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Paper

A new technique to estimate net groundwater use across large irrigated areas by combining remote sensing and water balance approaches, Rechna Doab, Pakistan

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Abstract Over-exploitation of groundwater resources threatens the future of irrigated agriculture, especially in the arid and semi-arid regions of the world. In order to reverse this trend, and to ensure future food security, the achievement of sustainable groundwater use is ranking high on the agenda of water policy makers. Spatio-temporally distributed information on net groundwater use—i.e. the difference between tubewell withdrawals for irrigation and net recharge—is often unknown at the river basin scale. Conventionally, groundwater use is estimated from tubewell inventories or phreatic surface fluctuations. There are shortcomings related to the application of these approaches. An alternative methodology for computing the various water balance components of the unsaturated zone by using geo-information techniques is provided in this paper. With this approach, groundwater recharge will not be quantified explicitly, but is part of net groundwater use, and the spatial variation can be quantitatively described. Records of routine climatic data, canal discharges at major offtakes, phreatic surface depth fluctuations, and simplified information on soil textural properties are required as input data into this new Geographic Information System and Remote Sensing tool. The Rechna Doab region (approximately 2.97 million ha), located in the Indus basin irrigation system of Pakistan, has been used as a case study. On an annual basis, an areal average net groundwater use of 82 mm year^{-1} was estimated. The current result deviates 65% from the specific yield method. The deviation from estimates using tubewell withdrawal related data is even higher.

Keywords Remote sensing - GIS - Water balance - Groundwater management - Net groundwater use - Recharge - Irrigation management - Sustainability - Rechna Doab, Pakistan

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Resumen La sobre-explotación de recursos de agua subterránea amenaza el futuro de la agricultura de riego, especialmente en las regiones áridas y semi-áridas del mundo. Para revertir esta tendencia, y para garantizar seguridad alimentaria futura, la meta del uso sostenible del agua subterránea se encuentra alto en la agenda de los políticos. Información espacial y temporal en cuanto al uso neto de agua subterránea- i.e. la diferencia entre las extracciones de agua de pozos entubados para riego y recarga neta- se desconoce frecuentemente a la escala de cuenca hidrográfica. Generalmente, el uso de agua subterránea se estima a partir de inventarios de pozos o fluctuaciones de superficies freáticas. Existen deficiencias en relación con las aplicaciones de estos enfoques. En este artículo se aporta una metodología alternativa para calcular los diferentes componentes del balance hídrico de la zona no saturada utilizando técnicas geoinformativas. Aunque con este enfoque no se cuantifica de manera explícita la recarga de agua subterránea, la cual es parte del uso neto de agua subterránea, puede describirse cuantitativamente la variación espacial. Para esta nueva herramienta de Sistemas de Información Geográfica y Sensores Remotos se requieren datos de entrada como registros rutinarios de datos climáticos, descargas de canales en salidas principales, fluctuaciones de profundidades de superficies freáticas, e información simplificada de las propiedades texturales de los suelos. Se ha utilizado como estudio de caso la región Rechna Doab (aproximadamente 2.97 millones ha), localizada en el sistema de riego de la cuenca Indus de Pakistán. Se ha estimado un uso promedio areal anual de agua subterránea de 82 mm año^{-1}. El resultado obtenido difiere en un 65% del método de productividad específica. La diferencia en relación a estimados provenientes de extracciones en pozos entubados es aún mucho más alta.

Résumé La surexploitation des ressources en eau souterraine menace le futur de l ’agriculture irrigué, spécialement dans les zones arides et semi-arides du monde. De manière à renverser la tendance, et d ’assurer la sécurité alimentaire, l ’utilisation durable des eaux souterraines est devenue une priorité dans l ’agenda des politiques de l ’eau. La distribution spatio-temporelle de l ’usage net de l ’eau souterraine (la différence entre l ‹eau pompée et la recharge nette) est rarement connue à l ’échelle d ’un bassin versant. Conventionnellement, l ’utilisation des eaux souterraines est estimée à partir des données de rabattement ou les données de fluctuation du niveau de la nappe phréatique. Il y a des défauts dans ces approches. Une méthodologie alternative pour calculer les différents composants de la balance hydrologique est présentée dans cet article. Avec cette approche, la recharge des eaux souterraines ne sera pas quantifiée de manière explicite, mais sera considérée comme une part de l ’utilisation nette en eau souterraine, et la variation spatiale peut être décrite quantitativement. Les chroniques des données climatiques, les débits du réseau hydrographique majeur, les fluctuations de la surface de la nappe phréatique, et des données basiques sur la texture du sol sont nécessaires et sont rentrées dans un nouveau Système d’Information Géographique et outil de télédétection. La région de Rechna Doab au Pakistan, environ 2.97 millions d’hectare, localisée dans le bassin irrigué de l’Indus, a été utilisé comme cas d’étude. Sur base annuelle, l’utilisation nette de l’eau souterraine est estimée à 82 mm. en moyenne. Le résultat obtenu diffère de 65% du résultat de la méthode du débit spécifique. La différence avec le résultat obtenu en observant le rabattement des puits est encore plus élevée.

Introduction

Many large nations rely on irrigated land for more than half of their domestic food production. On irrigated farms, two or three crops per year can be grown and yields are usually high; therefore, the spread of irrigation has been the key to the previous century’s rise in food production. The other side of the story is that two thirds of the world’s diverted fresh water is being used for irrigation—with an appreciable contribution coming from groundwater resources. Most of the 750–800 billion m^3 year^{-1} of global groundwater withdrawals are used for agriculture (Shah et al. 2000). During the last 10 to 20 years, there has been a significant increase in the utilization of groundwater resources for agricultural irrigation because of their widespread distribution and low development costs (Clarke et al. 1996). Groundwater has been the heart of the green revolution in agriculture across many Asian nations, and has permitted cultivation of high value crops. Today, the United States, China, India and Pakistan are the biggest consumers of groundwater and its use is still increasing (Postel 1999). In the Punjab of Pakistan, use of groundwater for irrigation has rapidly increased, which was mainly initiated in the 1960s with the launch of Salinity Control and Reclamation Projects (SCARPs). Under this program, a number of large-capacity public pumps (0.084–0.14 m^3 sec^{-1}) were installed to control waterlogging and provide supplementary irrigation supplies. Thereafter the Government of Pakistan encouraged the installation of private pumps for irrigation. Presently, the greatest proportion of groundwater supplies comes from thousands of small-capacity (0.028 m^3 sec^{-1} or less) private tubewells, which was minimal in the initial stages of the development of this resource. Reliability of timing and supply, and better control over volumes of water applied are just few of the many reasons why farmers have adopted groundwater irrigation on a massive scale (Scott and Shah 2004). The rapid development of tubewells is a clear indication of the current level of farmer reliance on groundwater to irrigation.

In most irrigation systems, the sustainability of groundwater is impacted by two factors: (1) rise of the phreatic surface into the root zone and (2) declining phreatic surface in aquifers that are overused. The major reason for a rising phreatic surface is seepage from irrigation canals and irrigated fields. In fresh groundwater areas (total dissolved salts less than 500 mg L^{-1}), depletion of the aquifer and fall of the phreatic surface are caused by unplanned over-utilization of groundwater. If extraction of groundwater exceeds replenishment, aquifer levels will drop with adverse consequences to entire rural economies and the livelihood of farmers. This drop in groundwater levels can lead to deterioration of groundwater quality due to saltwater intrusion from saline zones. Persistent reliance on such groundwater in irrigated areas has also resulted in the transport of salts from deep aquifers into the root zone resulting in secondary salinity and sodicity. To avoid these undesirable scenarios, it is necessary to assimilate groundwater pumpage and recharge data in solid aquifer exploitation plans.

Adequate management of groundwater systems is feasible only when all groundwater flow terms are known. This can be achieved by means of numerical groundwater flow models that simulate flows on the basis of locally measured geo-hydrological properties and hydraulic heads. The set-up of a sophisticated groundwater flow model and its calibration is a rather time-consuming effort and is often overlooked because of the absence of sufficient resources and data. Groundwater flow models are, therefore, not commonly used in the South Asian irrigation context.

Groundwater extractions are computed using simpler techniques. For large irrigated areas, the statistical method (Utilization Factor U_F-Method) is used to define the relationship between tubewell extraction and tubewell utilization time, as well as site characteristics (NESPAK-SGI *1991*; Maupin *1999*). Tubewell utilization time is usually estimated from electricity/fuel usage bills or through field surveys. These field survey data are sometimes biased because certain countries have water quotas or volumetric water pricing. The water table fluctuation or specific yield method is based on the changes of water storage in the saturated zone, with the basic assumption that all outflow is related to withdrawals. The shortcomings of these conventional approaches are:

- The utilization factor method reflects pumping only, and recharge is disregarded. The many small and large tubewells are operated by different rules, and an average extraction is difficult to establish.
- The specific yield method requires a dense network of piezometers and accurate measurements of phreatic levels that are often absent—besides it ignores lateral groundwater flow, which makes it difficult to get a reliable picture of spatial variations at the regional scale.

