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Modelling the response of paddy water balance on groundwater level fluctuations in Central Punjab

Samanpreet Kaur, Ramandeep Singh, Bharat Bhusan Vashisht, K. K. Gill and Rajan Aggarwal

ABSTRACT

The present study employs a process-based DSSAT (Decision Support System for Agrotechnology Transfer) model for estimating agriculture water use and its evaluation for simulating groundwater fluctuations. A field experiment was performed during *kharif* season with PR 121 variety (rice) at Punjab Agricultural University, Ludhiana. There were six treatments with three dates of transplanting – June 5 (D_1), June 20 (D_2) and July 5 (D_3), one cultivar – PR121 (V) and two irrigation regimes – 2-day drainage (I_1) and tensiometer-based (I_2). Both simulation and experimental results showed that paddy transplanted on June 20 (D_2) and tensiometer-based irrigation treatment (I_2) gave 23 and 32% higher yield in comparison to June 5 (D_1) and July 5 (D_3) with maximum water use efficiency of 1.69 kg/m^3. The validated DSSAT model was simulated for a historical time slice (1998–2014) and indicated that 66% of applied water in the form of rainfall or irrigation in paddy fields was lost as drainage component. The simulated change in storage (rainfall minus evapotranspiration) was able to explain groundwater level fluctuations in terms of trends/magnitude in most of the years.

Key words | DSSAT, groundwater, rice, water balance

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HIGHLIGHTS

- In this research, a process based DSSAT (Decision Support System for Agro technology Transfer) model was used to estimate crop water use in paddy fields.
- Both simulation and experimental results showed that paddy transplanted on June 20 (D2) and tensiometer based irrigation treatment (I2) gave 23 and 32% higher yield in comparison to June 5 (D1) and July 5 (D3) with maximum water use efficiency of 1.69 kg/m^3.
- The novelty of the research is that it tries to correlates the water use in paddy fields to explain the groundwater level fluctuations in the region.

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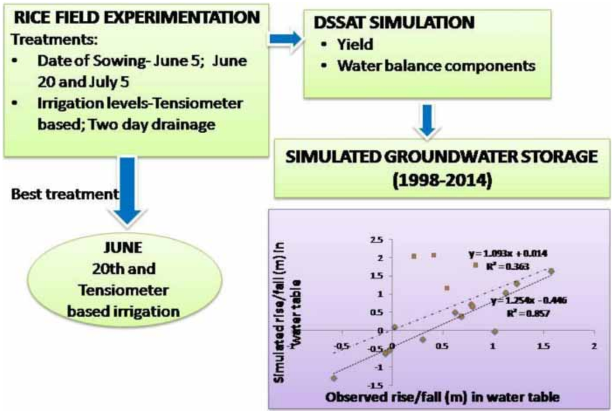
GRAPHICAL ABSTRACT



