Temporal trends of climatic variables and water footprint of rice and wheat production in Punjab, India from 1986 to 2017

Durba Kashyap and Tripti Agarwal

ABSTRACT

The agriculture sector is vulnerable to climate change and related changes in the hydrological cycle. In order to understand the changes in climatic variables and their implications for agricultural water consumption, the present study aims to analyse the temporal variability of climatic factors and water footprint (WF) of rice and wheat during the period 1986–2017 in Ludhiana, Punjab. Further, it aims to identify the dominant climatic factors that cause variation in reference evapotranspiration (ET_o) and WF of rice and wheat. WF was estimated using CROPWAT, and Path analysis was used to determine the dominant climate variables. Temporal trends of climate variables were analysed using the Mann–Kendall test. The total WF of both rice and wheat shows a significant declining trend over the past 32 years. Sunshine duration and wind speed were the dominant factors influencing the variability of total WF of rice and wheat, respectively, whereas rainfall strongly influenced the green and blue WF of rice and wheat. Rainfall had a high variability, and consequently, irrigation water requirement was highly fluctuating. This indicates the significant impact of present and projected erratic pattern of precipitation on agriculture due to climate change and reiterates the importance of adaptive measures like rainwater harvesting and capacity building.

Key words | agriculture, evapotranspiration, green water, irrigation water requirement, path analysis, rain water harvesting

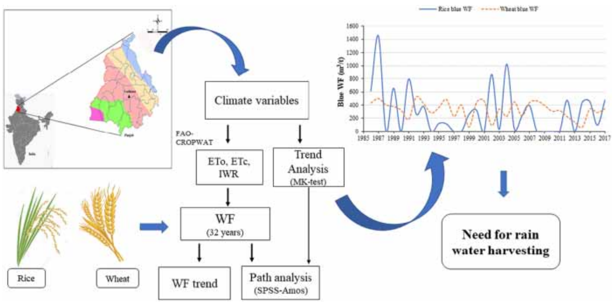
Durba Kashyap
Tripti Agarwal (corresponding author)
National Institute of Food Technology Entrepreneurship and Management,
Kundli, Sonipat, Haryana 131028,
India
E-mail: *tripti.niftem@gmail.com*

HIGHLIGHTS

- Influence of climate variables on WF of rice and wheat was analysed for the first time for India.
- Rainfall significantly influenced both green and blue WF of rice and wheat.
- High variability in rainfall and irrigation water requirement highlights the urgent need for green water management.
- Assessment of long-term trends in climate and WF is crucial for strategizing cropping patterns.
- The study confirms the existence of 'evaporation paradox' and 'solar dimming' in Punjab, India.

doi: 10.2166/wcc.2020.093

GRAPHICAL ABSTRACT



INTRODUCTION

The agriculture sector is one of the most vulnerable sectors to the risks of climate change and related changes in the hydrological cycle (Smit & Skinner 2002). Large-scale changes in the hydrological cycle like increase in atmospheric water vapour, changes in precipitation, soil moisture and run-off have been linked to global warming (Bates *et al.* 2008). Climatic factors along with non-climatic drivers like 'population growth, economic development, urbanization, land use changes and water management responses' competing for water resources can have profound impacts on water availability for both rainfed and irrigated agriculture (Cisneros *et al.* 2014). Irrigation accounts for 70% of global water withdrawals and more than 90% of consumptive water use (IPCC 2007). With the projected expansion in irrigated area and cropping intensity, it is estimated that future irrigation water demand would surpass water availability in various regions under climate change scenario (Wada *et al.* 2013).

Water footprint (WF) is, in general, an indicator of direct and indirect freshwater appropriation, measured in terms of water volumes consumed (evaporated or incorporated into a product) and polluted per unit of time. The volumetric WF comprises three components: green WF refers to the consumption of rainwater; the blue WF refers to water consumed from surface and groundwater sources; while grey WF is an indicator of volume of water polluted, i.e. the freshwater volume required to assimilate the pollutant load to bring it to natural condition/ambient standards (Hoekstra *et al.* 2011). Temporal trends in WF reflect changes in crop water use over time for a given place (Lu *et al.* 2016). The WF_{green} and WF_{blue} are computed based on reference evapotranspiration (ET_o) and precipitation and therefore directly associated with water availability in a given region. ET_o is a measure of the 'evaporative demand of the atmosphere' which solely depends on climatic parameters (Allen *et al.* 1998). ET_o is a key variable in the hydrological process and determines the availability of water for plant growth (Gao *et al.* 2017). Future changes in temperature, evapotranspiration and soil moisture might ultimately affect crop yields and crop water use in multiple and non-linear ways (Fader *et al.* 2010). Many studies have been conducted on spatial and temporal variability of evapotranspiration and the effect of climatic factors on evapotranspiration (Dinpashoh *et al.* 2011; Fan & Thomas 2013; Wang *et al.* 2015; Gao *et al.* 2017). But, there have been fewer studies on the temporal trends of WF and the influence of climatic factors on WF of crops (Sun *et al.* 2012, 2013; Lu *et al.* 2016; Kayatz *et al.* 2019).

