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ORIGINAL PAPER

Modelling the long-term potential effects of modern irrigation systems on soil–water and salt balances, and crop-water productivity in semi-arid regions

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Abstract

Modernization of irrigation systems is considered to improve irrigation efficiency, save water, and increase crop yields in water-scare semi-arid regions. This study conducted a long-term (10-years) simulations evaluating the potential effects of three different irrigation scenarios on soil water and salt balances, and crop water productivity of cotton-wheat cultivation in the Hakra Branch Canal command of Punjab, Pakistan. The physically based agro-hydrological model, Soil–Water-Atmosphere-Plant (SWAP) was applied to simulate the long-term (2007–2017) effects of three irrigation scenarios; (1) current surface irrigation (*baseline reference*) based on local farmers observations, (2) improved precision surface irrigation system (*PSIS*), and (3) a high-efficiency irrigation system (*HEIS*). The *HEIS* scenario without a leaching fraction (noted as *HEIS_noLF*), defined as using sprinkler irrigation to bring the soil back to the field capacity, resulted in about 48% less long-term average irrigation needs (830 mm yr^{-1}) as compared to the baseline scenario (1590 mm yr^{-1}). This reduction in irrigation, however, resulted into a relatively higher average soil salt build-up (as 35 mg cm^{-2}) causing a reduction of 18%—30% in the wheat crop yields. The *HEIS* scenario with a leaching fraction (noted as *HEIS_LF*), with an additional irrigation of 60 mm at the start of crop season followed by an additional 10 mm with each irrigation interval, reduced the average salt build up (as 13 mg cm^{-2}) and its adverse effects of the crop yields. However, *HEIS_LF* scenario resulted in the similar average irrigation amounts (955 mm yr^{-1}), soil water and salt balances, crop yields and water productivity values as achieved by the *PSIS* scenario, defined as a fixed depth of 80 mm surface irrigation at each flexible irrigation intervals. This suggests limited scope for irrigation savings by adopting high-efficiency irrigation systems, such as sprinkler, with marginal quality (>0.9 dS m^{-1}) irrigation waters in semi-arid regions of Pakistan. Application of an appropriate leaching fraction is essential for controlling soil salinity build-up from irrigations marginal and saline groundwater in the study area. This reduces any gain to be made by high-efficiency (such as sprinkler) irrigation systems to save irrigation waters. However, there appears scope of improving surface irrigation (e.g. *PSIS*) by reducing irrigation depths (through field levelling) and introducing flexible irrigation scheduling, as compared to the current (baseline) irrigation practices.

Introduction

Irrigated agriculture in Pakistan, nationally and specifically in rural areas, is a significant source of livelihoods, food security, and a major component in poverty alleviation (Bhutto and Bazmi 2007). However, the growing population and projected climatic change are putting increasing pressure on limited water supplies for irrigated agriculture in Punjab Pakistan (Ringler and Anwar 2013; Sharma et al. 2013), as well as in other semi-arid and arid regions worldwide (Connor et al. 2012; Dehghanisanij et al. 2006).

Adoption of new technologies and high-efficiency irrigation systems such as sprinkler and drip irrigation is suggested to improve irrigation efficiency, save water, and

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increase crop yields in water-scare semi-arid and arid regions of Pakistan (DGA 2011; Latif et al. 2016) and similar conditions elsewhere (Varela-Ortega and Sagardoy 2002; Ward and Darghouth 2006; Sanchis-Ibor et al. 2017; Huang et al. 2020). Narayanamoorthy (2006) reported 30 to 60% savings of irrigation water, and 20 to 80% increase in crop yield by using drip and sprinkler irrigation systems in India. Numerous studies have highlighted the benefits of high-efficiency such as sprinkler and drip irrigation systems in terms of irrigation water savings, reduced labour cost, and increased crop yields (Jones 2004; Smith, 2010; Almarshadi and Ismail 2011; Işık et al. 2017; Koech and Langat 2018; Rizwan et al. 2018).

However, modernisation of irrigation practices could lead to unintended consequences in terms of reduction of groundwater recharge, and the risk of salt build-up in the soil profile, particularly in semi-arid and arid-irrigation systems. Raine et al. (2007) found that drip and trickle irrigation affected the spatially variable soil salt build up over about 10% of the irrigated area in the Murray and Murrumbidgee Irrigated Areas of Australia. The change in irrigation practices can considerably impact soil water and salt balances and their relationship with crop productivity and local hydrology (Malash et al. 2008; Nagaz et al. 2012; Assouline et al. 2015). Therefore, programmes focused on improving irrigation efficiency must be evaluated in terms of robust regional water accounting and the long-term effects on soil salinity in crop production, particularly in semi-arid and arid regions (Perry and Hellegers 2012; Kooij et al. 2013; Grafton et al. 2018). However, in a recent review, Perry et al. (2017) found that "*there are rather few examples of carefully documented impacts of hi-tech irrigation, while there are many examples of projects and programmes that assume that water will be saved and productivity increased.*" There is a lack of site-specific assessment of the potential effects of modern irrigation practices on long-term soil water and salt balances, and crop water productivity, particularly in semi-arid and arid regions across developing countries such as Punjab, Pakistan.

Long-term field experiments to evaluate potential effects of changes in irrigation practices on soil water and particularly on soil salinity and its effects on crop water productivity in irrigated crops, are expensive, laborious and time consuming. However, well-developed agro-hydrological models, such as the SWAP (van Dam et al. 1997), offers the opportunity to integrate local field observations and simulation modelling to evaluate potential effects of proposed irrigation practices on the long-term soil water and salt balances, and crop water productivity at field scale, as well as at regional scale (Singh et al. 2006b, 2006c; Mostafazadeh-Fard et al. 2009). Woldegebriel (2011) demonstrated the application of the SWAP model to simulate salt accumulation under drip irrigation system in Gediz basin of Turkey. Xue and Ren (2016) used SWAP to evaluate crop water productivity under sprinkler irrigation at regional scale in Hetao irrigation area in China. In combination with field experiments, SWAP provides detailed insights into the potential effects of various irrigation scenarios on soil water and salt flows in interaction with crop growth and its yields (Singh et al. 2006a; van Dam et al. 2008; Vazifedoust et al. 2008).

This study presents a methodological development by integrating local farmer's field observations with field-scale agrohydrological simulations to predict long-term potential effects of modern irrigation practices on soil water and salt balances, and water productivity of the two main crops (wheat and cotton) grown in the Hakra branch canal (HBC) command, located in Punjab, Pakistan. The objectives of the study were to first calibrate and validate SWAP model, using the field observations at two local farmer fields during 2016–17, and then apply the SWAP model to simulate long-term (10 years, 2007–2017) potential effects of precision surface irrigation and high-efficiency sprinkler irrigation systems as compared to current irrigation practices observed at the farmer's fields. The study aimed to analyse potential long-term changes in soil water percolation, soil salt content, and crop water productivity of cotton-wheat cultivation. It generates new insights into the long-term potential effects of improved irrigation efficiency and its management to help develop productive and sustainable crop production systems in semi-arid regions of Punjab, Pakistan, and other similar conditions elsewhere.

Materials and methods

Hakra command and its biophysical environment

The Hakra Branch Canal (HBC) command is located in Pakistan Punjab (Fig. 1), as part of the wider Indus Basin Irrigation System (IBIS) in Pakistan. The HBC command is faced by the typical problems of low irrigation efficiencies, declining groundwater levels, waterlogging and secondary salinization, and low crop water productivity that are widespread across the Indus basin (Usman 2012) and other semi-arid regions (Foster et al. 2018). The annual cropping intensity in HBC is 129%, composed of 55% during the *kharif* (summer) season and 74% during the *rabi* (winter) season. Wheat is mainly cultivated during *rabi* season (November – March), and cotton or rice during *kharif* season (April – October). The cotton-wheat rotation is the dominant cropping system covering over 60% of the command area (~ 204 thousand ha), followed by the wheat-rice crop rotation covering about 10% of the command area. The wheat-rice crops are mainly cultivated near head reaches of the canal network where groundwater water quality is relatively good (< 1 dS m^{-1}).

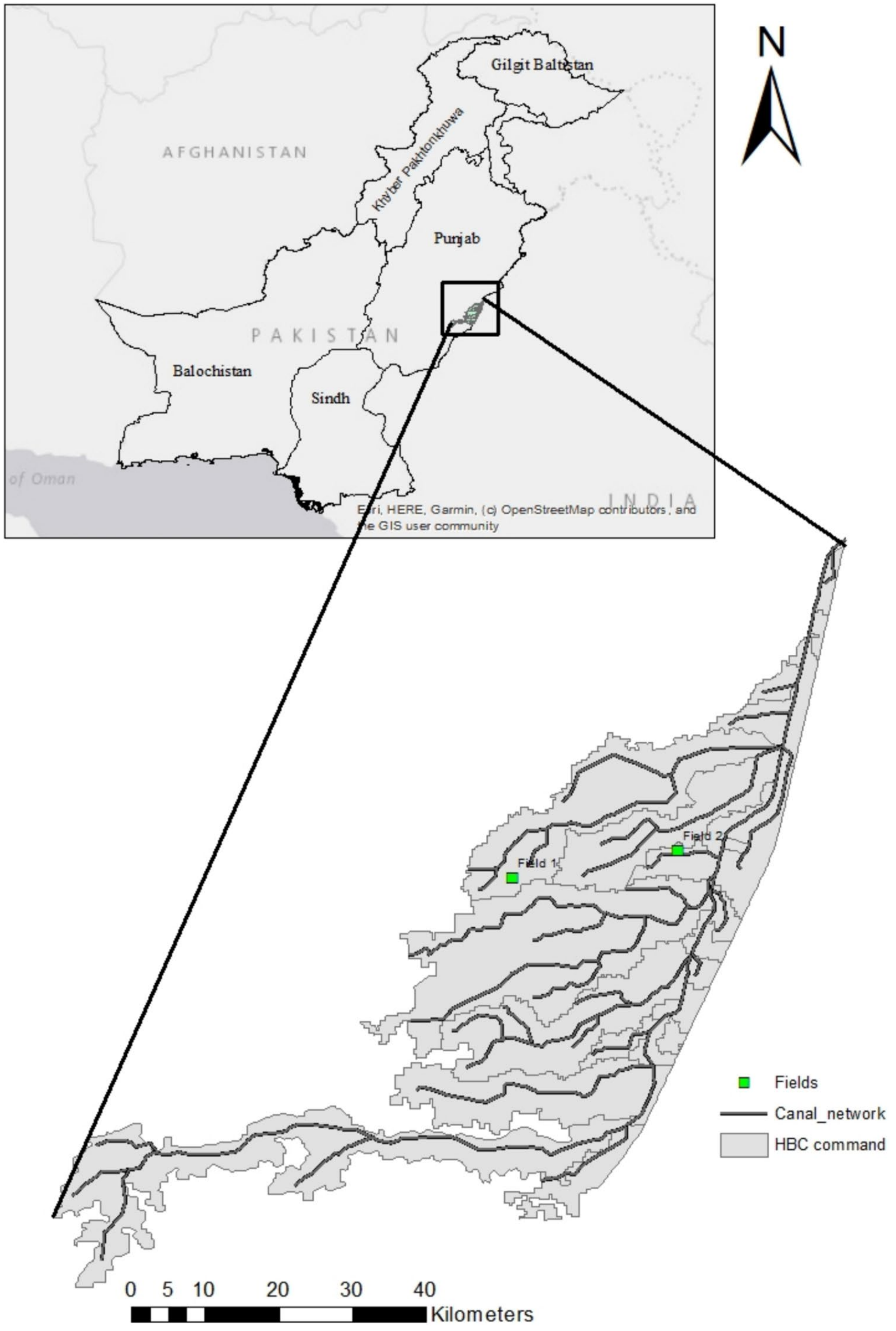


Fig. 1 Location of Hakra canal command covering 0.2 million ha in the Indus Basin Irrigation System, Punjab Pakistan. The 'Fields' shows location of the farmers fields used for data collection and calibration of the model used in the study

The average annual rainfall in the region is about 250 mm, less than 15% of the average annual reference evapotranspiration of about 1800 mm (de Vries and Anwar 2015). June is the hottest month, during which the temperature frequently exceeds 48 °C. The difference between crop water requirement and rainfall is fulfilled by irrigation through the Hakra Branch Canal offtake from the Sulemanki head works on the Sutlej River, as well as pumping of groundwater within the HBC command area. The canal water distribution takes place through a controlled fixed rotational system known as 'Warabandi', a irrigation distribution system common across the whole Indus Basin Irrigation System (IBIS). The canal water availability in HBC is on average about 0.21 l s^{-1} ha^{-1} (Anwar and Ul Haq 2013), which supplies approximately 660 mm of canal water annually. With this limited canal water availability, the farmers are highly dependent on groundwater for fulfilling the crop water requirements.