INTRODUCTION

Long-term abstraction of groundwater resources, in particular for irrigation, has resulted in severe decline and deterioration of water resources in many arid and semi-arid regions of the world (Konikow & Kendy 2005; Rodell *et al.* 2009; Scanlon *et al.* 2012; Feng *et al.* 2013; Yang *et al.* 2013; Famiglietti 2014; Chinnasamy & Ganapathy 2018). Rice (*Oryza sativa* L.), an important cereal and staple food for more than half of the global population, accounts for 40% of all global irrigation, and 17% of global groundwater depletion. The global average water footprint per kilogram of rice is 2,500 litres (Bouman 2009), with India at 2,800 litres and the State of Punjab has the highest footprint of 4,500 litres. Here, rice covers nearly 75% of the total cropped area and requires nearly 800–2,000 mm of irrigation water depending upon climate and soil type. The rainfall and surface water resources are not sufficient to meet the total irrigation needs. The percentage of irrigated area from canals and tube wells in the state is 28 and 72%, respectively. This has led to a 'silent revolution of intensive groundwater use' (Lamas & Martinez-Santos 2005) with the number of energized tube wells increasing from 0.19 in 1970 to 1.475 million in 2019 (Anon 2019). Consequently, there is huge pressure on the groundwater aquifers, more so in the central districts of the state where the water table has registered a steep decline (>1 m/year). Many researchers in the past have emphasized water saving in rice through adoption of improved technologies, such as laser land levelling, alternate wetting and drying (AWD), use of tensiometers for irrigation scheduling, delayed transplanting, shorter duration rice varieties and even drip irrigation systems (Singh *et al.* 2001a, 2001b; Kukal *et al.* 2005; Aggarwal *et al.* 2009; Minhas *et al.* 2010; Eberbach *et al.* 2019). It is often likely that these practices may reduce deep drainage, with very little effect on evapotranspiration (ET). Reducing deep drainage may not 'save water' or reduce the rate of decline of the water table (Humphreys *et al.* 2010). Researchers have also argued that the major loss, i.e., ET in rice, ranges about 30–40% (Jalota *et al.* 2018) and the drainage from paddy fields may not be considered as a loss because the water can be captured and reused downstream (Bouman *et al.* 2007). In a study elsewhere, in Iran, it was concluded that water saving irrigation systems (e.g,. drip and sprinkler) conserve water but they can reduce potential groundwater recharge (PGR) compared with traditional systems (e.g., furrow) and may impair sustainability, particularly in arid and semi-arid regions (Porhemmat *et al.* 2018). Further, rice is grown in *kharif* season and the region receives nearly 80% of the annual rains during this period. As rice is a tolerant crop, its yield is not adversely affected and the standing rainwater in the fields slowly joins the water table. Seasonal trends of the region also showed that the water table rose after *kharif* season (mid-June to mid-October) and fell during the *rabi* season (mid-October to mid-June) (Jalota *et al.* 2018). It becomes imperative to establish a relationship between water balance dynamics and groundwater changes (Yang *et al.* 2006), but systematic studies on this aspect are seldom seen for the region. This requires complex information about the soil vegetation system, which is usually lacking, and there are financial and technical limitations involved in gathering a large amount of data. In most of the earlier studies, groundwater use has been related to the number of tubewells and unit draft (Aggarwal *et al.* 2005; Miglani *et al.* 2015), and these assessments do not indicate the desired saving in water in order to decrease or stop groundwater decline which require continuous measurements of long-term agricultural water use. Alternatively, process-based crop models such as CERES (Crop Environment Resource Synthesis), DSSAT (Decision Support System for Agrotechnology Transfer), EPIC (Environmental Policy Integrated Climate), etc., can provide insights into crop water use and drainage phenomena from a simplified input of climate, soil and water management. For instance, Jalota *et al.* (2014) used CropSyst to simulate the effect of climate change on the global irrigation water use under designed climate change scenarios. Dar (2016) examined the applicability of the DSSAT model in analysing the impact of water-related options on rice yield and water use for enhancing water productivity in irrigated environments of Punjab and found the model performed reasonably well. With the above background, the present research was planned to evaluate the DSSAT model for quantifying the impact of water balance components on groundwater levels in rice crop.

MATERIAL AND METHODS

Experimental details

The field experiment was conducted at the Research Farm of the Department of Soil Science, Punjab Agricultural University, Ludhiana (30°56′ N, 75°52′ E and 247 m above mean sea-level) during the rainy (*kharif*) season of 2014. The soil of the experimental field was deep alluvial loamy sand Typic Ustipsamment developed under hyperthermic regime (USDA classification). At the start of the experiment, depthwise soil physical and chemical properties of the field were determined following the standard procedures (Table 1). The meteorological data (daily maximum and minimum temperatures, rainfall, pan evaporation, sunshine hours, morning and evening relative humidity) were collected from the meteorological observatory of the Punjab Agricultural University, Ludhiana located at a distance of 100 m from the experimental field.

Rice was grown in sandy loam soil under different irrigation conditions, since the genetic parameters for cultivar ‘PR111’ of rice have been calibrated previously (Vashisht *et al.* 2015). In the experiment, the effects of three sowing dates (June 5, D1, June 20, D2 and July 5, D3) and two irrigation regimes (2-day drainage (I_1) and tensiometer-based, (I_2) level were evaluated on growth and yield of rice.

