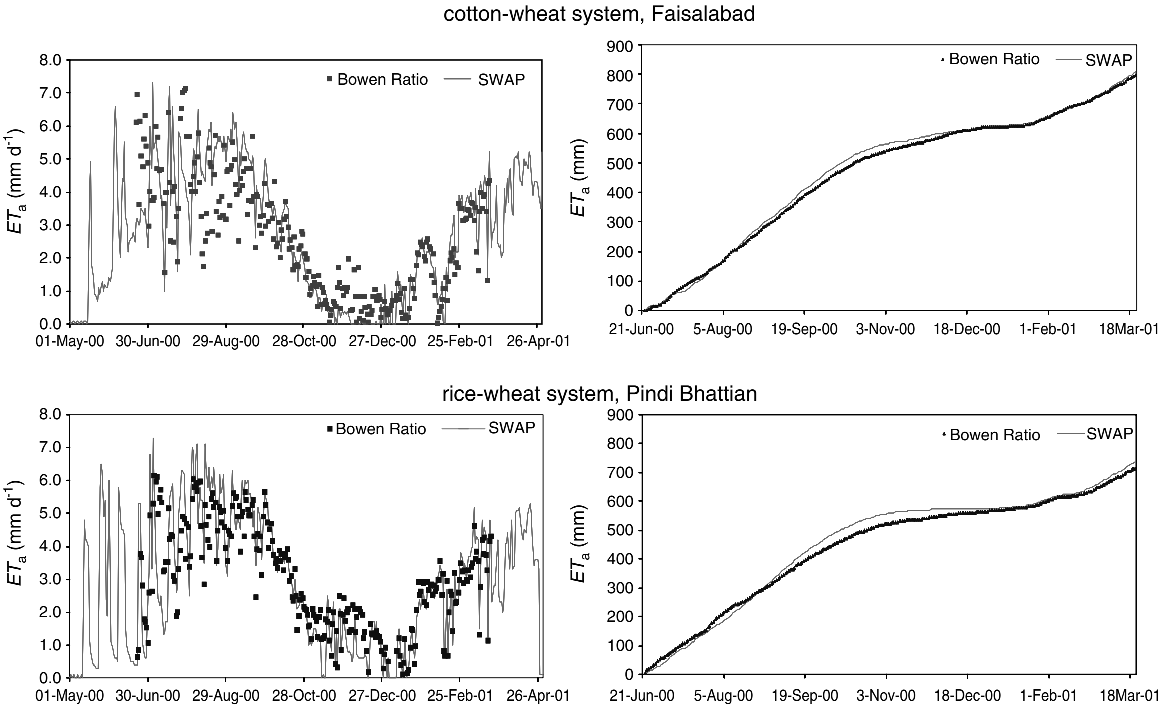

Figure 3. Comparison of daily and cumulative actual evapotranspiration (ET_a) estimated from SWAP and the Bowen ratio system for the cotton–wheat system, (Faisalabad) and the rice–wheat system (Pindi Bhattian)

Table IV. Seasonal and annual water balance for cotton–wheat system, Faisalabad

Period		Measured		Simulated				
	Crop	P (cm)	I_{rr} (cm)	q_{bot} (cm)	P_{i} (cm)	T (cm)	E (cm)	ΔW (cm)
May 1–May 24, 2000	Fallow	0.00	7.60	−1.11	0.00	0.00	1.78	4.71
May 25–Dec. 5, 2000	Cotton	19.70	33.20	−10.60	0.66	53.19	11.60	−23.15
Dec. 6–Dec. 22, 2000	Fallow	0.00	0.00	−0.56	0.00	0.00	0.03	−0.59
Dec. 23–Apr 30, 2001	Wheat	9.32	43.60	−7.44	0.39	28.83	3.79	12.47
May 1, 2000–April 30, 2001		29.02	84.40	−19.71	1.05	82.02	17.20	−6.56

Gross rainfall P, interception losses P_{i}, irrigation I_{rr} from both canal and groundwater, crop transpiration T, soil evaporation E, change in storage ΔW and bottom flux q_{bot}. (Positive upward).