Among crops, rice and wheat have the largest blue water footprints, together accounting for 45% of the global blue WF (Mekonnen & Hoekstra 2011). India is a major food producer, where the agriculture sector accounts for 90% fresh water use (Dhawan 2017). It is also a water-stressed country that is expected to face severe water constraints by 2050 (OECD 2012). High water stress has been found to contribute to high virtual water content values (Fader *et al.* 2010). The study region Punjab also known as the 'bread basket of India' is one of the largest producers of rice and wheat in India (Department of Food Civil Supplies & Consumer Affairs Govt. of Punjab 2019). In Punjab, 85% of water consumption is accounted for by the agriculture sector (Gulati *et al.* 2017), of which groundwater accounts for 90–97% of the irrigation in the Central Zone of Punjab (Sarkar *et al.* 2009). Punjab is facing a massive depletion in its water table at the rate of 70 cm/year (2008–2012) (Gulati *et al.* 2017). Climate change poses an additional threat to the availability of water. Climatic change would affect both the water consumption of crops and crop yield (Sun *et al.* 2012). With the projected decline in rainfall, there is a high risk of increased crop water utilization in tropical and subtropical regions (Fader *et al.* 2010). WF as a measure of crop water consumption can be used to assess the impact of climate change on crop water use in the long term, as well as to derive foresights for future actions.

Therefore, it is important to understand the changes in climatic factors and crop water use over the years as well as their implications for agriculture so that relevant policy measures can be derived for future action in regions facing a similar water crisis. In this context, the present study aims to analyse the temporal variability of climatic factors and WF of rice and wheat production during the period 1986–2017 in Ludhiana, Punjab. Further, it aims to identify the dominant climatic factors that cause variation in both ET_o and WF of rice and wheat.

METHODS

Study area

The state of Punjab is located in north-western India. It extends from 29° 32′ to 32° 32′ north latitude and 73° 55′ to 76° 50′ east longitude and comprises a geographical area of 5.03 million hectares (Mha), i.e. 1.54% of the total geographical area of India. Of this, 83.4% of the land (4.20 Mha) is cultivated, and rice and wheat are the major crops. The groundwater in 80% of the geographical area in Punjab is overexploited (Gulati *et al.* 2017). Punjab is divided into five agroclimatic zones (ACZ), of which the 'Central plain zone', comprising 36% of the total area of Punjab, is the largest (Rang *et al.* 2011). The Central plains also account for two-thirds of the total rice and wheat production in Punjab (Sarkar *et al.* 2009). The study district Ludhiana is located in the Central plain zone of Punjab and is therefore assumed to be representative of Punjab (Figure 1).

Data collection

Meteorological data for Ludhiana for the year 1986–2018 was acquired from the Department of Agrometeorology, Punjab Agriculture University, Ludhiana. The data included maximum temperature, minimum temperature, relative humidity (RH), wind speed, sunshine hours and rainfall. Yield data for rice and wheat production of Ludhiana district for the duration 1986–2017 were derived from statistical abstracts of Punjab (Singh & Kalra 2002; Statistical abstract of Punjab 2018).

Calculation of reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c)

The FAO-CROPWAT model was used to estimate reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) or crop water requirement (CWR). The CROPWAT model developed by the Land and Water Development Division of U.N. Food and Agriculture Organization (FAO) is a decision support tool that uses data on climate, soil properties and crop characteristics as input to estimate crop water requirements and irrigation requirements of a region.

ET_o represents evapotranspiration from a 'standardized vegetated surface' which is a hypothetical reference crop (resembling grass) with a height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference evapotranspiration (ET_o), which denotes the evaporation power of the atmosphere, is affected by the climatic parameters (Allen *et al.* 1998). The CROPWAT software uses the Penman–Monteith (PM) method (Allen *et al.* 1998) to calculate reference evapotranspiration based on the input of climate parameters.

