Estimation of potential recharge through direct seeded and transplanted rice fields in semi-arid regions of Punjab using HYDRUS-1D

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Abstract

The present study utilizes soil water balance and HYDRUS-1D for estimating and predicting potential recharge in groundwater declining region of central Punjab, respectively. A field experiment was conducted at Punjab Agricultural University, Ludhiana. Two treatments viz direct-seeded (DSR) and transplanted rice (TPR) with three replications, were sown/transplanted during *kharif* season of 2019. The amount of water applied through rainfall/irrigation was recorded and bottom flux was measured using frequency domain reflectometry (FDR) and then predicted using HYDRUS-1D in order to assess potential groundwater recharge which was further compared with deep percolation determined using soil water balance. The performance of the HYDRUS-1D was evaluated using RMSE, NSE, and R^2 and found to be performing well. The paired *t*-test ($t = 1.28$ and $t = 1.30$ for TPR and DSR, respectively) was found to be non-significant at $P = 0.05$ which showed the correspondence between predicted and estimated parameters. The percentage change between estimated and predicted potential groundwater recharge was found to be 0.7% and 2.32% in TPR and DSR, respectively. The study revealed that there was 9% water saving and 14.6% more deep percolation (cumulative bottom flux) in DSR as compared to TPR that may potentially contribute to groundwater recharge.

Keywords Direct seeded rice · Groundwater recharge · HYDRUS-1D · Transplanted rice · Water balance method

Introduction

Rice (*Oryza sativa* L.) is one of the most important crop and staple food for almost half of the world's population and providing more than one-fifth of the calories consumed by humans worldwide (Smith 1998) and accounts for 40% of all global irrigation, and 17% of global groundwater depletion. The global average water footprint per kilogram of rice is 2500 L (Bouman 2009), in India is 2800 L and

the State of Punjab has the highest footprint of 5000 L which is mainly satisfied through tubewell irrigation (Kaur and Singh 2017). In Punjab, rice is grown over 3.07 Mha which accounts about 75% of total cultivable area with the production of 13.38 million tons (Anon 2019) and requires about 800–2000 mm water depending on the climate, soil characteristics, crop, and water management practices followed in a region (Tyagi et al. 2000). Varying ranges of water requirement (775–3000 mm) have been reported by Lu et al. (2000), Tyagi et al. (2000), Zawawi et al. (2010). Out of the 99.9% irrigated area in Punjab, 72% area is irrigated through groundwater pumping and 28% is irrigated through canal water. So, there is a lot of stress on water resources, especially on groundwater resources. In traditional method of rice cultivation, the actual water requirements (evapotranspiration losses) range from 450 to 1000 mm in the semi-arid region (Chahal et al. 2007), but crop needs standing water to control growth of weeds. Therefore, irrigation requirement comes out to be 800–2000 mm. The rice cultivation by traditional method is one of the main reasons for declining water level of the state, so there is need to explore alternative

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management practices that can reduce water application with minimum losses of yield. Rice can be cultivated either by the traditional method of transplanting/puddled or by direct-seeded rice (DSR), in which seeds are sown directly in the soil rather than transplanting seedlings from nursery. This practice of DSR helps to save both labor and time (Mann and Ashraf 2004; Jehangir et al. 2007). During *kharif* season of year 2020, the area under DSR in Punjab increased from 387 thousand hectares to 519 thousand hectares. This increase of more than 34% for rice under DSR was due to dearth of migrant labor caused by COVID-19 pandemic (Chaba 2020). Many studies in the past had emphasized water saving in rice cultivation through adoption of improved technologies, such as laser land leveling, alternate wetting and drying (AWD), intermittent irrigation, use of tensiometers for irrigation scheduling, delayed transplanting, shorter duration rice varieties, and even drip irrigation systems (Khepar et al. 2000; Singh et al. 2001a, 2001b; Kukal et al. 2005; Aggarwal et al. 2009; Minhas et al. 2010; Eberbach et al. 2019). However, limited work has been done on estimation of potential recharge through rice fields since it is complex phenomenon. Yadav et al. 2011 and Mohammad et al. 2018 estimated deep percolation, water movement, and surface runoff were asserted for transplanted and direct-seeded rice fields using soil water balance approach. Anuraga et al. (2006) integrated soil–water–atmosphere–plant (SWAP) model and geographical information system to evaluate the effect of soil and land use on the groundwater balance at sub-watershed scale and found that the recharge was more affected by soil type compared to land use whereas the groundwater balance depended more on the amount of groundwater withdrawal than on the rate of recharge. Various researchers have used water movement and solute transport numerical model to predict potential groundwater recharge and simulation of water movement in different soil layers (Martinez et al. 2009; Phogat et al. 2010; Lu et al. 2011; Singh et al. 2013; Khatal et al. 2018; Mo'allim et al. 2018). Many researchers in past have assessed potential groundwater recharge from flooded rice field under diverse climate change scenarios by means of HYDRUS-1D numerical model and MODFLOW (Kambale et al. 2017; Patle et al. 2017). The overall results from the study reveal that HYDRUS-1D was a reasonable and effective tool for simulating water flow in both rice growing techniques viz direct-seeded and transplanted rice.