Groundwater pumping is an integral part of irrigated agriculture with a 65% dependency in the head reaches, to over 90% in the tail reaches of the command area (Qureshi 2014). The depth to water table varies from less than 1 m below surface in head reaches, to more than 25 m below surface in tail reaches of the command area. The groundwater quality also varies from less than 1 dS m^{-1} along the main canals due to seepage of good quality canal water, to as high as 20 dS m^{-1} in the tail reaches of the canal (Qureshi et al. 2008).

Observations at local farmer's fields

The study monitored two local cotton-wheat fields for observations of detailed irrigation applications, soil water and solute dynamics, and crop growth parameters during the agricultural year (2016–17) (see Fig. 1 for the location of the study fields). Cotton was sown and harvested from May 10th 2016 to November 25th 2016 (198 days) at field1 (0.4 ha), and from May 5th 2016 to November 27th 2016 (205 Days) at field2 (0.4 ha), whereas wheat was sown and harvested from December 4th 2016 to April 13th 2017 (130 Days) at field1 and from December 10th 2016 to April 14th 2017 (125 days) at field2.

The fields were irrigated as per the Warabandi schedule and canal rotation using traditional surface basin flood irrigation method. The crop water requirement could not be fulfilled by the limited canal water supplies, hence they were supplemented by groundwater. Field1 was located in the tail reach (Fig. 1), where no supply of canal water was received during *kharif* (cotton) season, resulting in the use of only poor quality (*EC* of 3.21 dS m^{-1}) groundwater for cotton irrigation. Field2 was in the middle reach (Fig. 1) and used both canal water (*EC* of 0.57 dS m^{-1}) and marginal quality (*EC* of 1.67 dS m^{-1}) groundwater for cotton and wheat irrigations. The canal water was applied after every groundwater application. This helps in leaching salt build-up from the root zone. The cotton crop received 7 irrigations at field1 and 12 irrigations at field2, adding to 830 mm and 1100 mm of irrigation during the *kharif* (cotton) season at field1 and field2, respectively. The wheat crop received 4 irrigations at field1 and 5 irrigations at field2, adding to 275 mm and 490 mm irrigation during the *rabi* season at field1 and field2, respectively. Overall, field1 received an irrigation total of 1105 mm from May 2016 to April 2017, including 170 mm of canal water and 935 mm of groundwater. Field2 received irrigation of 1590 mm during the same period, including 1210 mm of canal water and 380 mm of groundwater. The relative irrigation depths applied at both fields represent the prevailing water management in the HBC, in which the tail reaches are short of canal water supply and depend on the use of poor-quality groundwater. The head reaches have sufficient access to canal water and good to marginal quality of groundwater.

Soil samples were taken, from both fields, at the sowing of the cotton (May 2016) and analysed for initial moisture content, soil salinity and basic physio-chemical properties including soil texture, bulk density, and organic carbon (Table 1). The field's soil texture varied from sandy loam to silt loam, with a bulk density from 1.46 to 1.76 g cm^{-3} (Table 1), a typical representation of soil texture in HBC area.

The profiles of soil moisture and soil salinity (measured as *EC* 1:5) were observed before and after each irrigation, after rainfall events, and finally at the crop harvest at the study fields. The soil samples were taken from three locations diagonally across the field. The samples were approximately from the same location. At each location the samples were taken from 0 – 15 cm, 15 – 30 cm, 30 – 60 cm, 60 – 90 cm and 90 – 120 cm depths. The collected soil samples were analysed for their soil moisture (using the gravimetric method) and soil salinity levels (measured as *EC* 1:5) in the laboratory at the international water management institute field office Haroonabad district Bhawalnagar. The crop height, plant density (number of plants per unit area) and rooting depth were also monitored fortnightly. The above-ground biomass of plants was calculated fortnightly by randomly sampling 3 plants from three different locations in the fields and partitioned them into stem, leaves and storage organs. The final crop yields were recorded at 1.30 and 2.40 t ha^{-1} for cotton (seed) at field1 and field2, respectively, and 3.40 and 4.20 t ha^{-1} for wheat at field1 and field2, respectively. The observed soil, water and crop parameters at the

Table 1 Soil properties at local farmer field2 (values in brackets for field1) in Hakra canal command, Punjab Pakistan, observed during the kharif (cotton sowing) season of 2016

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	Organic carbon (%)	Soil texture*
0–15	7 (9)	23 (15)	73 (76)	1.60 (1.46)	0.45 (0.39)	*SL (SL)*
15–30	6 (8)	22 (16)	72 (76)	1.65 (1.46)	0.44 (0.39)	*SL (SL)*
30–60	8 (4)	26 (28)	66 (70)	1.68 (1.71)	0.35 (0.43)	*SL (SL)*
60–90	5 (10)	25 (16)	70 (74)	1.74 (1.64)	0.22 (0.47)	*SL (SL)*
90–120	19 (4)	55 (20)	26 (76)	1.76 (1.58)	0.27 (0.26)	*SiL (LS)*

*SL refers to sandy loam, SiL refers to silt loam and LS refers to loamy sand study fields were used to calibrate and validate SWAP model (van Dam et al. 1997) simulation of a cotton-wheat rotation cultivation in the study area.

Soil–Water-Atmosphere-Plant (SWAP) model and its calibration

The SWAP is a physical-based one-dimensional model which simulates soil water and solute flow processes in a dynamic interaction with crop growth in the soil–water-atmosphere-plant continuum (van Dam et al. 1997). The model applies the Richards' equation (Eq. 1) to simulate transient soil water flow in the soil profile, as described in van Dam and Feddes (2000), as follows:

$$\frac{\partial\theta}{\partial t}=\frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z}-S_a(h)-S_d(h)-S_m(h) \tag{1}$$

where, θ is the volumetric water content (L^3L^{-3}), $K(h)$ is the hydraulic conductivity (LT^{-1}), h is the soil water pressure head (L), z is the vertical coordinate (L), taken positive upward, $S_a(h)$ is the soil water extraction rate by plant roots ($L^3\ L^{-3}\ d^{-1}$), $S_d(h)$ is the drainage discharge in the saturated zone (d^{-1}), and $S_m(h)$ is the exchange rate with macro pores (d^{-1}).

Solute transport is governed by convection, diffusion and dispersion processes in the soil profile. In SWAP, the salt transport is simulated by a dynamic, one-dimensional, convective–dispersive solute transport in unsaturated and saturate soils (Eq. 2) (van Dam et al. 1997), as follows:

$$J=qC+qL_{dis}\frac{\partial C}{\partial z} \tag{2}$$

where q is the water flux density ($L\ T^{-1}$), C the salt concentration ($M\ L^{-3}$), and L_{dis} the dispersion length (L) and z is the vertical coordinate [L] (positive upward).

Crop growth is simulated by a detailed generic crop growth model, *WOrld FOod STudies* (WOFOST) (Spitters et al. 1989; Supit 1994) with a dynamic interaction between the crop growth and water and salt stress conditions (van Dam et al. 1997). The SWAP applies a well-known water stress reduction function, developed by Feddes et al. (1978) to account for effects of water stress on crop water uptake and its growth. The crop specific thresholds for the soil–water pressure head (h) are defined as input variables to account for the reduction in crop water uptake under non-optimal soil moisture conditions (Feddes et al. 1978; van Dam et al. 1997). In case of salt stress, the crop water uptake is linearly reduced to the soil water electrical conductivity (EC) after a crop-specific threshold is reached (EC_{max}) (Maas and Hoffman 1977; van Dam et al. 1997). As per the recommendation of Cardon and Letey (1992), SWAP simulates the product of both water and salt stress on crop water uptake in the soil–water-plant continuum (van Dam et al. 1997). The detailed descriptions of soil water, salt transport and crop growth in SWAP are described in van Dam et al. (1997).

Evapotranspiration, rainfall and irrigation applications: The SWAP model requires inputs of daily reference evapotranspiration (ET_p), rainfall, and any irrigation applied, to define the upper boundary conditions. The ET_p is calculated by using the Penman–Monteith model (Allen et al. 1998) using the daily meteorological data. The required daily meteorological data are the minimum and maximum temperature, relative humidity, vapour pressure, solar radiation, wind speed, and rainfall. These were obtained from a metrological station operated by International Water Management Institute (IWMI) field office in Haroonabad, located within the case study area. Figure 2 shows the variation of daily meteorological observations in the Hakra canal command during *rabi* (winter) and *kharif* (summer) seasons of the agriculture year 2016–17. The maximum temperature reached 48 °C on the individual day during *kharif* (summer) season and the minimum temperature reached 2 °C during *rabi* (winter) season. The total annual rainfall measured at 115 mm only, out of which 98 mm occurred during the *kharif* (monsoon) season.

The SWAP model requires input of the irrigation schedule including the irrigation application days, the depth of irrigation, the quality of irrigation water and type of irrigation being either surface or sprinkler. The irrigation inputs were defined as per the observations at the local farmer's fields (see Sect. "Observations at local farmer's fields") and the defined irrigation scenarios (see Sect. "Irrigation scenarios").

Crop parameters: The SWAP model includes three crop growth modules: a simple module, a detailed module for arable crops, and detailed module for grass growth (van Dam et al. 1997). The detailed crop module, as used in this study, simulates the crop growth in close interaction with the water and salt flows in the soil profile. The detailed crop module is based on the *WOFOST* model, which simulates a potential crop growth in terms of its phenological development, light interception, CO_2 assimilation, and dry matter formation and its partitioning between root growth, leaves, stems and the yield of the storage organs (Spitters et al. 1989; Supit 1994).

The detailed crop module requires input parameters of crop height, temperature sums required for crop development stages, light use efficiency, CO_2 assimilation rate, dry matter partitioning, and crop water uptake and salinity stress conditions (Table 2). The crop parameters such as crop developmental stages (sowing, emergence, panicle initiation, anthesis, maturity and harvest), plant height, dry matter partitioning, and rooting depth were based on observations at the local famers' fields during *rabi* (winter) and *kharif* (summer) seasons of the agriculture year 2016–17 (*see* Sect. "Observations at local

