Remote Sensing and GIS Based Analysis of Conjunctive Water Use in the Rechna Doab, Pakistan

Mobin-ud-Din Ahmad[1] and Wim G.M. Bastiaanssen[2]

ABSTRACT

Irrigation is practiced in the fresh groundwater quality areas in the Indus river basin with both canal and groundwater resources, i.e. conjunctive use. The total groundwater abstraction is unknown and this is a disadvantage for strategic groundwater resources management planning. The availability of satellite images gives a new opportunity to describe more comprehensively soil moisture in the root zone and actual evapotranspiration from irrigated crops. Knowledge on evapotranspiration has the advantage that it describes the real water depletion, which in water scarce conditions can differ significantly from the crop's maximum consumptive use obtainable from theoretical crop water requirement calculations. The resulting satellite based maps of actual evapotranspiration and soil moisture have been validated at two experimental fields. A detailed physically based agro-hydrological model (SWAP) is used to compute the water fluxes in the – sometimes deep – unsaturated zone. The combined use of the transient model output on soil water storage and moisture fluxes together with the remote sensing estimates has been used to obtain the seasonal soil water balances and net groundwater use of irrigated crops.

INTRODUCTION

Growing food and fibre demands require more effective use of the limited land and water resources, or to produce more yield with less resources (Guerra et al., 1998). The knowledge of existing land and water use patterns is of prime importance for natural resources managers; especially in developing countries where consumption in rural areas swallows the bulk of the water resources. The irrigation sector withdraws an estimated 80 percent of freshwater resources in developing countries (FAO, 1994). Although the public perception is that the irrigation sector wastes freshwater resources, this opinion is not necessarily correct. Vast volumes of canal water that initially missed the crop can be recaptured in the irrigation system by pumping groundwater from shallow aquifers, downstream capillary rise to crops, and return flow into tributaries or the main river itself. Recycling irrigation water considerably increases the overall irrigation efficiency and productivity of water (Bastiaanssen 2002a).

The development of evaluating irrigation systems has undergone major modifications during the last 20 years from classical irrigation efficiencies (Bos and Nugteren, 1974; Jensen 1977) to

---

[1] Ph. D. Fellow, International Water Management Institute (IWMI)
[2] Professor of Remote Sensing, International Institute for Geo-information Science and Earth Observation (ITC), Enschede, The Netherlands

performance indicators (Bos et al., 1994; Clemmens and Bos, 1990) and, more recently, into the framework of water accounting and regional scale water depletion processes (Molden, 1997; Burt et al., 1997; Clemmens and Burt, 1997). These analytical frameworks help in describing and understanding the flow path of water. One of the prerequisites to the application of those frameworks is accessibility to water balance data. This paper describes how total water use in an irrigated river basin can be evaluated through the quantification of the crop evapotranspiration and evaporative fraction by means of the surface energy balance. Since there is a direct link between the actual evapotranspiration and the soil water availability at various stages in the growing season, behaviour of evapotranspiration is information on soil moisture at the same time.

Evapotranspiration is usually estimated by conventional techniques based upon routinely collected data. This data is then used to compute the reference evapotranspiration, which differs considerably from the actual evapotranspiration and is not meaningful for the description of actual soil moisture status, or for soil water balance determinants. Note that the reference evapotranspiration can be as large as 10 mm d^{-1} and the actual evapotranspiration of the same land use classes, 1 mm d^{-1}.

Actual evapotranspiration can nowadays be estimated from satellite remote sensing (Engman and Gurney, 1991; Kustas and Norman, 1996; Bastiaanssen et al. 1999). Emerging developments in the field of remote sensing make it possible to overcome information limitations on soil water status and the actual evaporative depletion. As surface energy balances and crop water stress are directly linked to conjunctive use, variations in space and time are thought to be highly indicative for adequacy, reliability and equity in water use.

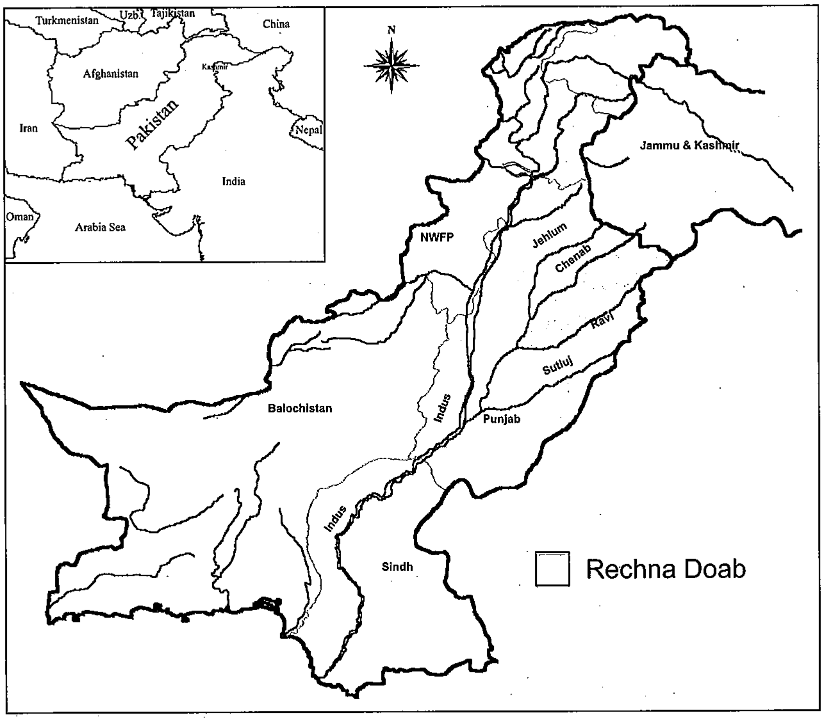
The objective of this paper is to create awareness about the technical feasibility of estimating net groundwater use at a multitude of scales up to the tertiary unit systems with the use of remote sensing and GIS data. To combat the 21st century's water scarcity, we have to transcend current applications and apply modern information technology creatively. The objective of this paper is to show how information technology can be applied to asses net groundwater use.