Precise estimation of recharge flux and other losses using modeling technique under different cultivation methods of rice would help in judicious groundwater management and thus help in sustaining groundwater resources. Rice is the major crop of Punjab and because of high water demand of rice crop, groundwater level is declining at an alarming rate in the state, so it is important to undertake a study to assess impact on groundwater recharge under different establishment method of rice. Direct seeding of rice in dry and wet

condition is efficient method for water saving in terms of irrigation as well as more deep percolation of water which may ultimately contribute to groundwater recharge (Kumar et al. 2015; Choudhary et al. 2016). The studies on potential groundwater recharge through water balance and modeling for the direct seeded (DSR) and transplanted rice (TPR) are lacking. Keeping this in view, the study was undertaken to simulate the potential groundwater recharge from DSR and TPR fields in the Ludhiana district of Punjab in India so that the potential water saving in terms of water application and groundwater recharge in DSR over TPR is estimated.

Methodology

Experimental details

The field experiment was conducted at Research farm of department of Agronomy, Punjab Agricultural University (PAU), Ludhiana (Fig. 1). It is situated at 30°56' N latitude and 75°52' E and at an altitude of 247 m above the mean sea level. Ludhiana is centrally located district in Malwa region of Punjab with river Sutlej demarcated its northern periphery. Rice–wheat is the dominant cropping system in the district. The area experiences a semi-arid climate with normal annual precipitation of 680 mm which is unevenly distributed over the district with July being the wettest month of the year. The monsoon season contributes 78% of the precipitation and the rest of 22% is received in post-monsoon and during winter season. The soil of the research farm belongs to order Inceptisols, Typic Ustochrepts having alluvial sandy loam in texture. At the start of the experiment, depth-wise soil physicochemical properties of the field were determined by using the standard procedure (Table 1).

Two treatments viz transplanting and direct sowing of rice (variety PR 126) with three replications each were adopted for field experiment during *kharif* season of 2019. The size of each plot was 6 × 2.6 m and 27 × 2.4 m, respectively, for transplanted and direct-seeded rice whereas, for estimation of potential recharge, unit area was considered. For the rice nursery, seeds were sown in the third week of May in water ponded field by adopting the method described in University Package of Practices, PAU. Two seedlings per hill of 25–30 days old were manually transplanted in the flat puddled field. The irrigation method adopted was continuous in which irrigation water was applied immediately after disappearance of the ponded water. For DSR, before sowing of rice, the field was properly plowed and leveled followed by planking to ensure better germination, and sowing was done using rice seed drill with inclined plate metering device with the seed rate of 3.5 kg/acre. After sowing, the field was irrigated until surface soil gets saturated. The irrigation method adopted was of continuous in which irrigation

Fig. 1 Location map of study area **Table 1** Physico-mechanical properties of soil profile

Depth(cm)	Soil texture			Bulk density(Mg m ⁻³)	Field capacity(m ³ m ⁻³)	Saturated water content(m ³ m ⁻³)	Saturated hydraulic conductivity(cm day ⁻¹)
	Sand(%)	Silt(%)	Clay(%)				
0–10	59.0	23.6	17.4	1.59	0.243	0.340	9.17
10–20	56.8	25.6	17.8	1.61	0.250	0.360	6.24
20–30	56.2	25.8	18.0	1.62	0.253	0.365	14.14
30–40	57.4	25.2	17.4	1.61	0.244	0.358	10.56
40–60	55.1	26.4	18.5	1.63	0.255	0.368	8.78
60–100	55.1	26.4	18.5	1.62	0.255	0.368	11.30

water was applied immediately after top soil surface gets dry. The total growth period after transplanting/sowing was 111 and 130 days for TPR and DSR, respectively. The crop was harvested during first and second fortnight of October, respectively, for TPR and DSR.