Each treatment was replicated three times with a plot size 6×4 m^2 in a split-plot design. Irrigation treatments were started following continuous flooding for 15 days after transplanting. The amount of irrigation each time was 75 mm. For tensiometer-based irrigation, the soil

Table 1 | Physico–chemical properties of the experimental soil

Depth (cm)	pH	EC (dS^{-1})	OC (%)	NH_4-N (ppm)	NO_3-N (ppm)	P (kg ha^{-1})	K (kg ha^{-1})	Bulk density (g cm^{-3})	Hydraulic sonductivity (cm hr^{-1})	Cation exchange capacity (meq/100 g)	Texture
0–15	6.67	0.230	0.26	12.84	25.67	44.0	117.6	1.52	0.04	9.91	Sandy loam
15–30	6.33	0.077	0.17	12.84	16.34	25.3	72.8	1.60	1.26	8.72	Sandy loam
30–60	7.00	0.114	0.08	14.00	16.34	22.4	89.6	1.55	1.83	11.89	Sandy clay loam
60–90	7.76	0.184	0.08	11.67	14.00	15.8	56	1.54	1.89	13.10	Sandy clay loam
90–120	7.74	0.242	0.06	8.17	12.84	14.9	72.8	1.45	0.41	11.12	Sandy loam
120–150	7.87	0.150	0.03	9.34	12.84	10.8	33.6	1.29	0.82	6.74	Sandy loam
150–180	7.72	0.158	0.04	7.00	10.50	6.8	50.4	1.45	1.36	7.91	Sandy loam

water suction was measured with tensiometers installed at 20 cm soil depth. In 2-day drainage, irrigation was applied 2 days after the ponded water had infiltrated into the soil. Fertilizer dose of N, P, K was applied following the procedure given in a package of practices for crops of Punjab (www.pau.edu). Plant parameters (plant height, number of tillers m^{-2} and dry matter accumulation) and yield attributes (grain loop length, per cent filled grains, thousand grain weights and grain and straw yield) were recorded.

The actual ET was computed from the water balance equation:

$$ET = (P + I) - (R + D + \Delta S) \tag{1}$$

where P, I, R, D, ΔS and ET are precipitation, irrigation, runoff, drainage, change in soil water storage and evapotranspiration, respectively. The precipitation and actual irrigation were recorded. Changes in soil moisture storage were computed at regular intervals by gravimetric method. The amount of runoff was negligible. Drainage was experimentally computed using the equation in Ogata & Richards (1957) between soil water storage (W) and time (T):

$$W = AT^B \tag{2}$$

Drainage rate was obtained as

$$dW/dT = AB(W/A)^{(B-1)/B} \tag{3}$$

To get the above constants of A and B, a bunded and fully saturated plot on the bare soil was covered with a polyethylene sheet in order to stop the evaporation completely. Profile soil moisture storage was estimated from the plot at the depths of 15, 30, 45, 60, 90, 120, 150 and 180 cm at days 1, 3, 5 and 7 up to 39 days. From the relation between W and T, the values of A and B were 38.13 and 0.09 (Figure 1).

Water use efficiency (WUE) was calculated as:

$$WUE = Yield/Evapotranspiration \tag{4}$$

Simulation study

Simulations for yield and water balance were run using the DSSAT model (Jones *et al.* 2003). In the model, certain crop parameters were modified slightly (within the given range) to match the periodic biomass and yield and the rest of the parameters were equivalent to those previously reported (Vashisht *et al.* 2015). The location parameters included longitude, latitude, daily weather data files and ET models. The methods selected in the simulation were Priestley–Taylor – evapotranspiration, Soil Conservation Service – infiltration, canopy curve (daily) photosynthesis, Ritchie water balance – hydrology, CERES–Godwin – organic matter and Ritchie-CERES – soil evaporation.

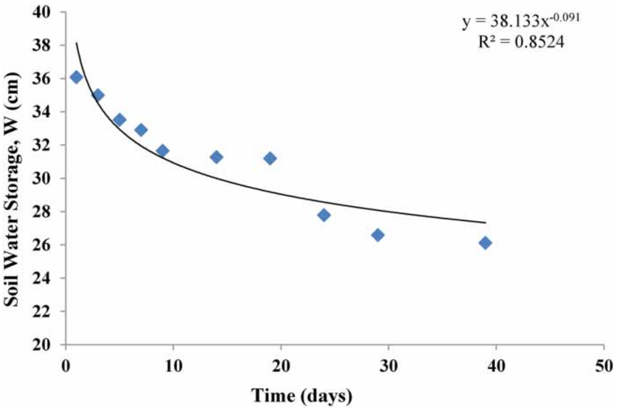


Figure 1 | Relation between soil water storage and time.

