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Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan

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ABSTRACT

Irrigation policy makers and managers need information on the irrigation performance and productivity of water at various scales to devise appropriate water management strategies, in particular considering dwindling water availability, further threats from climate change, and continually rising population and food demand. In practice it is often difficult to access sufficient water supply and use data to determine crop water consumption and irrigation performance. Energy balance techniques using remote sensing data have been developed by various researchers over the last 20 years, and can be used as a tool to directly estimate actual evapotranspiration, i.e., water consumption. This study demonstrates how remote sensing-based estimates of water consumption and water stress combined with secondary agricultural production data can provide better estimates of irrigation performance, including water productivity, at a variety of scales than alternative options. A principle benefit of the described approach is that it allows identification of areas where agricultural performance is less than potential, thereby providing insights into where and how irrigation systems can be managed to improve overall performance and increase water productivity in a sustainable manner. To demonstrate the advantages, the approach was applied in Rechna Doab irrigation system of Pakistan's Punjab Province. Remote sensing-based indicators reflecting equity, adequacy, reliability and water productivity were estimated. Inter- and intra-irrigation subdivision level variability in irrigation performance, associated factors and improvement possibilities are discussed.

1. Introduction

Judicious management of precious land and water resources is emerging as one of the biggest challenges of the 21st century. Both water and land resources are finite, but competitive demand from other sectors is increasing. The agricultural sector is one of the biggest consumers of water resources, accounting for more than 70% of the world's fresh diverted water use from rivers and groundwater, although in Asia and the Pacific region it is as high as 90% (Barker and Molle, 2005). The use of this irrigation water plays a major role in increasing land productivity. Globally, about 40% of agricultural outputs and 60% of grain production is produced from irrigated areas which together make up only 20% of the total arable land.

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While irrigation has greatly increased global and regional food security, further rapid increases in agricultural production will be required to meet future food and fiber demands. This goal can be achieved either by bringing more area under irrigation or by increasing the yields of existing cropped area whilst using similar or even reduced water resources.

Most large-scale irrigation systems are located in the arid and semi-arid regions of the world, and water is one of the most limiting factors in increasing agricultural production (Seckler, 1996; Thenkabail et al., 2006). Prospects for finding new water sources in these areas are relatively slim (Navalawala, 1995), because most of the surface and groundwater resources have already been exploited. Therefore, further expansion in irrigated area is often limited by water availability. Thus it is important to find ways to increase agricultural production by careful evaluation of existing irrigated lands. This strategy will not only help to meet future food demands but may also ease competition with other sectors and help to ensure water availability for nature (Hamdy et al., 2003).

The science of evaluating irrigation systems has undergone major development during the last 30 years, moving from a focus on classical irrigation efficiencies (Bos and Nugteren, 1974; Jensen, 1977) to performance indicators (Bos et al., 1994; Clemmens and Bos, 1990) and more recently, to frameworks of water accounting and productivity (Molden, 1997; Burt et al., 1997; Clemmens and Burt, 1997). The water accounting and productivity framework developed by Molden (1997) can easily be applied to evaluate the amount of water used by different processes to determine the efficiency and productivity of water use at various scales (i.e., crop, field, farm, irrigation system and basin). Public domain internet satellite data and scientific development makes remote sensing an attractive option to assess irrigation performance from individual fields to scheme or river basin scale (Bastiaanssen and Bos, 1999; Bos et al., 2005; Akbari et al., 2007). Such spatial information is increasingly important for large irrigation systems and river basins such as the Indus basin irrigation system of Pakistan to help identify suitable water management strategies across scales. This is particularly important because the means to improve water productivity lie substantially at farm scale in terms of crop management and at system scale in terms of irrigation water distribution and possible allocation.

The Indus basin irrigation systems of Pakistan were developed to drought proof the region, prevent famine, provide tax revenue and settle a partly nomadic population. Almost all the water available in the system is committed to agriculture, and there has been a revolution in groundwater use over the last 20 years as private pumping has progressively displaced public owned pumped drainage. This has changed the nature of irrigation from being ‘‘protective’’ to being ‘‘productive’’. In Rechna Doab, 98% of water use is conjunctive (from groundwater to surface water), a figure typical of the entire upper Indus basin today. In general, productivity is low due to erratic canal supplies and salinity in the groundwater. However, the best farmers in the best conditions are highly productive. High rates of groundwater development and use have occurred, particularly through the drought period from 1999 to 2004 (Ahmad et al., 2007).

There are a number of well known and emerging irrigation management objectives and needs in Pakistan. In the Punjab, large quantities of irrigation flows are derived from unaccounted groundwater, and there are fears of long term over-abstraction and also of degradation due to salt mobilization from existing saline areas. The surface system is supplied by snow-melt from the Himalaya, and varies with snowfall and glacier melt behavior, which is now thought to be being severely modified by global warming. In addition to supply side challenges, water distribution in Pakistan is complex and easily subject to manipulation. Although groundwater use is widespread, surface water is highly valued for its good quality, but equity in distribution is known to be poor, with tail-enders suffering irregular and limited deliveries. Surface and groundwater interactions and their quantification at basin scale are not well understood, but underpin the long term sustainability of irrigated agriculture in the region. Remote sensing, GIS and geo-statistics approaches, along with limited field data, were used to solve distributed water balance and estimate net groundwater use for agriculture (Ahmad et al., 2005).

In 2006, the Government of Punjab launched a new program to maintain a computerized database for irrigation releases to improve irrigation management, reduce rent seeking, increase transparency and demonstrate which users are getting what quantity of water (http://irrigation.punjab.gov.pk). It is expected that these initiatives will improve data management and availability of surface supplies. But to work, information on overall water consumption (surface and groundwater) at various scales will be essential for judicious and efficient water resources management in Pakistan. There is a need to study water distribution and consumption patterns and the impacts of this on productivity.

It is also very useful for policy makers to be able to link water allocation and irrigation system management performance to productivity in order to address the continuing challenge of feeding the population. Better estimates of crop area and actual water consumption are required, since surface water supplies are not only used directly in the field, but also provide a substantial, but unquantified portion of groundwater recharge. Remotely sensed estimates of actual evapotranspiration take account of factors that reduce water consumption below potential, such as salinity, crop condition and poor irrigation scheduling—all of which are important in Pakistan. It also allows spatial and temporal variation to be analyzed and better understand the effectiveness and equity of system operation and (in conjunction with delivery data) understand the role and extent of groundwater consumption, either conjunctively or on its own.

The objectives of this paper are:

- application of the Surface Energy Balance Algorithm for Land (SEBAL) to estimate actual evapotranspiration (ET_a) in Punjab, with particular focus on Rechna Doab, an approximately 3 million ha alluvial plain that lies between the Ravi and Chenab rivers;
- quantification of agricultural water consumption in different irrigation subdivisions of Rechna Doab;
- understanding the seasonal and spatial patterns of evapotranspiration in Rechna Doab and their linkage to groundwater consumption and quality; and

- completion of irrigation and water use performance diagnoses in terms of crop water productivity and water consumption at nested scales, using secondary agricultural statistics.