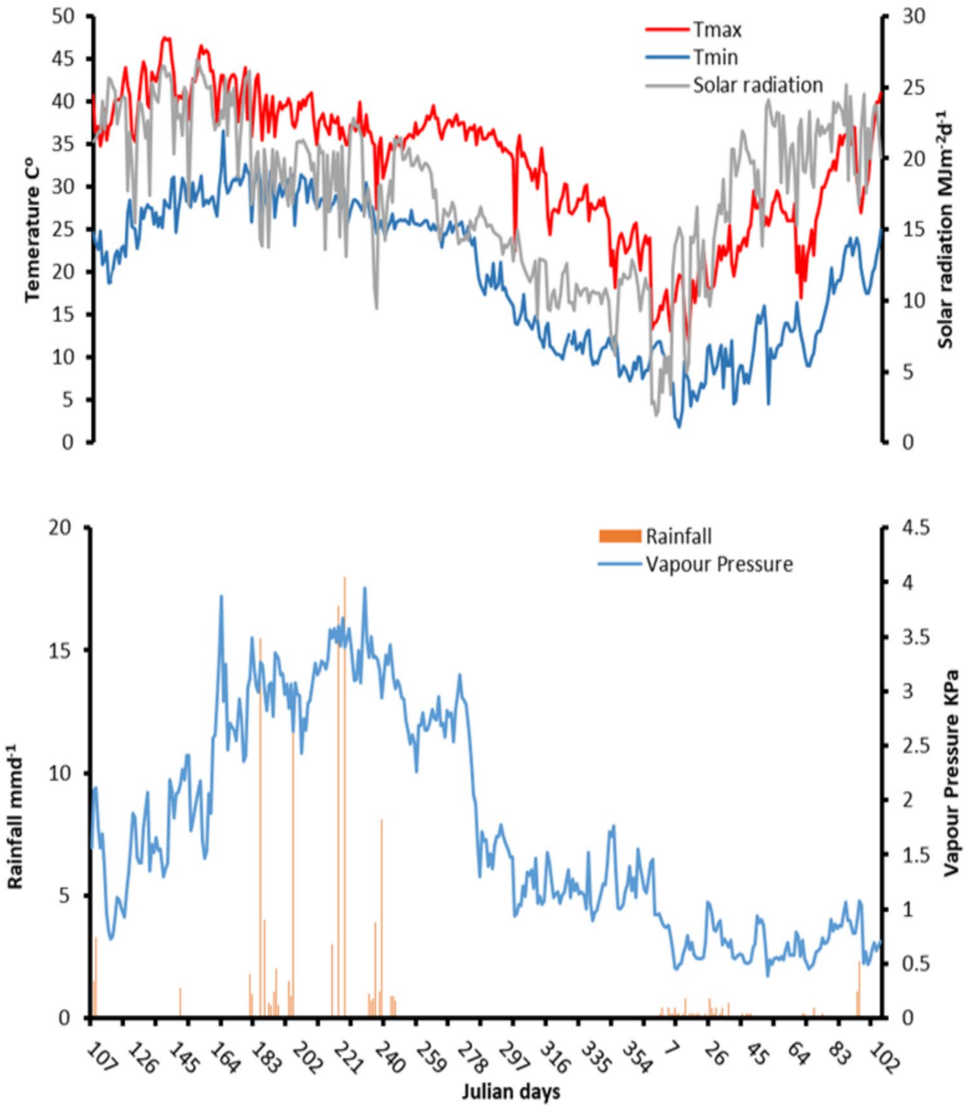


Fig. 2 Variation of climatic conditions in Hakra canal command in Punjab (Pakistan) during the agricultural year 2016–17

Table 2 Crop input parameters in *SWAP-WOFOST* model used for cotton-wheat crop simulation in Hakra canal command, Punjab Pakistan

Parameters	Cotton	Wheat
Temperature sum from emergence to anthesis, TSUMEA (°C)	2690	1393
Temperature sum from anthesis to maturity, TSUMAM (°C)	880	897
Specific leaf area, S_{la} (ha kg^{-1})	0.0022	0.0022
Minimum canopy resistance, r_{crop} (s m^{-1})	70	70
Light use efficiency $\grave{\varepsilon}$ (kg ha^{-1} h^{-1} / Jm^{2} s^{-1})	0.45	0.45
Maximum CO_2 assimilation rate, A (kg ha^{-1} h^{-1})	56	40
Salinity		
Critical level, $EC_{\max}$ (dS m^{-1})	7.7	6.0
Decline per unit EC, EC_{slope} (%dS m^{-1})	5.2	7.1

farmer's fields" *above*). A range of realistic values for the crop parameters such as assimilation, light use efficiency, conversion of assimilation into biomass, pressure head for crop water use, salt stress limit at which root water uptake decline and root density distribution, that were not measured in the local farmer's fields, were estimated based on experimental data and relevant information from existing studies for wheat and cotton crops under similar conditions in Sirsa district (Haryana), India (Singh 2005; van Dam and Malik 2003; van Dam et al. 1997). In this study, these parameters were adjusted by running the model with several combination of their values within a realistic range (Table 2), and by comparing the simulated crop growth variables such as crop yield and above ground biomass with the observations at the local farmers' fields.

Soil hydraulic parameters and drainage conditions: A soil profile depth of 160 cm was simulated as divided into two soil layers based on the soil texture observed at the local farmers fields (Table 1). As most of hydrological processes prevail in top soil layers (van Dam et al. 1997), the soil domain was further discretized spatially into 30 compartments with a nodal distance of 1 cm for the top 10 compartments, followed by 5 cm for the next 10 compartments, and 10 cm for the remaining soil profile. According to Jacobsen (1991) the dispersion length (L_{dis}) (Eq. 2) was set to 5 cm for salt transport through the soil profile. The initial salinity levels in the soil profile were based on the field observations, ranging from 1.05 to 5.04 mg cm^{-3} in the different soil layers. A coefficient of 0.35 cm d^{-1} was used to limit the soil evaporation rate (Black et al. 1969). Considering the deep groundwater levels (> 3 m) observed at the farmers' fields, a free drainage condition was specified as a lower boundary condition of the soil profile. In this case the pressure head gradient ($h+z$) is assumed as zero at the bottom of soil profile, implying that the bottom flux equals the hydraulic conductivity of the lowest soil compartment (van Dam et al. 1997).

The SWAP model simulates soil water flow based on the Richards' equation (Eq. 1) using he soil hydraulic functions proposed by van Genuchten (1980) and Mualem (1976) (VGM) to define relationships between soil hydraulic conductivity K, soil moisture θ and soil water pressure head h, as follows:

$$\theta(h) = \frac{\theta_{sat} - \theta_{res}}{\left[1 + |\alpha h|^{n}\right]^{\frac{n-1}{n}}} \tag{3}$$

$$K(\theta) = K_{sat}S_e^{\lambda}\left[1 - \left(1 - {S_e}^{n}\!/n - 1\right)^{\frac{n-1}{n}}\right]^{2} \tag{4}$$

where, $\theta_{sat} and \theta_{res}$ are the saturated and residual soil moisture contents [L^3 L^{-3}], α [L^{-1}] and n [-] are the empirical shape factors, K_{sat} is the saturated soil hydraulic conductivity, S_e is the relative saturation [-], and λ is an empirical coefficient [-].

Soil input parameters describing the soil hydraulic function (Eqs. 3 and 4), the saturated soil hydraulic conductivity and the saturated soil moisture contents (Table 3) were determined based on the observations at the farmers' field (Table 1). However, the other soil hydraulic function variables, such as the residual soil moisture content, the empirical shape factor, and the empirical coefficient, are difficult to measure directly in the field. They are first derived by pedotransfer functions (Wösten et al. 1998) using the soil texture, bulk density and percent organic carbon (Table 1) and then calibrated and validated in SWAP for local field conditions (Singh et al. 2006c; Vazifedoust et al. 2008; Yuan et al. 2019). In this study, two soil parameters of the empirical shape factors, α and n (Table 3), were calibrated and validated using the soil moisture and salinity profiles observed during the field experiments. An automatic calibration procedure, called inverse modelling, was applied in which the non-linear *parameter estimation program*, PEST (Doherty 1994) was linked with SWAP to calibrate the soil parameters (α and n) for each soil layer, using the objective function *O(b),* as follows:

$$O(b) = \sum_{i=1}^{N}\Big[\left\{W_{\theta}\left(\theta_{obs}\left(t_i\right) - \theta_{sim}\left(b, t_i\right)\right)\right\}^2 + \left\{W_{EC}\left(EC_{obs}\left(t_i\right) - EC_{sim}\left(b, t_i\right)\right)\right\}^2\Big] \tag{5}$$

where, N is the number of observations, $\theta_{obs}\left(t_i\right)$ and $EC_{obs}\left(t_i\right)$ are the observed soil moisture and salinity at time t_i, $\theta_{sim}\left(b, t_i\right)$ and $EC_{sim}\left(b, t_i\right)$ are the simulated soil moisture and salinity using an array with parameter values b. Here, W_{θ} and W_{EC} are the weights associated with the observed soil moisture and soil salinity, respectively.

The weights are associated with different observation types in the objective function (Eq. 5) to overcome any undue preference to an observation due to its magnitude differences with others. Gribb (1996) suggested the weights of each different data type by taking the inverse square of the mean values. However, Singh et al. (2006c) accounted for observation differences of θ and EC by using $W_{\theta} = 1$ and $W_{EC} = 10\%$ of average $\frac{\theta_{obs}}{EC_{obs}}$ in calibration of soil hydraulic

Table 3 Soil hydraulic parameters input in *SWAP-WOFOST* model used for cotton-wheat crop simulation in Hakra canal command, Punjab Pakistan. Parameter $\boldsymbol{\alpha}$ and $\boldsymbol{n}$ were optimized

Field	Soil layer (cm)	Texture	Soil hydraulic parameters					
			θ_{res} (cm^3 cm $^{-3}$)	θ_{sat} (cm^3 cm^{-3})	K_{sat} (cm d^{-1})	α (cm ^{1})	n [-]	λ [-]
Field1	0–90	*SL*	0.01	0.29	59.12	0.069	1.21	– 0.12
	90–160	*LS*	0.01	0.34	48.24	0.015	1.90	1.13
Field2	0–90	*SL*	0.01	0.34	31.0	0.026	1.41	0.31
	90–160	*SiL*	0.01	0.34	9.36	0.053	1.10	– 0.83

parameters for SWAP simulations of cotton-wheat cultivation similar conditions in Sirsa district (Haryana) India. The latter method was followed for the observations' weights, which gave relatively more weight to soil moisture observations in the calibration of soil hydraulic parameters. The weights were varied from 0.012 to 0.1 with mean value of 0.042 for the soil moisture.

The Root Mean Square Error *(RMES)* was quantified between the observed and simulated soil moisture and salinity profiles during both the calibration and validation periods, as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left[Obs\left(t_i\right) - Sim(t_i, b)\right]^2}{N}} \tag{6}$$

where, $Obs\left(t_i\right)$ and $Sim(t_i, b)$ are the observed and simulated values of output variable at time t_i and N is the total number of observations. The *RMSE,* considered among the 'best' overall measures of the model performance, quantified the average absolute error in the simulated and observed soil moisture and salinity profiles (Willmott 1982).

Irrigation scenarios

The calibrated and validated SWAP model was applied to simulate two different irrigation options, either a fixed predefined schedule, or a flexible irrigation schedule (van Dam et al. 1997). In the fixed irrigation mode, the day and depth of irrigation application, quality of irrigation water, and type of irrigation system are needed as input to SWAP. However, in the flexible irrigation schedule, SWAP calculates irrigation scheduling according to type of irrigation, irrigation time criterion of the allowable daily crop stress (defined as the relative transpiration being the ratio of actual transpiration to potential transpiration, T_a/T_p) and irrigation depth criteria of fixed depth or back-to-field capacity. Using these options, a total of three irrigation scenarios were defined and simulated for cotton-wheat cultivation in the study area, as follows.

Reference irrigation scenario: The reference irrigation scenario represents the current fixed rotation (Warabandi) system in the HBC. In reference scenario, as per the local field observations (field2) conjunctive use of canal and groundwater of 1100 mm irrigations with an average irrigation depth of 92 mm was specified for the cotton crop; and 480 mm irrigations with an average irrigation depth of 98 mm specified for the wheat crop. The irrigation intervals started 19 days after cotton crop emergence and as 6 days after wheat crop emergence. The quality of conjunctive irrigation water use sourced from canal and groundwater was specified as 0.96 dS m^{-1} based on the field observations. The reference scenario was simulated over a period of 10 years from May 1st, 2007 to April 30th, 2017 (sourced from Pakistan Metrological Department) and served as a basis for further analysis and comparisons with modern irrigation scenarios as follows.

Precision surface irrigation system (PSIS): Laser-based land levelling and flexible water supplies are recommended to help improve water-use efficiency of surface irrigation applications in cropping systems (Clemmens et al. 1999; Ahmad et al. 2007; Maqsood and Khalil 2013; Shahani et al. 2016; Miao Q, 2017; Rizwan et al. 2018). This modernised land levelled gravity-fed surface irrigation system, aka 'precision surface irrigation system (*PSIS*)', was defined and simulated by using scheduling with a fixed irrigation depth criterion in SWAP model. The timing of irrigation was based on the relative transpiration (T_a/T_p) as the crop stress criterion for flexible irrigation applications. A fixed depth irrigation was applied when the crop reached a pre-defined level of the crop water and salt stress level. A total of six irrigation scheduling criteria, noted as *I0.5*, *I0.6*, *I0.7*, *I0.8*, *I0.9*, and *I0.95*, were set corresponding to different targeted crop T_a/T_p ratios of 0.5, 0.6, 0.7, 0.8, 0.9 and 0.95, respectively.