DESCRIPTION OF THE STUDY AREA

This research work was carried out in the Rechna Doab area of the Indus Basin irrigation system. The Rechna Doab is the interfluvial area between the Chenab and Ravi Rivers (Figure 1). It lies between longitude 71° 48' to 75° 20' East and latitude 30° 31' to 32° 51' North. The gross area of this Doab is 2.97 million ha, with a maximum length of 403 km and maximum width of 113 km, including 2.3 million ha of cultivated land. It is one of the oldest and most intensively developed irrigated areas of Punjab, Pakistan. The area falls in the rice-wheat and sugarcane-wheat agro-ecological zones of the Punjab province, with rice, cotton and forage crops dominating in summer season (*Kharif*), wheat and forage in winter season (*Rabi*). In some parts sugarcane is also cultivated which is an annual crop. Time series data hydrological and meteorological data has been collected from Water and Power Development Authority (WAPDA), Pakistan Meteorological Department and International Water Management Institute (IWMI).

For detailed analysis and understanding of different components at a field level, two sites Pindi Bhattian and Faisalabad were selected. The experimental site from where field scale data was collected is at Soil Salinity Research Institute (SSRI), Pindi Bhattian, which is located on the western border of Rechna Doab (co-ordinates: 73° 20' 50.2" eastern longitude 31° 52' 34.2" northern latitude). The site is flat and situated at an altitude of 212 m above sea level. The average precipitation is approximately 500 mm yr^{-1}. Rice-wheat rotations are common practice. The phreatic surface is approximately 2 m deep from the soil surface.

Figure 1: Location of Rechna Doab in Punjab, Pakistan



The second site is the experimental field of the Cotton Research Institute of Ayub Agricultural Research Institute (AARI), Faisalabad, which is situated in the centre of Rechna Doab (co-ordinates: 73° 2’ 49.8” eastern longitude 31° 23’ 26.2” northern latitude). 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. Cotton-wheat rotations are practiced in this area and phreatic surface fairly deep, approximately 10 m below the surface.

Field data on various agronomic aspects and water balance components were collected for two growing season, *Kharif* (summer season) 2000 and *Rabi* (winter season) 2001. Bowen ratio towers were installed and operated from, June 21, 2000 to March 21, 2001, at both experimental plots. Near-surface atmospheric profiles of temperature, humidity and wind speed were measured along with precipitation and incoming solar radiation. For missing days, climatic data of nearest meteorological stations was collected. The irrigation regime was monitored with the help of cut-throat flumes and a current meter. Daily phreatic surface was recorded precisely in piezometers with *Diver* (automatic recorders) and manual measurement with sounding devices. Soil moisture content in the root zone (up to 100 cm) was monitored in the field with the help of a theta probe based on the frequency domain technique. The theta probe measures the volumetric soil moisture content by measuring changes in the dielectric constant.

FIELD SCALE METHODS AND RESULTS

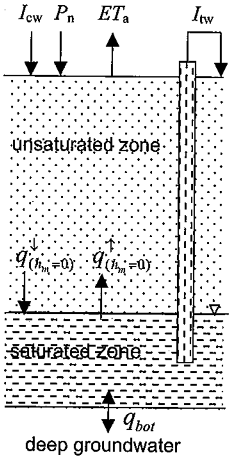
In this study, the one-dimensional physically based Soil-Water-Atmosphere-Plant (*SWAP*) model is used. The SWAP model is based on the Richard's equation, which combines the Darcy's law and continuity equation, for moisture transfer and the advection-dispersion equation for solute transfer. SWAP predicts the dynamic interaction between soil, water, atmosphere and plant on a daily time step (Van Dam et al. 1997). It has been tested for a number of hydrological studies related under a wide range of climate and agricultural systems (e.g. Feddes et al., 1988). SWAP has been applied and validated for the irrigation conditions in Pakistan and India before (Bastiaanssen et al., 1996; Van Dam and Feddes, 1996; Smets et al., 1997; Beekma et al., 1997 and Sarwar et al., 2000).

In the present study, special consideration is given to divergence of the vertical soil moisture fluxes in the unsaturated zone. The SWAP model is calibrated and validated with *in situ* measurement of root zone θ and actual evapotranspiration ET_a for cotton-wheat and rice-wheat cropping system under deep and shallow phreatic surface condition respectively, which is unique to have them available under Pakistani conditions. The root mean square error (RMSE) between measured and simulated soil moisture content is found 0.021 and 0.027 $cm^3\ cm^{-3}$ and for evapotranspiration 1.073 and 0.99 mm d^{-1} for Faisalabad and Pindi Bhattian respectively (Ahmad et al., 2002).

TEMPORAL PATTERN OF RECHARGE AND GROUNDWATER USE

Not all the water for irrigation is consumed by evapotranspiration. A fraction of the water infiltrated through the surface is reaching the groundwater system (figure 2).