2. Materials and methods

2.1. Research locale

This study was conducted for the upper Indus basin irrigation system in Pakistan, with particular focus on Rechna Doab, a land unit lying between the Ravi and Chenab rivers of Pakistan (Fig. 1). The gross area of the Doab is about 2.97 million ha, around 80% of which is currently cultivated. It has a maximum length of 403 km, maximum width of 113 km and lies between longitude 71° 48′ to 75° 20′ East and latitude 30° 31′ to 32° 51′ North. Climatologically, the area is subtropical and designated as semi-arid, and is characterized by large seasonal fluctuations in temperature and rainfall. Summers are long and hot, lasting from April through September with maximum daytime temperatures ranging from 21 °C to 49 °C. The winter season lasts from December through February with maximum temperatures ranging between 25 °C and 27 °C and sometimes falling below zero at night. Mean annual precipitation is about 650 mm in the upper Doab, falling to 375 mm in the central and lower area. Nearly 75% of the annual rainfall occurs during the monsoon season—from mid-June to mid-September.

The prevailing temperature and rainfall patterns govern two distinct cropping seasons: Kharif (summer season) and Rabi (winter season). Rechna Doab falls under the rice-wheat (upper parts) and sugarcane–wheat agro-climatic zone (middle to lower part of Rechna Doab) of the Punjab province, with rice, cotton and forage crops dominating in Kharif and wheat and forage the major crops in Rabi. In central Rechna Doab, sugarcane, a long season annual crop of around 11 months duration, is the dominant choice for farmers. Minor crops include oil seeds, vegetables and orchards.

As the total crop water requirement is more than double the annual rainfall, it is obvious that irrigation is essential to maintaining the current level of agricultural productivity. Irrigation water was originally provided through a network of irrigation canals and then supplemented with unaccounted

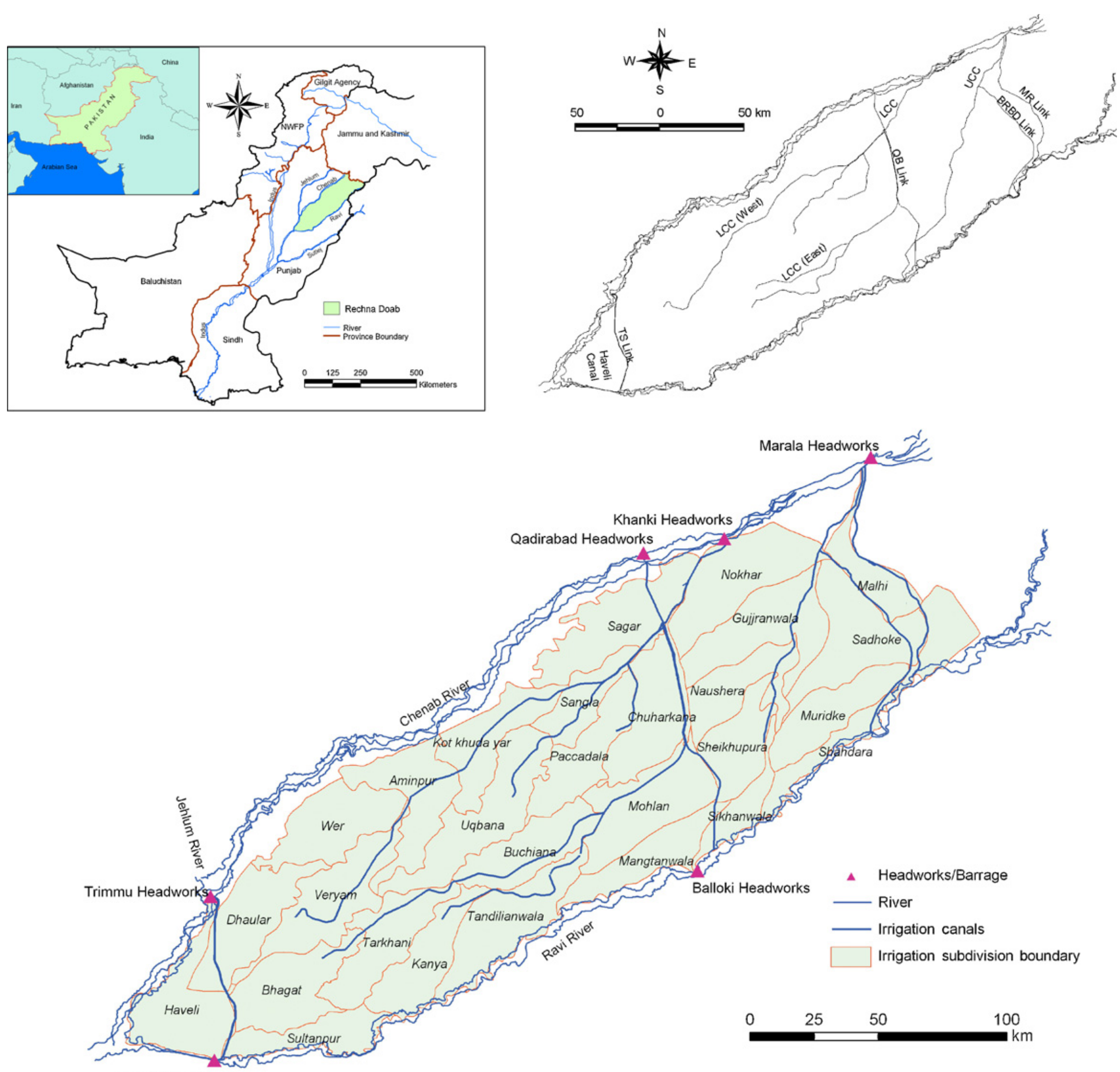

Fig. 1 – Location of Rechna Doab, Pakistan, and configuration of canal network and irrigation subdivision (lowest administrative unit of irrigation management in Pakistan) in Rechna Doab.

irrigation supplies from groundwater. Rechna Doab has both non-perennial and perennial irrigation systems. A non-perennial irrigation system is located in the upper Rechna Doab, an area underlain by fresh groundwater. This area is served by the Marala-Ravi (internal), the Upper Chenab Canal (UCC) and the Bambanwala-Ravi-Bedian-Depalpur (BRBD) (internal), which provide water only in the Kharif season. The middle and lower Rechna receive perennial canal supplies from Lower Chenab Canal System (LCC) and Haveli canal. The entire canal irrigation system is divided into 28 irrigation subdivisions, the lowest administrative unit of irrigation management. About 0.45 million ha of Rechna Doab region lies outside of the canal command area and most of this area is cultivated through groundwater irrigation, rather than rainfed. More detailed information about Rechna Doab can be found in Ahmad et al. (2007).

2.2. *Estimation of actual evapotranspiration*

SEBAL is used for actual evapotranspiration calculations, which is a well-tested and widely used method to compute ET_a (Bastiaanssen et al., 1998, 2002, 2005; Allen et al., 2007; Tasumi et al., 2003; Ahmad et al., 2006). SEBAL results have been validated in a number of countries using field instruments including weighing lysimeter, scintillometer, Bowen ratio and Eddy-correlation towers, indicating daily *ET* estimates have errors on the order of 16% or lower at 90% probability (www.waterwatch.nl). At longer time scales, such as a crop season, *ET* errors cancel out to 5% (Bastiaanssen et al., 2005).

SEBAL is an image processing model which computes a complete radiation and energy balance along with resistances for momentum, heat and water vapour transport for each pixel (Bastiaanssen et al., 1998; Bastiaanssen, 2000). From the reflectance and radiance measurements of the bands, first land surface parameters such as surface albedo (Liang, 2000; Liang et al., 2002), vegetation index, emissivity (van de Griend and Owe, 1993) and surface temperature are estimated (Tasumi, 2003). The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum. In addition to satellite images, the SEBAL model requires routine weather data parameters (wind speed, humidity, solar radiation and air temperature).