Water policymakers are now aware of the value of groundwater, and are committed to undertake proper action and even pursue lawsuits to ensure sustainable exploitation. The error margins related to the field data are, however, unacceptably high for implementing a sound groundwater policy. This paper attempts to develop a methodology for regional-scale applications, which relies on the combined use of remotely sensed information and GIS techniques for the estimation of net groundwater use for agriculture—without the inclusion of complex groundwater models. This method can be considered as a tradeoff between sophisticated groundwater flow modelling and the application of simplified analytical solutions. Some qualitative comparisons with the conventional methods are made for the sake of understanding the ball park figures of the differences.

Materials and methods

Definitions

For groundwater management, quantitative information on water exchange between the unsaturated and the saturated zone is essential, i.e. $q^{\downarrow}_{(h_m=0)}$, $q^{\uparrow}_{(h_m=0)}$ and tubewell irrigation I_{tw} (See Fig. 1). The *percolation* rate reaching the saturated zone $q^{\downarrow}_{(h_m=0)}$ is defined as *recharge*.

Throughout this paper, the $q^{\uparrow}_{(\mathrm{h}_m=0)}$ flux is referred to as *capillary rise*, also if this water does not reach the root zone. Then *net recharge* rate q_{nr} to the saturated zone is often defined as:

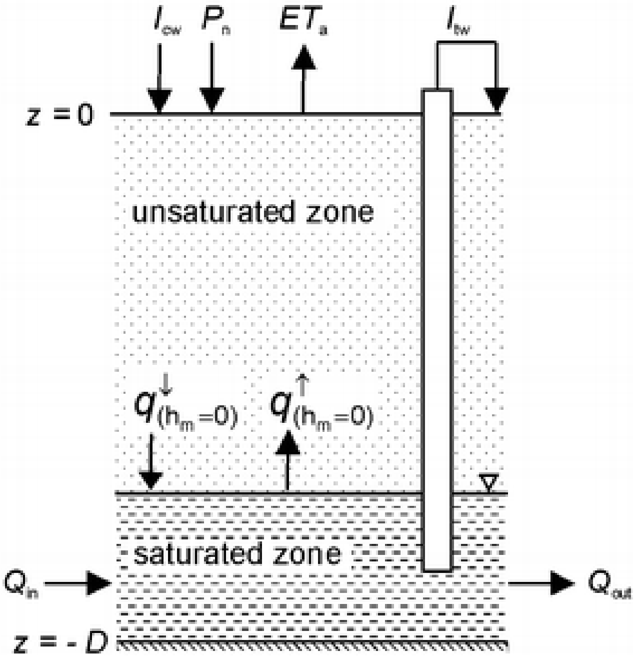


Fig. 1 Schematisation of different soil water fluxes in a phreatic aquifer (I_{cw} is canal water irrigation, P_{n} is net precipitation, ET_{a} is actual evapotranspiration, I_{tw} is tubewell irrigation, $q^{\downarrow}_{(\mathrm{h}_m=0)}$ is recharge, $q^{\uparrow}_{(\mathrm{h}_m=0)}$! is capillary rise, Q_{in} and Q_{out} lateral in-flow and lateral out-flow in the saturated zone respectively

$$q_{\mathrm{nr}} = q^{\downarrow}_{(\mathrm{h}_m=0)} - q^{\uparrow}_{(\mathrm{h}_m=0)} \tag{1}$$

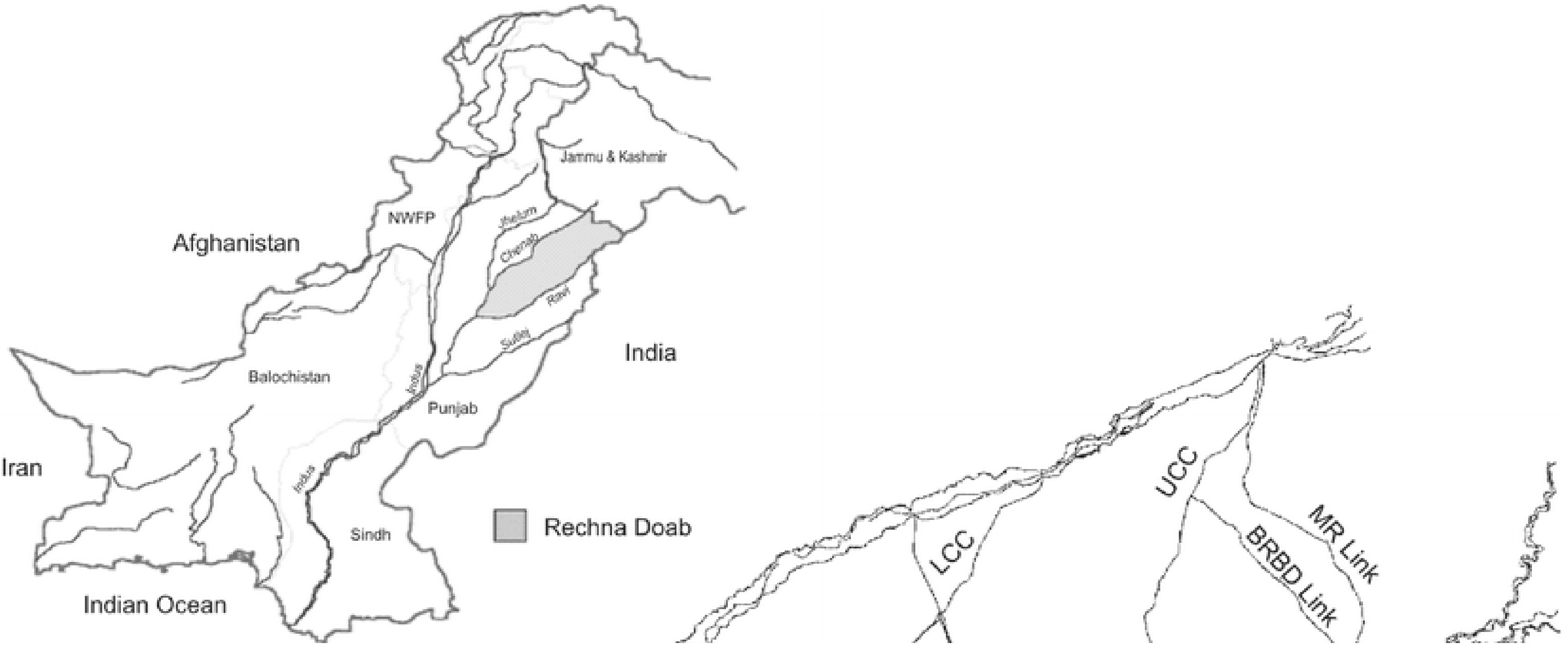
which describes the net amount of water vertically conveyed to the phreatic surface through the unsaturated zone.

In this paper, the difference between tubewell extractions I_{tw} and q_{nr} is defined as *net groundwater use* I_{ngw}, being mathematically expressed as:

$$I_{\mathrm{ngw}} = I_{\mathrm{tw}} - q_{\mathrm{nr}} \tag{2}$$

Description of the study area

This investigation was conducted in Rechna Doab (Fig. 2), which is located in the heart of the Indus River basin irrigation system in Pakistan. Rechna Doab is the interfluvial area between the Chenab and Ravi Rivers. It lies between longitude 71°48′E to 75°20′E and latitude 30°31′N to 32°51′N. The gross area of this Doab is approximately 2.97 million ha, with a maximum length of 403 km and a 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 the Punjab, Pakistan. The area falls in the rice-wheat and sugarcane agro-ecological zones of the Punjab province. Rice, cotton and forage crops dominate the summer season (kharif). Wheat and forage are the major crops in the winter season (rabi). In some parts, sugarcane is also cultivated, which is an annual crop.