Of the two options, i.e. 'crop water requirement' and 'irrigation schedule', offered by the CROPWAT model to calculate crop evapotranspiration, the 'irrigation schedule option' was used in this study since it is recommended and more accurate (Hoekstra *et al.* (2011). Crop evapotranspiration under standard conditions (ET_c) which denotes 'the amount of water lost through evapotranspiration' is identical in value to CWR which is defined as 'the amount of water required to compensate the evapotranspiration loss from the cropped field' (Allen *et al.* 1998). ET_c and CWR are identical in value, but since this study is focused

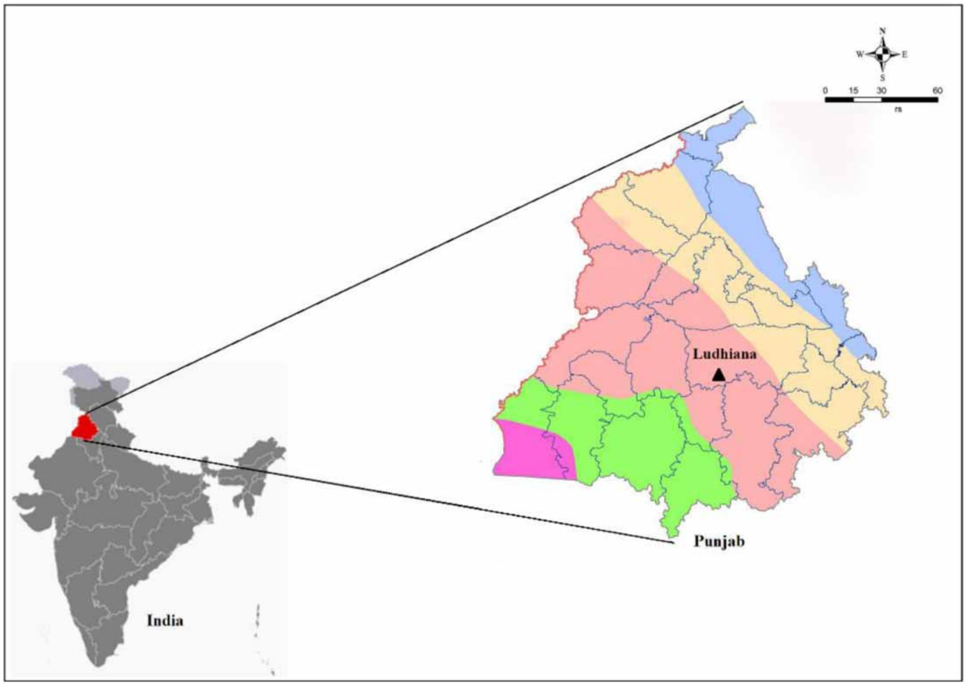


Figure 1 | Study area (Punjab) and the representative climate station, Ludhiana. (The five agroclimatic zones have been highlighted in different colours). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2020.093.

on water resources, the term 'crop water requirement' has been used for further analysis.

Calculation of WF

WF of a product is expressed as water volume per unit of product (in m^3/t). It generally has three components: blue water, green water and grey water. In this study, only WF_{green} and WF_{blue}, which are rainwater and irrigation water components, have been considered as these two depend on climate. WF_{green} and WF_{blue} have been computed as follows (Hoekstra *et al.* 2011):

$$WF_{green} = \frac{CWU_{green}}{Y}$$

$$WF_{blue} = \frac{CWU_{\ blue}}{Y}$$

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green}$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue}$$

$$ET_{green} = \min(ET_c, P_{eff})$$

$$ET_{blue} = \max(0,\ ET_c - P_{eff})$$

where CWU_{green} and CWU_{blue} are the green and blue water components, respectively, of crop water use that is equivalent to the summation of daily evapotranspiration (in mm/day) over the length (in days) of the growing period (lgp); Y is the crop yield (Y, tons/hectare or t/ha), ET_{green} represents green water evapotranspiration; ET_{blue}, i.e. the blue water evapotranspiration or field-evapotranspiration of irrigation water, also denoted as irrigation water requirement (IWR), is the difference between the total crop evapotranspiration and effective precipitation (P_{eff}). ET_{blue} is 0 when effective rainfall exceeds crop evapotranspiration. Crop evapotranspiration (ET_c) and effective rainfall (P_{eff}) were derived from CROPWAT output, which were further used to calculate green and blue WF. For the input in CROPWAT, Punjab-specific crop coefficients for wheat were derived from Kaur *et al.* (2017). The planting dates were kept constant for all years (25 June for rice transplantation and 5 November for wheat sowing). Using soil texture inputs from Singh *et al.* (2009), soil hydraulic properties were calculated online (http://resources.hwb.wales.gov.uk/VTC/envsci/module2/soils/soilwatr.htm) for soil inputs. The details of inputs used in CROPWAT for the estimation of evapotranspiration and IWR are presented in supplementary Tables A7 and A8. The WF of rice and wheat was calculated for each year (supplementary Table A5), followed by trend analysis using MS-Excel.