With this data, evapotranspiration is then calculated from the latent heat flux, and the daily averaged net radiation, R_{n24}. The latent heat flux is computed from the instantaneous surface energy balance at satellite overpass on a pixel-by-pixel basis:

$$\lambda E = R_n - (G_0 + H) \qquad (1)$$

where λE (W/m^2) is the latent heat flux (λ is the latent heat of vaporization and *E* is the actual evaporation), R_n (W/m^2) is the net radiation, G_0 (W/m^2) is the soil heat flux and *H* (W/m^2) is the sensible heat flux. The latent heat flux describes the amount of energy consumed to maintain a certain evapotranspiration rate.

The energy balance Eq. (1) can be decomposed further into its constituent parameters. R_n is computed as the sum of incoming and outgoing short-wave and long-wave radiant fluxes. G_0 is empirically calculated as a G_0/R_n fraction using vegetation indices, surface temperature and surface albedo. Sensible heat flux is computed using wind speed observations, estimated surface roughness, and surface to air temperature differences that are obtained through a self-calibration between dry ($\lambda E \approx 0$) and wet ($H \approx 0$) pixels. The dry and wet pixels are manually selected, based on vegetation index, surface temperature, albedo and some basic knowledge of the study area. The need for this technique makes SEBAL somewhat subjective and difficult to automate. SEBAL uses an iterative process to correct for atmospheric instability caused by buoyancy effects of surface heating. More details and recent references/literature on SEBAL is available at www.waterwatch.nl.

Then instantaneous latent heat flux, λE, is the calculated residual term of the energy budget, and it is then used to compute the instantaneous evaporative fraction Λ (–):

$$\Lambda = \frac{\lambda E}{\lambda E + H} = \frac{\lambda E}{R_n - G_0} \qquad (2)$$

The instantaneous evaporative fraction Λ expresses the ratio of the actual to the crop evaporative demand when the atmospheric moisture conditions are in equilibrium with the soil moisture conditions. The instantaneous value can be used to calculate the daily value, because the evaporative fraction tends to be constant during daytime hours, although the *H* and λE fluxes vary considerably. The difference between the instantaneous evaporative fraction at satellite overpass and the evaporative fraction derived from the 24-h integrated energy balance is often marginal and may in many cases be neglected (Brutsaert and Sugita, 1992; Crago, 1996). For time scales of 1 day, G_0 is relatively small and can be ignored, and net available energy ($R_n - G_0$) reduces to net radiation (R_n). At daily timescales actual evapotranspiration, ET_{24} (mm/day) can be computed as

$$ET_{24} = \frac{86{,}400 \times 10^3}{\lambda \rho_w} \Lambda R_{n24} \qquad (3)$$

where R_{n24} (W/m^2) is the 24-h averaged net radiation, λ (J/kg) is the latent heat of vaporization, and ρ_w (kg/m^3) is the density of water.

For timescales longer than 1 day, actual evapotranspiration can be estimated using the relation proposed by Bastiaanssen et al. (2002). The main assumption is that Λ specified in Eq. (3) remains constant over the entire time interval between capture of each remote sensing image so that:

$$ET_{int} = \frac{dt \times 86{,}400 \times 10^3}{\lambda \rho_w} \Lambda R_{n24t} \qquad (4)$$

where ET_{int} (mm/interval) is the time integrated actual evapotranspiration, and R_{n24t} (W/m^2) is the average R_{n24} for the time interval dt measured in days. R_{n24t} is usually lower than R_{n24}, because R_{n24t} also includes cloudy days.

2.3. *Remote sensing-based irrigation performance indicators*

A wide range of irrigation and water use performance indicators are available (Rao, 1993; Bastiaanssen and Bos, 1999; Bos et al., 2005) to assist in achieving efficient and effective use of water by providing relevant feedback to the scheme/river basin management at all levels. Remote sensing derived raster maps (such as actual evapotranspiration and evaporative fraction) can be merged with vector maps of the irrigation water delivery systems to understand the real time performance under actual field conditions. In this study, indicators representing *equity*, *adequacy*, *reliability*, and *water productivity* are used to evaluate the performance of irrigated agriculture in the Punjab, Pakistan.

Traditionally, *equity* is calculated from the supply side. But in a water scarce system, like in the Punjab, equity in water consumption is more relevant from the farmer's perspective and can be computed from remote sensing-based ET_a maps of an irrigation system.

Adequacy is the quantitative component, and is defined as the sufficiency of water use in an irrigation system. In contrast, *reliability* is the time component and defined as the correspondence of water supply upon request. Both, *adequacy* and *reliability* of water supplies to cropped area can be assessed using the evaporative fraction maps as they directly reveal the crop supply conditions (Alexandridis et al., 1999; Bastiaanssen and Bos, 1999). In this study, *adequacy* is defined as the average seasonal evaporative fraction and *reliability* as the temporal variability, i.e., temporal coefficient of variation of evaporative fraction in a season. Evaporative fraction values of 0.8 or higher indicate no stress (Bastiaanssen and Bos, 1999), and below 0.8 reflect increases in moisture shortage to meet crop water requirements as a result of inadequate water supplies. Similarly, the lower values of coefficient of variation represent the more reliable water supplies throughout the cropping season.

The term *water productivity* is defined as the physical mass of production or the economic value of production measured against gross inflows, net inflow, depleted water, process depleted water, or available water (Molden, 1997; Molden and Sakthivadivel, 1999). For systems comprised of multiple agricultural enterprises, the water productivity is often computed in monetary terms.

Water productivity as an indicator, requires an estimate of production in physical or financial terms (numerator) and an estimate of water supplied or depleted as evapotranspiration (denominator). As there are complex cropping patterns in Rechna Doab, land and water productivity in this study are discussed in terms of gross value of production (GVP) over actual evapotranspiration. The scale of analysis is taken as subdivision, the lowest administrative unit of Punjab Irrigation department.

2.4. *Data collection and preprocessing*

This study was conducted for the period May 2001 to May 2002, representing Kharif 2001 and Rabi 2001–2002 cropping seasons. Daily meteorological data on temperature, humidity, wind speed and sunshine hours for Faisalabad and Lahore were collected from the Pakistan Meteorological department for May 2001 to May 2002. Rainfall data were collected from eight gauging stations in and around Rechna Doab and were interpolated to obtain gridded values of seasonal and annual rainfall. Considering the type of vegetation and bunds around field, interception and runoff losses from cropped areas are minimal and therefore ignored in this analysis (Ahmad et al., 2002).

Nineteen cloud-free MODIS scenes (Table 1) from April 2001 to May 2002, covering the entire Rechna Doab, were downloaded from Earth Observing System Data Gateway (EOSDG) of NASA (currently this information is available at NASA Goddard Space Flight Center website (http://ladsweb.nascom.nasa.gov/data/search.html). For a few months during the monsoon period, especially June and July, the frequency of cloud-free image availability is reduced. This has some impact on overall ET_a estimation but was unavoidable. For SEBAL processing, only 9 bands (i.e., first 7 bands in the Visible and Infrared range and two thermal bands 31 and 32) of MODIS were used.

Data describing surface flow diversions at the heads of the main irrigation canals were collected for the same time period from the Punjab Irrigation and Power department for the main canal systems of Rechna Doab.

For the gross value of production estimation, data on crop area, production and output prices were collected from secondary sources including the Economic Wing of the Ministry of Food, Agriculture and Livestock (MINFAL), the Bureau of Statistics (BoS), the Government of Punjab, and the Directorate of Economics and Marketing of the Provincial Agriculture Department. Data on cropped area and production were available at district level with MINFAL and BoS for all Rabi and Kharif crops. District level GVP was transformed to the scale of irrigation subdivisions based on the fraction of district area falling in a specific irrigation subdivision using overlay analysis in GIS. This was mainly done to overcome the limitation of district boundaries, which do not match those of the irrigation subdivisions. GVP was computed on real prices and Wholesale Price Index (WPI) was used to convert the current/nominal prices into constant/real prices with a base year 2000–2001 (GoP, 2006).