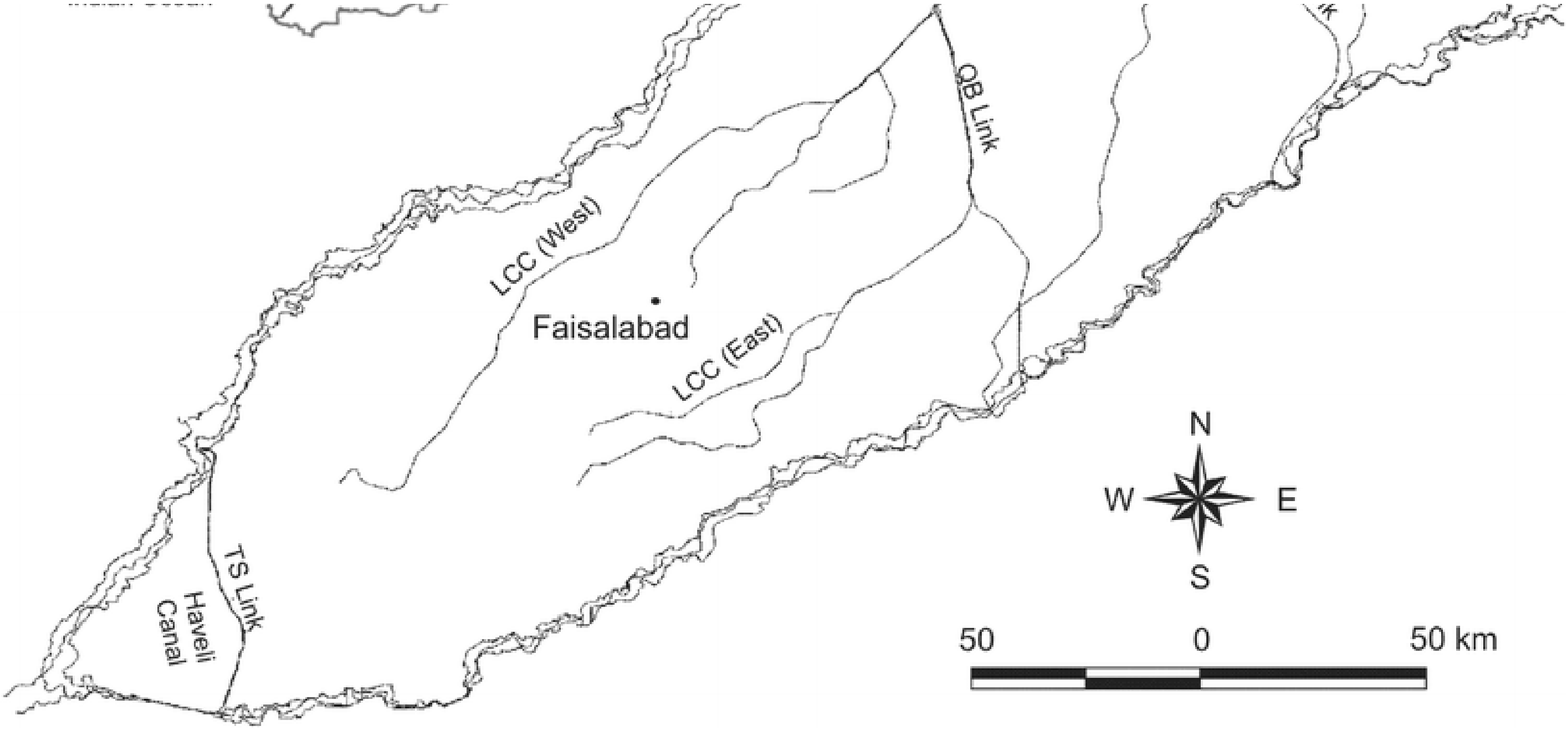


Fig. 2 Canal irrigation network in Rechna Doab, Pakistan. Upper Chenab Canal (UCC), Bambanwala-Ravi-Bedian-Depalpur (BRBD), Marala-Ravi (MR) Link, Qadirabad-Balluki (QB) Link, Lower Chenab Canal (LCC), Trimu-Sadhnai (TS) Link and Haveli Canal

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The climate is characterized by large seasonal fluctuations of air temperatures and rainfall. The summer is long and hot, lasting from April through September, with maximum air temperature ranging from 21 to 49 °C. Winter lasts from December through February, with maximum air temperature ranging from 25 to 27 °C and sometimes falling below zero at night. The annual precipitation is about 400 mm. The monsoon elapses from June to September and accounts for about 75% of annual rainfall. The climate records of Faisalabad along with the general crop calendar are shown in Fig. 3.

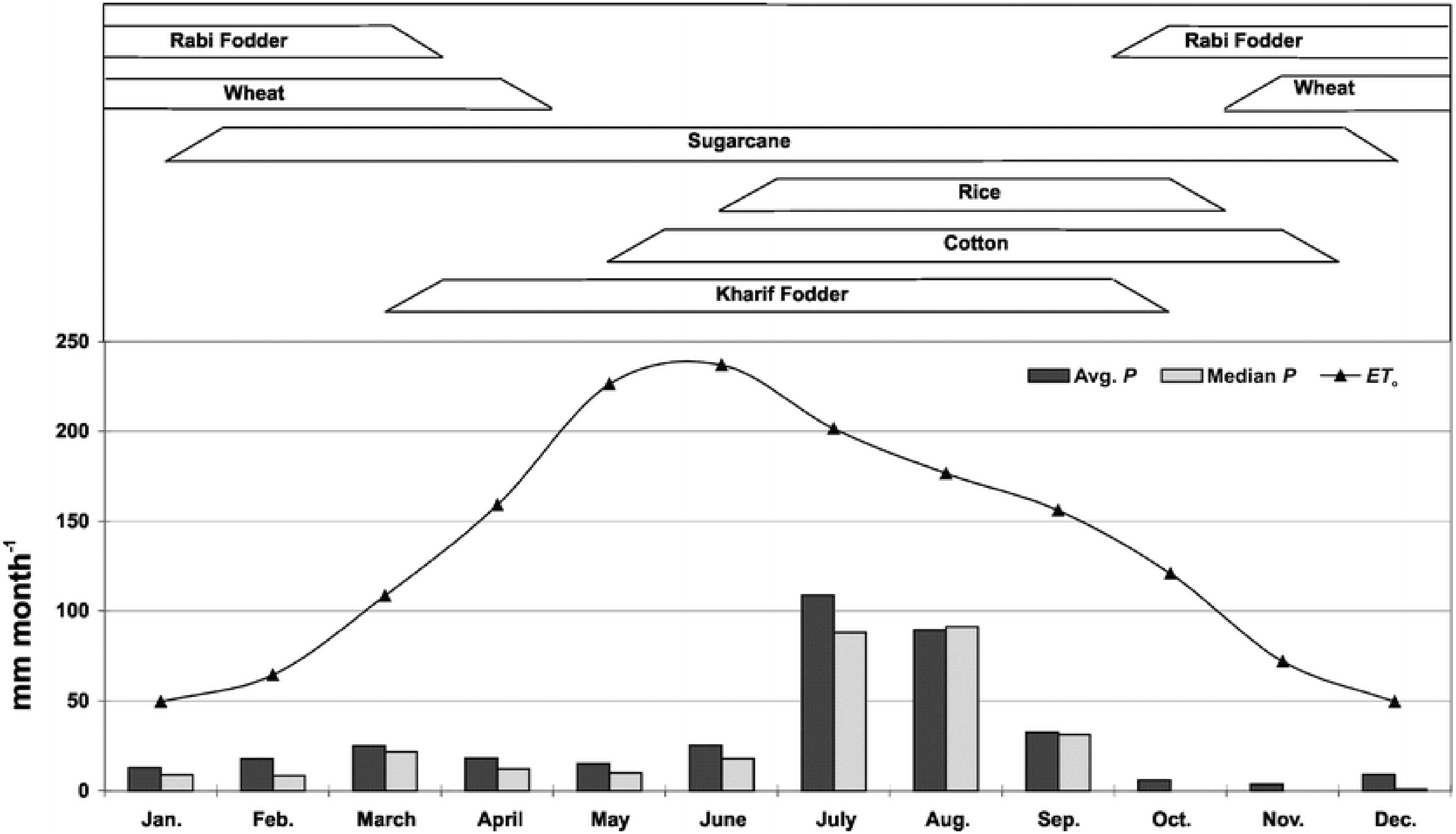

Fig. 3 Cropping calendar, monthly precipitation rate and reference crop evapotranspiration rate ET_o computed according to Penman-Monteith for Faisalabad

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The Rechna Doab soils consist of alluvial deposits transported by the Indus River and its tributaries. The soils textures are predominantly medium to moderately coarse, with favourable permeability characteristics and show a similarity throughout the area.