Figure 2: Schematisation of different water fluxes in vertical unconfined aquifer (I_{cw} is canal water irrigation, P_n is net precipitation, ET_a is actual evapotranspiration, I_{tw} is tubewell irrigation).



In order to assess sustainable groundwater pumping rates, the recharge as a result of irrigation returns flow/system losses in the cotton-wheat (table 1) and rice-wheat (table 2) cropping system to the phreatic surface (where matric head $h_m = 0$) has been quantified. The total irrigation in Table 1 and 2 is, therefore, broken down into canal water and groundwater irrigation. The net-groundwater use I_{ngw} ($I_{ngw} = I_{tw} + q^{\uparrow}_{(h_m=0)} - q^{\downarrow}_{(h_m=0)}$) is substantially less than the groundwater use I_{gw} ($I_{gw} = I_{tw} + q^{\uparrow}_{(h_m=0)}$) in both cases, which implies that recharge is a significant process.

Table 1: Net-recharge and net-groundwater use in cotton-wheat system at Faisalabad (Year 2000-01) with a deep phreatic surface.

Month	Recharge ↓ $q_{(h_m=0)}$ (cm)	Capillary Rise ↑ $q_{(h_m=0)}$ (cm)	Net Recharge q_{nr} (cm)	Canal Irrigation I_{cw} (cm)	Ground water Irrigation I_{tw} (cm)	Ground-water Use I_{gw}(cm)	Net ground-water use I_{ngw} (cm)	Groundwater recycling fraction υ (-)
May	1.36	0.00	1.36	7.62	0.00	0.00	0.00	0.00
Jun	1.35	0.00	1.35	0.00	0.00	0.00	0.00	0.00
Jul	1.17	0.00	1.17	0.00	0.00	0.00	0.00	0.00
Aug	1.73	0.20	1.53	19.28	0.00	0.20	0.00	0.00
Sep	2.42	0.42	2.00	0.00	8.63	9.05	6.63	0.19
Oct	1.93	0.69	1.24	5.28	0.00	0.69	0.00	0.00
Nov	3.00	1.12	1.88	0.00	0.00	1.12	0.00	0.00
Dec	0.89	0.46	0.43	10.00	0.00	0.46	0.00	0.00
Jan	1.32	0.91	0.41	0.00	0.00	0.91	0.00	0.00
Feb	2.84	0.50	2.34	0.00	8.44	8.94	6.10	0.28
March	2.79	0.09	2.70	14.88	3.76	3.85	1.06	0.14
April	2.45	1.30	1.15	0.00	6.51	7.82	5.36	0.08
Annual	23.26	5.70	17.56	57.06	27.34	33.04	19.15	0.16

Table 2: Net-recharge and net-groundwater use in rice-wheat system at Pindi Bhattian (Year 2000-01) with a shallow phreatic surface.

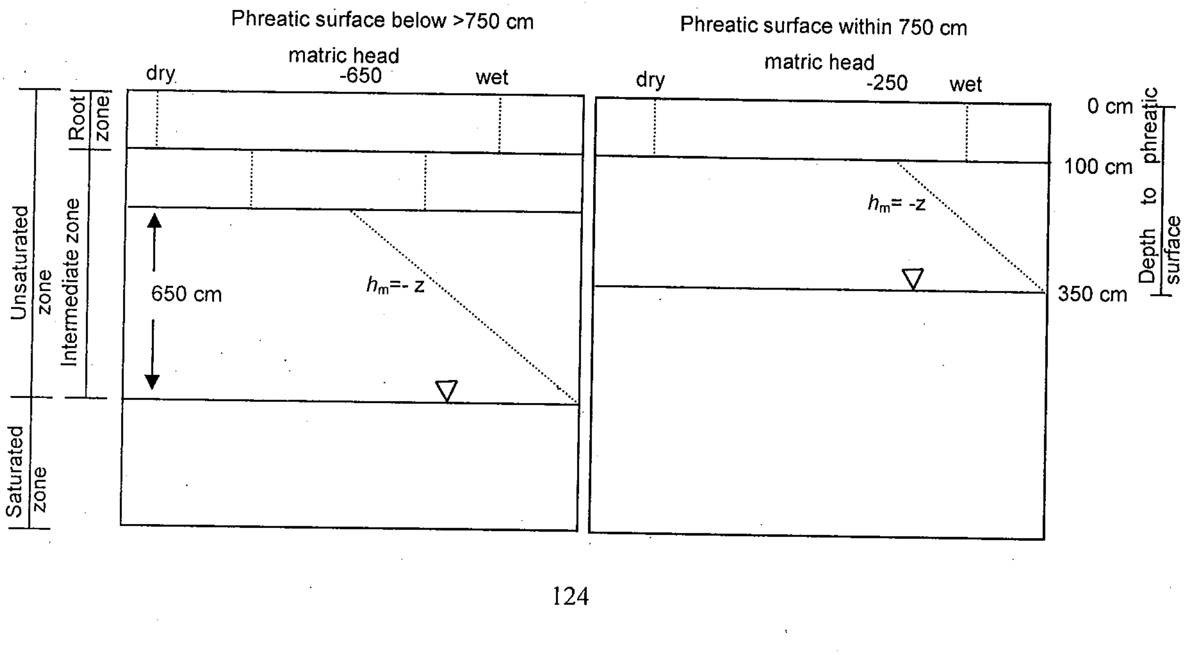
Month	Recharge ↓ $q_{(h_m=0)}$ (cm)	Capillary Rise ↑ $q_{(h_m=0)}$ (cm)	Net Recharge q_{nr} (cm)	Canal Irrigation I_{cw} (cm)	Ground-water Irrigation I_{tw} (cm)	Ground-water Use I_{gw} (cm)	Net ground-water use I_{ngw} (cm)	Ground-water recycling fraction υ (-)
May	0.00	2.56	0.00	0.00	0.00	2.56	2.56	0.00
Jun	0.00	2.68	0.00	5.00	5.00	7.68	7.68	0.00
Jul	2.62	0.78	1.84	4.07	4.08	4.86	2.24	0.13
Aug	16.93	0.32	16.61	9.15	23.16	23.48	6.55	0.41
Sep	9.63	0.00	9.63	0.00	14.52	14.52	4.89	0.52
Oct	2.37	0.06	2.31	0.00	0.00	0.06	0.00	0.00
Nov	0.92	0.85	0.07	0.00	8.09	8.94	8.02	0.00
Dec	1.04	0.38	0.66	0.00	0.00	0.38	0.00	0.00
Jan	2.21	0.25	1.96	0.00	6.98	7.23	5.02	0.27
Feb	1.29	0.12	1.17	0.00	6.41	6.53	5.24	0.17
March	1.24	0.18	1.06	0.00	6.10	6.28	5.04	0.16
April	0.66	0.26	0.40	0.00	6.75	7.00	6.35	0.05
Annual	38.91	8.44	30.48	18.22	81.09	89.52	53.59	0.23