In surface irrigation systems, the depth of irrigation application ranges from 50 to 150 mm depending upon size of fields and their levelling, number of border strips, soil texture affecting the infiltration rate, irrigation discharge rate, and other climatic conditions (Lecina et al. 2005; Laghari et al. 2010; Chen et al. 2013; Mohan Reddy 2013; Anwar et al. 2016). In the *PSIS* scenario, two irrigation depth scenarios, 60 and 80 mm for each irrigation event, were simulated representing surface irrigation depths that are observed when the field is properly levelled and water is uniformly distributed as improved surface irrigation (Wagan et al. 2015; Anwar et al. 2016; Shahani et al. 2016; Ashraf et al. 2017).

High-efficiency irrigation system (HEIS): Pressurized irrigation systems that include sprinkler and drip irrigation systems are promoted as highly efficient irrigation systems that can apply a specific amount of irrigation when required by a crop. To quantify the potential effects of the shift from conventional surface irrigation to high-efficiency 'sprinkler' irrigation system (*HEIS*), the irrigation scheduling with a sprinkler irrigation system based on "back to field capacity" irrigation depth criterion was adopted in SWAP model. In this scenario, a total of six irrigation scheduling criteria, noted as *I0.5*, *I0.6*, *I0.7*, *I0.8*, I0.9, and *I0.95* corresponding to different targeted crop T_a/T_p ratios of 0.5, 0.6, 0.7, 0.8, 0.9 and 0.95, respectively, were used to trigger an irrigation event and bring the soil condition "back to field capacity" at each irrigation event.

To explore the potential effects of irrigation systems on soil salinity, simulations of the *HEIS* irrigation scenario were performed first without a leaching fraction (*HEIS no LF*), and then with a leaching fraction (*HEIS with LF*). In case of *HEIS with LF* an additional irrigation depth (60 mm) was applied before the crop sowing, and the subsequent irrigations also received 10 mm of additional irrigation to the calculated 'back to field capacity' irrigation depths.

The quality of the irrigation water was specified at 0.96 dS m^{-1}, same as in the *reference baseline*, for the *PSIS* and *HEIS* irrigation scenarios, representing a conjunctive use of canal and marginal quality groundwater.

Performance indicators

The long-term simulations over 10 years, from May 1st, 2007 to April 30th, 2017 of the three irrigation scenarios were analysed using the following performance indicators:

Percolation (Q_{bot}): Soil percolation quantifies the potential effects of irrigation practices on groundwater, where a negative value represents recharge to groundwater system. Under free drainage conditions as simulated in this study, SWAP simulates the percolation flux assuming the pressure head gradient equals zero at the bottom of soil profile, implying that the percolation flux equals the hydraulic conductivity of the lowest soil compartment (van Dam et al. 1997). In this study, the SWAP-calculated daily percolation values were accumulated to quantify the average seasonal and annual percolation (Q_{bot}) under different irrigation scenarios.

$$Q_{bot} = -(P + I - R_s - P_i - T - E - E_w \pm \Delta W) \quad (7)$$

where, Q_{bot} is the water percolation from soil profile bottom (positive upward, negative downward) [L]. P is the rainfall [L], I is the irrigation [L], R_s is the surface runoff [L], P_i is the rainfall intercepted by vegetation [L], T is the actual transpiration [L], E is the actual evaporation from the soil surface [L], E_w is the evaporation from the ponding water surface [L], and ΔW is the change soil storage [L].

Change in salt storage (ΔC): Changes in salt storage (ΔC) in the soil profile can be used to quantify the potential effects of irrigation practices on the soil salinity trends and helps in understanding salinity problems at the field scale as well as at the regional scale (Qureshi et al. 2004; Singh et al. 2006c). In this study, SWAP quantified ΔC (per unit area) by solving the salt balance equation as follows:

$$\Delta C = PC_p + IC_i \pm Q_{bot}C_{bot} \quad (8)$$

where, ΔC is the change in salt storage [M L^{-2}], C is the solute concentration [M L^{-3}], P is the precipitation [L], I is the irrigation [L], Q is the percolation [L] (positive upward, negative downward) and subscript 'p' refer precipitation, 'i' refers to irrigation and *bot* refers to bottom flux.

Water productivity (WP_{ET}): Water productivity (WP) analysis has been suggested as a useful indicator for assessing on-farm irrigation practices of a crop production system (; Singh et al. 2006c; Fernández et al. 2020). According to Molden et al. (2003), water productivity accounts for crop dry-matter produced per unit amount water used. From a biophysical perspective, the numerator of WP is the crop yield, but the definition of denominator, such as transpiration, evapotranspiration, or total water applied, varies according to the purpose, scale and domain of the analysis (Singh et al. 2006c; Fernández et al. 2020). From an agronomic perspective, the crop evapotranspiration ET represents the actual amount of water consumed in crop production systems and WP can expressed as:

$$WP_{ET} = \frac{Y_g}{ET} \quad (9)$$

where, WP_{ET} is the water productivity in terms of water used in stratifying evapotranspiration [ML^{-3}], Y_g crop grain (or seed) yield [ML^{-2}], and ET is the evapotranspiration [L].

In terms of actual amount of irrigation water used, the denominator in the WP equation is replaced by total irrigation depth applied and can be expressed as:

$$WP_{Irr} = \frac{Y_g}{I} \quad (10)$$

where, WP_{Irr} is the water productivity in terms of irrigation water applied during the entire crop period [ML^{-3}], Y_g crop grain (or seed) yield [ML^{-2}], and I is the irrigation depth applied [L].

Results and discussion

Model calibration and validation

The calibration and validation of SWAP input parameters (Tables 2 and 3) was evaluated by comparing simulations of soil moisture, soil salinity and crop growth with their observations at the local farmers fields during *rabi* (winter) and *kharif* (summer) seasons the agricultural year 2016–17. The calibration of soil hydraulic parameters (Table 3) was performed using the first sub-set of observations over three months from June 2016 to August 2016, and the validation was performed using the second sub-set of observations over eight months from September 2016 to April 2017 (Table 4).

Figure 3 shows the observed and simulated soil moisture and $EC_{1:5}$ at different soil depths of 15, 30, 60, 90, and 120 cm during the calibration and validation periods at field2. The observed soil moisture varied from 0.12 to 0.34 cm^3 cm^{-3} with a slightly higher variation in the topsoil layers (< 60 cm), while the observed soil salinity $EC_{1:5}$ varied from 0.08 to 0.26 dS m^{-1} with less variation (as compared to the soil moisture) across the soil depths. The simulated soil moisture and salinity profiles show a close agreement with the field observations both for field2 (Fig. 3) and field1(the data are not shown).

Table 4 Number of observations (*N*) and the root mean square error (*RMSE*) between the observed and simulated soil moisture and salinity profiles at local farmer fields in Hakra canal command, Punjab Pakistan, during agriculture year 2016–2017

Fields	Depth (cm)	Calibration				Validation			
		Soil moisture (θ) ($cm^3\ cm^{-3}$)		Soil Salinity ($EC_{1:5}$) ($dS\ m^{-1}$)		Soil moisture (θ) ($cm^3\ cm^{-3}$)		Soil Salinity ($EC_{1:5}$) ($dS\ m^{-1}$)	
		N	*RMSE*	*N*	*RMSE*	*N*	*RMSE*	*N*	*RMSE*
Field1	15	9	0.06	9	0.05	17	0.03	17	0.02
	30	9	0.07	9	0.06	17	0.03	17	0.02
	60	9	0.05	9	0.06	17	0.02	17	0.02
	90	9	0.02	9	0.06	17	0.01	17	0.03
	120	9	0.02	9	0.06	17	0.01	17	0.03
Field2	15	14	0.01	14	0.03	18	0.05	18	0.09
	30	14	0.01	14	0.02	18	0.03	18	0.07
	60	14	0.01	14	0.02	18	0.03	18	0.08
	90	14	0.02	14	0.02	18	0.05	18	0.14
	120	14	0.01	14	0.02	18	0.09	18	0.11

Comparing the simulations and field observations, the *RMSE*) values (Eq. 6) varied between 0.01 and 0.09 $cm^3\ cm^{-3}$ for the soil moisture content, and from 0.01 to 0.14 $dS\ m^{-1}$ for the soil salinity $EC_{1:5}$ at both fields, field1 and field2 (Table 4). The *RMSE* values for the soil moisture and salinity were obtained similar between the calibration and validation periods, supporting effective calibration and validation of soil hydraulic parameters (Table 3). The lower *RMSE* values (Table 4) and absence of any systematic under- or over-prediction of soil moisture content and $EC_{1:5}$ values (Fig. 3) suggest that soil water flow and salt transport dynamics at the study fields were simulated quite well, and that the calibrated and validated SWAP could be used with confidence for further irrigation scenarios analysis.

Figure 4 reproduces the SWAP simulated and observed wheat and cotton yields at the farmers' fields. It is worth noting that SWAP simulated crop yields only by considering water and salt stress, and not any potential nutritional and disease/pest stress (van Dam et al. 1997). The water and salt limited yields were simulated 14 to 30% higher than the observed cotton yields, and from 24 to 30% higher than the observed wheat yields at the farmer's field (Fig. 4). In the HBC command area, the actual crop yield ($t\ ha^{-1}$) over the period of 10 years (2007–2017) was recorded at 2.00 $t\ ha^{-1}$ for cotton (seed) and 3.00 $t\ ha^{-1}$ for wheat by the Crop Reporting Services, Punjab Agriculture Department (CRS 2017). The average cotton (seed) and wheat yields were observed at 2.4 and 4.2 $t\ ha^{-1}$, respectively at the local farmer fields during 2016–2017 (Fig. 4). This shows there were no significant differences between the average actual and simulated yield for cotton, whereas the average wheat yield was simulated to be almost double (about 89% higher, at 5.69 $t\ ha^{-1}$) as compared to the average actual (recorded) (at 3.00 $t\ ha^{-1}$). This could be attributed to the fact that SWAP did not take into account any other crop stresses such as nutrient deficiency, pests and disease, and indicates scope for further study into agronomic practices to improve wheat crop yields in the study area. However, the systematic agreement between the simulated water and salt, and the observed crop yields (Fig. 4) supports the applicability of the model to simulate and evaluate potential effects of different irrigation scenarios on the cotton-wheat cultivation and their water productivity values (Singh et al. 2006a, 2006b).

Potential effects of irrigation practices on long-term soil water and salt balances, and crop water productivity

Reference (baseline) scenario

Table 5 summarizes the potential effects of current irrigation practices on soil water and salt balances, crop yields and crop water productivity values as simulated for the cotton-wheat cultivation over the period of 10 years (2007–2017). Ullah et al. (2001) estimated average annual reference evapotranspiration (ET_p) of about 1289 mm for cotton-wheat cultivation across all canal commands of the IBIS, including the HBC. Liaqat et al. (2016) quantified seasonal average ET_p of 906 mm during *kharif* (cotton) and 485 mm during *rabi* (wheat) using the surface energy balance system (SEBS) model for HBC over a period from 2008 to 2014. In this study, the long-term SWAP simulated seasonal ET_p ($E_p + T_p$) varied from 1011 to 1143 mm with an average of 1078 mm during *kharif* (cotton), and from 390 to 490 mm with an average of 452 mm during *rabi* (wheat) season (Table 5). The SWAP simulated ET_p values showed a close agreement with the ET_p values quantified by Ullah et al. (2001) and Liaqat et al. (2016).