Due to scanty and erratic rainfall, successful agriculture is only possible in Rechna Doab through irrigation. The canal irrigation system (Fig. 2) was introduced in 1892 with the construction of the Lower Chenab Canal (LCC). Presently, almost 2/3 of Rechna Doab is fed by a perennial canal system; i.e. the irrigation water flows constantly into a secondary (distributary) and tertiary (watercourse) canal system as long as there is need for water and sufficient flow in the rivers. A normal flow period per year is about 340 days. Non-perennial irrigation systems receive water during the kharif, which are restricted to the upper Chenab Canal (UCC) and Marala-Ravi Link (MR Link) canal. The outlets (moghas) from the distributaries are not gated and are designed to deliver a fixed quantity of water when the canals are flowing at full capacity.

The design flows in the distributaries are based on the historical size of the command area. This system was designed to spread a limited amount of canal water over the entire area supporting a cropping intensity of approximately 65%. The original design objective of the irrigation development was to protect against crop failure and to prevent famine. However, in the last two to three decades cropping intensities have increased up to 150%, being enabled by additional supplies from groundwater extraction. On a weekly or 10-day rotation period (locally called “warabandi”), each farmer is allotted a fixed quantity of canal water proportional to his land holdings. To ameliorate the impact of crop water deficits, public and private tubewells were installed on a large scale. Canal and ground water are now commonly used in conjunction.

Traditional methods for the estimation of groundwater use

Due to unplanned and rapid development of private tubewells, no mechanism is in place to calculate electricity or fuel usage of tubewells in Pakistan. Therefore NESPAK-SGI (*1991*) has worked out utilization factors U_{F} (ratio of daily tubewell working hours to number of hours in a day) through field surveys in different areas of Pakistan. U_{F} can be used to compute I_{tw} from the number of tubewells N_{tw} in an irrigated area A and their average discharge capacity Q_{tw} as:

$$I_{\mathrm{tw}} = \frac{U_{\mathrm{F}}\, N_{\mathrm{tw}}\, Q_{\mathrm{tw}}}{A} \qquad (3)$$

This statistical approach is known in Pakistan as the *Utilization Factor* U_{F}-method.

The *Saturated zone* water balance method is based on the transient water balance of the saturated zone:

$$I_{\mathrm{ngw}} = \frac{Q_{\mathrm{in}} - Q_{\mathrm{out}}}{A} - S_{\mathrm{y}}\frac{\mathrm{d}h}{\mathrm{d}t} \tag{4}$$

where Q_{in} and Q_{out} represents lateral groundwater inflow and outflow respectively, S_{y} specific yield, dh change in phreatic surface and dt change in time. Net groundwater use I_{ngw} calculation through Eq. (4) requires data on the phreatic surface fluctuation dh, specific yield S_{y} and lateral groundwater flows Q_{in} and Q_{out}. In groundwater modelling studies lateral flows are determined from piezometer measurements of the height of the phreatic surface above a certain reference level, knowing the transmissivity of the aquifer (Boonstra and Bhutta *1995*). Phreatic surface measurements are not generally available at small time intervals. Therefore conventionally, at larger time steps, e.g. a year or more, Q_{in} and Q_{out} may be assumed to be equal and then the rise or fall of the phreatic surface is only attributed to $-S_{\mathrm{y}}\frac{\mathrm{d}h}{\mathrm{d}t}$, i.e. net groundwater use:

$$I_{\mathrm{ngw}} = -S_{\mathrm{y}}\frac{\mathrm{d}h}{\mathrm{d}t} \tag{5}$$

This method is known as the specific yield S_{y}-method. The accuracy and validity of the results is based on the reliability and density of the observation points (often less than desirable for a dense network with a fine mesh) as well as the assumption that lateral groundwater flows can be ignored.

Geo-information techniques for the estimation net groundwater use

The use of geo-information techniques is a new method to calculate net groundwater use for agriculture. Whereas the S_{y}-method studies the saturated zone, this approach describes the water balance and the changes of the unsaturated zone. Net groundwater use I_{ngw} must be determined as a residual term from water balance analysis of the unsaturated zone over a specific period dt (Fig. 1), which reads as:

$$P_{\mathrm{n}} + I_{\mathrm{cw}} + I_{\mathrm{tw}} - ET_{\mathrm{a}} + q^{\uparrow}_{(\mathrm{h}_m=0)} - q^{\downarrow}_{(\mathrm{h}_m=0)} = \frac{\mathrm{d}W_{\mathrm{u}}}{\mathrm{d}t} \tag{6}$$

where

$$\frac{\mathrm{d}W_{\mathrm{u}}}{\mathrm{d}t} = \int_{z=-z_2}^{z=0} \theta_{(z,t_2)}\,\mathrm{d}z - \int_{z=-z_1}^{z=0} \theta_{(z,t_1)}\,\mathrm{d}z \tag{7}$$

where dW_{u} represent the change in the unsaturated zone storage and θ in the volumetric soil moisture content. Note that z_1 and z_2 differ which implies that Eq. (7) is valid for changing water table conditions. Combining Eqs. (1), (2) and (6), yields a new expression to compute net groundwater use I_{ngw} as a function of land surface processes that can be obtained nowadays from remote sensing and GIS techniques:

$$I_{\mathrm{ngw}} = ET_{\mathrm{a}} - P_{\mathrm{n}} - I_{\mathrm{cw}} + \frac{\mathrm{d}W_{\mathrm{u}}}{\mathrm{d}t} \tag{8}$$

Equation (8) excludes the need to explicitly solve lateral in- and out-flows. ET_{a} can be calculated using satellite imagery and routine meteorological data using a remote sensing parameterization of the surface heat fluxes. Several models are available (Kustas et al. *2003* for a recent review). The surface energy balance algorithm for land (SEBAL) developed by Bastiaanssen et al. (*1998*, *2002*, personal communication) has been used in this case study. Since there is a direct link between actual evapotranspiration ET_{a}, potential evapotranspiration ET_{p} and root zone volumetric soil moisture content θ at various stages in the growing season (see ‘non-ideal circumstances’ in Allen et al. *1998*), soil moisture θ can be estimated on a pixel-to-pixel basis from ET_{a} and ET_{p}. Using the evaporative fraction of the energy balance, Scott et al. (*2003*) made two-weekly estimates of soil moisture in the root zone for the total Indus Basin system. Together with bi-annual measurements of phreatic surface, that describes the moisture conditions in the capillary fringe, unsaturated zone soil moisture storage W_{u} is computed. Ahmad and Bastiaanssen (2003) developed a new method for this purpose.

On an annual basis in Rechna Doab, net precipitation rate P_{n} is not a major water balance component. Therefore, monthly estimates of precipitation on a pixel-wide basis were obtained from linear interpolation of gauge readings collected at 8 meteorological stations throughout Rechna Doab. Since Rechna Doab is relatively flat and irrigation fields have bunds, runoff has been ignored. Canal water diversions to all major irrigation canal systems of Rechna Doab have been measured at the head works by the Punjab Irrigation department and Water And Power Development Authority (WAPDA). With the lack of high-resolution satellite images covering the entire Rechna Doab for a complete annual cycle (October 1993- October1994), canal water distribution was disaggregatated using the spatial surfaces of National Oceanic Atmospheric Administration-Advanced Very High Resolution Radiometer based Normalized Difference Vegetation Index (NDVI) maps. NDVI was thus used as a determinant for canal water availability, which has been done before by Menenti et al. (1989). Equation (8) can neither quantify recharge $q^{l}_{(h_m=0)}$ or net recharge q_{nr}, but the net draft I_{ngw} is the most important for management purposes. This whole approach is more elaborated by Ahmad (2002).

Results and Discussion

Net groundwater use estimates from geo-information techniques

Spatially distributed values

The maps showing the spatial distribution of the various water balance components derived from remote sensing and geo-information techniques are presented in Fig. 4. Spatial distributions of ET_{a}, varying from 600 to 1,100 mm year^{-1}, are found in the cultivated areas across Rechna Doab. A large tract with higher ET_a exists in the rice growing area in the upper Rechna Doab. These spatial variations in actual evapotranspiration rate ET_{a} can be attributed to different cropping systems, the conditions of the atmospheric boundary layer and the amount of irrigation water supplied, including groundwater. Figure 3 has demonstrated that reference evapotranspiration can be as high as 240 mm month^{-1}. If the irrigation canal network does not provide sufficient surface water resources, in fresh groundwater quality areas, farmers will shift to groundwater irrigation. The peak evapotranspiration occurs in the months of June to August from rice areas due to high ambient temperatures and monsoon rains. The lowest evapotranspiration occur in the month of January that is related to low ambient temperatures and to canal closing in Punjab for routine maintenance.