There is more recharge in Pindi Bhattian than in Faisalabad. The monthly rate of recharge ranges between 0.89 to 3.00 cm at Faisalabad and 0 to 16.93 cm at Pindi Bhattian respectively. In Pindi Bhattian, 81% of the annual recharge occurs during the *Kharif* season. Such high range of recharge in Pindi Bhattian area is attributed to rice crop and shallow phreatic surface conditions. A sharp decline in phreatic surface is observed during the rice-growing season. This is the result of a high rate of groundwater extraction for irrigation. The annual groundwater resource ratio has been found to be 0.24 and 0.60 at Faisalabad and Pindi Bhattian respectively, i.e. the fraction of the total water supply results from groundwater irrigation. This reflects that the rice-wheat systems of Pindi Bhattian rely more on groundwater irrigation than the cotton-wheat area of Faisalabad. But an appreciable amount of groundwater is recharging the aquifer as a result of percolation. The monthly rate of recycling varies between 8% to 28% at Faisalabad and 5% to 52% at Pindi Bhattian. This suggests that less groundwater can be pumped in February (Faisalabad), August and September (Pindi Bhattian). The net groundwater use in wheat-cotton system is with 19 cm for better than the 53 cm for rice-wheat systems.

SOIL MOISTURE STORAGE

The estimation of unsaturated soil moisture storage W_u is not straightforward from satellite imagery, as satellites cannot measure soil moisture content θ below the root zone. Field measurements of W_u for very large depths are practically cumbersome to achieve, especially under rice basins. Transient moisture profiles from SWAP have been used instead to get this daily information for larger depths. The results of the SWAP model has been used to develop a new simple parameterisation of matric pressure head distribution to calculate W_u in an alternative way. For this, the unsaturated zone is divided into two zones: 100 cm deep from the surface representing a root zone of constant depth and a variable intermediate zone i.e. between root zone and phreatic surface. In the root zone soil moisture storage W_{rz} can be obtained from satellite imagery with reasonable accuracy for large areas as demonstrated by Scot et al. (2002). Two conditions need to be considered with respect to phreatic surface: up to 750 cm and below 750 cm from ground surface. The areas where the phreatic surface is within 750 cm from ground surface, linear decrease in matric pressure head (h_m) is plausible from phreatic surface (h_m=0) to the bottom of root zone with maximum value of h_m= -650 when phreatic surface is at 750 cm. For very deep phreatic surface areas (greater than 750 cm), the intermediate zone is further sub-divided into two layers: one layer with a fixed depth of 650 cm above phreatic surface and one layer representing the remaining part. The depth of the upper part of intermediate zone is variable and equal to the difference between phreatic surface depth and 750 cm. In the lower layer of the intermediate zone, a linear decrease in absolute h_m is considered from phreatic surface, whereas in the upper part average value of h_m is calculated from h_m of the root zone and lower layer, which is -650 cm (as shown in Fig. 3).

Figure 3: Schematic diagram showing the new simple parameterisation scheme for matric pressure head distribution in the unsaturated zone.



To verify the accuracy of the new simple parameterisation of matric pressure head distribution, daily model output of W_u from SWAP is compared with the result of the new parameterisation using soil moisture in the root zone and a value for the phreatic surface. A good agreement with an absolute RMSE of 7 cm is found. No systematic deviations between shallow and deep phreatic surface conditions were noticed (Ahmad and Bastiaanssen 2002).

For practical purposes, it is important to know the absolute error, which could occur at different levels of probability of exceedance. The absolute deviation in daily W_u of the new parameterisation from the SWAP model is computed for a year for both shallow and deep phreatic surface conditions and plotted against its probability of occurrence. The maximum error that could occur in W_u estimation is 18.24 cm d^{-1} with the new parameterisation. However there are 85% chances that error in W_u estimation will be within the range of 0-10 cm d^{-1}. The average error is less than 5 cm d^{-1}.