3. Results and discussion

3.1. *Spatio-temporal variation in actual evapotranspiration*

Daily evaporative fraction Λ and actual evapotranspiration (ET_a) were calculated by Eqs. (1)–(3) using cloud/haze free MODIS images for May 2001–May 2002. Then daily values were integrated at appropriate intervals [Eq. (4)] to calculate

Table 1 – List of MODIS images used for surface energy balance analysis in Rechna Doab, Pakistan.

	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
2001				21	11, 27	3		2, 20, 29	25	18	22	1, 23
2002	27	25	4, 16	10, 21	3							

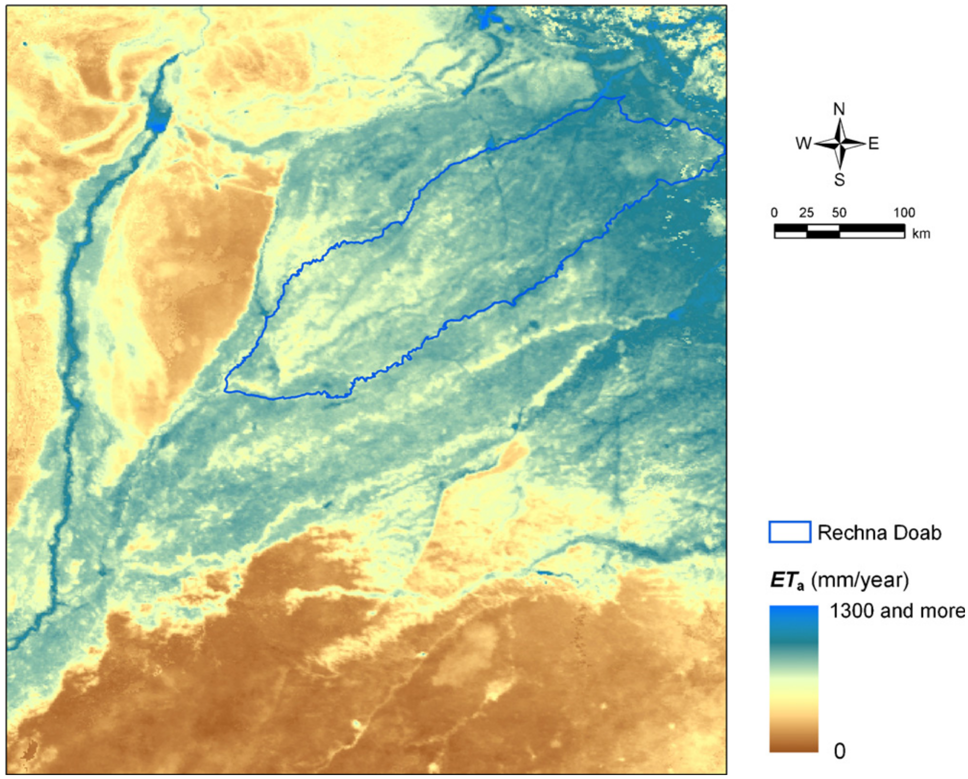

Fig. 2 – Annual actual evapotranspiration (May 2001–May 2002) in Rechna Doab and other parts of the upper Indus basin, Pakistan.

monthly, seasonal and annual evapotranspiration. The resultant map showing the annual variation in actual evapotranspiration in May 2001–2002 is presented in Fig. 2.

The annual ET_a varies from less than 100 mm/year in desert/barren areas to about 1650 mm/year over large water bodies in the processed image covering Rechna Doab and other parts of the upper Indus basin. However annual ET_a from cropped areas ranges between 500 mm/year and 1050 mm/year in Rechna Doab. Brown areas in the image delineate the desert and barren areas with lowest evapotranspiration,

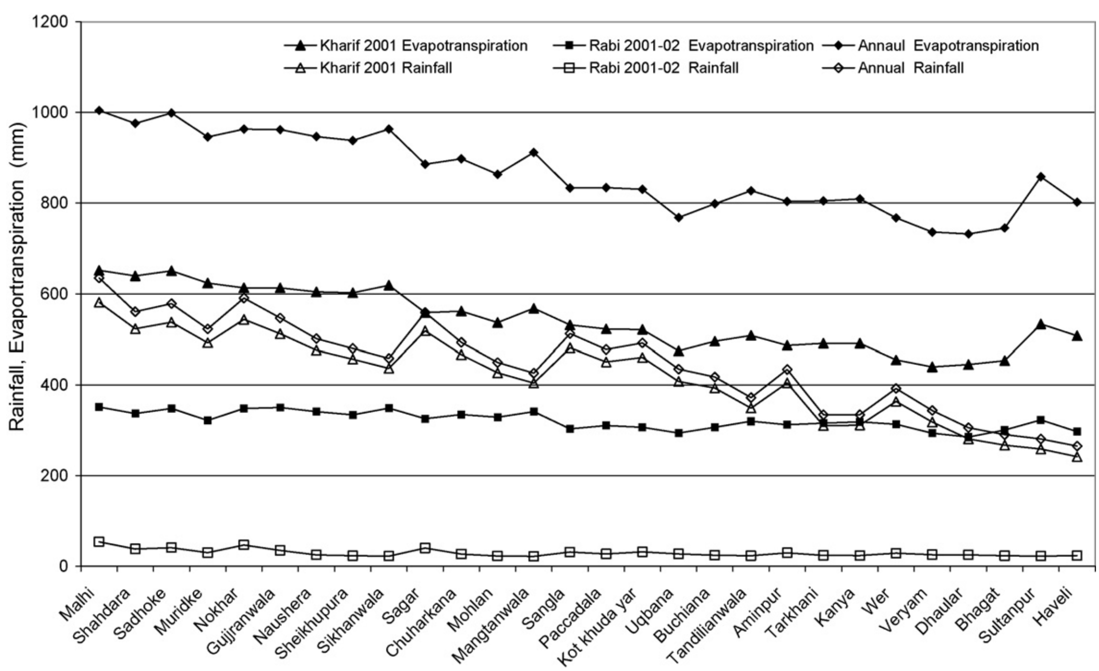

Fig. 3 – Seasonal and annual variation in rainfall (*P*) and actual evapotranspiration (ET_a) for irrigation subdivisions in year 2001–2002, arranged in order of upper to lower Rechna.

whereas the dark green-blue line features showing high ET_a in the image represent the rivers and canal network. Due to heterogeneous cropping pattern, it was difficult to identify pure pixels for particular crops. However, for the Punjab rice–wheat area in upper Rechna the average ET_a is about 970 mm/year, whereas it is generally much lower, i.e., 800 mm/year or less in lower Rechna under Punjab sugarcane–wheat zone due to lower cropping intensity, cultivation of less water intensive crops and possibly the effects of salinity. The average ET_a over Rechna Doab is about 850 mm/year which is almost double average rainfall and almost 60% of the reference crop evapotranspiration. The irrigated areas close to the main canals or river have higher ET_a, due to better access to canal and groundwater for agriculture, and are distinct in Fig. 2. The magnitude, seasonal and annual ranges of ET_a of this study are similar to an earlier study conducted in Rechna Doab (Bastiaanssen et al., 2002) on SEBAL validation for the Indus basin by comparing the results from a field-scale transient agro-hydrological model, in situ Bowen ratio measurements, and residual water balance for Rechna Doab. Their study showed that the accuracy of assessing time-integrated annual ET_a from SEBAL varied from 0 to 10% at a field scale to 5% at the regional level.