The seasonal rainfall received equated only 21% of the ET_p during the *kharif* season, and 11% of the ET_p during the

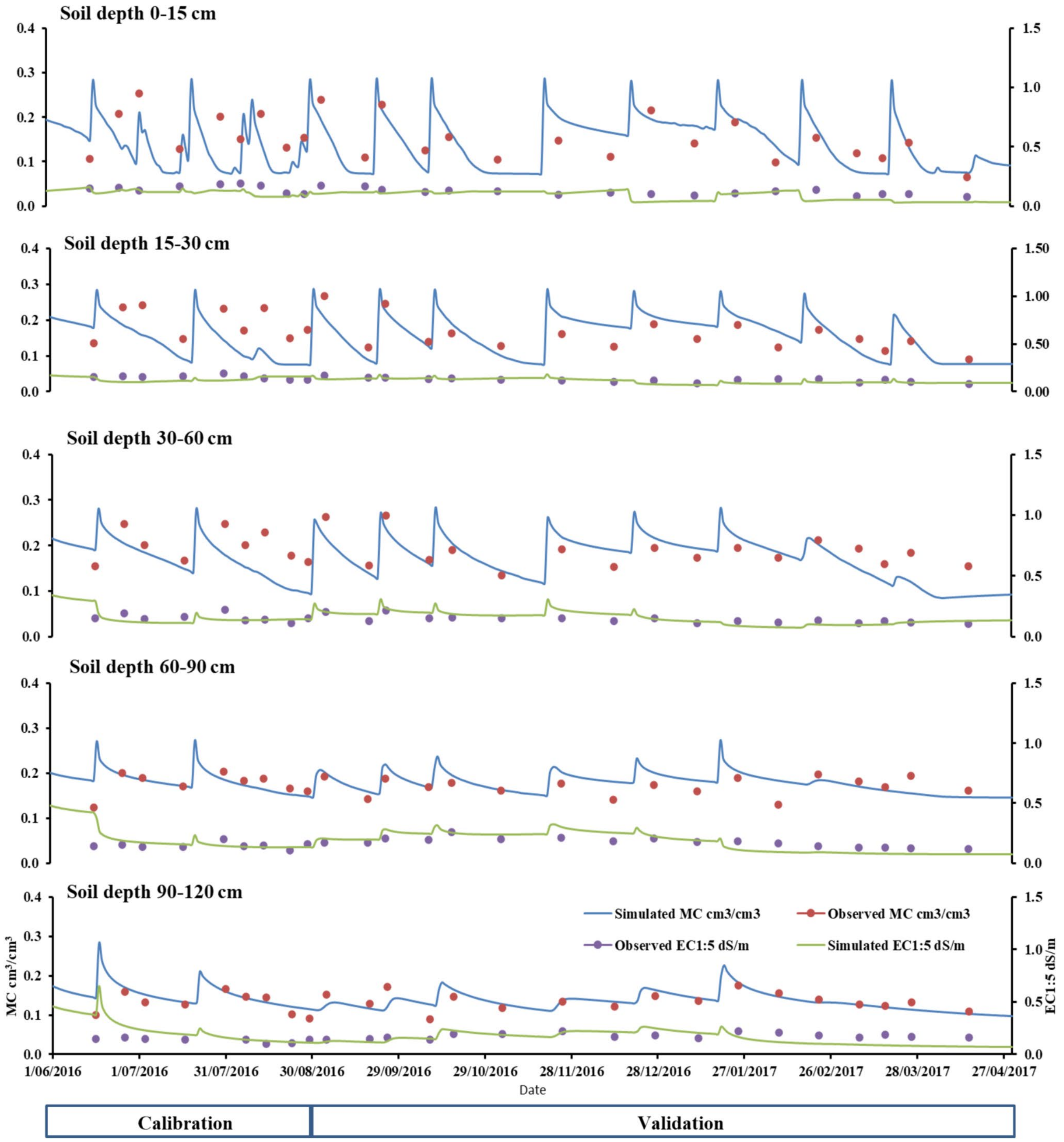


Fig. 3 The observed and simulated soil moisture and salinity profile at a local farmer field (field1 under cotton-wheat cultivation in Hakra canal command, Punjab Pakistan

rabi season (Table 5). The seasonal irrigation under *reference* irrigation scenario was applied at 1100 mm during the *kharif* season and 490 mm during the *rabi* season based on the observations at the local farmers' fields (Table 5). This resulted into SWAP simulated seasonal actual evapotranspiration (ET_a) from 684 to 818 mm, with an average value of 760 mm for cotton crop, and from 282 to 357 mm with an average value of 327 mm for wheat crop. Awan et al. (2016) estimated annual ET_a, based on the well-known surface energy balance algorithm for land (SEBAL), from a minimum of 85 mm to a maximum of 1091 mm across all distributary commands of HBC during the year 2013–2014.

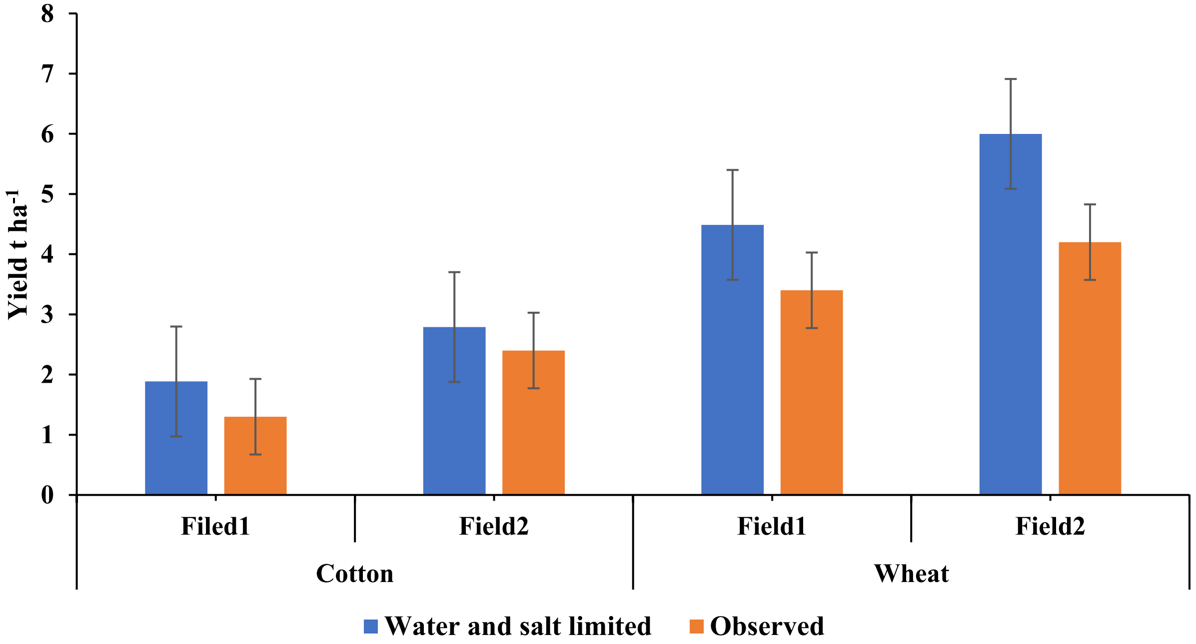


Fig. 4 Simulated and observed cotton (seed) and wheat yields at local farmer fields (field1 and field2) during agricultural year 2016–2017 in Hakra canal command, Punjab Pakistan

Table 5 SWAP simulated mean soil water and salt balance components of cotton-wheat crops under ‘business-as-usual’ reference (baseline) irrigation scenario for 10 years (2007–2017) in Hakra canal command, Punjab Pakistan

Soil water and salt balances, and crop water productivity	Kharif Season (Cotton)		Rabi Season (Wheat)	
	Mean	CV	Mean	CV
Rain(mm)	231	0.42	51	0.63
Irrigation (mm)	1100	–	490	–
E_p (mm)	354	0.04	186	0.09
T_p (mm)	724	0.08	265	0.11
T (mm)	665	0.08	259	0.11
T_a/T_p (mm)	0.92	0.02	0.98	0.01
ET_a (mm)	760	0.06	327	0.08
Q_{bot} (mm)	− 557	− 0.24	− 222	− 0.16
ΔW (mm)	16	3.04	− 9	− 2.22
IC_i (mg cm^2)	73	–	31	–
C_{bot} (mg cm^2)	− 73	− 0.21	− 30	− 0.3
ΔC (mg cm^2)	− 0.38	− 40.4	1	10.01
Cotton seed yield (kg ha^{-1})	2978	0.18	5707	0.16
WP_{ET} (kg m^{-3})	0.39	0.2	1.75	0.18
WP_{Irr} (kg m^{-3})	0.27	0.18	1.17	0.16

The symbols E is evaporation, T is transpiration ET is evapotranspiration, Q is percolation, ΔW change in water storage, I is irrigation, C is solute concentration, ΔC is change in solute concentration, WP is water productivity. Subscripts p is potential, a is actual, bot is bottom, ET is evapotranspiration, Irr is irrigation, CV is the coefficient of variation

Applying the surface energy balance system (SEBS) model, Liaqat et al. (2016) estimated seasonal average ET_a of 641 mm during the *kharif* season and 322 mm in *rabi* season with an annual average ET_a of 963 mm for HBC over the period from 2008 to 2014. These ET_a values are in close agreement with the SWAP simulated ET_a values in this study (Table 5).

The average annual water supply of 1872 mm yr^{-1}, accounting both the average annual rainfall (282 mm yr^{-1}) and irrigation (1590 mm yr^{-1}), amounted to 1.2 times of the average annual reference evapotranspiration ET_p predicted at 1513 mm yr^{-1} (Table 5). About 42% of the average annual water supply was simulated to be percolated Q_{bot} (−779 mm yr^{-1}) to groundwater, including an average about −557 mm during *kharif* (cotton) season and about −222 mm during *rabi* (wheat) season (Table 5). This high percolation rate could be attributed to high irrigation applications (Table 5) and the sandy texture of the soil in HBC (Table 1). Liaqat et al. (2016) also reported seasonal groundwater recharge of 330 mm during the *kharif* season and of 235 mm during the *rabi* season, with an average annual groundwater recharge of 565 mm across the whole command of HBC during period from 2008 to 2014. Liaqat et al. (2016) also reported an average annual groundwater abstraction of 680 mm yr^{-1} for irrigation in the HBC during the same period. Awan et al. (2016) reported about 40% of annual irrigation abstraction to be from groundwater in the HBC during 2013–2014. They also found that groundwater pumping was 45% higher in head reaches of the canal network.

This corresponds to this study observations of 30 to 85% of annual irrigations of 1100 and 1590 mm sourced from groundwater at the local farmers' fields located in the middle and tail reaches of the canal network (*see* Sect. "Observations at local farmer's fields"). This highlights that groundwater abstraction is indeed an integral part of irrigation in the HBC, which varies in its quality from less than 1 to 20 dS m^{-1} in the study area. Furthermore, this stresses the role played by percolation in sustaining the groundwater resource.

In arid and semi-arid areas, a high use of marginal- and poor-quality groundwater with high levels of salts can lead to a salt build-up in the soil profile (Smedema and Shiati 2002; Datta and De Jong 2002; Garg and Hassan 2007; Condon, 2014; Mukherjee et al. 2015). The salinity levels in the soil profile must be maintained below the crop-specific threshold level (EC_{max}) (Maas and Hoffman 1977), beyond which crop yields are reduced due to salt stress on crop growth (van Dam et al. 1997). In this study, a mixture of good quality canal water ($EC = 0.57$ dS m^{-1}) and marginal quality groundwater ($EC = 1.66$ dS m^{-1}) were used to simulate a representative conjunctive use of canal and groundwater ($EC = 0.96$ dS m^{-1}) for a cotton-wheat rotation over period of 10 years in the study area. This resulted in a salt balance from −26 mg cm^{-2} (− 2600 kg ha^{-1}) to 28 mg cm^{-2} (+ 2800 kg ha^{-1}) during the *kharif* season, and from − 15 mg cm^{-2} (− 1500 kg ha^{-1}) to 20 mg cm^{-2} (+ 2000 kg ha^{-1}) during the *rabi* season (Table 5). This variation in the soil salt balance can be attributed to variations in the rainfall received which causes significant salt leaching during high rainfall years such as 2010–2013 and 2015–16. The results showed that high applications of irrigation (1100 mm yr^{-1}) resulted into a negligible salt-built up of 0.38 mg cm^{-2} (38 kg ha^{-1} yr^{-1}) during the *kharif* season. Also, the salt balance was simulated to be on average at 1 mg cm^{-2} (100 kg ha^{-1} yr^{-1}) during the *rabi* season, causing no significant change in soil salinity on annual basis under *reference* irrigation scenario (Table 5). The average soil salinity at the end of simulation period was simulated as 1.76 dS m^{-1}, significantly lower than the crop threshold salinity levels of 7.7 dS m^{-1} for cotton and 6.0 dS m^{-1} for wheat (Table 2). Overall, this suggests that negligible soil salinity stress was observed by the cotton-wheat crops under the *reference* scenario. This could be attributed to a significant percolation Q_{bot} simulated from −532 mm yr^{-1} to − 1043 mm yr^{-1}, with an average of −780 mm yr^{-1} (i.e., about 50% of irrigation) as a leaching fraction under *reference* irrigation practices at the farmer fields.