REGIONAL SCALE METHODS AND RESULTS

In this study, the Surface Energy Balance Algorithm for Land (SEBAL) proposed by Bastiaanssen et al. (1998) is used for the computation of actual evapotranspiration ET_a in the study area. The annual period October 1993 to September 1994 was taken because additional water balance information was available for this period. NOAA AVHRR images covering the complete growing annual cycle (October 93 to September 1994) are processed surface albedo, solar radiation, the vegetation index and surface temperature. This data is applied to obtain radiation and energy balances at a spatial resolution of 1.1 km. Evapotranspiration is calculated from the instantaneous evaporative fraction, Λ, and the daily averaged net radiation, R_{n24} (Figure 4).

Validation in the Indus Basin was realized through a field scale transient moisture flow model, in situ Bowen ratio measurements and a water balance residual analyses for an area of 2.97 million ha of Rechna Doab. The accuracy of assessing time integrated actual evapotranspiration was found to vary from 0 % to 10 % at field scale to 5 % at the regional scale (Bastiaanssen et al. 2002b). The monthly ET_a in Rechna Doab is presented in Figure 5.

From these evaporative fraction maps Λ (latent heat flux/net available energy), the relative soil moisture content θ / θ_{sat} (-) in the root zone is computed for the Rechna Doab. The soils of the Rechna Doab are predominantly coarse to moderately coarse. An average value of θ_{sat} 0.35 cm^3cm^{-3} is used to compute the root zone θ for all 18 images of Rechna Doab. The soil moisture storage in the root zone W_{rz} (cm) is determined from root zone θ considering a constant depth of 1 meter. Using the matric pressure head distribution approach explained in Fig. 3, soil moisture storage in complete unsaturated zone is obtained for the Rechna Doab (Figure 6).

Figure 4: Annual actual evapotranspiration (ET_a) for the Indus Basin: Year October 1993 to October 1994.

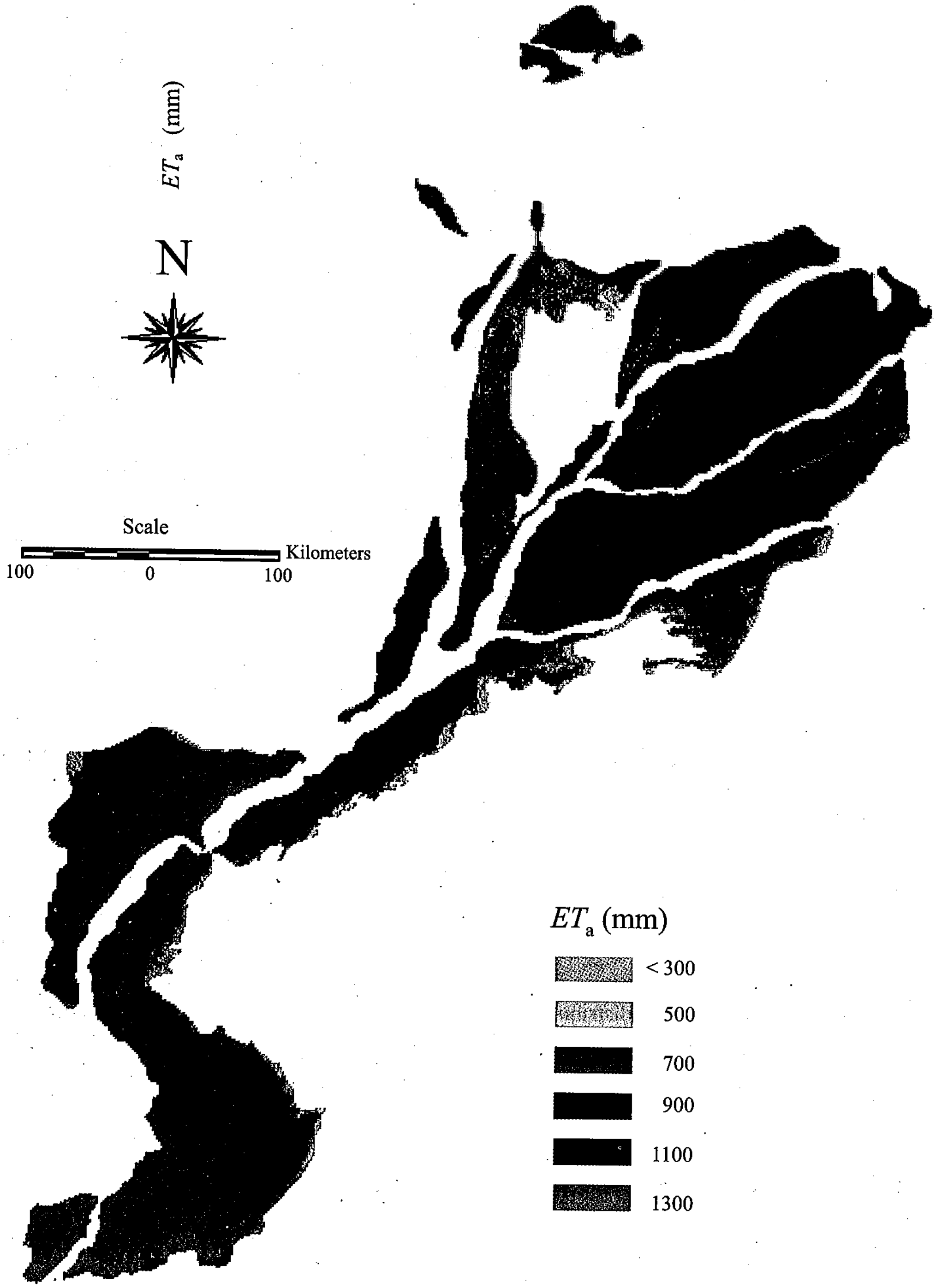


Figure 5: Monthly actual Evapotranspiration (ET_a) in the 2.97 million ha of Rechna Doab.