The farmers practice was followed while irrigating both transplanted and directed seeded rice field. The amount and distribution of irrigation and rainfall during crop season is shown in Fig. 2. During the experimentation, the amount of each irrigation was kept as 50 mm and the number of irrigations applied were 24 for TPR and 22 for DSR which accumulates to total irrigation water of 1200 mm and 1100 mm for TPR and DSR, respectively. In case of DSR, the irrigation was stopped 30 days prior to the harvesting.

During the entire growing season, the daily meteorological data which includes maximum and minimum air temperature, maximum and minimum air relative humidity, wind speed, sunshine hours and rainfall was collected

from meteorological observatory, Department of Climate Change and Agricultural Meteorology, PAU which is located at the distance of 20 m from experimental field. The total amount of rainfall received during the growing period of transplanted and direct seeded rice was 835.5 mm which was 30% higher than average rainfall of 642.7 mm received during the crop growth period for Ludhiana district with highest single day rainfall of 145 mm was occurred on 64 days after transplanting or days after sowing (Fig. 2.).

The daily moisture content of soil at depth of 10, 20, 30, 40, 60, and 100 cm was monitored and recorded with the help of Delta PR2 probe. Leaf area index was measured with SS1 SunScan plant canopy analyzer (Delta-T Devices Ltd) at various growth stages for transplanted as well as direct seeded rice. It was assumed that the leaf area index will increase linearly throughout growth period (Patle et al. 2017). The average value of leaf area index for transplanted and direct seeded rice

Fig. 2 **a** Distribution of rainfall, irrigation and estimated cumulative surface runoff in transplanted rice field (2019) **b** Distribution of rainfall, irrigation and estimated cumulative surface runoff in direct-seeded rice field (2019)

Table 2 Leaf area index for transplanted and direct seeded rice during different crop stages

Stage of crop		Initial	Development	Maturity	Harvesting
Treatment	Transplanted Rice	0.43	1.81	5.8	0.74
	Direct seeded rice	0.32	1.72	5.3	0.62

during initial, development, maturity and harvesting stage are given in Table 2.

Model description

The HYDRUS-1D is a mathematical model (Šimůnek et al. 2008) for simulating water flow, solute and heat movement in one-dimensional unsaturated, partially saturated or fully saturated uniform or non-uniform soil conditions. HYDRUS-1D uses the Richards equation (Richards 1931) for simulating variably saturated flow. To account for water uptake by plant roots, the flow equation also includes a sink term. The modified form of Richards equation for homogeneous or uniform soil is defined as:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right] - S(h, t) \quad (1)$$

Initial conditions:

$$h(z, 0) = h_0(z) < 0, \quad 0 \leq z \leq \infty, \quad t = 0 \quad (1a)$$

$$-K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \Big|_{z=0} = q_o(t) \quad (1b)$$

Boundary conditions:

$$\frac{\partial h}{\partial z}(L, t) = 0 \quad (1c)$$

or

$$h(L, t) = h_L(t) \quad (1d)$$

$$h = h_i > 0, \quad z \geq 0, \quad t > 0$$

where h is water pressure head [L], θ is volumetric water content [$L^3 L^{-3}$], z is spatial coordinate in vertical direction [L], $S(h, t)$ is sink term (root water uptake in space and time) [$L^3 L^{-3} T^{-1}$], $K(h)$ is unsaturated hydraulic conductivity of soil at head h [LT^{-1}] and h_0 , h_L is initial and boundary conditions potentials, respectively.

There are numerous inbuilt soil hydraulic models in HYDRUS-1D and in present study the Van Genuchten–Mualem model with an air-entry value of -2 cm was used. Van Genuchten (1980) proposed the equation for soil hydraulic properties.

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (2)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad (3)$$

$$m = 1 - 1/n \quad n > 1 \quad (4)$$

where θ_s is saturated water content, θ_r is residual water content, α is parameter in the soil water retention function [L^{-1}], S_e is effective water content, K_s is saturated hydraulic conductivity [LT^{-1}], $K(h)$ is unsaturated hydraulic conductivity of soil at head h [LT^{-1}] and m and n is empirical parameters.