The SWAP model predicts the intensity of combined water and salt stresses by reduction in relative transpiration of the crop. Under *reference* irrigation practices, the predicted relative transpiration (T_a/T_p) varied from 0.90 to 0.95 with an average of 0.92 for the cotton crop, whereas it varied from 0.96 to 0.98 with an average of 0.97 for the wheat crop. These high T_a/T_p values also revealed no significant water and salt stress experienced by the cotton-wheat crops simulated under *reference* irrigation practices. The predicted water and salt limited crop yields varied from 2.4 to 4.07 t ha^{-1}, with an average of 2.98 t ha^{-1} for cotton, and from 3.55 to 6.69 with an average of 5.70 t ha^{-1} for wheat (Table 5). The predicted crop water productivity based on actual evapotranspiration, WP_{ET} (kg m^{-3}) varied from 0.30 to 0.55 with an average value of 0.39 for cotton, and from 1.10 to 2.13 with average value of 1.75 for wheat (Table 5).

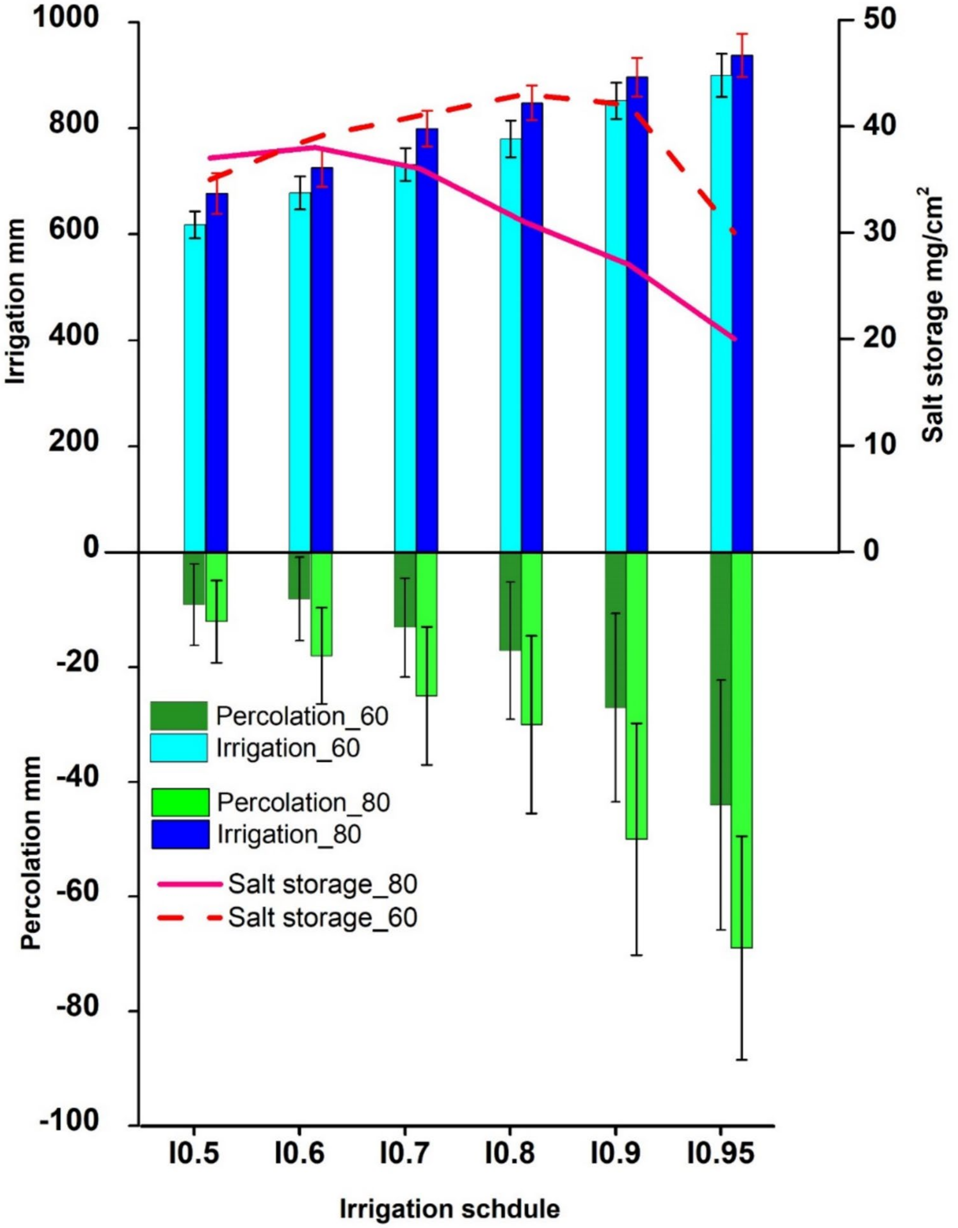
Whereas, the crop water productivity based on irrigation WP_{Irr} (kg m^{-3}) varied from 0.22 to 0.37 with an average value of 0.27 for cotton and from 0.73 to 1.37 with average value of 1.17 for wheat (Table 5).

According to Zwart and Bastiaanssen (2004), the global WP_{ET} values (kg m^{-3}) were expressed as 0.63 for cotton and 1.08 for wheat. Usman (2012) reported the WP_{ET} values (kg m^{-3}) of 0.26 for cotton and 1.12 for wheat in the cotton-wheat zone of Punjab Pakistan. Combining the field observations and SWAP predictions, Singh et al. (2006c) quantified the average WP_{ET} values of 0.31 and 2.01 kg m^{-3} for cotton and wheat, respectively, and the average WP_{Irr} values of 0.26 and 1.67 kg m^{-3} for cotton and wheat, respectively at 3 – 5 farmers' fields during the year 2001–02 in the Sirsa Irrigation Circle of Haryana state of India, an irrigation area very close to the study area. These indicative WP_{ET} and WP_{Irr} values showed a close agreement with the predicted results (Table 5) and provided evidence that the model simulations were accurate enough to do further scenario analysis. Also, the simulated average WP_{Irr} values were about 2/3rd (~ 65–68%) of the average WP_{ET} values for both cotton and wheat crops (Table 5), suggesting scope to improve irrigation applications at the study fields.

Precision surface irrigation scenario

Figure 5 shows the predicted effects of 'precision surface irrigation scenario, noted as *PSIS*'. This involves a comparison of fixed irrigation depth of 60 mm and 80 mm for each irrigation event on average annual irrigation amounts, percolation and soil salt storage in the soil profile under the cotton-wheat cultivation in the study area. Over the long-term, the cotton-wheat cultivation under the *PSIS* scenario required an average annual irrigation from 618 mm yr^{-1} under *I0.5* irrigation scheduling, to 900 mm yr^{-1} under *I0.95* irrigation scheduling with a fixed irrigation depth of 60 mm (Fig. 5). It required from 664 mm yr^{-1} under *I0.5* to 920 mm yr^{-1} under *I0.95* with a fixed irrigation depth of 80 mm (Fig. 5). This suggests a potential savings of the cotton-wheat irrigation amounts from 3% under *I0.95* to 8% under *I0.5* when applied the *PSIS* with a fixed irrigation depth of 60 mm, as compared

Fig. 5 Simulated effects of 'precision surface irrigation system (*PSIS*)' scenario with a fixed irrigation depth of 60 mm and 80 mm on the long-term (10 years) average irrigation applied, percolation and salt storage under cotton-wheat cultivation in Hakra canal command, Punjab Pakistan



to 80 mm. However, under the *PSIS* with *I0.95* irrigation scheduling, the salt storage was predicted at 30 mg cm^{-2} (~ 3.1 t ha^{-1}, a soil salinity of 6.65 dS m^{-1}) with 60 mm irrigation depth, whereas it was predicted at 20 mg cm^{-3} (2.0 t ha^{-1}, salinity 5.7 dS m^{-1}) with 80 mm irrigation depth (Fig. 5). The predicted soil salinity values with 60 mm irrigation depth, particularly under the *PSIS I0.5 to I0.80* irrigation scheduling, were higher than the critical thresholds EC_{max} of 6.0 and 7.7 dS m^{-1} for wheat and cotton crops, respectively (Table 2). It is evident from the results that the *PSIS* with 80 mm of fixed depth irrigation resulted into relatively lower salt storage in the soil profile, particularly under the lowest daily crop-stress criterion of the *I0.95* irrigation scheduling (Fig. 5).

Figures 6 and 7 show the predicted effects of changes in irrigation amounts and salt storage, with respect to the set daily crop stress of the transpiration ratio criterion under different scenarios, over the long-term crop yield and water productivity values of the cotton-wheat cultivation. A two-way ANOVA was performed to analyse the effect of irrigation schedules and irrigation scenarios on crop water productivity (WP_{ET} and WP_{Irr}) values with 95% confidence interval. The ANOVA results revealed that there was a statistically significant interaction between the effects of irrigation schedules and irrigation scenarios ($F = 10$ to 118 and a *P-value* < 0.05). The results showed a positive relationship in which the crop yields increased with an increase in the crop transpiration (Fig. 6). The less

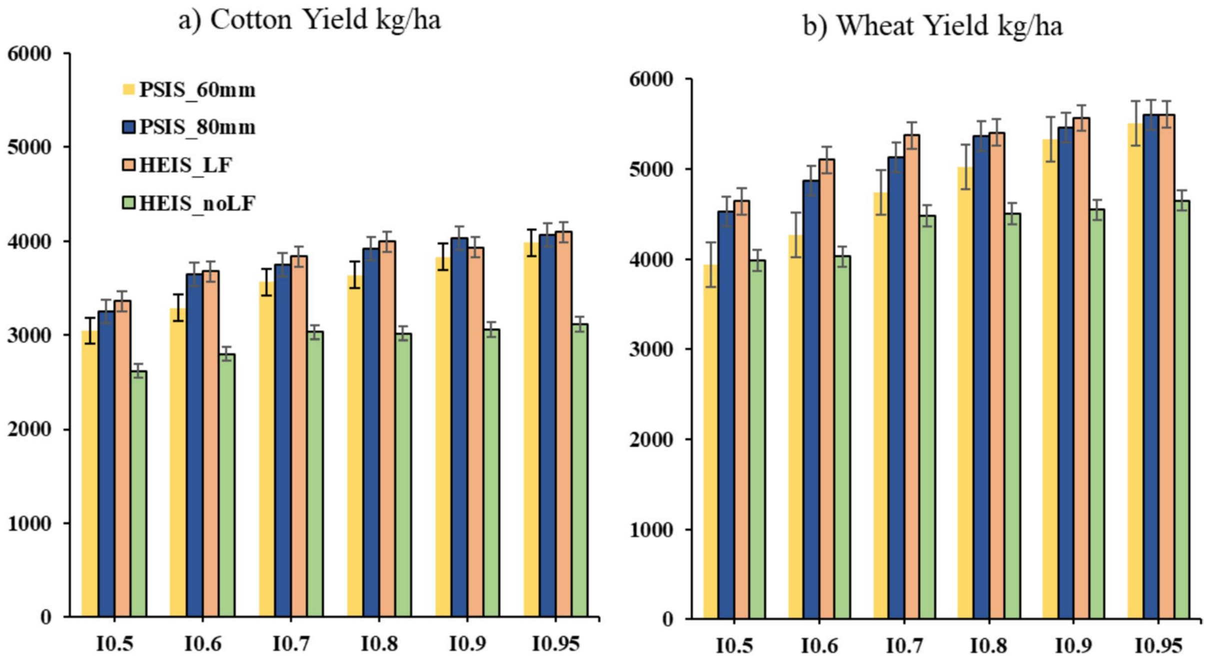


Fig. 6 Simulated effects of the 'precision surface irrigation system (*PSIS*) with a fixed irrigation depth of 60 mm (*PSIS_60mm*) and 80 mm (*PSIS_80mm*) and the 'high efficiency irrigation system (*HEIS*)', with a leaching fraction (*HEIS_LF*) and without a leaching fraction (*HEIS_no LF*) on the long-term (10 years) average crop yields (a and b) of cotton-wheat cultivation in Hakra canal command, Punjab Pakistan

irrigation and relatively high soil salinity levels under the *I0.5* and *I0.6* criteria for irrigation scheduling affected the crop water uptake and resulted in relatively lower crop yields (Fig. 6a&b).