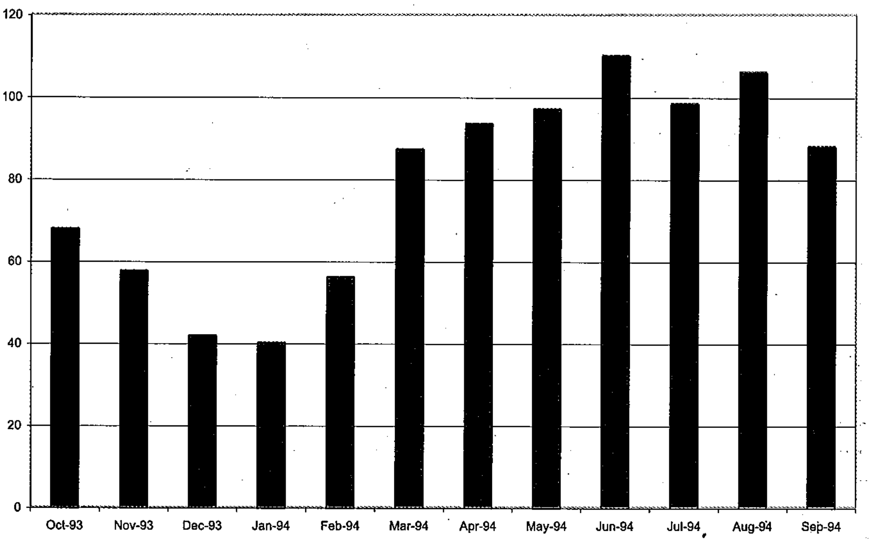
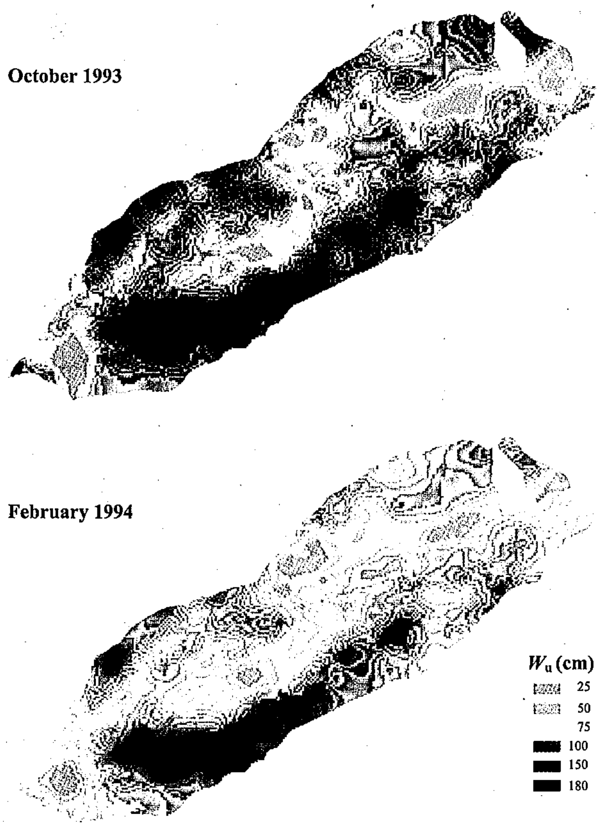


Figure 6: Spatial variation in soil moisture storage Wu of the entire unsaturated zone in the Rechna Doab.



The monthly changes in phreatic surface Δh and unsaturated soil moisture storage ΔW_u for shallow and deep phreatic surface areas are summarized for two locations in table 3. A considerable change in monthly W_u has been observed during May: result of end of *Rabi* and start of *Kharif* season.

Table 3: Monthly changes in phreatic surface and unsaturated zone storage in the shallow and deep phreatic surface areas in Rechna Doab.

Month	Shallow phreatic surface Pixel (100 ha) at latitude 73.32 longitude 31.78				Deep phreatic surface Pixel (100 ha) at latitude 72.59 longitude 30.90			
	Depth to phreatic surface (cm)	Change in phreatic surface (cm per month) Δh	Unsaturated zone storage (cm) W_u	Change in unsaturated zone storage (cm per month) ΔW_u	Depth to phreatic surface (cm)	Change in phreatic surface (cm per month) Δh	Unsaturated zone storage (cm) W_u	Change in unsaturated zone storage (cm per month) ΔW_u
Oct. 93	184.2		65.9		1040.5		154.4	
Nov. 93	191.3	7.1	64.6	-1.3	1030.8	-9.7	139.1	-15.3
Dec. 93	198.2	6.9	63.2	-1.4	1021.4	-9.4	129.2	-10.0
Jan. 94	205.4	7.1	57.5	-5.7	1011.7	-9.7	122.5	-6.7
Feb. 94	212.5	7.1	52.0	-5.5	1002.0	-9.7	115.7	-6.8
Mar. 94	218.9	6.4	51.7	-0.3	993.2	-8.8	131.5	15.8
April 94	226.0	7.1	71.5	19.8	983.5	-9.7	129.9	-1.6
May 94	232.9	6.9	58.8	-12.7	974.1	-9.4	96.1	-33.8
June 94	231.4	-1.6	65.4	6.6	959.4	-14.7	109.9	13.8
July 94	229.8	-1.5	65.7	0.3	945.2	-14.2	108.8	-1.0
Aug 94	228.2	-1.6	65.4	-0.3	930.4	-14.7	100.0	-8.9
Sep 94	226.7	-1.6	65.1	-0.3	915.7	-14.7	93.4	-6.6