Table V. Seasonal and annual water balance for rice–wheat system, Pindi Bhattian

Period		Measured		Simulated				
	Crop	P (cm)	I_{rr} (cm)	q_{bot} (cm)	P_{i} (cm)	T (cm)	E (cm)	ΔW (cm)
May 1–June 29, 2000	Fallow	13.75	0.00	5.24	0.00	0.00	11.62	7.37
June 30–Oct. 31, 2001	Rice	18.65	64.98	−30.74	0.44	27.15	27.24	−1.94
Nov. 1–Nov. 8, 2000	Fallow	0.63	8.09	0.41	0.00	1.21	3.15	4.77
Nov. 9–Apr 28, 2001	Wheat	3.42	26.24	−4.27	0.64	31.36	3.22	−9.83
Apr. 29–Apr 30, 2001	Fallow	0.00	0.00	−0.02	0.00	0.00	0.03	−0.05
May 1, 2000–April 30, 2001		36.45	99.31	−29.38	1.08	59.72	45.26	0.32

Gross rainfall P, interception losses P_{i}, irrigation I_{rr} from both canal and groundwater, crop transpiration T, soil evaporation E, change in storage ΔW and bottom flux q_{bot}. (Positive upward).

This has resulted in considerable recovery of soil moisture storage during the cool winter period. However, on the annual cycle there is a negative change in storage for the cotton–wheat area of Faisalabad. The decrease in soil moisture storage of −6.6 cm is mainly the result of a negative bottom flux of −19.7 cm occurring during the irrigation seasons due to deeper groundwater extractions occurring in the neighborhood. During the fallow period outside the cropped seasons the bottom flux is negligibly small, indicating that groundwater extractions in the region do not occur.

In the rice–wheat growing area of Pindi Bhattian, there is a 7.4 cm increase in storage during the fallow period before the rice transplantation, which is typically related to land preparation. During the *kharif* season there was a high application of irrigation (65 cm), mainly from groundwater resources. The significant groundwater extraction to irrigate the rice crop is debited to the downward bottom flux ($q_{\mathrm{bot}} = -30.7$ cm). On an annual basis there is only a slight increase in soil moisture storage ($\Delta W = 0.3$ cm), which implies that the system, for this year of study at least, is in equilibrium. Another remarkable result is the very high soil evaporation of the rice crop during land preparation and before closure of the canopy; the actual transpiration and evaporation rates are similar.

Subsoil water fluxes

One of the main objectives of this study was to quantify the soil water fluxes. Figure 4 presents the time–depth domain of the water fluxes, which synthesizes all the moisture movements in one graph. The vertical coordinate of this graph represents depth below the ground surface, the x-axis represents the time. In this way, days in the season with a high percolation flux can be detected, and also the variation of water flux with depth can be noted. The soil water flux is represented in different shading intensities. The negative value of soil water flux represents the downward flow of water while positive fluxes represent upward flow.

In both cases it is obvious that whenever there is irrigation or rain, there is infiltration followed by a downward soil water movement. The effect of infiltration is clearly pronounced at shallow depths up to