Temporal variation of climatic factors and ET_o

The non-parametric Mann–Kendall (MK) test (Kendall 1948; Mann 1945) was used to reveal the temporal trend in meteorological data, ET_o and crop water use. The MK has been recommended by the World Meteorological Organization for the evaluation of significant trends in hydro-meteorological time series. A modified M–K test (Hamed & Rao 1998) was used to eliminate the effect of autocorrelation in data. The tests were carried out using XLSTAT software. For seasonal climate trends, the year was equally divided into two major seasons, i.e. the rice-growing season (*Kharif*) and wheat growing season (*Rabi*). For the rice-growing *Kharif* season, climate data from May to October was used as input; while for *Rabi* season, data from November to April of the following year were used to analyse the seasonal trends. The M–K test was used for analysing seasonal trends of climate variables. For annual climate trends (including ETo), daily weather data were averaged over a month and months were averaged for a single year (January–December) for the entire study duration, following which the modified M–K test was applied. Similarly, for seasonal trends, daily data were averaged for the respective months, then the average of months was considered for a single year. The standardized M–K value Z indicates the direction of trend, where a positive Z value denotes an upward trend, while a downward trend is indicated by negative Z value. The slope computed by Theil–Sen's estimator, also known as Sen's slope, is a robust indicator of the magnitude of trend, i.e. the rate of change of variables. It has been widely used in identifying the slope of the trend line in hydrological time series (Dinpashoh *et al.* 2011).

The standardized MK statistic, denoted by Z, was computed using the following equations (Dinpashoh *et al.* 2011):

$$Z = \frac{S-1}{\sqrt{\mathrm{VAR}(S)}},\quad S > 1$$

$$Z = 0,\qquad S = 0$$

$$Z = \frac{S+1}{\sqrt{\mathrm{VAR}(S)}},\quad S < 1$$

where S statistic and VAR(S) were derived from MK test output in XLSTAT.

Impact of climatic factors on WF

Path analysis and correlation analysis were used to ascertain the dominant climatic factors affecting WF of rice and wheat crops. Since the data were not normally distributed, the Spearman correlation was used. Path coefficient analysis developed by Wright (1921) is an extension of regression and provides estimates of magnitude and significance of the hypothesized relationship between two sets of variables. It can be used to separate the direct and indirect effect of independent variables on the dependent variable (Dewey & Lu 1959; Lu *et al.* 2016). The climatic parameters used as inputs in path analysis of rice WF were averaged for the months of May to October of a single year. Similarly, for wheat, climate parameters were averaged for the months of November to April of the following year. Path analysis was carried out in SPSS-Amos software. The simplified flow chart of the methodology is presented in Figure 2.

RESULTS

Temporal variations of climatic factors

The descriptive statistics of climatic factors and results of the MK test for annual and seasonal trends are presented in Table 1. Temporal trends of annual climatic factors are presented in Figure 3(a)–3(g). The climate variables, minimum temperature (Min. Temp), maximum temperature (Max. Temp), mean temperature (Figure 3(a)) and RH (Figure 3(c)) showed an increasing trend over the study

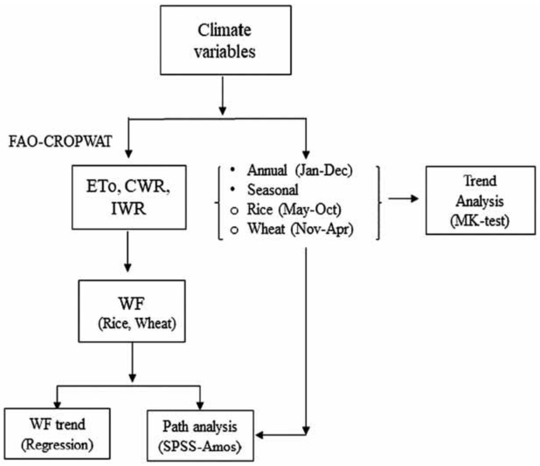


Figure 2 | Flow diagram of methodology.