Seasonal and annual variations in rainfall (P) and ET_a in different irrigation subdivisions of Rechna Doab were computed through overlay analysis using GIS coverage of irrigation subdivisions and seasonal and annual ET_a and P maps. Fig. 3 illustrates the average seasonal and annual variation of P and ET_a in irrigation subdivisions of Rechna Doab. The annual P has sharp declining trend from upper to lower Rechna Daob, i.e., 635 mm/year to 265 mm/year during 2001–2002. Similarly, ET_a also has a declining trend but it is not as sharp as P due to irrigation with canal and groundwater. ET_a variations in Rabi, dominated by wheat and fodder, between different subdivisions is 64 mm and overall Rabi ET_a has a slightly declining trend from subdivisions in upper Rechna to the middle and lower Rechna Doab. This declining trend of ET_a from the upper to lower Rechna is much more profound in Kharif and governs the annual variations, except for Sultanpur subdivision. The reason for higher ET_a in Sultanpur subdivision, which is

Table 2 – Subdivision level variation in water consumption and groundwater quality.

Subdivision	Groundwater quality[a]	Actual evapotranspiration 2001–2002			
		Average depth (mm)	Standard deviation (mm)	Coefficient of variation	Volume (million m^3)
Punjab rice–wheat zone					
Malhi	Good	1004	44	0.04	491
Shahdara	Good	976	48	0.05	835
Sadhoke	Good	999	28	0.03	1,133
Muridke	Good	946	54	0.06	704
Nokhar	Good	963	42	0.04	1,114
Gujjranwala	Good	962	32	0.03	1,055
Naushera	Good	947	32	0.03	663
Sheikhupura	Good	938	39	0.04	626
Sikhanwala	Good	963	42	0.04	364
Transition from Punjab rice–wheat to sugarcane–wheat zone					
Sagar	Good	886	55	0.06	1,012
Chuharkana	Marginal to good	898	42	0.05	874
Mohlan	Marginal to good	864	47	0.05	973
Mangtanwala	Good	912	39	0.04	622
Punjab sugarcane–wheat zone					
Sangla	Marginal to good	833	68	0.08	430
Paccadala	Poor to marginal	834	48	0.06	652
Kot khuda yar	Good	830	63	0.08	675
Uqbana	Poor	768	49	0.06	915
Buchiana	Marginal to good	798	56	0.07	648
Tandilianwala	Marginal to good	827	37	0.05	916
Aminpur	Poor	804	60	0.07	743
Tarkhani	Poor to marginal	805	40	0.05	710
Kanya	Poor to marginal	809	37	0.05	627
Wer	Poor to marginal	767	45	0.06	720
Veryam	Poor to marginal	736	68	0.09	796
Dhaular	Good	732	76	0.10	718
Bhagat	Poor to marginal	745	94	0.13	718
Sultanpur	Good	858	53	0.06	519
Haveli	Poor	802	90	0.11	794
ET_a from canal command area					21,046
ET_a from Rechna Doab					25,326

[a] Groundwater quality is based on farmers' perception (Source: IWMI Socio-economic survey, 2004).

located in lower Rechna, is its proximity to the river Ravi, the availability of good soil and good groundwater quality due to recharge from the river.

3.2. Performance of agricultural water use

3.2.1. Equity

ET_a maps were used to calculate the equity and variability in water consumption within different subdivisions (Table 2). The results show that the upper Rechna (Punjab rice–wheat zone) and subdivisions proximate to rivers have higher ET_a and lower intra-subdivision level variability—an indication of equitable water consumption through surface and groundwater resources. Higher ET_a in these areas is related to fresh groundwater availability for irrigation. Subdivisions with poor groundwater quality, falling in the middle and lower Rechna Doab, showed the highest value of coefficient of variation representing high inequity in water consumption. Competition for surface water was greater in irrigation subdivisions of middle and lower Rechna as compared to upper Rechna mainly due to the quality of groundwater, leading to higher inequality in the distribution of surface

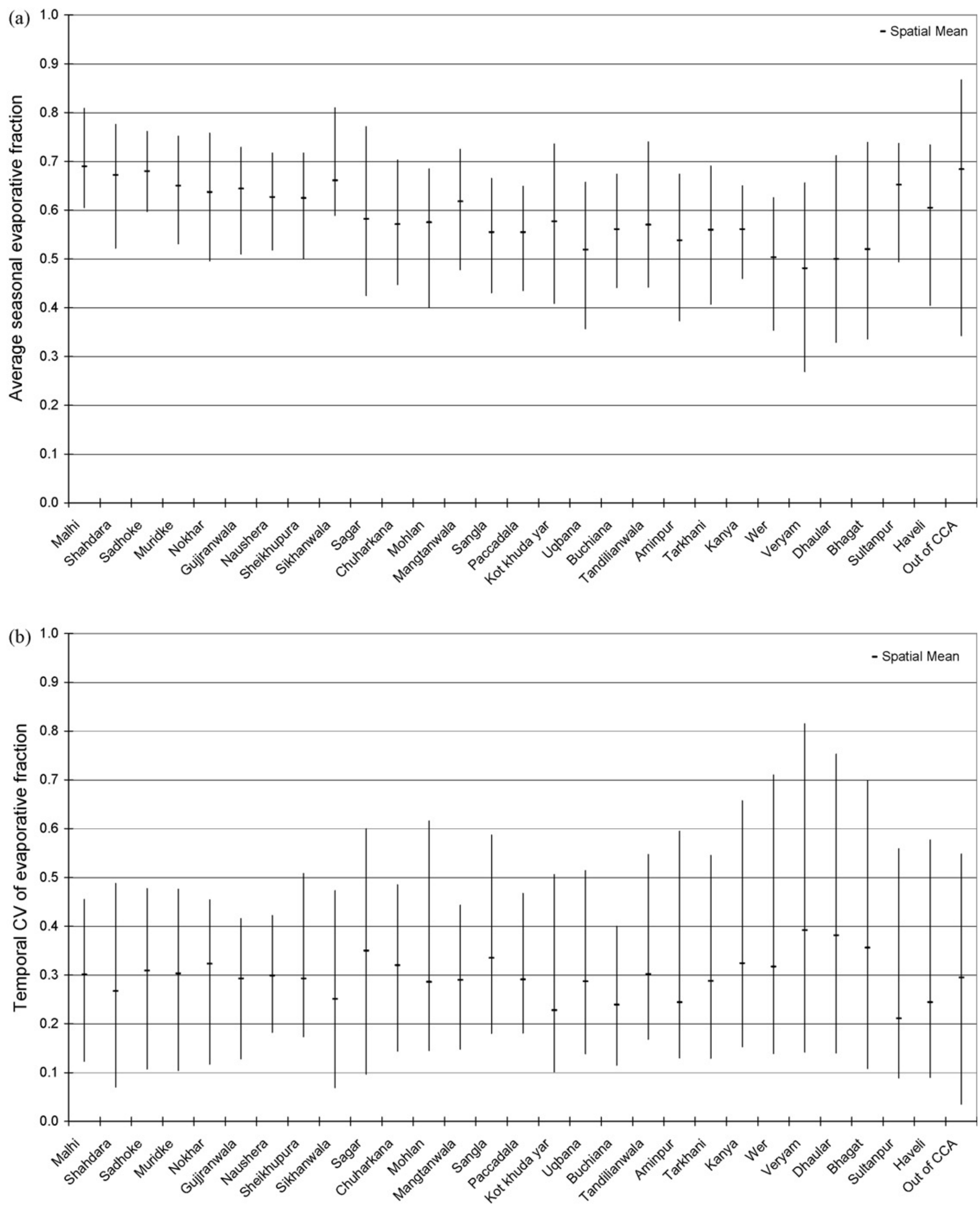

Fig. 4 – Inter- and intra-subdivision level variation in (a) average seasonal evaporative fraction in Kharif 2001 indicating adequacy of water availability, and (b) temporal coefficient of variation (CV) in evaporative fraction in Kharif 2001 indicating the reliability of water availability.

water. The information summarized in Table 2 is useful to water managers for evaluating options for additional water requirements or re-allocation between different parts of Rechna Doab to achieve equity.