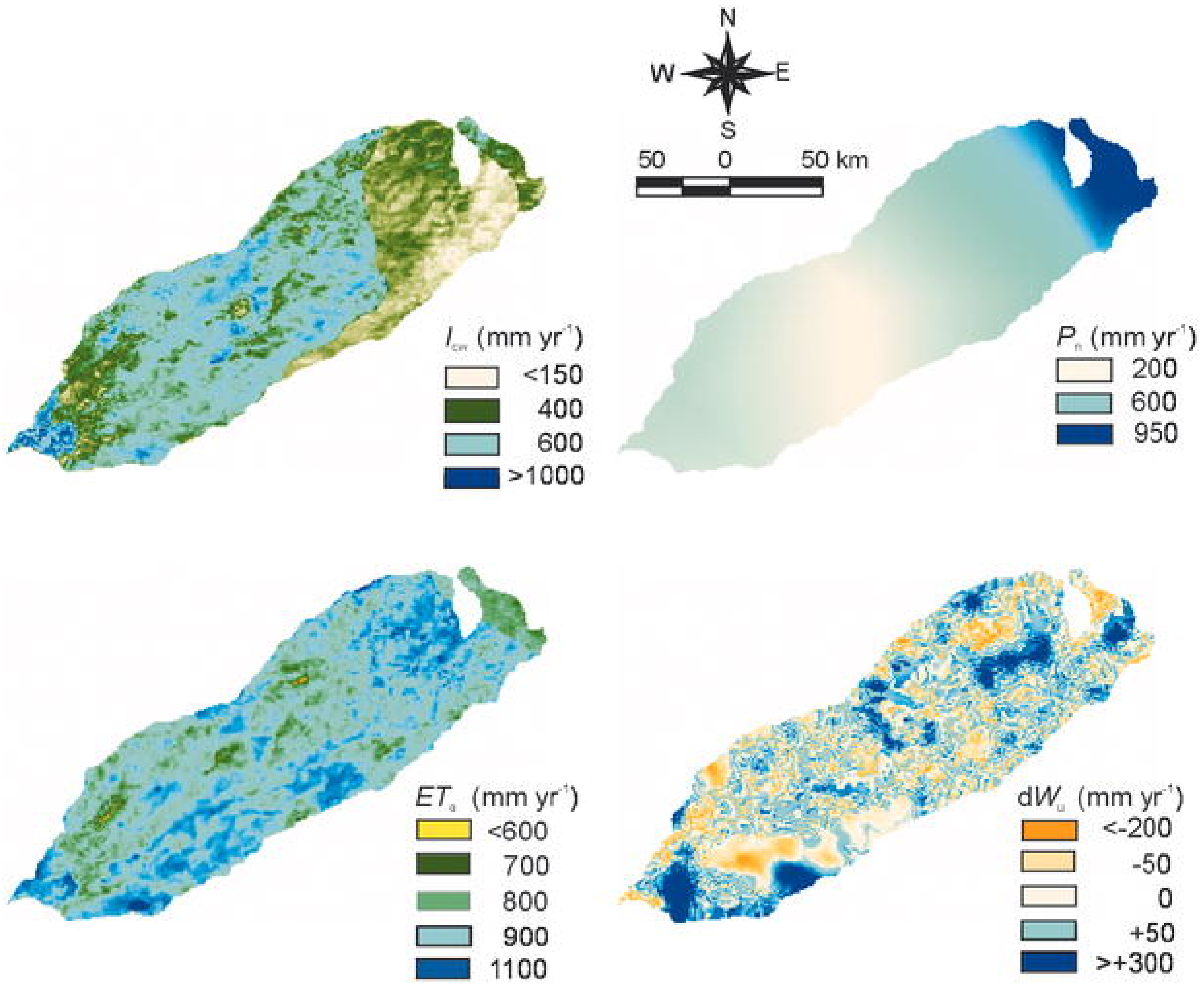

Fig. 4 Maps showing the distribution of annual irrigation rate with canal water I_{cw}, net precipitation rate P_n, actual evapotranspiration rate ET_a and change in the unsaturated zone soil moisture storage dW_u from October 1993 to October 1994 in Rechna Doab

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Spatial variability in annual I_{cw} between canal commands is mainly the result of the non-perennial system (little or no water supplies in rabi) in the upper Rechna Doab. Despite the low canal water supplies, the upper Rechna Doab (served by Marala-Ravi MR Link, Bambanwala-Ravi-Bedian-Depalpur BRBD Link and Upper Chenab Canal UCC) is the most intensively cultivated area. Crop water requirement is met by an additional supply from groundwater extraction by tubewells, with some contribution from precipitation. Upper Rechna Doab, in particular the MR canal command, receives 2 to 3 times more precipitation than the middle and lower part of the Doab. The highest rate of irrigation with canal water I_{cw} was estimated in the Haveli Canal, because there are large uncertainties in the gross irrigated areas as reported by the irrigation department and WAPDA (calculated from canal command coverage). The value of I_{cw} varies between 150 and 1,100 mm. The variation in I_{cw}, P_n and ET_a causes positive as well as negative changes in soil moisture storage W_u in Rechna Doab.

Finally, for each pixel, net groundwater use I_{ngw} was estimated by means of Eq. (8). First monthly I_{ngw} values were calculated and then accumulated to annual values (Fig. 5). Positive I_{ngw} values in Fig. 5 represent net groundwater use, negative values represent net replenishment. The data shows that annually an amount of 300 to 600 mm is net extracted, thus 0.8 to 1.6 mm day^{-1}. The highest I_{ngw} is observed in the UCC and BRBD, which are areas containing non-perennial canals. Other fragmented pockets of high I_{ngw} are in the LCC (East), which have higher annual ET_a because of rice cultivation or higher cropping intensities. Scattered patterns of groundwater replenishment (negative values of I_{ngw}) are also observed across the LCC system, particularly in the head reach with a rice–wheat cropping system. But, most of the groundwater replenishment occurs in the command areas of MR and Haveli. The replenishment in MR is mainly because of a higher net precipitation rate P_n, while in Haveli it is because of higher canal water supplies. Most of the replenishment occurs during the monsoon months when canals are flowing at peak discharge. This water is not necessarily lost as groundwater, as it may be used elsewhere at a later time.

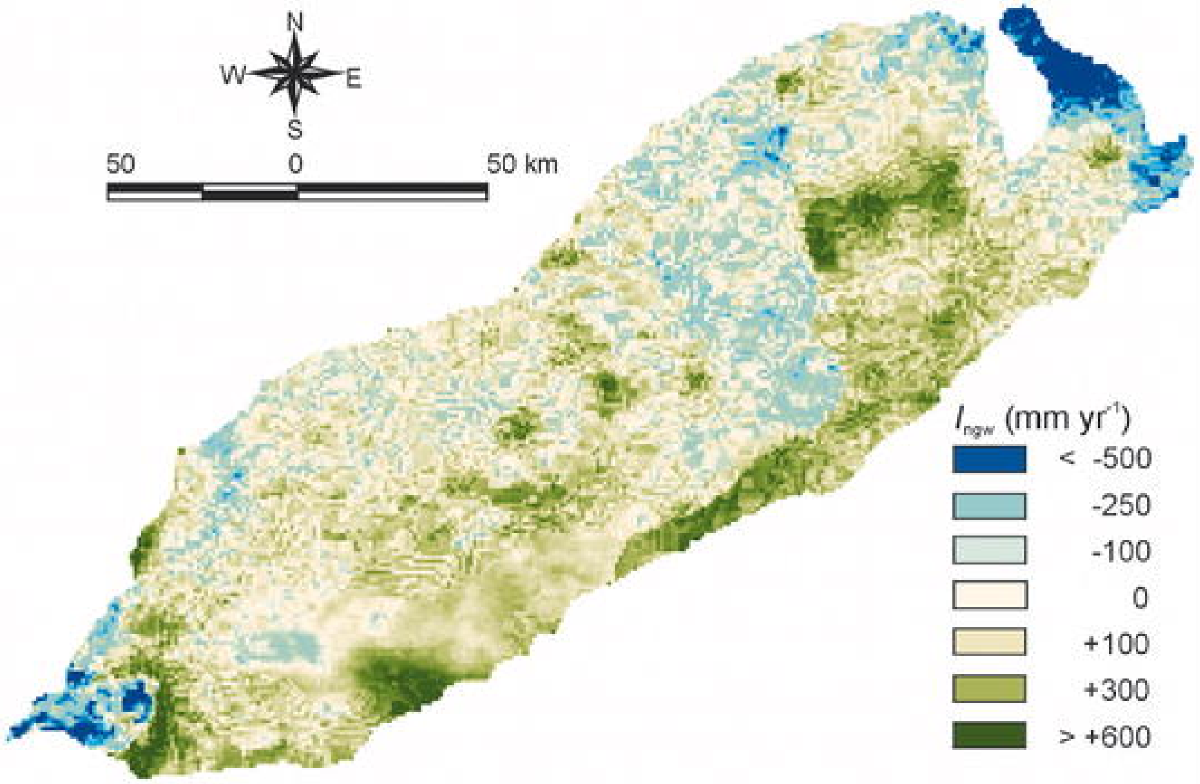

Fig. 5 Distributed annual net groundwater use I_{ngw}, Eq. (8), from October 1993 to October 1994, as computed using remote sensing and geo-information techniques in Rechna Doab

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Accuracy assessment

The estimated values of net groundwater use I_{ngw} from geo-information techniques are prone to errors due to the uncertainty in the assessment of each input water balance component. Thus it is essential to compute the influence of errors in each individual component, ET_{a}, P_{n}, I_{cw} and $\mathrm{d}W_{\text{u}}/\mathrm{d}t$, on overall computation of $I_{\text{ngw}}$from Eq. (8) and see whether the errors in individual components will cancel or propagate.