Input parameters for HYDRUS-1D

The soil hydraulic properties were determined using Van Genuchten (1980) model as described above. The different water flow parameters θ_s , θ_r , α , n , K_s and l were determined for six different soil layers using bulk density and sand, silt, clay as input data in Neural Network Predictor (Schaap et al. 2001) inbuilt in HYDRUS-1D model.

In simulation process of HYDRUS-1D, soil evaporation (E_s) and crop transpiration (T_c) terms are required as separate input parameters for soil water dynamics and root water uptake. Penman–Monteith equation given in Allen et al. (1998) was used to calculate reference evapotranspiration (ET_o) from available climate parameters. The reference evapotranspiration (ET_o) was converted into crop evapotranspiration (ET_c) by multiplying it with the crop coefficient values (K_c) given by Kaur et al. (2017).

$$ET_c = K_c \times ET_o \quad (5)$$

The bifurcation of crop evapotranspiration into soil evaporation (E_s) and crop transpiration (T_c) (Fig. 3) was achieved using leaf area index (LAI) which is function of crop development stage in equation suggested by Belmans et al. (1983).

$$E_p = ET_c \times e^{-K_{gr} \times LAI} \quad (6a)$$

$$T_c = ET_c - E_s \quad (6b)$$

where K_{gr} is extension coefficient for global solar radiation and its value is taken as 0.3 (McCauley et al. 2001; Phogat et al. 2010; Sheehy and Mitchell 2013).

Root water uptake function

The root water uptake was modelled using the equation given by Feddes et al. (1978) which assumes that actual root depth is the product of the maximum rooting depth and a root growth function. Root growth was simulated using measured root depth during the growing season as input to the model.

Fig. 3 **a** Soil evaporation (E_s), crop transpiration (T_c) and crop evapotranspiration (ET_c) in transplanted rice **b** Soil evaporation (E_s), crop transpiration (T_c) and crop evapotranspiration (ET_c) in direct-seeded rice

$$S(h) = \lambda(z)\alpha(h)T_c \quad (7)$$

where $\lambda(z)$ is relative root distribution function, $\alpha(h)$ is water stress response function ($0 \leq \alpha \leq 1$) and T_c is crop transpiration rate.

The governing values of water stress response function for rice crop were optimized by Singh et al. (2003) as P_0 (h_1) = 100 cm, P_{opt} (h_2) = 55 cm, P_2H (h_3) = -160 cm, P_2L (h_3) = -250 cm, and P_3 (h_4) = -15,000 cm. Parameter h_1 – h_4 represent different pressure head values, which affect root water uptake in the soil and this water stress response function was proposed by Feddes et al. (1978) and Homaei et al. (2002) in which P_0 is value of pressure head below which root start to extract water from the soil, P_{opt} is value of

pressure head below which root start extract water at the maximum possible rate, P_2H is value of limiting pressure head below which roots can no longer extract water at the maximum rate (assuming the transpiration rate at r_{2H}), P_2L is value of limiting pressure head below which roots can no longer extract water at the maximum rate (assuming the transpiration rate at r_{2L}) and P_3 is value of pressure head below which rootwater uptake ceases (usually taken at the wilting point).

Initial and boundary conditions

To simulate water movement and therefore potential groundwater recharge in rice field, the depth of soil

profile was considered as 100 cm and six soil layers at 10, 20, 30, 40, 60, and 100 cm from the ground surface were taken for mass balance. Initial conditions in both treatments viz. TPR and DSR were defined on the basis of moisture content of the soil profile. Initial moisture content of soil profile for TPR and DSR was taken equal to saturated moisture content and soil moisture at field capacity, respectively. Upper boundary was defined as the atmospheric boundary condition with specified values for time dependent parameters of evaporation, transpiration, irrigation, precipitation and minimum allowed pressure head for evaporation. Lower boundary of flow domain was set as free drainage as water table was much below (20.6 m in 2018 by Aggarwal et al. 2020) the considered flow domain (Šimůnek et al. 2013). Left and right of flow domain was taken as no flux boundary which define there was no lateral movement of water. Schematic diagram of flow domain describing boundary conditions and water fluxes for rice field is shown in Fig. 4.