period. Of this, the trends of minimum temperature and mean temperature were found to be statistically significant ($p < 0.05$) with an annual growth rate of 0.05 °C and 0.03 °C per annum (a), respectively. In contrast, rainfall (Figure 3(b)), wind speed (Figure 3(d)), sunshine duration (Figure 3(e)) and radiation (Figure 3(f)) showed a downward trend. The declining trend of sunshine duration, radiation and wind speed was found to be statistically significant. The rate of decline for wind speed, sunshine duration and radiation was found to be 0.01 kmph/a, 0.07 h/a and 0.09 MJ/m^2/a, respectively (Table 1). Since sunshine duration and radiation are strongly correlated ($\rho = 0.99$), only sunshine duration was used in further analysis. The coefficient of variation (CV) of rainfall was found to be 34%, and the highest annual rainfall was

Table 1 | Statistical description and results of MK test for climatic factors and ET_o

Statistical description	Min. Temp (°C)	Max. Temp (°C)	Mean Temp (°C)	Rainfall (mm)	RH (%)	Wind speed (kmph)	Sunshine duration (h)	Radiation (MJ/m^2)	ETo (mm)
Time period	Annual (January–December)								
Minimum	16.00	28.20	22.45	385.10	62.00	3.29	6.60	16.40	3.56
Maximum	18.50	30.70	24.50	1,316.80	71.00	4.58	9.10	19.50	4.22
Mean	17.19	29.73	23.46	787.28	65.88	4.27	7.86	18.00	3.87
Std dev	0.57	0.58	0.49	266.79	2.32	0.28	0.75	0.93	0.15
CV(%)	3	2	2	34	4	7	10	5	3.83
MK value (Z)	**4.37**	1.19	**3.19**	−0.70	1.72	−**3.15**	−**5.82**	−**5.62**	−**0.28**
Sen's slope	0.05	0.01	0.03	−4.17	0.09	−0.01	−0.07	−0.09	−0.01
Time period	Rice-growing season (*Kharif*: May–October)								
Minimum	22.52	33.03	28.33	292.20	57.83	3.74	6.42	18.15	4.53
Maximum	25.18	35.65	30.25	1,254.80	71.67	5.28	9.77	22.82	5.59
Mean	23.89	34.81	29.35	695.20	64.56	4.81	8.17	20.59	5.03
Std dev	0.63	0.58	0.48	284.45	3.19	0.31	0.83	1.16	0.23
CV(%)	3	2	2	41	5	6	10	6	4.67
MK value (Z)	**2.70**	0.07	**2.50**	−1.30	0.71	0.40	−**0.40**	−**3.90**	−**0.16**
Sen's slope	0.24	0.07	0.20	−41.29	0.17	−0.04	−0.41	−0.57	−0.01
Time period	Wheat growing season (*Rabi*: November–April)								
Minimum	9.43	23.28	16.64	36.60	63.00	68.17	6.05	13.72	2.50
Maximum	11.73	26.08	18.78	245.50	73.83	109.00	8.93	17.00	2.87
Mean	10.57	24.75	17.66	116.64	67.20	90.13	7.53	15.41	2.71
Std dev	0.61	0.83	0.61	51.84	2.64	8.83	0.76	0.83	0.11
CV(%)	6	3	3	44	4	10	10	5	3.99
MK value (Z)	**2.21**	−0.30	0.50	0.30	**2.01**	−**2.21**	−**4.50**	−**4.50**	−**0.27**
Sen's slope	0.19	−0.02	0.09	10.70	0.68	−3.38	−0.44	−0.47	−0.05

Values in bold are significant at $\alpha = 0.05$.