To understand the error behaviour under different agro-climatic and hydrological conditions in Rechna Doab, two pixels representing cotton–wheat and rice–wheat cropping rotation, are selected for detailed investigation. These pixels represent deep and shallow phreatic surface conditions respectively. The annual estimated values for different water balance components from geo-information techniques are presented in

Table 1. ET_a is one of the largest water balance components in Rechna Doab and obviously errors in its computation will have a major influence on I_{ngw}. Recent studies in Rechna Doab indicate that the accuracy of time-integrated SEBAL ET_a varies from 0 to 10% at field scale, and 5% at the regional scale (Bastiaanssen et al. *2002*). Similarly for the same area the accuracy in dW_u/dt was found to be around 6% (Ahmad and Bastiaanssen *2003*). The expected accuracy of I_{cw} and P_n is about 15% but this could not be validated at the 1 km grid size because of the unavailability of data at appropriate scale in Rechna Doab. Due to the absence of a time series field for these selected locations, random data series are generated for ET_a, P_n, I_{cw} and dW_u/dt with ±10, ±15, ±15 and ±6% deviations from its estimated values, respectively.

Table 1 Annual water balance components estimated from geo-information techniques at selected 1 km grid in the cotton–wheat system at Faisalabad (73°2′49.8″E 31°23′26.2″N) and rice–wheat system at Pindi Bhattian (73°20′50.2″E 31°52′34.2″N), in Rechna Doab

Water Balance Component (mm $year^{-1}$)	Faisalabad cotton–wheat system	Pindi Bhattian rice-wheat system
ET_a	870	810
P_n	195	370
I_{cw}	410	565
dW_u/dt	–45	85

Using these generated data series I_{ngw} is computed using Eq. (8) for 1,000 different combinations of random input parameters. For both locations, similar deviations are observed. Finally, the absolute deviation I_{ngw} is estimated from geo-information techniques using random data series and is plotted against its probability of occurrence (Fig. 6). The figure shows that the maximum error that could occur in the geo-information techniques is 190 mm $year^{-1}$ for similar hydrological conditions. However, there is a 70% chance that the error I_{ngw} will be within the range of 75 mm $year^{-1}$. The average error (50% probability) is less than 50 mm $year^{-1}$. The areas where the rate of net groundwater use is high—300 mm $year^{-1}$ or more—i.e. the priority areas for groundwater management, this error is within the acceptable range (25% or less).

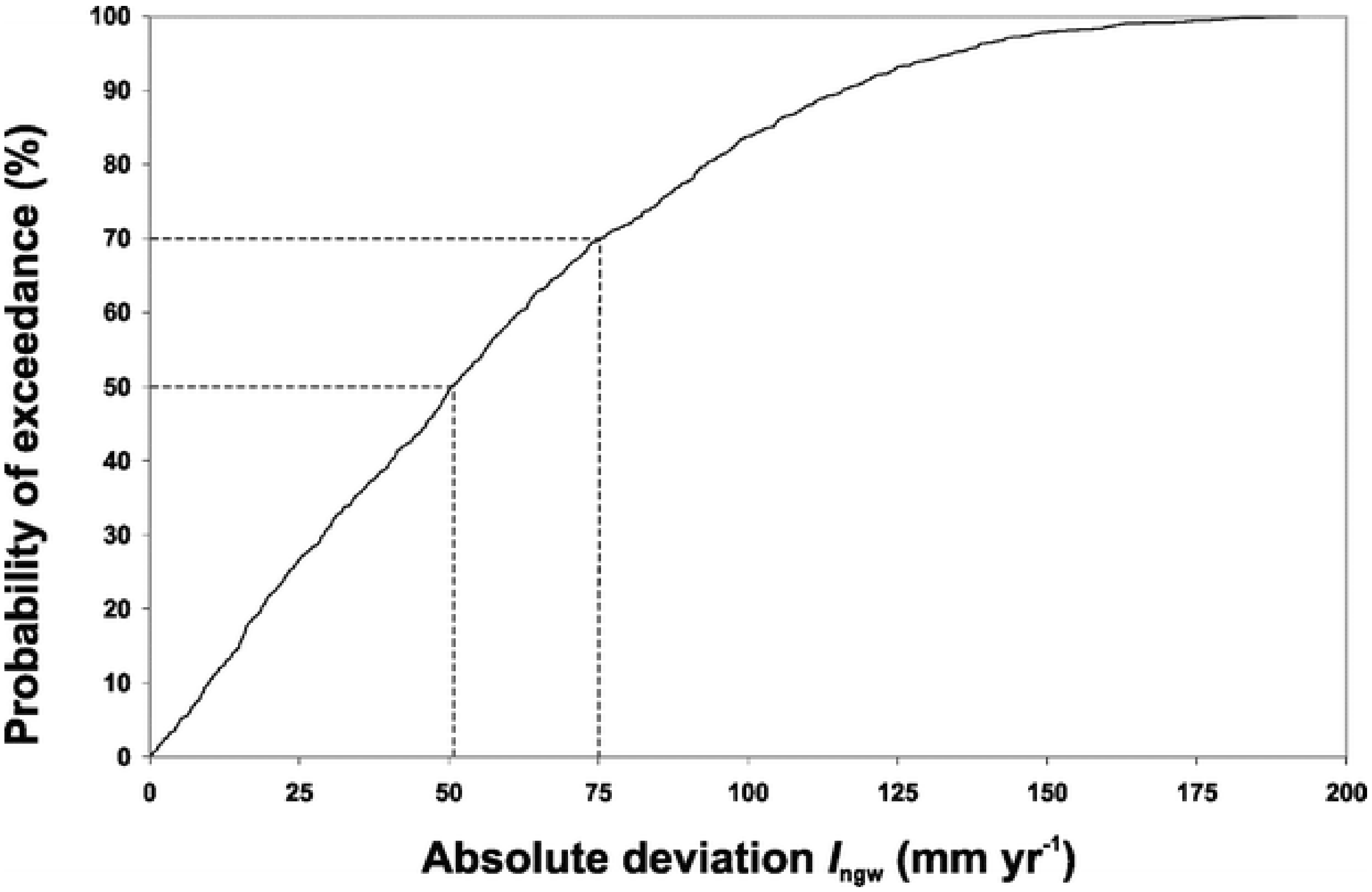

Fig. 6 Distribution of absolute deviation of net groundwater use I_{ngw} from geo-information techniques estimates using random input data series in Rechna Doab

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Aggregated values at canal command level

Monthly estimates of I_{ngw} in different canal commands of Rechna Doab, as calculated from the geo-information based water balance analysis, are presented in Fig. 7. Positive and negative values of I_{ngw} were observed in all canal commands during both the rabi and kharif. The highest values are found in February and May (>150 mm month^{-1}) due to the high crop water requirement (more pumping, positive I_{ngw}). The peak in February can be explained by the flowering stage of wheat and in May for the land preparation for cotton (see cropping calendar of Fig. 3). The values of I_{ngw} in MR, UCC, and BRBD are much higher than in other canal commands during the rabi, since little or no canal water is being diverted to these canal commands. During the monsoon months (July, August and September), I_{ngw} was often negative, which implies that groundwater systems are replenished in most of the canal commands. Accumulated results on an annual basis reveal that the UCC, BRBD and LCC use considerable amounts of net groundwater: 170, 108 and 85 mm year^{-1} respectively. In MR and Haveli, the aquifer was replenished with 405 and 201 mm year^{-1} respectively, which is a significant quantity. Although not specifically investigated, it is plausible that excessive groundwater flows from MR to BRBD and UCC; the same for Haveli to LCC.