Treatment-specific irrigation management operations, performed on different dates in the experiments, were entered in the crop management file. The model performance was evaluated for yield and water balance component in rice transplanted during 2014 using the Nash–Sutcliffe modelling efficiency (ME) (Nash 1970) and the root mean square error (RMSE), respectively.

Estimating seasonal groundwater level fluctuations using CERES-Rice

Rice yield and water balance components were simulated for 16 years (1998–2014) using the validated CERES-Rice model. Before 2008, the rice was planted in the first week of June but after the implementation of Preservation of Sub-Soil Water Act in 2008 (Singh 2009), the rice planting was shifted to after June 10. Hence, in the model, the transplanting date was kept as June 5 until 2007 and afterwards was kept as June 20. The water use was simulated based on IW/CPE ratio which was considered as 2.5 for sandy loam and 2.0 for loam and silt loam soil, respectively. The change in groundwater storage (m) was estimated as:

$$\pm \Delta S_g = \frac{(D - I)*1000}{specific\ yield} \tag{5}$$

In the present study, the difference in subsurface inflow and outflow is taken as nil (Kaur *et al.* 2015) and irrigation from groundwater was not considered as a fraction of the total withdrawal contribution to water table decline which is used as ET. The specific yield was assumed to be 0.20 (Kaur *et al.* 2014).

Site-specific groundwater level data (pre- and post-monsoon) from 1998 to 2014 was obtained by employing *krigging* interpolation technique (Dhillon *et al.* 2018) on the nearby observation wells.

RESULTS

Experimental results

Rice yield was significantly influenced by the date of transplanting. The maximum yield of rice was observed on June 20 (D2), which was higher than that in June 5 (D1) and July 5 (D3), i.e., 24 and 31% (Table 2). These observations confirm the field and simulated results reported by other researchers (Singh *et al.* 2001a, 2001b; Chahal *et al.* 2007; Safdar *et al.* 2008; Jalota *et al.* 2009). Late planting (July) showed a decline in grain yield due to delayed panicle formation and grain filling in the season where temperature and solar radiation are less (IRRI 1993). With respect to irrigation, I_2 recorded 11% more yield than I_1, although irrigation was 21% higher in 2-day drainage-based treatment. Kukal *et al.* (2005) also reported that irrigation at 160 ± 20 cm soil metric suction helped save 30–35% irrigation water as compared to 2-day drainage-based irrigation with no yield penalty. ET observed was higher in D_1 (550 mm) than D_2 (514 mm) and D_3 (546 mm).

Table 2 | Measured yield (t ha^{-1}), water balance components (mm) and water use efficiency (%) under different treatments

Treatment	Yield	P	I	ET	D	ΔS	WUE (%)
D_1I_1	5.86	418	1,995	552	1,601	260	1.06
D_1I_2	5.92	418	1,854	549	1,461	262	1.08
D_2I_1	6.7	418	2,226	520	1,851	273	1.29
D_2I_2	7.88	418	1,764	509	1,399	274	1.55
D_3I_1	5.12	420	1,959	550	1,575	254	0.93
D_3I_2	5.9	420	1,492	543	1,115	254	1.09
D_1	5.89	418	1,924	550	1,531	261	1.07
D_2	7.29	418	1,995	514	1,625	273	1.42
D_3	5.57	420	1,725	546	1,345	254	1.02
I_1	5.89	419	2,060	541	1,676	262	1.09
I_2	6.56	419	1,703	534	1,325	263	1.23

D_1 – June 5, D_2 – June 20, D_3 – July 5; I_1 (2-day drainage), I_2 (tensiometer-based irrigation).

The water balance components and WUE changed with treatments (Table 2). Precipitation was nearly the same for all the dates of transplanting. D_2 received 16 and 4% more irrigation than that of D_3 and D_1, respectively. Measured ET by water balance equation was higher in D_1, i.e., 550.5 mm than D_2 and D_3. The highest water use efficiency in D_2 is ascribed to relatively greater decrease in ET (denominator) compared to the yield (numerator). Averaged across irrigation treatments, WUE in I_2 was 13% more than I_1.