The average change in phreatic surface and soil moisture storage for the 2.97 million ha area is presented in table 4. The change in soil moisture storage ΔW_u ranges between -12.1 to +7.1 cm month^{-1} but cumulative change in storage is in the order of –8.06 cm from Oct. 93 to Sep 94 (table 4) thereby indicating that the phreatic surface is net rising. There are both negative and positive changes in monthly W_u for the Rechna Doab as one total system. The positive and negative variations in W_u are the result of rainfall and different irrigation and agronomic practices.

Table 4: Average monthly changes in phreatic surface and unsaturated zone soil moisture storage in the 2.97 million ha area of Rechna Doab.

Month	Depth to phreatic surface (cm)	Change in phreatic surface (cm month^{-1}) Δh	Unsaturated zone storage (cm) W_u	Change in unsaturated zone storage (cm month^{-1}) ΔW_u	Cumulative change in unsaturated zone storage (cm)
Oct. 93	464.3		93.6		
Nov. 93	472.8	8.4	91.4	-2.3	-2.3
Dec. 93	480.9	8.2	91.7	+0.3	-1.9
Jan. 94	489.3	8.4	88.3	-3.4	-5.4
Feb. 94	497.8	8.4	84.1	-4.2	-9.5
March 94	505.4	7.6	91.2	+7.1	-2.4
April 94	513.8	8.4	89.2	-2.1	-4.5
May 94	521.9	8.2	77.1	-12.1	-16.5
June 94	515.4	-6.6	83.9	+6.8	-9.7
July 94	509.0	-6.4	83.7	-0.2	-9.9
Aug 94	502.4	-6.6	84.5	+0.7	-9.2
Sep 94	495.8	-7.6	85.6	+1.1	-8.1

NET-GROUNDWATER USE

The fraction of irrigation with groundwater, which is not replenished by recharge is called as net groundwater use and can also be estimated as the residual of the soil water balance:

$$I_{\text{ngw}} * \Delta t = (ET_{\text{a}} - I_{\text{cw}} - P_{\text{n}} + \frac{\Delta W_{\text{u}}}{\Delta t}) * \Delta t$$

Using the spatial data seasonal and ignoring the precipitation interception losses, a net groundwater use I_{ngw} is estimated for selected canal commands in the Rechna Doab. The preliminary results are presented in Table 5. The higher values of net groundwater use during *Rabi* in the BRBD and UCC canal command is the result of non-perennial canals (i.e. less water is diverted from canal for irrigation).

Table 5: Seasonal net groundwater use in 4 selected canal command areas

Canal Command	*Rabi* 1993-94					Kharif 1994				
	P_{n} (mm)	I_{cw} (mm)	ET_{a} (mm)	W_{u} (mm)	I_{ngw} (mm)	P_{n} (mm)	I_{cw} (mm)	ET_{a} (mm)	W_{u} (mm)	I_{ngw} (mm)
Gugera	25	222	356	-49	60	270	338	604	-88	-92
Jhang	25	131	344	-52	136	284	119	565	-58	104
BRBD	53	24	345	-42	226	444	263	618	65	-24
UCC	26	55	346	-33	232	410	281	633	33	-25

Note: only +ive values of I_{ngw} *represent net-groundwater use.*

CONCLUSIONS

The aim of the present endeavour was to develop a methodology, which relies heavily on the use of remotely sensed information and geo-informatics techniques, to estimate net groundwater in large irrigated river basin.

Quantitative insight of field level water balance terms and water fluxes in the sub-soil, including groundwater recycling and changes in soil moisture storage in the unsaturated zone has been obtained using transient SWAP model. SWAP shows that a considerable fraction of groundwater irrigation is returning back to the same groundwater system in both the rice-wheat and cotton-wheat systems of Rechna Doab. Consequently, tubewells extractions do not give a good picture on the amount of groundwater extracted. Using SWAP results a new and simple parameterisation of matric pressure head distribution is developed which can estimate the unsaturated zone storage from root zone storage and depth to phreatic surface data with sufficient accuracy.

Seasonal and annual actual evapotranspiration and soil moisture storage is estimated using the satellite imagery. Seasonal and spatial variation in groundwater use in selected canal commands within Rechna Doab has been found. Net groundwater use in *Rabi* is much more than in *Kharif*, during which the aquifers are net recharged (except Jhang canal command area). This innovative approach can be applied in data scarce environment for better planning and management of conjunctive use.

REFERENCES

Ahmad, M.D. and W.G.M. Bastiaanssen 2002, Retrieving soil moisture storage in the unsaturated zone from satellite imagery and bi-annual phreatic surface fluctuations. *Irrigation and Drainage Systems* (submitted).