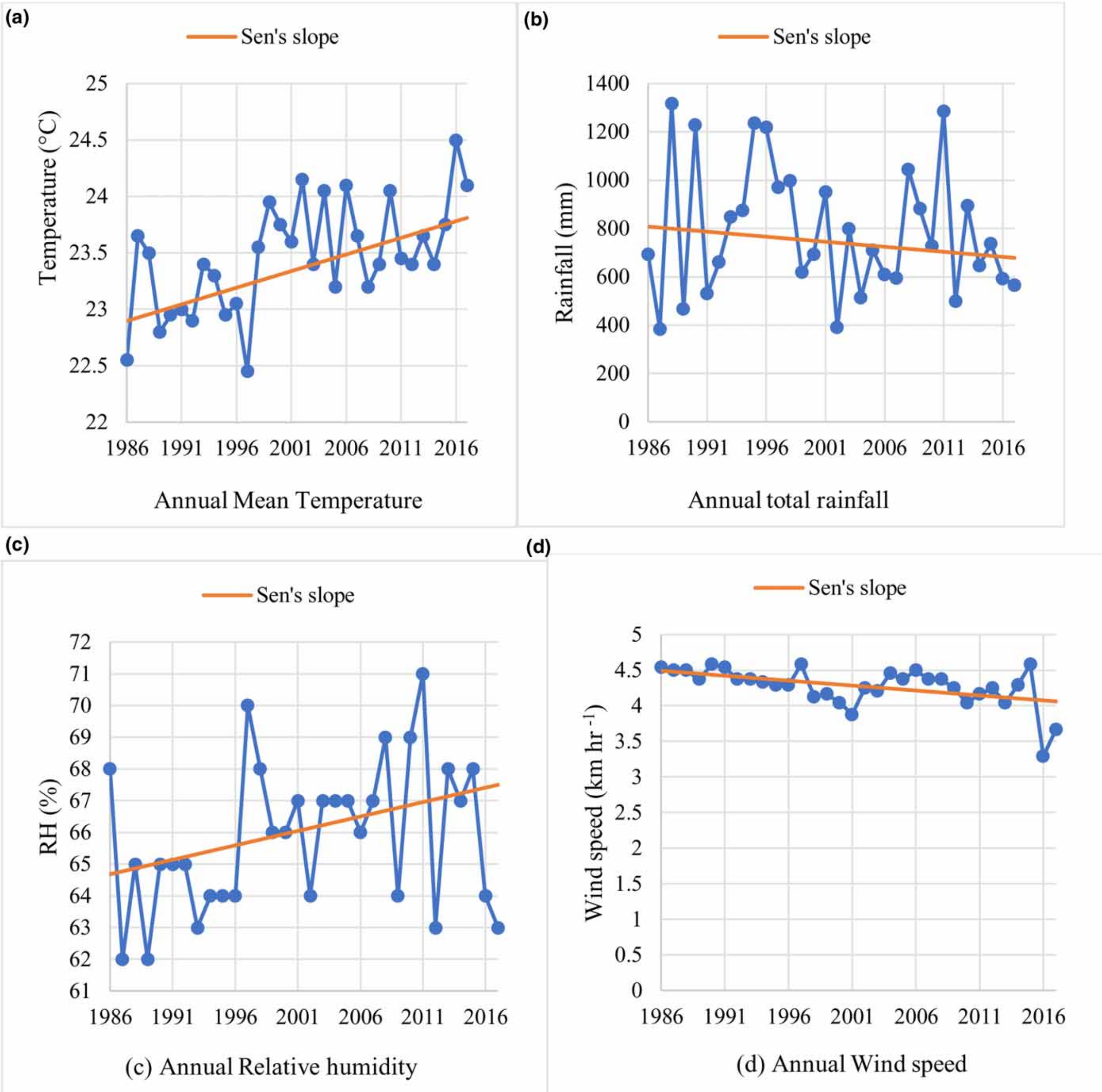


Figure 3 | (a–g) Temporal variation of climatic factors and ET_o with Sens's slope. *(continued.)*.

almost 3.5 times the lowest annual rainfall. This was followed by CV of sunshine duration (10%), wind speed (7%), radiation (5%), RH (4%) and mean temperature (2%). The results of the M–K test for the seasonal data are presented in Table 1. The climate factors in *Kharif* season showed a pattern similar to the annual trends. Minimum and mean temperature showed a significant upward trend, whereas sunshine duration and radiation showed a significant downward trend. Rainfall in *Kharif* (rice-growing) season was found to have the highest Sen's slope indicating a decline at a rate of 41.3 mm/a; nearly 10 times higher than the annual rate. In the wheat growing season, minimum temperature and humidity were found to have a significant upward trend. Wind speed, sunshine duration and radiation showed a significantly decreasing trend.