Simulation study

Simulated grain yield and ET had trends similar to measured responses, although there were differences in their magnitude (Figure 2 and Table 3). Statistical parameters such as RMSE and Nash–Sutcliffe ME during validation were 0.09 and 0.99 for grain yield. The coefficient of determination (R^2) between simulated and observed yield was 0.96 and was 0.86 in the case of ET.

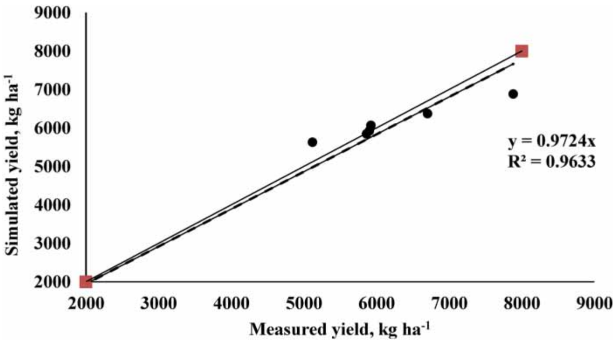


Figure 2 | Comparison of simulated and measured grain yield for the year 2014.

Table 3 | Simulated and computed ET (Equation (1)) and yield under different sowing dates and irrigation regimes

	ET (mm)		Yield (t/ha)	
Treatment	**Observed**	**Simulated**	**Observed**	**Simulated**
D_1I_1	427	552	5.8	5.9
D_1I_2	433	549	6.1	5.9
D_2I_1	414	520	6.4	6.7
D_2I_2	408	509	6.9	7.9
D_3I_1	430	550	5.6	5.1
D_3I_2	423	543	5.9	5.9
D_1	430	550	6.0	5.9
D_2	411	514	6.6	7.3
D_3	427	546	5.8	5.5
Average	**423**	**537**	**6.1**	**6.2**

D_1 – June 5, D_2 – June 20, D_3 – July 5; I_1 (2-day drainage irrigation), I_2 (tensiometer-based irrigation).

Effect of crop water balance on groundwater level changes

The model simulated crop yield, irrigation, daily ET and drainage from 1998 to 2014 for the site (Table 4), using the historic climate data. The highest yield of paddy was obtained in 2014, i.e., 6.6 t/ha, the lowest yield in 2010, i.e., 5.5 t/ha and the average yield of 17 years is 6.0 t/ha which closely agrees with the data provided by government agencies (Statistical Abstracts Punjab, Various issues).

The average *kharif* season's rainfall computed from the daily records (for the years 1989–2014) was 594 mm. The irrigation requirements of rice ranged from 1,020 to 1,994 mm with an average of 1,443 mm. The ET, which is one of the major losses, from the rice field varied from 387 to 597 mm during different years with an average loss as 438 mm. The drainage component which is assumed equal to potential recharge ranged between 61 and 70% of total water applied (precipitation + irrigation) during different years, with an average drainage of 66%, i.e., 1,342 mm (Table 4), of which, precipitation contributes 19.2%. However, a significant variation in contribution to potential recharge individually from precipitation and irrigation is witnessed for different years (Figure 3). Increased precipitation bears a linear positive relationship for contribution to potential recharge and vice versa relationship for irrigation.

Table 4 | Yield and water balance components during different years

Year	Yield (t/ha)	*P*	*I*	*ET*	*D*	Δ*SWS*
1998	5.8	758	1,317	435	1,364	276
1999	6.0	542	1,393	419	1,275	241
2000	6.4	269	1,960	597	1,354	278
2001	6.0	846	1,237	398	1,449	236
2002	6.5	293	1,942	452	1,539	243
2003	5.7	580	1,282	402	1,224	236
2004	5.9	348	1,630	410	1,303	264
2005	6.5	596	1,331	430	1,260	237
2006	5.8	496	1,408	400	1,268	236
2007	5.8	409	1,459	387	1,222	259
2008	6.1	887	1,189	479	1,323	274
2009	6.5	817	1,389	529	1,423	254
2010	5.5	906	1,020	391	1,271	264
2011	5.7	905	1,060	397	1,308	260
2012	6.2	305	1,662	440	1,289	238
2013	5.9	720	1,262	462	1,242	278
2014	6.6	418	1,994	426	1,696	290
Average	**6.0**	**594**	**1,443**	**438**	**1,342**	**257**