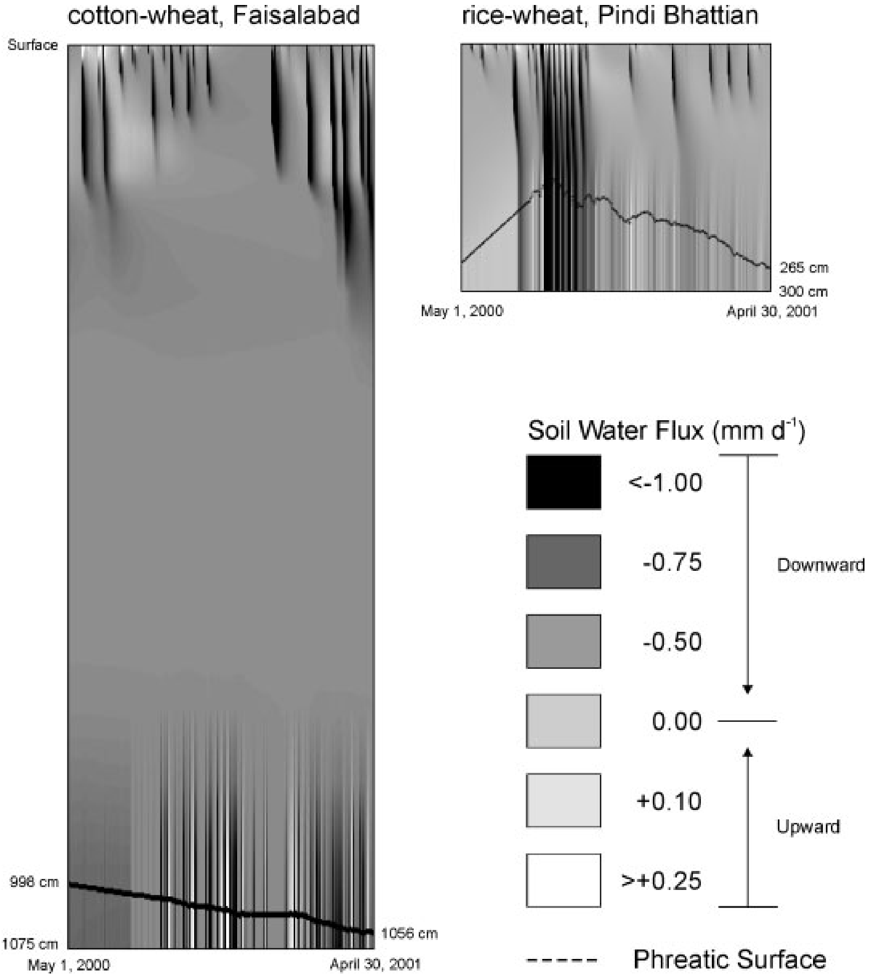

Figure 4. Depth–time domain of vertical soil water fluxes in the unsaturated–saturated zone for a cotton–wheat system at Faisalabad and a rice–wheat system at Pindi Bhattian. The vertical axis represents the depth and the horizontal axis the time

50–70 cm from the ground surface. The redistribution of water in the unsaturated zone is governed by the gradient in soil moisture potential. After irrigation, the soil water flux is downward. During periods of zero infiltration and high evaporative demand, the gradient reverses and the direction of the water fluxes changes to an upward orientation towards the evaporating surface. As a consequence, a zero flux plane is present. This process is typical for intensively irrigated soils, and Figure 4 basically opens the soil as a black box.

In the rice-growing area, the downward soil water flux reaches the phreatic surface. This process is rapid because of higher frequency of irrigation, shallow phreatic surface conditions and hence less travel time. In the cotton–wheat area with deep phreatic surface conditions, a continuous flow process is not observed; the soil water fluxes in the zone between 3 and 8 m are essentially nil. However, groundwater extraction induces downward soil water fluxes in the capillary fringe just above the phreatic surface, which ultimately affects the moisture redistribution in the whole soil profile. The groundwater extraction pulls the phreatic level down when lateral inflow cannot meet the artificial extraction rates. The consequence is a soil water flux from the unsaturated zone to the saturated groundwater system, and this is a recharge induced by groundwater pumpage.

A summary of the soil water flux analysis is presented in Tables VI and VII for both Faisalabad and Pindi Bhattian respectively. These results show that divergence of soil water flux in the sub-root zone occurs especially in the Faisalabad area. In Faisalabad, the magnitude of the annual total soil water amount leaving

Table VI. Soil water flux at various depths in the cotton–wheat area, Faisalabad

Month	Soil water flux at 2 m depth (cm)		Soil water flux at 8.75 m depth (cm)		Soil water flux at variable phreatic surface (cm)		Bottom flux q_{bot} at 10.75 m depth (cm)
	$q^{\downarrow}$	$q^{\uparrow}$	$q^{\downarrow}$	$q^{\uparrow}$	$q^{\downarrow}_{(h_\mathrm{m}=0)}$	$q^{\uparrow}_{(h_\mathrm{m}=0)}$	
May	0.35	0.00	0.68	0.00	1.36	0.00	−1.45
Jun	1.05	0.00	0.63	0.00	1.35	0.00	−1.51
Jul	0.44	0.00	0.54	0.00	1.17	0.00	−1.37
Aug	0.08	0.00	0.59	0.03	1.73	0.20	−1.63
Sep	0.02	0.00	0.74	0.06	2.42	0.42	−2.32
Oct	0.00	0.00	0.55	0.11	1.93	0.69	−1.32
Nov	0.00	0.00	0.71	0.15	3.00	1.12	−2.26
Dec	0.00	0.01	0.26	0.06	0.89	0.46	−0.47
Jan	0.00	0.01	0.29	0.14	1.32	0.91	−0.44
Feb	0.06	0.00	0.53	0.03	2.84	0.50	−2.57
Mar	3.58	0.00	0.56	0.00	2.79	0.09	−3.02
Apr	2.74	0.00	0.40	0.11	2.45	1.30	−1.35
Annual	8.32	0.02	6.49	0.69	23.26	5.70	−19.71

Table VII. Soil water flux at various depths in the rice–wheat area, Pindi Bhattian