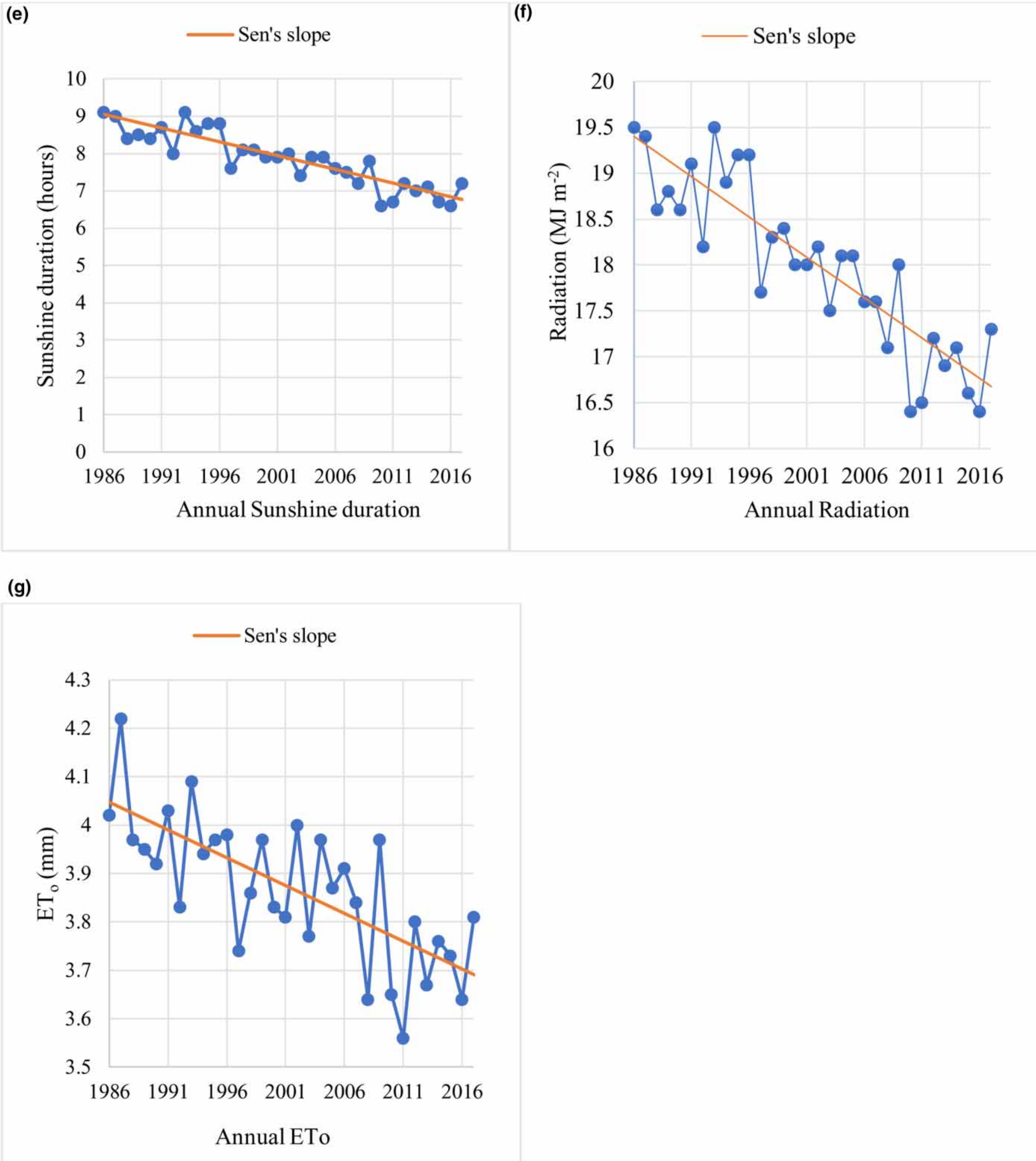


Figure 3 | Continued.

Temporal variations of ET_o, CWR and IWR

ET_o showed a statistically significant downward trend in the duration 1986–2017 ($p < 0.05$) (Figure 4). It was found to be decreasing at the rate of 0.012 mm/a (Table 1). The average annual ET_o for the study period was found to be 3.87 mm. Thus, the trend of increasing air temperature and decreasing evapotranspiration confirms the existence of an 'evaporation paradox' in Ludhiana, Punjab. A significant downward trend was also found for seasonal ET_o in the