Ahmad, M.D., W.G.M. Bastiaanssen and R.A. Feddes 2002, Recycling and sustainable use of groundwater in irrigated fields: a numerical analysis of the subsoil water fluxes. *ICID Journal of Irrigation and Drainage*, John Wiley & Sons Ltd (submitted).

Bastiaanssen, W.G.M., R. Singh, S. Kumar, J.K. Schakel and R.K. Jhorar 1996. *Analysis and recommendations for integrated on-farm water management in Haryana, India: a model approach*. Report 118. DLO Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, The Netherlands. pp 152.

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes and A.A.M. Holtslag, 1998. A remote sensing surface energy balance algorithm for land (SEBAL), part 1: formulation, *Journal of Hydrology*. 212-213: 198-212.

Bastiaanssen, W.G.M., R. Saktivadivel and A. van Dellen, 1999. "Spatially delineating actual and relative evapotranspiration from remote sensing to assist spatial modeling of non-point source pollutants, in (eds.) Corwin et al."; *Assessment of non-point source pollution in the vadose zone, Geophysical Monograph 108*, American Geophysical Union: 179-196

Bastiaanssen, W.G.M., M.D. Ahmad and Z. Tahir 2002a. Upscaling water productivity in irrigated agriculture using remote sensing and GIS technologies. Forthcoming proceeding of the *Water Productivity Workshop*. International Water Management Institute (IWMI), Colombo. Nov. 15-16, 2001.

Bastiaanssen, W.G.M., M.D. Ahmad and Y. Chemin 2002b. Satellite surveillance of evaporative depletion across the Indus Basin. *Water Resources Research*, American Geophysical Union (submitted).

Beekma, J., T.J. Kelleners, TH.M. Boers, M.R. Chaudhry and J.C. Van Dam, 1997. Recharge from irrigated lands. In: I. Simmers (Ed.), *Recharge of Phreatic Aquifers in (Semi-) Arid Areas*. A.A. Balkema, The Netherlands: 115-127.

Bos, M.G. and J. Nugteren, 1974. On irrigation efficiencies, *International Institute for Land Reclamation and Improvement* (ILRI), Wageningen, The Netherlands: 138 pp.

Bos, M.G., D.H. Murray-Rust, D.J. Merrey, H.G. Johnson and W.B. Snellen, 1994. Methodologies for assessing performance of irrigation and drainage management; *Irrigation and Drainage Systems* 7: 231-261

Burt, C.M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L.A. Hardy, T.A. Howell and D.E. Eisenhauer, 1997. Irrigation performance measures: efficiency and uniformity; *Journal of Irrigation and Drainage Engineering* 123(6): 423-442

Clemmens, A.J. and C.M. Burt, 1997. Accuracy of irrigation efficiency estimates; *Journal of Irrigation and Drainage Engineering*, vol. 123(6): 443-453

Clemmens, A.J. and M.G. Bos, 1990. Statistical methods for irrigation system delivery performance evaluation; *Irrigation and Drainage Systems* 4: 345-365

Engman, E.T., and R.J. Gurney, 1991. Remote sensing in hydrology; Chapman and Hall, London

Feddes, R.A., P. Kabat, P.J.T Van Bakel, J.J.B. Bronswijk and J. Halbertsma 1988. Modelling soil and water dynamics in the unsaturated zone—State of the Art. *Journal of Hydrology*, 100 (1988) 69-111.

Food and Agricultural Organization of the United Nations, 1994. Water for life, *FAO*, Rome, Italy

Guerra, L.C., S.I. Bhuiyan, T.P. Tuong and R. Barker, 1998. Producing more rice with less water from irrigated systems, *SWIM paper no. 5*; *International Water Management Institute*, Colombo, Sri Lanka.

Jensen, M.E., 1977. Water conservation and irrigation systems: climate tech. sem. proc., Columbia, MO

Kustas, W.P. and J.M. Norman, 1996. Use of remote sensing for evapotranspiration monitoring over land surfaces; *Hydr. Sci. J.* 41(4): 495-516

Molden, D., 1997. Accounting for water use and productivity, *SWIM Paper 1; International Water Management Institute*, Colombo, Sri Lanka: 16 pp.

Sarwar, A, W.G.M. Bastiaanssen, J.C. van Dam and M.Th. Boers, 2000. Evaluating drainage design parameters for the fourth drainage project, Pakistan by using SWAP model: Part I – calibration. *Irrigation and Drainage Systems*. 14, 257-280.

Scott, C.A, W.G.M. Bastiaanssen and M.D. Ahmad, 2002. Mapping root zone soil moisture using remotely sensed optical imagery. *ASCE Irrigation and Drainage Engineering* (submitted).

Smets, S.M.P., M. Kuper, J.C. Van Dam, R.A. Feddes, 1997, Salinization and crop transpiration of irrigated fields in Pakistan's Punjab. Agr. Water Management 35 (1997) 43-60.

Van Dam, J.C. and R. A. Feddes, 1996. Modelling of water flow and solute transport for irrigation and drainage. In: L.S. Pereira et al., (Eds.), Sustainability of Irrigated Agriculture, Kluwer Academic Publishers, The Netherlands: 211-231.

Van Dam, J.C., J. Hygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. van Walsum, P. Groenendijk and C.A. van Diepen, 1997. Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant Environment Theory of SWAP version 2.0. Report 71. Department of Water Resources, Wageningen Agricultural University, Technical Doc. 45 DLO Winand Staring Center, Wageningen. Agricultural University. 167pp.