Fig. 4 Schematic diagram of flow domain describing boundary conditions and water fluxes for rice field

Estimation of deep percolation using soil water balance method

The potential groundwater recharge represented by deep percolation component was also estimated using soil water balance method as described in FAO 56 (Allen et al. 1998).

$$DP = I + P - ET_c - R \mp \Delta SW \quad (8)$$

where DP is deep percolation, I is irrigation, P is precipitation/rainfall, ET_c is crop evapotranspiration, R is surface runoff which was estimated on daily basis using SCS curve number technique (Subramanya 2006) and ΔSW is soil water change (Mohammad et al. 2018).

Statistical analysis

Root Mean Square Error (RMSE), Nash–Sutcliffe modeling efficiency (NSE) (Nash 1970) and Coefficient of determination (R^2) were applied for calibration and validation of the model and paired t test (t) was used to test the difference in mean between observed and predicted values.

$$RMSE = \sqrt{\frac{1}{N} \sum (P_i - O_i)^2} \quad (9)$$

$$NSE = 1 - \frac{\sum (P_i - O_i)^2}{\sum (O_i - \bar{O})^2} \quad (10)$$

$$R^2 = \frac{[\sum (O_i - \bar{O})(P_i - \bar{P})]^2}{\sum (O_i - \bar{O})^2 \sum (P_i - \bar{P})^2} \quad (11)$$

$$t = \frac{\bar{d}}{\sqrt{\frac{S^2}{n}}} \quad (12)$$

where in all the above equations, N is the total number of observations and P_i and O_i are the i th predicted and observed values, respectively, and $\bar{P}$ and $\bar{O}$ average of predicted and observed values, respectively, n_o and n_p are indicative of their respective observed and predicted values; $\bar{d}$ is mean of difference of observed and predicted values and S is standard error of the mean.

Results and discussion

Model calibration and validation

For the calibration of initial estimates of soil hydraulic parameters of HYDRUS-1D for transplanted and direct-seeded rice, depth-wise moisture content observed at soil depths of 10, 20, 30, 40, 60, and 100 cm were used and soil parameters were adjusted such that there was good correspondence between observed and predicted soil moisture content at these depths. The calibrated parameters were then used to simulate the model for first 40 days and the remaining days until harvesting of rice were used to validate model using observed and predicted soil moisture values.

Calibration and validation for TPR

The calibration and validation of HYDRUS-1D for transplanted rice were carried out by comparing depth-wise

observed and predicted soil moisture content at the depth of 10, 20, 30, 40, 60, and 100 cm. The model was calibrated for the saturated hydraulic conductivity (K_s) and pore size distribution index (n) values. For the transplanted rice, it was observed that moisture content between 20 and 40 cm was comparatively more than other layers because of development of hardpan in these layers (Garg et al. 2009; Yadav et al. 2011). The observed and predicted soil moisture content was compared during initial 40 days after transplanting (DAT) and found a good relation between observed and predicted values for the soil moisture content which was supported by RMSE, NSE, and R^2 (Table 3). After calibration, the model was validated by using calibrated parameters for rest of the crop period and comparing depth-wise observed and predicted soil moisture content. Observed and predicted moisture content of few days during calibration and validation period is shown in Figs. 5 and 6.

Calibration and validation for DSR fields

Similarly, like TPR, calibration and validation were carried out by comparing depth-wise observed and predicted soil moisture content. Calibration was carried out for initial 40 days after sowing (DAS) and then calibrated parameters were used to validate model for rest of the crop period as shown in Figs. 7 and 8.

Table 3 Range of statistical parameters for calibration and validation in TPR and DSR

Statistical analysis	Transplanted rice (TPR)		Direct seeded rice (DSR)	
	Calibration	Validation	Calibration	Validation
RMSE (%)	0.87–1.17	0.92–1.80	0.57–1.40	0.74–1.33
NSE	0.46–0.78	0.50–0.73	0.20–0.68	0.65–0.82
R^2	0.63–0.86	0.64–0.92	0.70–0.97	0.73–0.97

Fig. 5 Depth wise observed and predicted moisture content during calibration of transplanted rice

Fig. 6 Depth wise observed and predicted moisture content during validation of transplanted rice

Fig. 7 Depth wise observed and predicted moisture content during calibration of direct-seeded rice

Assessment of potential groundwater recharge using HYDRUS-1D in transplanted and direct-seeded rice

The potential groundwater recharge from the transplanted (TPR) and direct-seeded rice (DSR) was predicted using mathematical model HYDRUS-1D. The model was used to simulate bottom flux, cumulative bottom flux (potential groundwater recharge), cumulative surface runoff,

cumulative evaporation and cumulative actual root water uptake in TPR and DSR cultivated in sandy loam soil.