The average wheat yield showed an increase of 40%, from 3.9 t ha^{-1} under *I0.5* irrigation scheduling, to 5.5 t ha^{-1} under *I0.95* irrigation scheduling with 60 mm irrigation depth, and an increase of 23% from 4.5 t ha^{-1} under *I0.5* to 5.6 t ha^{-1} under *I0.95* with 80 mm irrigation depth (Fig. 6b). Similarly, the average cotton yield increased by 25% and 20% when the irrigation scheduling increased from *I0.5* to *I0.95* with an irrigation depth 60 mm and 80 mm, respectively (Fig. 6a).

However, the average crop yields were predicted to be relatively lower for both the wheat and cotton crops under the *PSIS_60mm* as compared to the *PSIS_80mm,* particularly for under the *I0.5* and *I0.6* criteria for irrigation scheduling (Fig. 6a&b). The *PSIS_60mm* and *PSIS_80mm* irrigation at > *I0.9* criteria resulted into a higher percolation facilitating salt leaching (lower salt storage) (Fig. 5), causing minimal water and salt stress and average higher crop yields (Fig. 6). Interestingly, the average WP_{ET} and WP_{Irr} values showed no significant variation for both the wheat and cotton crops when the irrigation schedule increased from *I0.5* to *I0.95* (Fig. 7). Also, the changes in the fixed irrigation depth from 60 to 80 mm showed no significant effect on the average WP_{ET} and WP_{Irr} values for both the wheat and cotton crops (Fig. 7). This could be attributed to almost a linear increase in the crop *ET* with the increase in the crop yields.

Overall, the wheat and cotton yields and WP_{ET} values under the *PSIS* scenario were, however, achieved highest with the *I0.95* irrigation scheduling with 80 mm irrigation depth (Figs. 6 and 7). The analysis of *PSIS* scenario (Figs. 5, 6, 7) suggested that a precise application of surface irrigations with a fixed irrigation depth of 80 mm using a lower daily crop stress criterion (> *I0.90*) would be beneficial in terms of maintaining soil salinity (Fig. 5), and achieving relatively higher wheat and cotton yields (Fig. 6) and water productivity values (Fig. 7) in the study area.

High-efficiency irrigation scenario

Figure 8 shows the predicted effects of using a 'high-efficiency irrigation system (*HEIS*)' with a leaching fraction (*HEIS_LF*), and without a leaching fraction (*HEIS_no LF*), on the long-term average of annual irrigation amounts, percolation and soil salt storage in the soil profile for the cotton-wheat cultivation in the study area. Under *HEIS_no LF*, the cotton-wheat average annual irrigation was predicted to be from 635 mm yr^{-1} under *I0.5*, to 830 mm yr^{-1} under *I0.95*, while under *HEIS_LF* it was predicted to be from 720 mm yr^{-1} under *I0.5* to 955 mm yr^{-1} under *I0.95* (Fig. 8). This resulted in potential savings of irrigation water from 12 to 15% under *HEIS_no LF* irrigations. However, *HEIS_no*

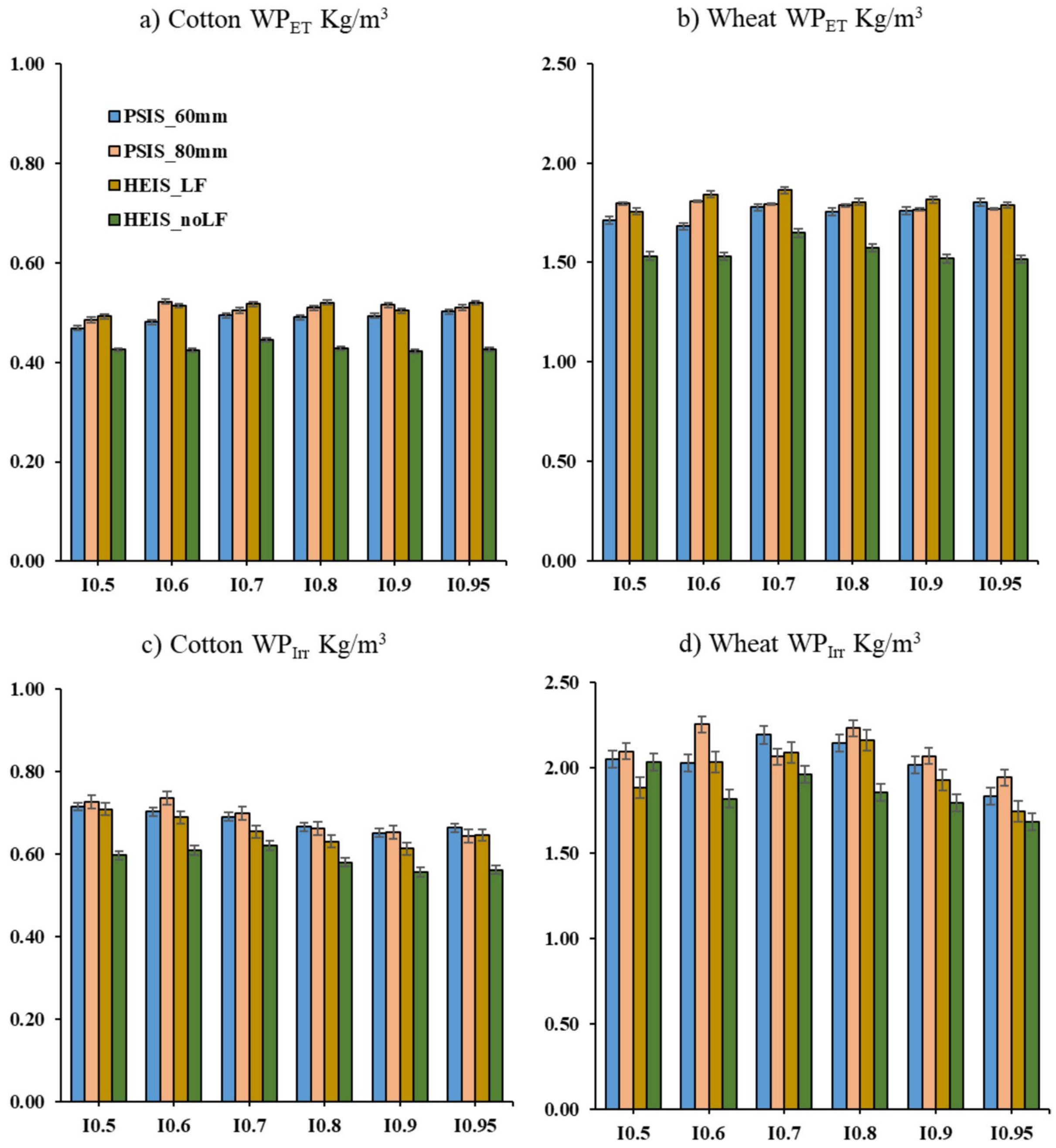


Fig. 7 Simulated effects of the 'precision surface irrigation system (*PSIS*) with a fixed irrigation depth of 60 mm (*PSIS_60mm*) and 80 mm (*PSIS_80mm*) and the 'high efficiency irrigation system (*HEIS*)', with a leaching fraction (*HEIS_LF*) and without a leaching fraction (*HEIS_no LF*) on the long-term (10 years) average water productivity of cotton-wheat cultivation in Hakra canal command, Punjab Pakistan

LF showed the risks of an adverse salt build up in the soil profile, and a significant reduction in percolation as recharge to the groundwater system (Fig. 8).

The *HEIS_no LF* scenario as compared to *HEIS_ LF* resulted into the average salt storage predicted from 10 to 67% higher, whereas the average annual percolation predicted from 61 to 73% lower (Fig. 8). Under *HEIS_no LF* scenario, the salt storage was simulated at 35 mg cm^{-2} (~ 8.8 dS m^{-1} soil *EC*) under *I0.5*, and at 34 mg cm^{-2} (~ 8.1 dS m^{-1} soil *EC*) under *I0.95* (Fig. 8). These soil salinity levels were higher as compared to the critical thresholds EC_{max} of 6.0 and 7.7 dS m^{-1} for wheat and cotton crops, respectively (Table 2). This suggested a potentially adverse effects of *HEIS_no LF* irrigations on crop water uptake and crop yields of the cotton-wheat cultivation in the study area. The average wheat and cotton yields were predicted to be from 17

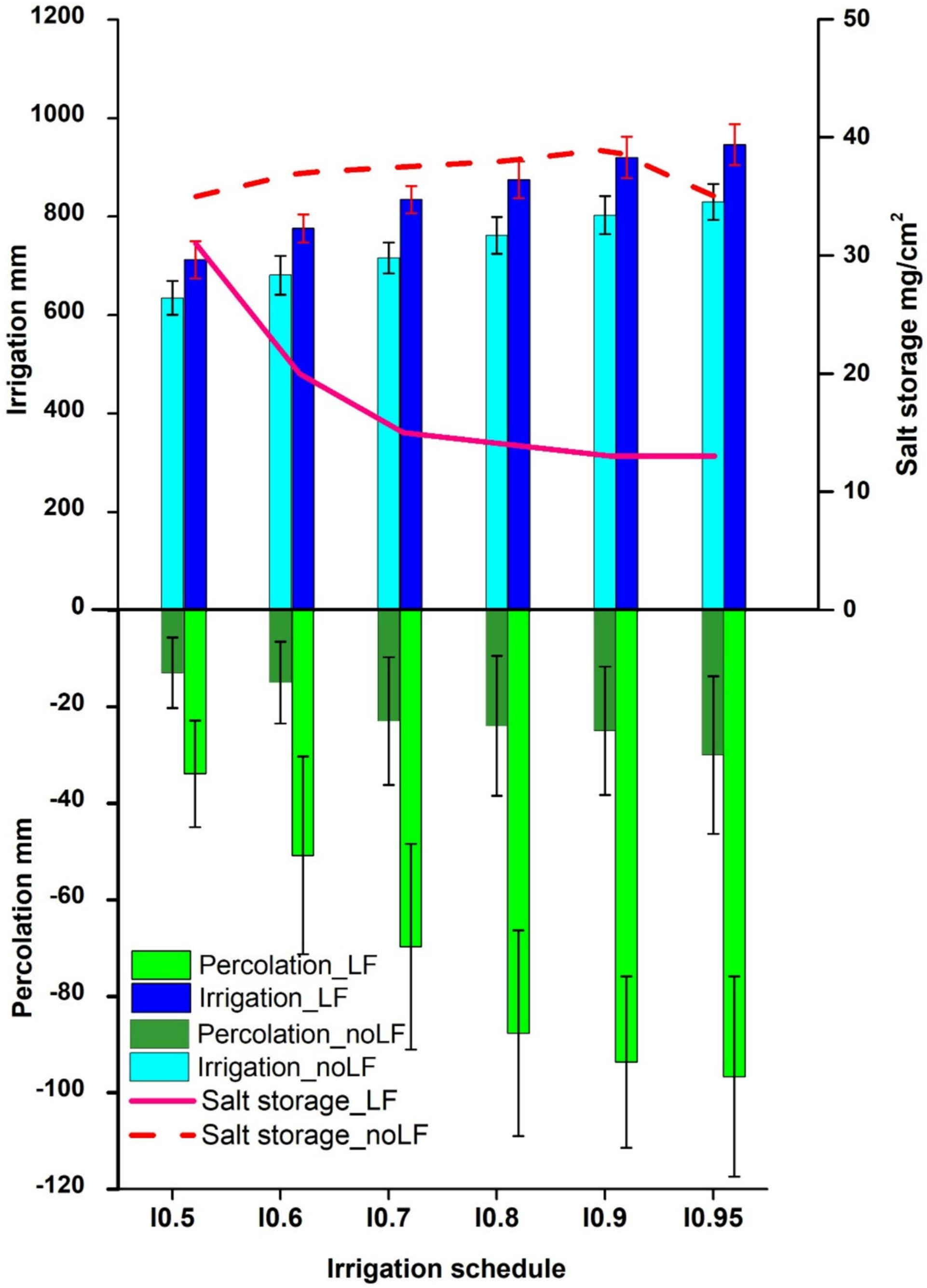


Fig. 8 Simulated effects of 'high efficiency irrigation system (*HEIS*)', with a leaching fraction (*HEIS_LF*) and without a leaching fraction (*HEIS_noLF*) scenario on the long-term (10 years) average irrigation applied, percolation and salt storage under cotton-wheat cultivation in Hakra canal command, Punjab Pakistan

to 24% lower under *HEIS_noLF* irrigations as compared to *HEIS_ LF* (Fig. 6 a&b). This resulted in reduction of 3% to 12% in the wheat and cotton WP_{Irr} values (Fig. 7 c&d), and a reduction from 13 to 18% in the wheat and cotton WP_{ET} values under *HEIS_noLF* irrigation (Fig. 7 a&b).