3.2.2. *Adequacy and reliability*

Using the series of evaporative fraction maps, *adequacy* and *reliability* were computed for different subdivisions of Rechna Doab and presented in Figs. 4 and 5, respectively for Kharif and Rabi. The analysis reveals that crops in the subdivisions of the upper Rechna Doab have relatively reliable and adequate water supplies in both seasons. This is also evident from the results of a socio-economic study (unpublished) conducted by IWMI in Rechna Doab during 2003–2004, indicating a marginally higher proportion (3.45%) of sample farmers in Upper Rechna reporting receipt of adequate canal water as compared to 2.97% in lower and only 0.88% in middle Rechna. Similarly, canal water reliability (in terms of availability of adequate quantity at right time) was also reported higher (11% of the sample farmers) in upper Rechna when compared with middle

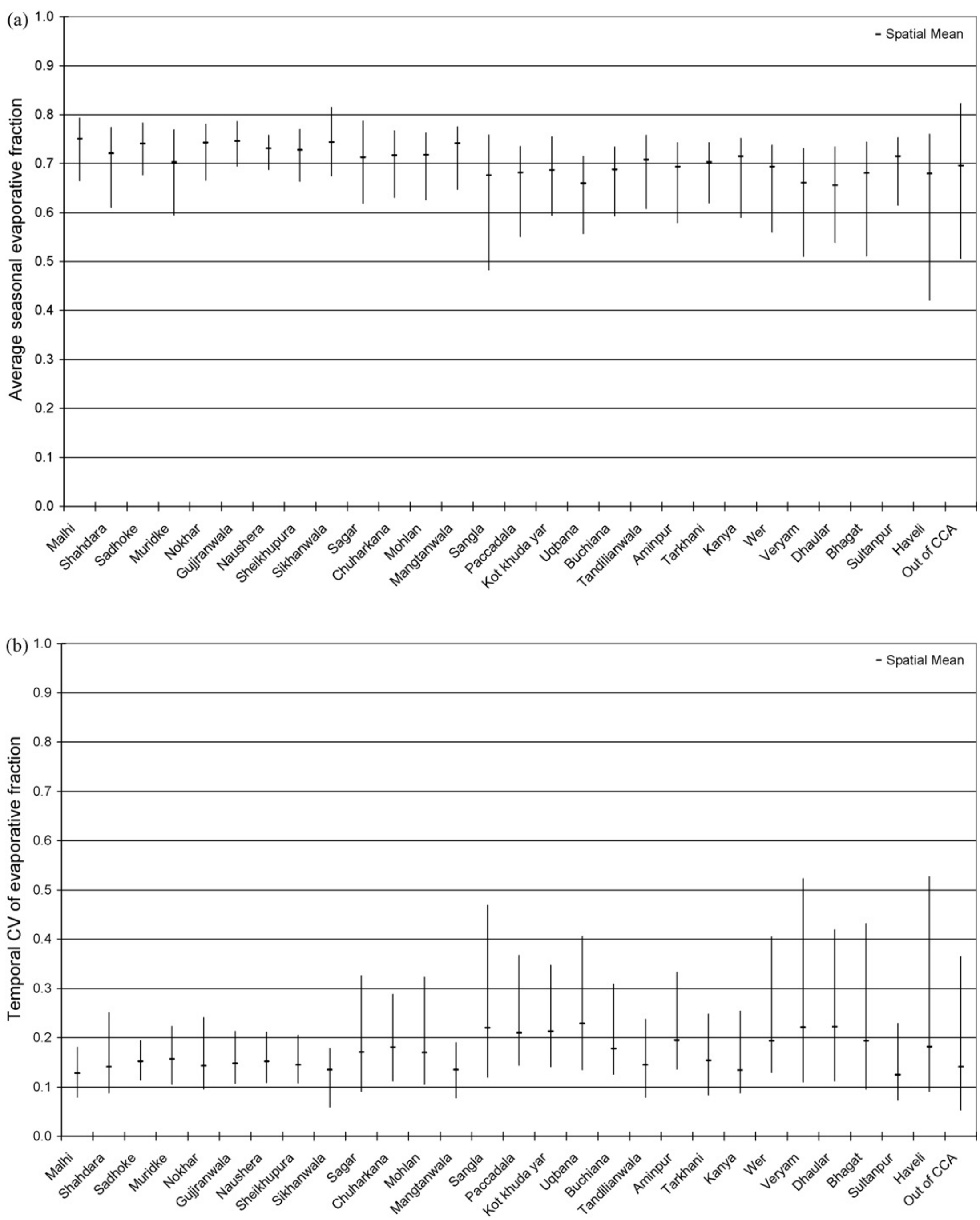

Fig. 5 – Inter- and intra-subdivision level variation in (a) average seasonal evaporative fraction in Rabi 2001–2002 indicating adequacy of water availability, and (b) temporal coefficient of variation (CV) in evaporative fraction in Rabi 2001–2002 indicating the reliability of water availability.

Table 3 – Seasonal and annual variation in rainfall (P), canal supplies (I_{cw}), actual evapotranspiration (ET_a) and net contributions from groundwater (I_{ngw}) in Rechna Doab.

Canal command	Kharif 2001 ($\times 10^6$ m^3)				Rabi 2001–2002 ($\times 10^6$ m^3)				Annual ($\times 10^6$ m^3)			
	P	I_{cw}	ET_a	I_{ngw}	P	I_{cw}	ET_a	I_{ngw}	P	I_{cw}	ET_a	I_{ngw}
MR and BRBD (Internal)	1,708	684	2,068	−323	128	12	1094	954	1,836	696	3,162	631
UCC	2,268	1695	2,828	−1135	148	293	1612	1171	2,416	1988	4,440	36
LCC	5,953	4369	7,785	−2536	420	2147	4857	2290	6,373	6516	12,642	−246
Haveli	239	N.A	503	N.A.	23	N.A.	294	N.A.	262	N.A.	797	N.A.
Out of command	2,537	0	2,803	266	240	0	1475	1235	2,777	0	4,278	1501
Total CCA	10,168	N.A.	13,184	N.A.	719	N.A.	7857	N.A.	10,887	N.A.	21,041	N.A.
Overall Rechna Doab	12,705	N.A.	15,987	N.A.	959	N.A.	9332	N.A.	13,664	N.A.	25,319	N.A.

Note: (1) Canal supplies for command area served by Haveli canal in Rechna Doab are not readily available. (2) Canal water represents the water diversion for irrigation at the head of the main canal system. MR and BRBD (Internal): Malhi, Shahdara, Shadhoke Muridke subdivisions; UCC: Nokhar, Gujjranwala, Naushera, Sheikupura, Mangtanwala, Sikhanwala; Haveli: Haveli; remaining subdivisions of Rechna Doab are part of LCC system.