Actual root water uptake

The HYDRUS-1D predicted actual root water uptake which represents transpiration for transplanted and direct-seeded rice and is shown in Fig. 9. During initial days of crop, actual root water uptake was less and was nearly zero for initial

Fig. 8 Depth wise observed and predicted moisture content during validation of direct-seeded rice

Fig. 9 Actual and cumulative root water uptake for transplanted and direct-seeded rice predicted using HYDRUS-1D

seed germination stage in DSR then increased gradually with the growth of crop. Phogat et al. (2010); Li et al. (2014) had reported similar results for root water uptake under DSR crop. Daily actual root water uptake was maximum during maturity stage of rice for both TPR and DSR and declined drastically near to harvesting stage of the crop. The overall daily and cumulative actual root water uptake was more in TPR compared to DSR due to more LAI in TPR. From the cumulative actual root water uptake (Fig. 9), it can be seen that for initial 20 days, root water uptake was less than increased rapidly until 92 DAT and 106 DAS for TPR and DSR respectively, and then decreased drastically for rest

of the days. The cumulative actual root water uptake was 238 mm and 210 mm, respectively. Therefore, HYDRUS-1D can predict root water uptake values quite reasonably as they were very close to values estimated in crop experiment.

Evaporation

The predicted cumulative evaporation for TPR and DSR using HYDRUS-1D model is shown in Fig. 10. The cumulative evaporation for TPR and DSR was 288 mm and 296 mm, respectively, during crop period. There were more evaporation losses during initial 20 days as there was no

Fig. 10 Cumulative evaporation for transplanted and direct-seeded rice predicted using HYDRUS-1D

Fig. 11 Cumulative bottom flux for transplanted and direct-seeded rice predicted using HYDRUS-1D

sufficient crop cover. Li et al. (2014) reported similar trend for evaporation losses using HYDRUS-1D under DSR during 2008 and 2009 seasons in China. After 90 days, evaporation losses were decreased drastically as less irrigation water was applied during harvesting stage of crop. The evaporation curve was almost flat after 118 DAS in DSR as irrigation was stopped at that stage of crop. The predicted crop evaporation losses with HYDRUS-1D model were comparable with estimated evaporation losses.

Bottom flux

The cumulative bottom flux values which represents the potential groundwater recharge was predicted with model for

both treatments as shown in Fig. 11. The potential groundwater recharge for TPR and DSR were predicted as 1131 mm and 1336 mm, respectively. Cumulative bottom flux (potential groundwater recharge) was predicted more in case of DSR than to TPR as topsoil layers between 10 and 30 cm were more disturbed and compact in case of TPR because of puddling which cause decrease in hydraulic conductivity of soil by about 1.5–2.3 times in these layers and these plowed soil layers of low hydraulic conductivity often play role of an obstruction or buffering on vertical flow of water (Kukul and Aggarwal 2003; Liu et al. 2005; Filipović et al. 2013). The cumulative bottom flux curve is nearly flat during harvesting stage in DSR as irrigation application was stopped at that stage of crop. Additionally, it can be seen cumulative bottom

flux was less in DSR compared to TPR during initial 40 days while it increases afterward mainly because of the different water management. During initial period water input predominately accomplished by irrigation while in later period, it was mainly by rainfall. Furthermore, it can be inferred from Fig. 10 that after intense rainfall period between 55 to 65 DAT/DAS, cumulative bottom flux in DSR surpassed TPR as water infiltrate and thus percolate rapidly in DSR as topsoil layers are non-puddled which offers higher soil hydraulic conductivity values and may contribute to groundwater recharge while in TPR because of puddled field and thus low hydraulic conductivity more water contributes to surface runoff losses instead of bottom flux.

Estimation of deep percolation using soil water balance method

Deep percolation was estimated using soil water balance equation and it was 1139.4 mm and 1305.6 mm in transplanted and direct-seeded rice, respectively, as shown in Table 4. About 14.6% more deep percolation was estimated in case of DSR as compared to TPR due to higher infiltration rate in non-puddled and porous root zone soil in case of DSR (Yadav et al. 2011; Fujihara et al. 2013).