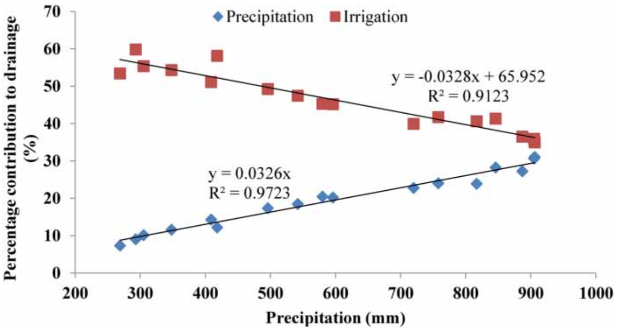


Figure 3 | Impact of precipitation on contribution to potential recharge.

An average post-monsoon rise of 0.74 m in groundwater levels at the site was observed with exceptions in the years 2000, 2002 and 2012, when the water table dropped post-monsoon. These exceptional years were due to deficit rainfall coupled with high irrigation water use. Although a graph between groundwater fluctuations in response to rainfall and irrigation water use for the experimental site indicates that June to October is the period when groundwater level responds relative poorly to irrigation water requirement, since soil water from the rainy season is also absorbed, yet, there was general agreement between potential recharge and seasonal groundwater level changes (Figure 4).

The simulated change in storage (Equation (5)) was able to fairly estimate the groundwater water fluctuations rather than potential recharge (drainage – irrigation) alone (Figure 5), more so when years with rainfall greater than 800 mm were excluded. In a recent study by Jalota *et al.* (2018), the annual water table fluctuations were approximated by computing the water deficit [evapotranspiration – (rainfall + surface water)], which can approximate the water table decline/rise rather than groundwater withdrawal alone.

CONCLUSIONS

In view of shrinking water resources and the anticipated effects of climate change, there is a need to have a better understanding of crop water balance relationship with groundwater dynamics. The outcome of the study indicates that delaying the transplanting date to June 20 and tensiometer-based irrigation can result in higher yield (34%) and water saving (10%) in comparison to June 5 and 2-day drainage-based irrigation. The findings are in tune with the government recommendations of delaying the transplanting date of paddy to mid-June. Simulated CERES-Rice model was then applied to quantify change in storage while analysing groundwater fluctuations. The estimated change in storage was able to explain groundwater level fluctuations in terms of trends/magnitude in most of the years barring the high rainfall as there are still limitations when we directly try to link groundwater level changes and crop water use. First, the simulation results might be more accurate for recent years than for earlier years. Second, the effect of different crop cultivars was not used in historical simulations and the genetic parameters of PR 121 were used for the whole simulation period. Third, if actual groundwater level observations were available we could have computed more realistic regression. Aside from the application of the agricultural model, a more accurate estimation of groundwater use to reflect the change of groundwater level in multiple aquifers through the application of a groundwater model might be necessary. However, with all these limitations, such type of study still provides information on crop behaviour under different conditions, and thus can be helpful for formulating management intervention for increasing productivity and water use efficiency and also give insights on agricultural water use and groundwater fluctuations.

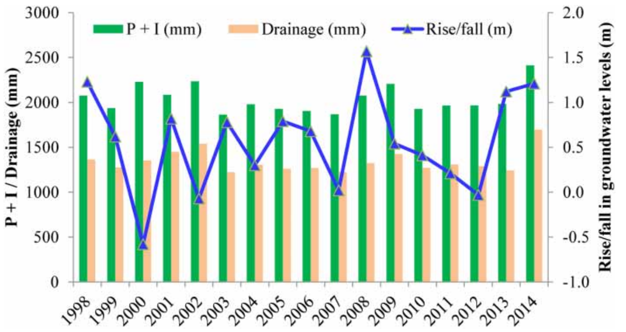


Figure 4 | Relation between simulated water input ($P + I$), potential recharge and groundwater (GW) level changes.