(4%) and lower (less than 1%) Rechna. This better performance can be attributed to both higher canal supplies to subdivisions located close to canal head and/or access to good quality groundwater for irrigation (as also evident from Sultanpur subdivision in lower Rechna). The temporal coefficient of variation of the evaporative fraction in Kharif (Fig. 4b) is much higher than in Rabi (Fig. 5b), indicating less reliable supplies in the Kharif season.

3.2.3. *Sustainability*

The impact of water consumption patterns on *sustainability* was assessed in terms of the extent and quality of groundwater consumption and its likely impact on secondary salinization in different parts of the basin. As illustrated in Table 2, annually more than 25,000 million m^3 of water is evaporated from Rechna Doab. It is interesting to note that about 4000 million m^3 of water is evaporated outside the command areas (areas outside of canal irrigation network). A significant proportion of ET_a from out of command area (mostly in upper Rechna Doab) is due to unaccounted groundwater irrigation in a nominally rainfed area. As discussed earlier, even in canal command areas, a large proportion of irrigation supplies come from groundwater pumpage, but despite this it can be seen that the evaporative fraction is typically less than 0.8 in all subdivisions. Satellite-based ET_a results were compared with canal supplies and rainfall to calculate the net groundwater contribution in different seasons in the main canal commands of Rechna Doab—as subdivision level canal flow data for the period of study was not easily accessible (Table 3). The analysis showed that in Kharif, due to higher rainfall and canal supplies, there is generally net groundwater recharge (indicated by negative values), except outside of the command area where net groundwater contribution to ET_a was about 10%. It is important to remember that canal head flow data are used to compute net groundwater contribution at canal command level and this is different from irrigation from groundwater. In reality, as much as 50–60% percent of canal head water flows percolate from the earthen conveyance system and irrigated fields and a large fraction is pumped back for irrigation by farmers through private tubewell (Ahmad et al., 2002).

The *sustainability* of the system is evaluated by comparing the location of net groundwater use (Ahmad et al., 2005) in irrigated areas in consideration with groundwater quality. The net groundwater use is the difference between ET_a and inflows from precipitation, canal supplies and changes in unsaturated zone soil moisture storage—however changes in soil moisture storage at seasonal and annual scales and the interaction of rivers and link canals with groundwater are not considered in this study. Highest net groundwater use was found in Rabi, with 47% (LCC) to 87% (MR and BRBD internal) net contribution to ET_a coming from groundwater (Table 3). High groundwater reliance in (dry) Rabi compared to (wet) Kharif can be explained by annual canal closure period, low flows and (for MR and BRBD Internal) seasonally operated canals. In Kharif, it appears that most of the recharge is occurring in the LCC system which is largely underlain by a marginal to highly saline groundwater aquifer. As a result recharge from good quality canal water, after mixing with brackish groundwater, is becoming marginally fit to unfit for irrigation. Use of such brackish groundwater in these areas of Rechna Doab has already caused secondary salinization and sodicity (Khan et al., 2008). Considering the availability of detailed digital canal flow data for recent years from the Punjab Monitoring and Implementation Unit (PMIU), it is strongly suggested that these analyses be conducted at the irrigation subdivision or distributary command area scales for systematic tracking of vulnerable areas and for exploring management options to ensure the sustainability of irrigated agriculture in Rechna Doab.

3.2.4. *Land and water productivity*

Land and water productivity values were calculated using the subdivision level GVP (transformed from district level secondary agricultural statistics) and ET_a for the Kharif, Rabi and annual time step (Fig. 6). The analysis reveals that water productivity in Rabi is high and relatively less variable than Kharif values across Rechna Doab. This is mainly due to the higher percentage of cropped area in Rabi than in Kharif (Gamage et al., 2007). This is directly related to low evaporative demand in Rabi (winter season) and efficient use of limited canal supplies in marginal to poor groundwater quality areas. High Rabi water productivity is also partly related to government policies, especially the support price of wheat, which is the major Rabi crop. Lower water productivity in Kharif is offset by higher gross returns from rice and sugarcane per unit

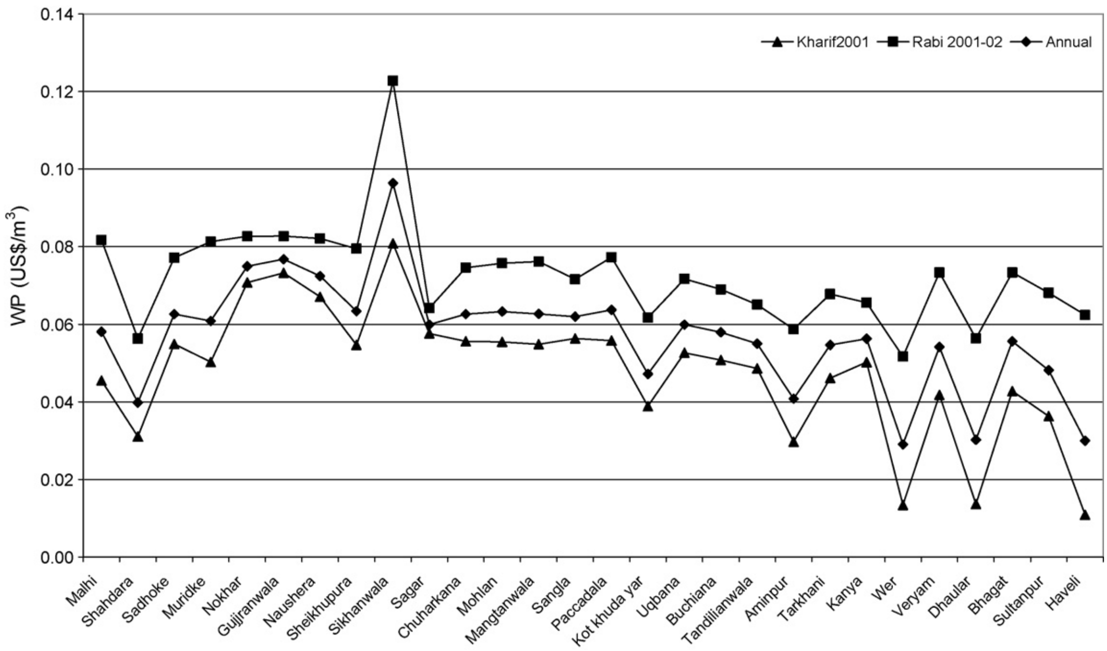

Fig. 6 – Seasonal and annual variation in subdivision level water productivity (WP) in terms of GVP per unit of ET_a in Rechna Doab. (1 US$ = PRs. 60.55).