The total measured water input from TPR and DSR was 2035.5 mm and 1935.5 mm respectively. Crop evapotranspiration was accounted 26.77% and 27.85% of total water input for TPR and DSR, respectively, runoff was accounted 20.43% and 7.89% of total water input for TPR and DSR, respectively, whereas the deep percolation after the depth of 100 cm was accounted for 55.95% and 67.45% of the total water input in TPR and DSR, respectively.

Comparison between estimated and predicted soil water balance parameters

The predicted values of parameters viz cumulative bottom flux, evaporation, actual root water uptake, and cumulative surface runoff show good correspondence with estimated parameters as shown in Table 5 for TPR and DSR. The percentage difference in potential groundwater recharge for TPR was 0.70% between estimated and predicted value while in case of DSR percentage difference was 2.32%

Table 5 Comparison between estimated and predicted parameters in TPR and DSR

Parameters	Estimated value (mm)	Predicted value (mm)	Percentage change
<i>TPR</i>			
Crop evapotranspiration	545	526	3.48
Surface runoff	416	442	7.28
Potential groundwater recharge	1139.4	1131	0.7
<i>DSR</i>			
Crop evapotranspiration	539	506	6.12
Surface runoff	152.9	152	0.58
Potential groundwater recharge	1305.6	1336	2.32

between estimated and predicted value. The sum of evaporation and actual root water uptake which represent crop evapotranspiration was 526 mm and 506 mm in TPR and DSR, respectively, was 3.48% and 6.12% less than calculated crop evapotranspiration value in TPR and DSR, respectively. The percentage change between estimated and predicted cumulative surface-runoff for TPR and DSR was 6.25% and 0.58% respectively.

Conclusions

The potential groundwater recharge for TPR and DSR during *kharif* season of 2019 was predicted using HYDRUS-1D model. The total amount of rainfall received during the growing period of transplanted and direct-seeded rice was 835.5 mm which was 30% higher than average rainfall received during the crop growth period which cause excessive surface runoff losses. The percolation losses were less in TPR compared to DSR because of puddling which hinders the vertical movement of surface water and may cause more surface runoff losses in TPR fields during heavy rainy days.

The HYDRUS-1D predicted moisture contents and soil water balance parameters were in good agreement with observed moisture content and estimated soil water balance parameters. The paired t-test was applied under both treatments ($t = 1.28$ and $t = 1.30$ for TPR and DSR, respectively) for mean of moisture content and found to be non-significant

Table 4 Soil water balance components in transplanted and direct seeded rice

Treatment	Water inputs			Water outputs		
	Rainfall (mm)	Irrigation (mm)	Crop evapotranspiration (mm)	Surface runoff (mm)	Soil moisture change (mm)	Deep percolation (mm)
Transplanted rice (TPR)	835.5	1200	545	416	64.9	1139.4
Direct seeded rice (DSR)	835.5	1100	539	152.9	62	1305.6

at $P=0.05$ which shows the correspondence between predicted and estimated parameters. Furthermore, statistical parameters endorsed that the HYDRUS-1D model can be successfully adopted for simulating potential groundwater recharge (deep percolation) in TPR and DSR fields under sandy loam soil conditions. HYDRUS-1D was successfully able to quantify bottom flux, evaporation, transpiration, and surface runoff with marginal difference from estimated values under given conditions.

Apart from effectiveness of HYDRUS-1D to simulate soil water balance parameters under different establishment techniques of rice, water-saving in terms of irrigation and potential groundwater recharge was also observed in DSR fields. There was 9% more water applied in TPR field compared to DSR, as no water required during harvesting stage in DSR which helps in water saving. The cumulative bottom flux was 1131 mm (~55.6% of total water input) and 1336 mm (~69% of total water input) in TPR and DSR respectively, which results in 14.6% more deep percolation in DSR that may potentially contribute to groundwater recharge. Therefore, sum of 23.6% water in terms of irrigation and deep percolation was saved under DSR fields compared to TPR during crop period. If about 500 thousand hectares area is cultivated using this technology in Punjab, India, then about 2400 Mm³ can be saved. The HYDRUS-1D was fairly successful in simulating potential groundwater recharge under different establishment techniques of rice, thus can be helpful in judicious water management and sustaining groundwater resources.

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