The analysis of *HEIS* scenario (Figs. 6–8) suggested that high-efficiency irrigation systems such as sprinklers, without appropriate leaching fraction (*HEIS_noLF*), pose a significant risk build-up in the soil profile. Additional irrigation applications would be required to leach any excess salts and minimize soil salt build-up and its potentially adverse effects on crop yields and their water productivity. This was evident from the analysis of *HEIS_LF* scenario that resulted in relatively less salt storage (Fig. 8), and higher crop yields (Fig. 6) and water productivity values for the cotton-wheat cultivation (Fig. 7).

Comparison of different irrigation scenarios

Comparing the *reference*, and *PSIS_80mm* and *HEIS_LF* at *I0.95* scenarios (Table 6) suggested a scope of > 40% savings in irrigation amounts under the *PSIS_80mm* and *HEIS_LF*, compared to the *reference* (Table 6). Also, *PSIS_80mm* and *HEIS_LF* as compared to the *reference* resulted into similar average crop yields and WP_{ET} values for wheat crop, but an increase of nearly 30% in average crop yields and WP_{ET} values for cotton crop (Table 6). The WP_{Irr} values were simulated > 60% and > 40% higher, respectively for the wheat and cotton crops under the *PSIS_80mm* and *HEIS_LF* as compared to the *reference* (Table 6). This suggested a significant scope of improving the *reference* representing current irrigation practices observed at the local farmers' fields. Current farmer's irrigation practices can be improved to reduce excessive amounts fixed-schedule irrigations to better optimised amounts and flexible-schedule irrigations to save irrigation water, improve crop yields, maintain appropriate levels of soil salinity leaching, and potentially reduce costs of irrigation in the study area.

However, this study analysis clearly suggests that potential savings in irrigation amounts and improvements in the cotton-wheat yields (Fig. 6, Table 6) and water productivity values (Fig. 7, Table 6) are possible if the irrigation depths supplemented a sufficient leaching fraction preventing salt build-up in the soil profile (Fig. 5 and 8). A highly efficient irrigation system with minimum percolation (*HEIS_noLF*) poses a risk of the salt build-up and its potentially adverse effects on crop yields and their water productivity. This is demonstrated by predictions of relatively lower crop yields and water productivity WP_{ET} values, particularly for the wheat crop under *HEIS_noLF* scenario with a relatively lower percolation and relatively higher salt-build-up in the soil profile (Table 6). Irrigation with marginal to high level of salinity waters over a long period of time could result into salt build-up and affect crop yields in arid and semi-arid regions (Kahlown et al. 1998; Horneck et al. 2007;; Raine et al. 2007; Esteve et al. 2008; Condon, 2014; Mukherjee et al. 2015). However, this could be potentially mitigated by providing an appropriate leaching fraction to maintain, or reduce salt build-up, if no other alternate irrigation source available to replace poor quality of irrigation water.

In this study, all three irrigation scenarios; the *reference*, and the *PSIS_80mm* and *HEIS_LF* irrigation at *I0.95* irrigation scheduling, maintained the soil salinity levels (i.e. 0.51 – 13 mg cm^{-2}, ~ 1.76–4.23 ds m^{-1}) (Table 6) below the critical thresholds EC_{max} of 6.0 and 7.7 dS m^{-1} for wheat and cotton crops, respectively (Table 2). However, the depth of percolation in the *reference* scenario was predicted to be significantly higher by 8 to 11 times as compared to *PSIS_80mm* and *HEIS_LF*, due to very high depths of 1590 mm irrigation applied under the *reference* scenario as observed in the farmers' fields. This is because in the HBC the water is currently allocated to farmers' fields using Warabandi, irrespective of their crop water requirements. Also, farmers potentially consider that more irrigation is better for soil moisture and crop growth. This could be helpful in leaching the salts out from the root zone in areas with deeper groundwater levels. However, under shallow groundwater level conditions, the high percolation rate could cause waterlogging and secondary salinization, and potentially affect the crop growth.

In this study analysis (Table 6), both the *PSIS_80mm* and *HEIS_LF* irrigations at *I0.95* irrigation scheduling resulted into similar long-term average soil water and salt balances,

Table 6 Simulated effects of different irrigation scenarios on long-term (10 years, 2007–2017) average water and salt balances, crop yields and water productivity of cotton-wheat cultivation in Hakra canal command, Punjab Pakistan

Water and Salt balance/crop performance		*Reference (baseline)*		*PSIS_80mm*		*HEIS_LF*		*HEIS_noLF*	
		Mean	*CV*	*Mean*	*CV*	*Mean*	*CV*	*Mean*	*CV*
Irr (*mm yr*$^{-1}$)		1590	–	920	0.14	955	0.14	830	0.14
Q_{bot} (*mm yr*$^{-1}$)		– 779	– 0.17	– 69	– 0.9	– 97	– 0.74	– 30	– 1.71
ΔC (*mg cm*$^{-2}$)		0.51	19.42	20	2.05	13	3.59	35	0.73
T_a/T_p	*Cotton*	0.92	0.02	0.99	0.01	0.99	0.02	0.97	0.02
	Wheat	0.98	0.01	0.98	0.01	0.97	0.01	0.94	0.04
Yield (*t ha*$^{-1}$)	*Cotton*	2.98	0.16	4.06	0.06	4.09	0.06	3.12	0.08
	Wheat	5.7	0.17	5.61	0.14	5.61	0.14	4.65	0.17
WP_{ET} (*kg m*$^{-3}$)	*Cotton*	0.39	0.19	0.51	0.11	0.52	0.11	0.43	0.12
	Wheat	1.75	0.17	1.77	0.18	1.79	0.17	1.52	0.2
WP_{Irr} (*kg m*$^{-3}$)	*Cotton*	0.27	0.17	0.64	0.23	0.65	0.2	0.56	0.23
	Wheat	1.17	0.15	1.95	0.26	1.79	0.22	1.69	0.39

The *PSIS* stands for 'precision surface irrigation system with 80 mm fixed irrigation depth' (*PSIS_80mm*), and the *HEIS* stands for 'high efficiency irrigation system' with a leaching fraction (*HEIS_LF*) or without a leaching fraction (*HEIS_noLF*) and the cotton-wheat crops yields and water productivity values. This suggested a potential for improved as 'precision' surface irrigations to help maintain appropriate soil water and salt balances, and achieve improved crop yields and water productivity values for cotton-wheat cultivation in the study area. However, any gains in irrigation water savings by a high-efficiency irrigation systems (represented as *HEIS_noLF*) would be constrained by its potential risks to increase the soil salinity, and its adverse effects on the cotton-wheat crop yields and their water productivity values, as demonstrated in the *HEIS_noLF* scenario (Table 6). Moreover, installation of high-efficiency pressurised irrigation systems would require infrastructure changes and energy requirements potentially increasing cost of irrigation systems. Instead, a properly levelled gravity-fed precision surface irrigations with significantly less cost to the farmers could help achieve similar water savings and improvements in the cotton-wheat crop yields and their water productivity values, as demonstrated in the *PSIS_80mm* scenario (Table 6). Anwar et al. (2016) showed that if fields are maintained well graded, the surface irrigation in the context of Warabandi has potentially efficiency as high as 80% without any infrastructural changes. However, there are available limited studies available, especially in semi-arid regions like the study area, in which long-term effects of different irrigation systems are studied. The modelling simulations, such as analysed in this study, could be further validated by conducting long-term field studies and using their observations in reducing any potential uncertainties in prediction of potential effects of different irrigation systems.

Conclusions

The integration of local field-observations with the existing agro-hydrological model, the Soil–Water-Atmosphere-Plant (SWAP), offered a robust tool to assess long-term potential effects of different irrigation systems on the irrigation requirements, soil water balances including percolation, soil salinity, and crop yields and water productivity of cotton-wheat cultivation in Hakra Branch Canal command in Punjab Pakistan.

improved The *HEIS* scenario without a leaching fraction (noted as *HEIS_noLF*), defined as using sprinkler irrigation to bring the soil back to the field capacity, resulted in about 48% less long-term average irrigation needs (830 mm yr^{-1}) as compared to the baseline scenario (1590 mm yr^{-1}). This reduction in irrigation, however, resulted into a relatively higher average soil salt build-up (as 35 mg cm^{-2}) causing a reduction of 18%–30% in the wheat crop yields. The *HEIS* scenario with a leaching fraction (noted as *HEIS_LF*), with an additional irrigation of 60 mm at the start of crop season followed by an additional 10 mm with each irrigation interval, reduced the average salt build up (as 13 mg cm^{-2}) and its adverse effects of the crop yields. However, *HEIS_LF* scenario resulted in the similar average irrigation amounts (955 mm yr^{-1}), soil water and salt balances, crop yields and water productivity values as achieved by the *PSIS* scenario, defined as a fixed depth of 80 mm surface irrigation at each flexible irrigation intervals. This suggests limited scope for irrigation savings by adopting high-efficiency irrigation system.

The modelling results suggested that a precision surface irrigation system (*PSIS*) and/or a high-efficiency irrigation system with a leaching fraction (*HEIS_LF*) offer a scope of over 40% savings in th average irrigation amounts, an increase of about 30% in the average crop yield and evapotranspiration-based water productivity WP_{ET} value for the cotton crop, and an increase of > 50% in the irrigation-based water productivity WP_{Irr} values for both the wheat and cotton crops in the study area. However, the expected higher benefits of potential irrigation water savings associated with the high-efficiency irrigation system with no leaching fraction, *HEIS_noLF* were simulated as constrained by a potential risks of increase in soil salinity, and its adverse effects on the cotton-wheat crop yields and their crop water productivity values. This is due to the need for a significant leaching fraction to avoid further salt-build up in the soil profile and minimise its adverse effects on crop growth and its water productivity. The reduced soil percolation under high-efficiency irrigation systems, if not managed properly, could also potentially affect recharge to groundwater levels and further deteriorate quality of groundwater in the study area.

However, these modelling predictions are limited in scope to only field-scale simulations, with homogeneous soil, irrigation water quality and crop rotation assumptions in the study area. Further research is suggested to conduct long-term field experiments monitoring potential effects of high-efficiency (sprinkler) irrigation systems on the long-term soil water and salt balances, crop yields and crop water productivity values for cotton-wheat cultivation in study area and similar conditions elsewhere. Also, further research is suggested to assess the potential long-term effects of precision irrigation applications at the canal-command scale with heterogeneous soil, irrigation water quality, and crop rotation to determine if these findings apply over larger scales.

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Author contributions Mr. Khan did all the experiments and analysis and wrote the main manuscript. Mr. Ranvir provided support in the model calibrations and darfting of the Manuscript. Brent and Tonny reviewed the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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