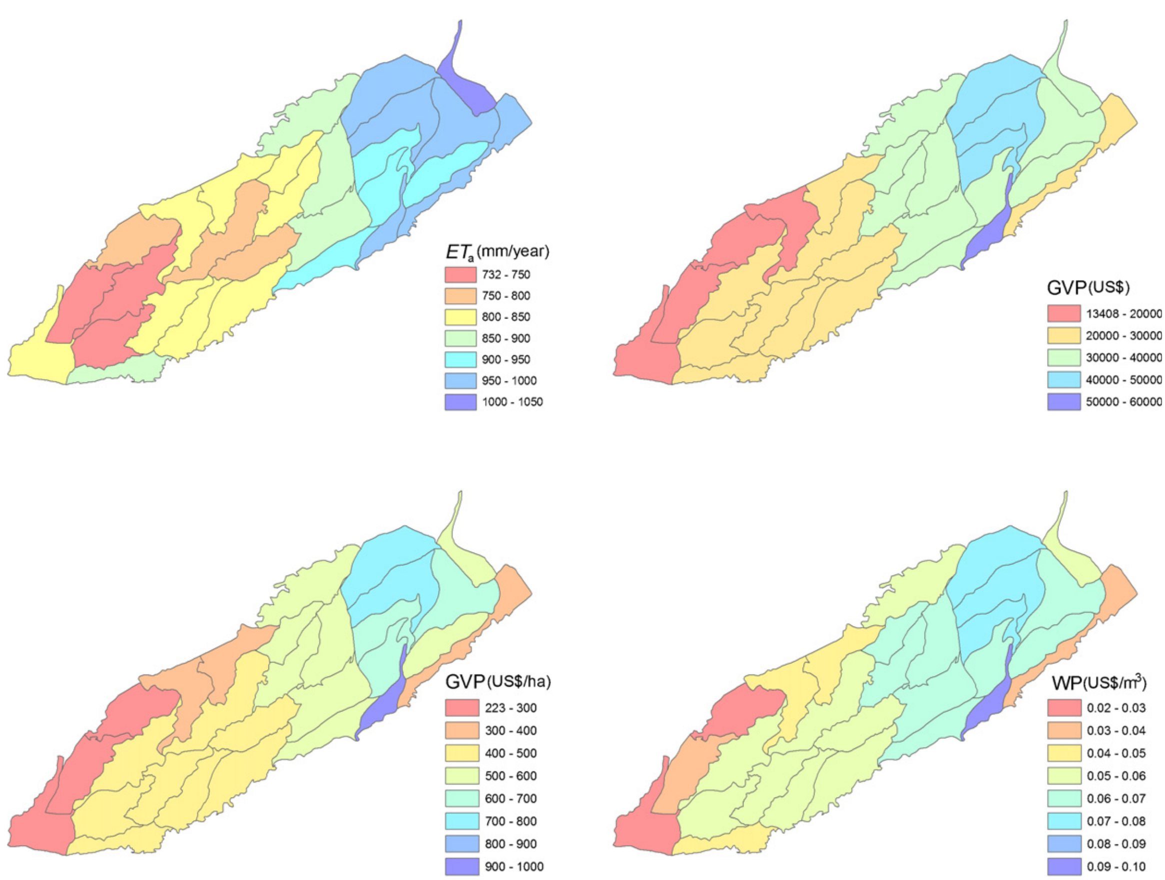

Fig. 7 – Spatial variation on subdivision level of actual evapotranspiration, gross value of production, and land and water productivity in Rechna Doab.

of land or farm—and reflects the incentives to farmers to grow high water using but high income generating crops (Jehangir et al., 2007).

The annual values of average ET_a, land and water productivity are presented in Fig. 7. High annual water productivity is found in subdivisions with good groundwater quality areas (mostly in upper Rechna) and with adequate and reliable water supplies. The highest water productivity was found in Sikhanwala subdivision which is attributed to high value fruit, vegetable cultivation, highest cropping (199%) and access to markets in Lahore city. However, the trend is not quite clear across all subdivisions in Rechna Doab. Water productivity, in terms of GVP per cubic meter of ET_a is generally higher for subdivisions with good quality water, but exceptions are there as in case of Dhular and Sultanpur. An additional reason may be the less adequate and reliable canal water supply, as indicated in Figs. 5 and 6.

4. Summary and conclusions

The paper shows that it is possible to use publicly available (NASA) satellite data to assess the performance of large irrigation systems when local flow monitoring records are unreliable or incomplete. This paper demonstrates the application of surface energy balance techniques to map spatial and temporal variation in actual evapotranspiration (ET_a) using freely available MODIS images and routine climatic data. The analysis shows that these data can be effectively combined with secondary cropping statistics that have been suitably transformed from their administrative domain to a hydrographic one.

The results of the remote sensing analysis show that the adequacy and reliability of combined surface water and groundwater deliveries decline towards the tails of the canals and towards the central and downstream parts of Rechna Doab. The causes of this are a combination of increasing groundwater salinity and more erratic surface water supplies.

The analysis reveals that sustainability of groundwater irrigation faces contrasting challenges. In upper Rechna Doab, groundwater consumption in irrigated areas is higher than recharge, indicating the possible decline in groundwater stocks (if the trends continue). In contrast, the challenge in the lower Rechna, where the recharge is more than groundwater use, is to reduce recharge to saline groundwater (sinks).

A similar pattern is seen in the water productivity values derived in both Kharif and Rabi seasons, and reflects the adaptation by farmers of planting lower value and more salt tolerant crops in the more downstream areas. The highest annual water consumption is seen in the upper and upper-middle reaches of the Doab, where both surface and ground water supply are plentiful, and rice and sugarcane are grown as summer/annual cash crops. Interestingly, although the gross margin for wheat is relatively low, especially compared to rice and sugarcane, the average winter water productivity is high for three reasons: low water consumption, judicious use of groundwater, and expanded areas compared to Kharif, resulting from a combination of the first two factors.

The one anomalous result is for a sub-district that runs close to the river Ravi (Sagar subdivision) and has good quality groundwater, fed directly by the river. Here water productivity and water consumption are both high.

The procedure does not allow for a detailed insight into the reasons for high and low water productivity as influenced by crop choice, and this requires other approaches such detailed crop production function analysis. However, it does show the bigger picture and shows where policy makers and water managers need to improve the effectiveness of water consumption. The main implication for water managers is to improve surface water supplies toward the tails of the distribution systems to allow better supply, better crop choice, and mitigate salinity. However, more detailed analysis is needed in order to understand: (1) how far the soil and salinity limitations of the downstream areas can be overcome by simply improving the adequacy, reliability, and quality of water delivered to the farmer; and (2) the longer term implications of increasing the use of fresh groundwater in the head reaches—the long term sustainability of a changed allocation policy would be compromised if the quality of currently fresh groundwater degrades due to the development of internal water table gradients that drive mixing from the saline areas. This analysis shows that managing water productivity to improve the overall system level average productivity through changed water allocation has long term perspectives.

Although there is some natural energy price and water quality control on groundwater abstraction in Pakistan, this analysis is also useful in identifying both where groundwater consumption is not accounted for and how much water is being consumed. This information can also be put into more sophisticated analyses in combination with surface water supply data within the command, for instance using seasonal and annual surface water supply data to each subdivision. Similarly analyses could be undertaken below subdivision level, as a second level of enquiry: this would require nested water balances to be calculated on an annual and seasonal basis, within the over-riding water balance of the whole Doab.

More specific analysis of the performance and the water productivity of different cropping systems would then require better crop mapping and identification. This could be done by higher resolution remote sensing, but would then require better spatial disaggregation of ET_a. It remains to be seen if the patterns observed in individual snapshots (using Landsat or Aster) are reflected in the seasonal water allocations, and this can be investigated in the future. However, the loss of Landsat ETM + functionality in 2003 due to failure of the scan line corrector (SLC), and the current low likelihood of a replacement satellite having a thermal band raise questions for high resolution applications in the future. Researchers are currently looking for alternatives that do not require thermal band information, but it remains to be seen how robust and accurate such techniques are.

In a country such as Pakistan, with dwindling water availability, and further threats from climate change, set against continually rising population and food demand, this information is vital for irrigation policy maker and managers. Both policy analysts and managers work in conditions in which it is difficult to obtain reliable data with field measurements, and techniques such as described offer an interim step to improving long term management of water resources and to making the required improvements in average water productivity.

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