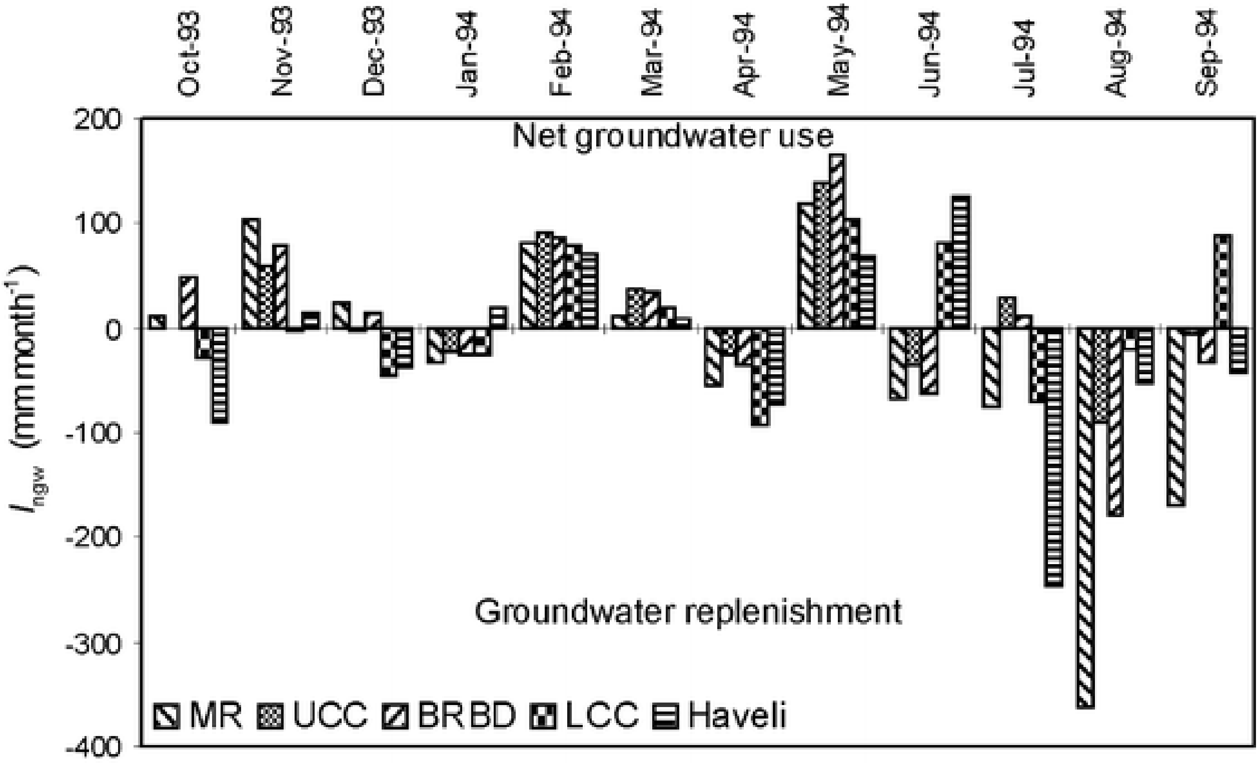

Fig. 7 Monthly net groundwater use I_{ngw}in different canal commands of Rechna Doab. Net groundwater use occurs during crop sowing periods while replenishment occurs during monsoon periods. Marala-Ravi Link MR, UCC Upper Chenab Canal, BRBD Bambanwala-Ravi-Bedian-Depalpur Canal, LCC Lower Chenab Canal and Haveli Canal

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Records of routine climatic data, canal discharges at major offtakes, fluctuations in phreatic level, and simplified information on soil textural properties are required as input data into this new geographic information system and remote sensing tool. The results are less sensitive to phreatic surface depth than the reliance of the specific yield method on this data. Hence, under the collection efforts practiced by the Pakistani line agencies, there is sufficient field data available to execute the new geo-information technology approach.

Net groundwater use estimates from conventional techniques

Utilization factor $U_F$method

Tahir and Habib (*2000*) used U_F, N_{tw} and Q_{tw} data (GOP *1994*) for the approximation of I_{tw}, Eq. (3), in the Punjab. As tubewell statistics were available for large aggregated districts, they first calculated I_{tw} for the district and then transformed it to a canal command scale, according to the proportion of the district to the specific command area. Estimated annual I_{tw} values for different canal commands of Rechna Doab are summarized in Table 2. The highest I_{tw} was found in the non-perennial canal commands that are located in the upper Rechna Doab: MR, UCC and BRBD (see Fig. 2). This area is in the rice–wheat agro-climatic zone of the Punjab and most groundwater withdrawals was used for rice cultivation.

Table 2 Annual estimates of groundwater withdrawal for irrigation I_{tw} (Eq. (<equationcite>3</equationcite>) for the year 1993–94, using utilization factors U_F in different canal commands of Rechna Doab. Marala-Ravi Link MR Link, UCC Upper Chenab Canal, BRBD Bambanwala-Ravi-Bedian-Depalpur Canal, LCC Lower Chenab Canal and Haveli Canal (partly after Tahir and Habib *2000*)

	Canal command				
	MR	**UCC**	**BRBD**	**LCC**	**Haveli**
I_{tw} (mm year^{-1})	932	629	729	460	540

Specific yield S_y method

Across Rechna Doab, the depth of the phreatic surface was measured twice a year, pre- and post-monsoon, with a nodal network of 981 piezometers by the SCARP Monitoring Organization (SMO) of Water and Power Development Authority (WAPDA) of Pakistan. They also conducted pumping tests at 47 different locations to calculate the specific yield S_y for Rechna Doab (Khan *1978*). These point data of specific yield and piezometric levels for October 1993 and October 1994 were acquired from WAPDA and interpolated using the kriging method.

Thereafter, the annual change in phreatic surface depth d*h* was calculated from the maps representing the depth of phreatic surface in October 1993 and October 1994. After combining the d*h* and S_y maps, the annual net groundwater use I_{ngw} was computed using Eq. (5) from October 1993 to October 1994 (Fig. 8), thus ignoring lateral inflow. The I_{ngw} phreatic surface have positive and negative values due to rising and falling. The spatial patterns of I_{ngw} follow the kriged phreatic surface level variations, and are thus somewhat artificial. Moreover, lateral transfer is entirely ignored, being a shortcoming of this approach.