Month	Soil water flux 2 m depth (cm)		Soil water flux at variable phreatic surface (cm)		Bottom flux q_{bot} at 3 m depth (cm)
	$q^{\downarrow}$	$q^{\uparrow}$	$q^{\downarrow}_{(h_\mathrm{m}=0)}$	$q^{\uparrow}_{(h_\mathrm{m}=0)}$	
May	0.00	1.63	0.00	2.56	2.66
Jun	0.00	2.30	0.00	2.68	2.68
Jul	2.52	0.78	2.62	0.78	−1.71
Aug	16.18	0.20	16.93	0.32	−17.54
Sep	9.41	0.00	9.63	0.00	−9.53
Oct	2.10	0.12	2.37	0.06	−2.06
Nov	0.69	0.91	0.92	0.85	0.17
Dec	0.61	0.55	1.04	0.38	−0.10
Jan	1.47	0.28	2.21	0.25	−1.35
Feb	0.92	0.02	1.29	0.12	−1.15
Mar	0.48	0.03	1.24	0.18	−1.08
Apr	0.09	0.14	0.66	0.26	−0.37
Annual	34.48	6.96	38.91	8.44	−29.38

the root zone (2 m) is at 8.3 cm higher than the percolating soil water flux of 6.5 cm at a depth of 8.7 m, which reveals moisture storage in the subsoil. The soil water flux at the phreatic surface for both cases is much higher than at shallow depth, but this is the result of groundwater extraction processes explained above. The capillary rise of 5.7 cm is reduced to 0.7 cm at 8.75 m depth and subsequently to zero at the bottom of the root zone. Hence, there is no direct groundwater contribution to crop evapotranspiration in Faisalabad. The data from Pindi Bhattian in Table VII show, however, that 7.0 cm of groundwater flows (upward flux) into the root zone at a depth of 2.0 m, and this is a considerable amount.

Temporal pattern of recharge and groundwater use

On both experimental sites, a conjunctive use of canal and groundwater resources is practised. The total irrigation in Tables VIII and IX is, therefore, broken down into irrigation by canal and groundwater. The net

Table VIII. Net recharge and net groundwater use in cotton–wheat system at Faisalabad

Month	Measured		Estimated					
	Irrigation with canal water I_{cw} (cm)	Irrigation with groundwater I_{tw} (cm)	Recharge $q^{\downarrow}_{(h_{\mathrm{m}}=0)}$ (cm)	Capillary rise $q^{\uparrow}_{(h_{\mathrm{m}}=0)}$ (cm)	Net recharge q_{nr} (cm)	Groundwater use I_{gw} (cm)	Net groundwater use I_{ngw} (cm)	Recharge index
May	7.62	0.00	1.36	0.00	1.36	0.00	0.00	0.00
Jun	0.00	0.00	1.35	0.00	1.35	0.00	0.00	0.00
Jul	0.00	0.00	1.17	0.00	1.17	0.00	0.00	0.00
Aug	19.28	0.00	1.73	0.20	1.53	0.20	0.00	1.00
Sep	0.00	8.63	2.42	0.42	2.00	9.05	6.63	0.27
Oct	5.28	0.00	1.93	0.69	1.24	0.69	0.00	1.00
Nov	0.00	0.00	3.00	1.12	1.88	1.12	0.00	1.00
Dec	10.00	0.00	0.89	0.46	0.43	0.46	0.00	1.00
Jan	0.00	0.00	1.32	0.91	0.41	0.91	0.00	1.00
Feb	0.00	8.44	2.84	0.50	2.34	8.94	6.10	0.32
Mar	14.88	3.76	2.79	0.09	2.70	3.85	1.06	0.73
Apr	0.00	6.51	2.45	1.30	1.15	7.82	5.36	0.31
Annual	57.06	27.34	23.26	5.70	17.56	33.04	19.15	0.42

Table IX. Net recharge and net groundwater use in rice–wheat system at Pindi Bhattian