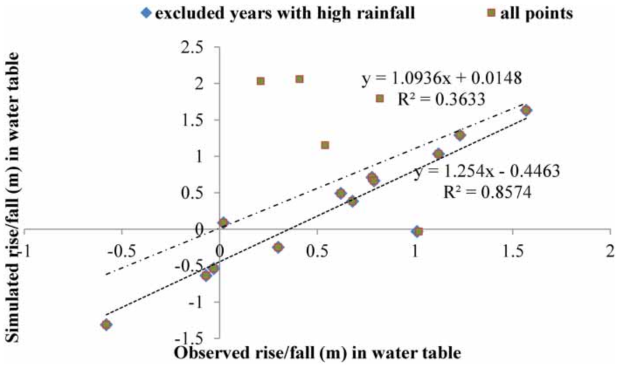


Figure 5 | Observed versus simulated rise/fall (m) in water table.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Aggarwal, R., Sondhi, S. K. & Kaushal, M. P. 2005 Integrated simulation-optimization model for groundwater management in Punjab, India. *International Agricultural Engineering Journal* **14** (4), 187–192.

Aggarwal, R., Kaushal, M., Kaur, S. & Farmaha, B. 2009 Water resource management for sustainable agriculture in Punjab, India. *Water Science and Technology* **60** (11), 2905–2911.

Anon 2019 Statistical abstract of Punjab. In: *The Economic Advisor to Goverment of Punjab*, Chandigarh, India.

Bouman, B. 2009 How much water does rice use. *Management* **69**, 115–133.

Bouman, B. A. M., Feng, L., Tuong, T. P., Lu, G., Wang, H. & Feng, Y. 2007 Exploring options to grow rice using less water in northern China using a modelling approach: II. Quantifying yield, water balance components, and water productivity. *Agricultural Water Management* **88** (1–3), 23–33.

Chahal, G. B. S., Sood, A., Jalota, S. K., Choudhury, B. U. & Sharma, P. K. 2007 Yield, evapotranspiration and water productivity of rice (Oryza sativa L.)–wheat (Triticum aestivum L.) system in Punjab (India) as influenced by transplanting date of rice and weather parameters. *Agricultural Water Management* **88** (1–3), 14–22.

Chinnasamy, P. & Ganapathy, R. 2018 Long-term variations in water storage in Peninsular Malaysia. *Journal of Hydroinformatics* **20** (5), 1180–1190.

Dar, M. U. D. 2016 *Modelling the Effect of Climate Change on Irrigation Requirements of Rice-Wheat System in Central Punjab. Doctoral dissertation*, Thesis submitted to the Punjab Agricultural University, Ludhiana, India.

Dhillon, M., Kaur, S., Sood, A. & Aggarwal, R. 2018 Estimation of carbon emissions from groundwater pumping in central Punjab. *Carbon Management* **9** (4), 425–435.

Eberbach, P. L., Humphreys, E. & Kukal, S. S. 2019 Estimating soil evaporation in dry seeded rice and wheat crops after wetting events. *Agricultural Water Management* **217**, 98–106.

Famiglietti, J. S. 2014 The global groundwater crisis. *Nature Climate Change* **4** (11), 945–948.

Feng, W., Zhong, M., Lemoine, J. M., Biancale, R., Hsu, H. T. & Xia, J. 2013 Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. *Water Resources Research* **49** (4), 2110–2118.

Humphreys, E., Kukal, S. S., Christen, E. W., Hira, G. S. & Sharma, R. K. 2010 Halting the groundwater decline in north-west India – which crop technologies will be winners? *Advances in Agronomy* **109**, 155–217.

IRRI 1993 *Rice Research in A Time of Change*. IRRI's Medium term Plan for 1994–1998. International Rice Research Institute, Manila, Philippines, p. 79.

Jalota, S. K., Singh, K. B., Chahal, G. B. S., Gupta, R. K., Chakraborty, S., Sood, A., Ray, S. S. & Panigrahy, S. 2009 Integrated effect of transplanting date, cultivar and irrigation on yield, water saving and water productivity of rice (Oryza sativa L.) in Indian Punjab: field and simulation study. *Agricultural Water Management* **96** (7), 1096–1104.

Jalota, S. K., Vashisht, B. B., Kaur, H., Kaur, S. & Kaur, P. 2014 Location specific climate change scenario and its impact on rice and wheat in Central Indian Punjab. *Agricultural Systems* **131**, 77–86.

Jalota, S. K., Jain, A. K. & Vashisht, B. B. 2018 Minimize water deficit in wheat crop to ameliorate groundwater decline in rice-wheat cropping system. *Agricultural Water Management* **208**, 261–267.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J. & Ritchie, J. T. 2003 The DSSAT cropping system model. *European Journal of Agronomy* **18** (3–4), 235–265.