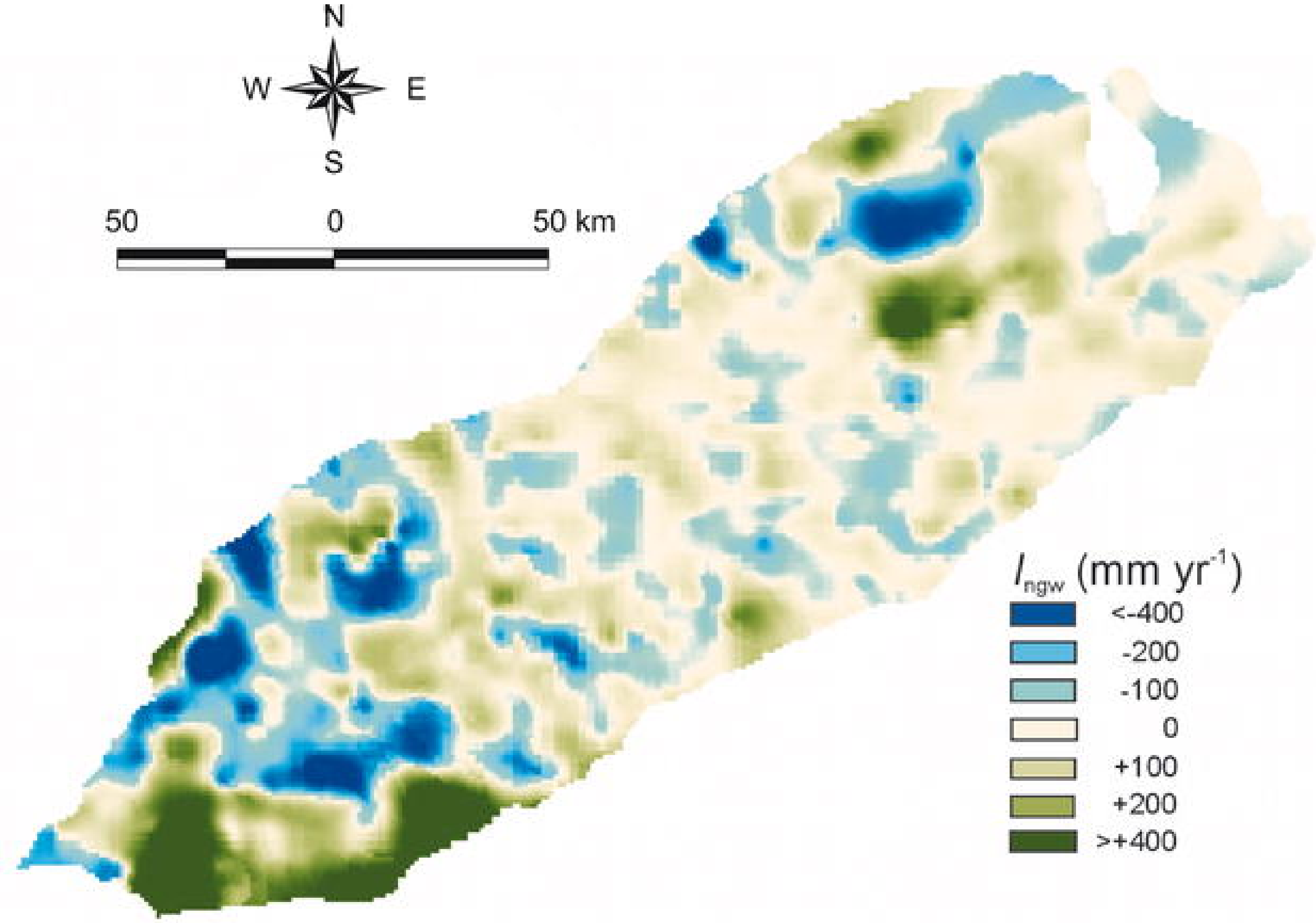

Fig. 8 Annual net groundwater use I_{ngw} (Eq.(5) (obtained from measurement of the phreatic surface on October 1993 and October 1994 and specific yield S_y data in Rechna Doab). Positive values show net groundwater use and negative values show net replenishment

Comparison between conventional and geo-information techniques

A comparison between Fig. 5 and Fig. 8 shows that the geo-information based analysis of Fig. 5 produce I_{ngw} values that give different spatial shapes, with more abrupt changes than the gradual patterns of Fig. 8. The effect of change in land use, soil types and irrigation practices on I_{ngw} is more pronounced in the geo-information based analysis than in an analysis that is based on kriged S_{y} and phreatic surface measurements. The geo-information based water balance analysis has a wide spread of values as compared to the S_{y} method due to the full description of agricultural and irrigation practices. In the positive range, the values from the geo-information techniques are significantly higher than the values from the S_{y} method, and thus the values of the S_{y}-method are systematically underestimated.

The main difference between the two methods is that the conventional approach (S_{y}-method) neglects groundwater lateral flow. The S_{y}-method, which ignores lateral groundwater flow, yielded a 65% underestimation of net groundwater use. Net lateral flows to Rechna Doab from October 1993 to October 1994 amounted to 1193 million m^3 $year^{-1}$ (which is equivalent to a water layer of 53 mm $year^{-1}$). The largest inflows were found in the LCC and UCC respectively. This also confirms that in highly permeable aquifers, such as in Rechna Doab, lateral groundwater flow cannot be ignored. Any localized change in the phreatic surface depth caused by groundwater withdrawals or irrigation activity tends to be offset by exchanging groundwater flows.

It is interesting to compare values for groundwater withdrawal by tubewells I_{tw} (a traditional way of referring to groundwater use for irrigation in Pakistan) using the U_{F}-method, Eq. (3), with net groundwater use I_{ngw} obtained by both the geo-information and the S_{y}-Method (Table 3). Except for Haveli, the geo-information and S_{y}-method show similar trends of annual net groundwater use in all commands. The net groundwater use from the $\mathrm{U_F}$ method is significantly higher (550%) than the results obtained from the geo-information techniques. This can be partially explained by the net recharge component that is not considered in the U_{F}-Method. Moreover the use of one average utilization factor for different types of private tubewell is, with different discharge capacities, may be one of the other reasons that resulted in this overestimation.

Table 3 Comparison of annual net groundwater use I_{ngw} computations from the geo-information techniques (Eq. (8) and the S_{y}-method (Eq. (5) with groundwater withdrawal by tubewells I_{tw} calculated using the utilization factors U_{F} (Eq. (3) in the different canal commands of Rechna Doab from October 1993 to October 1994. Q_{in} and Q_{out} represent respectively the groundwater lateral in-flow and out-flow. (Marala-Ravi MR Link, UCC Upper Chenab Canal, BRBD Bambanwala-Ravi-Bedian-Depalpur Canal, LCC Lower Chenab Canal and Haveli Canal.). Negative values express and positive values are net replenishment groundwater use

Canal commands	Geo-information	S_y-Method	U_F-Method	Geo-information	S_y-Method	U_F-Method	Geo-information
	I_{ngw} mm year^{-1}	I_{ngw} mm year^{-1}	I_{tw} mm year^{-1}	I_{ngw} 10^6 m^3 year^{-1}	I_{ngw} 10^6 m^3 year^{-1}	I_{tw} 10^6 m^3 year^{-1}	Q_{in}- Q_{out} 10^6 m^3 year^{-1}
MR	–405	–54	+932	–264	–35	+606	–229
UCC	+170	+24	+629	+732	+103	+2702	+629
BRBD	+108	+13	+729	+191	+23	+1292	+168
LCC	+85	+34	+460	+1289	+511	+6979	+778
Haveli	–201	+65	+540	–115	+37	+308	–152
Rechna Doab (10^6 m^3 year)$^{-1}$)				+1833	+639	+11882	+1193
Rechna Doab (mm year^{-1})				+82	+28	+529	+53

Summary and Conclusions

In this paper, net groundwater use I_{ngw} was computed using remote sensing and geo-information system methods for calculating the unsaturated zone water balance, Eq. (8). The annual average water balance components in Rechna Doab are summarized in Fig. 9. In Rechna Doab an amount of 82 mm is skimmed off from the groundwater resources every year.

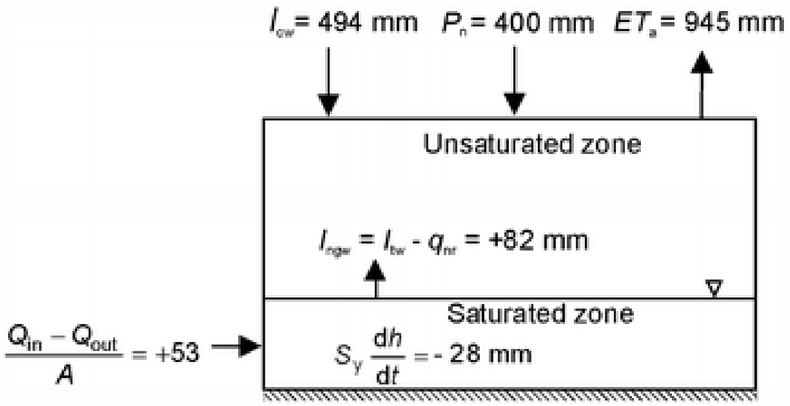

Fig. 9 Annual water balance from October 1993 to October 1994 over the Rechna Doab as estimated from geo-information techniques, where I_{ngw} is net groundwater use, I_{cw} is rate of irrigation with canal water, P_n is rate of net precipitation, ET_a is rate of actual evapotranspiration, I_{tw} is rate of irrigation with groundwater withdrawal from tubewells,
q_{nr} is net recharge, and Q_{in} and $Q_{out}$are lateral in-flow and out-flow in the saturated zone ($dW_u/dt=+31$ mm)

The specific yield method produced a 65% lower net groundwater use as compared to the geo-information techniques. This difference is explained by groundwater lateral flows that bring in a net amount of 53 mm, which prevents the phreatic surface from declining too rapidly. This implies that in highly permeable phreatic aquifers the groundwater withdrawal by tubewells or net recharge from irrigated fields cannot be inferred from occasional monitoring of the phreatic surface. Despite limited phreatic surface measurements are useful for trend analysis, they cannot be used for a quantitative assessment of groundwater withdrawals for agriculture. This finding has significant consequences for groundwater use, exploitation and policy making in general.

Also, groundwater withdrawal computations using utilization factors, Eq. (3), differ greatly from the net groundwater use calculations, Eq. (8). In this method, return flows towards the aquifer are not considered, which is an important process in groundwater irrigated agricultural systems.

Even at canal command level, geo-information techniques provide more accurate results than the conventional techniques. This is because geo-information based net groundwater use combined with the S_y-method depicts whether the rise or fall of the phreatic surface can be ascribed to net lateral groundwater flow or to vertical interactions. Such information is of strategic importance when considering localized or regional options for sustainable groundwater management.

Hence, geo-information techniques provide a comprehensive, efficient, and standardized opportunity of quantifying net groundwater use for agriculture with a minimal need of field data. The technique is especially suitable for large scale applications such as for river basins with rapidly falling phreatic surfaces.

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