Month	Measured		Estimated					
	Irrigation with canal water I_{cw} (cm)	Irrigation with groundwater I_{tw} (cm)	Recharge $q^{\downarrow}_{(h_{\mathrm{m}}=0)}$ (cm)	Capillary rise $q^{\uparrow}_{(h_{\mathrm{m}}=0)}$ (cm)	Net recharge q_{nr} (cm)	Groundwater use I_{gw} (cm)	Net groundwater use I_{ngw} (cm)	Recharge index
May	0.00	0.00	0.00	2.56	0.00	2.56	2.56	0.00
Jun	5.00	5.00	0.00	2.68	0.00	7.68	7.68	0.00
Jul	4.07	4.08	2.62	0.78	1.84	4.86	2.24	0.54
Aug	9.15	23.16	16.93	0.32	16.61	23.48	6.55	0.72
Sep	0.00	14.52	9.63	0.00	9.63	14.52	4.89	0.66
Oct	0.00	0.00	2.37	0.06	2.31	0.06	0.00	1.00
Nov	0.00	8.09	0.92	0.85	0.07	8.94	8.02	0.10
Dec	0.00	0.00	1.04	0.38	0.66	0.38	0.00	1.00
Jan	0.00	6.98	2.21	0.25	1.96	7.23	5.02	0.31
Feb	0.00	6.41	1.29	0.12	1.17	6.53	5.24	0.19
Mar	0.00	6.10	1.24	0.18	1.06	6.28	5.04	0.19
Apr	0.00	6.75	0.66	0.26	0.40	7.00	6.35	0.09
Annual	18.22	81.09	38.91	8.44	30.48	89.52	53.59	0.40

groundwater use is substantially less than the groundwater use in both cases, because the phreatic aquifer is replenished by recharge.

There is more recharge in Pindi Bhattian (38.9 cm) than in Faisalabad (23.3 cm). Due to the frequent irrigations in rice systems, the monthly rate of recharge ranges between 0.9 and 3.0 cm at Faisalabad and 0 and 16.9 cm at Pindi Bhattian. In Pindi Bhattian, 81% of the annual recharge occurs during the *kharif* season. A sharp decline in the phreatic surface is observed in the field during the rice-growing season. The annual groundwater resource ratio has been found to be 0.2 and 0.6 at Faisalabad and Pindi Bhattian respectively. This reflects that the rice–wheat systems of Pindi Bhattian rely more on irrigation with groundwater than the cotton–wheat area of Faisalabad. But an appreciable amount of groundwater flows back to the aquifer as a result of percolation. A simple index for expressing recharge is

$$\text{Recharge Index} = \frac{(I_{\mathrm{gw}} - I_{\mathrm{ngw}})}{I_{\mathrm{gw}}} \tag{2}$$

The monthly values during the monsoon of this recharge index vary between 27 and 100% at Faisalabad and 54 and 100% at Pindi Bhattian. This suggests that recharge is a dominant hydrological process at times, and that electricity costs can be saved by reducing the groundwater extractions. The recharge of Faisalabad is fairly constant but for Pindi Bhattian the recharge is high in August (16.9 cm) and September (9.6 cm).

An annual recharge of 23.3 cm is estimated for the cotton–wheat area. Despite that, a decline in phreatic surface is observed, which indicates that lateral inflow and recharge cannot compensate for the annual groundwater extraction of 27.3 cm. Sustainability is obtained if the annual groundwater extraction is reduced from 27.3 cm to the net recharge, i.e. 17.6 cm, or a reduction by 36%. In the rice–wheat area, irrigation with groundwater (81.1 cm) far exceeds the net recharge of 30.5 cm, but the phreatic surface is not declining. A reduction of 62% in groundwater extraction is possible to reach sustainability of groundwater use at field scale.

CONCLUSIONS

The aim of this study was to quantify the subsoil water fluxes in an environment with groundwater irrigation and to understand the impact of surface irrigation with groundwater resources on soil moisture movement. The SWAP model could be well calibrated against measurements of actual evapotranspiration conducted with the Bowen ratio surface energy balance system, and against soil moisture profiles.

The application of the SWAP model provides a quantitative insight into water balance terms and soil water fluxes in the subsoil, which cannot be straightforwardly measured by field instruments. Detailed time–depth profiles of the subsoil water fluxes are presented (see Figure 4). It has been found that recharge takes place, even in areas having a deep phreatic surface, due to man-induced groundwater sinks. The percolation flux varies significantly from month to month and across the unsaturated zone. The flux direction can reverse at larger depths. The water flux leaving the root zone at 2.0 m depth cannot be considered—especially not in deep phreatic surface conditions—as the deep percolation rate. Besides applying a transient soil moisture model for water flux determinations, the same model can also be used to investigate the impact of groundwater management scenarios on crop growth and longer-term aquifer storage.

This case study in Pakistan reveals that a considerable fraction of recharge is due to losses from irrigation with groundwater. This reflects that not all groundwater extracted for agriculture is consumed and that irrigation savings can be practised.

Sustainability of irrigation with groundwater systems is currently studied by means of phreatic surface monitoring networks. Although this is very suitable, it does not provide information on field-scale processes and how rising and falling phreatic surfaces can be halted. The method shown can help in quantifying the direct interactions at the phreatic surface.

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