Kaur, S., Aggarwal, R., Jalota, S. K., Vashisht, B. B. & Lubana, P. P. S. 2014 Estimation of groundwater balance using soil-water-vegetation model and GIS. *Water Resources Management* **28** (12), 4359–4371.

Kaur, S., Jalota, S. K., Singh, K. G., Lubana, P. P. S. & Aggarwal, R. 2015 Assessing climate change impact on root-zone water balance and groundwater levels. *Journal of Water and Climate Change* **6** (3), 436–448.

Konikow, L. F. & Kendy, E. 2005 Groundwater depletion: a global problem. *Hydrogeology Journal* **13** (1), 317–320.

Kukal, S. S., Hira, G. S. & Sidhu, A. S. 2005 Soil matric potential-based irrigation scheduling to rice (Oryza sativa). *Irrigation Science* **23** (4), 153–159.

Lamas, M. R. & Martinez-Santos, P. 2005 Intensive groundwater use: silent revolution and potential source of social conflicts. *Journal of Water Resources Planning and Management* **131** (5), 337–342.

Miglani, P., Aggarwal, R. & Kaur, S. 2015 Groundwater simulation model for Sirhind Canal tract of Punjab. *Journal of Engineering & Technology* **5** (1), 31–35.

Minhas, P. S., Jalota, S. K., Arora, V. K., Jain, A. K., Vashist, K. K., Choudhary, O. P., Singh Kukal, S. & Vashisht, B. B. 2010 Managing water resources for ensuing sustainable agriculture: situational analysis and options for Punjab. *Research Bulletin* **2** (2010), 40.

Nash, J. E. 1970 River flow forecasting through conceptual models, I: a discussion of principles. *Journal of Hydrology* **10**, 398–409.

Ogata, G. & Richards, L. A. 1957 Water content changes following irrigation of bare-field soil that is protected from evaporation. *Soil Science Society of America Journal* **21** (4), 355–356.

Porhemmat, J., Nakhaei, M., Dadgar, M. A. & Biswas, A. 2018 Investigating the effects of irrigation methods on potential groundwater recharge: a case study of semiarid regions in Iran. *Journal of Hydrology* **565**, 455–466.

Rodell, M., Velicogna, I. & Famiglietti, J. S. 2009 Satellite-based estimates of groundwater depletion in India. *Nature* **460** (7258), 999–1002.

Safdar, M. E., Ali, A., Muhammad, S., Sarwar, G. & Awan, T. H. 2008 Effect of transplanting dates on paddy yield of fine grain rice genotypes. *Pakistan Journal of Botany* **40** (6), 2403–2411.

Scanlon, B. R., Longuevergne, L. & Long, D. 2012 Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. *Water Resources Research* **48**, 4.

Singh, K. 2009 Act to save groundwater in Punjab: its impact on water table, electricity subsidy and environment. *Agricultural Economics Research Review* **22**, 365–386.

Singh, K. B., Gajri, P. R. & Arora, V. K. 2001a Modelling the effects of soil and water management practices on the water balance and performance of rice. *Agricultural Water Management* **49** (2), 77–95.

Singh, R., Kaler, D. S. & Singh, S. 2001b Growth analysis of durum wheat (Triticum durum desf). *Indian Journal of Environment and Ecoplanning* **5**, 119–124.

Statistical Abstracts of Punjab 1998–2014 The Economic Advisor to Government of Punjab, Chandigarh, India. Various issues.

Vashisht, B. B., Jalota, S. K. & Vashist, K. K. 2015 Yield, water productivity and economics of rice (Oriza sativa) as influenced by transplanting dates, varieties and irrigation regimes in central Punjab. *Indian Journal of Agronomy* **60** (1), 65–69.

Yang, Y., Watanabe, M., Zhang, X., Hao, X. & Zhang, J. 2006 Estimation of groundwater use by crop production simulated by DSSAT-wheat and DSSAT-maize models in the piedmont region of the North China Plain. *Hydrological Processes* **20** (13), 2787–2802.

Yang, A. L., Huang, G. H., Qin, X. S., Li, L. & Li, W. 2013 Seeking optimal groundwater pumping strategies at Pinggu District in Beijing, China. *Journal of Hydroinformatics* **15** (2), 607–619.

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