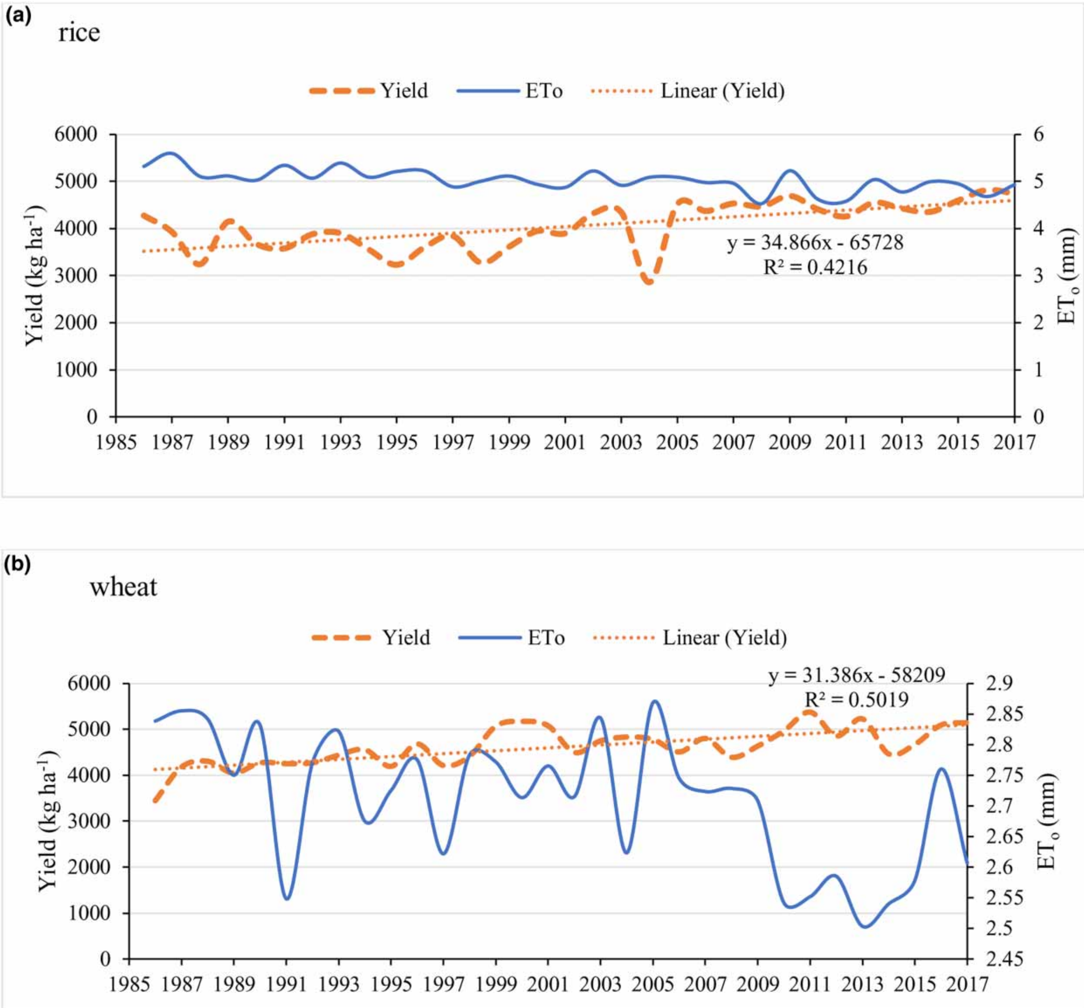


Figure 4 | Temporal trend in yield (in kg/ha) and seasonal ETo (in mm) of (a) rice and (b) wheat from 1986 to 2017.

rice and wheat growing season, which declined at a rate of 0.16 mm/decade for rice and 0.067 mm/decade for wheat. The seasonal average ET_o was 5.03 and 2.71 mm/a for rice and wheat growing season, respectively. The interannual variability in yield and seasonal ET_o of rice and wheat is presented in Figure 3(g). Stepwise multiple regression was applied to identify the dominant climatic factors influencing ET_o (Dinpashoh *et al.* 2011; Gao *et al.* 2017). The results of multiple regression (supplementary Table A10) revealed that sunshine duration followed by minimum temperature and wind speed were the dominant factors influencing the annual ET_o in Ludhiana, Punjab.

Figures 5 and 6 show the interannual variability of CWR and IWR of rice and wheat in the duration 1986–2017. The CWR of both rice and wheat showed a significant declining trend at 2.6 and 1 mm/a, respectively ($p < 0.05$). The IWR showed a non-significant declining trend at the rate of 2.05 and 0.93 mm/a for rice and wheat, respectively. As compared to CWR, IWR showed a greater fluctuation because of variability in rainfall. If rainfall is less, the same amount of water is compensated by irrigation; therefore, a high variability in rainfall consequently leads to high variability in IWR of crops. IWR (CV = 294%) for rice was found to have a greater variation than wheat IWR (CV = 29%) (Table A6), which could be because rice is grown in the monsoon season and rainfall was found to have CV of 41%. Further, correlation analysis was used to determine the relationship between CWR (ET_c) and climatic factors.

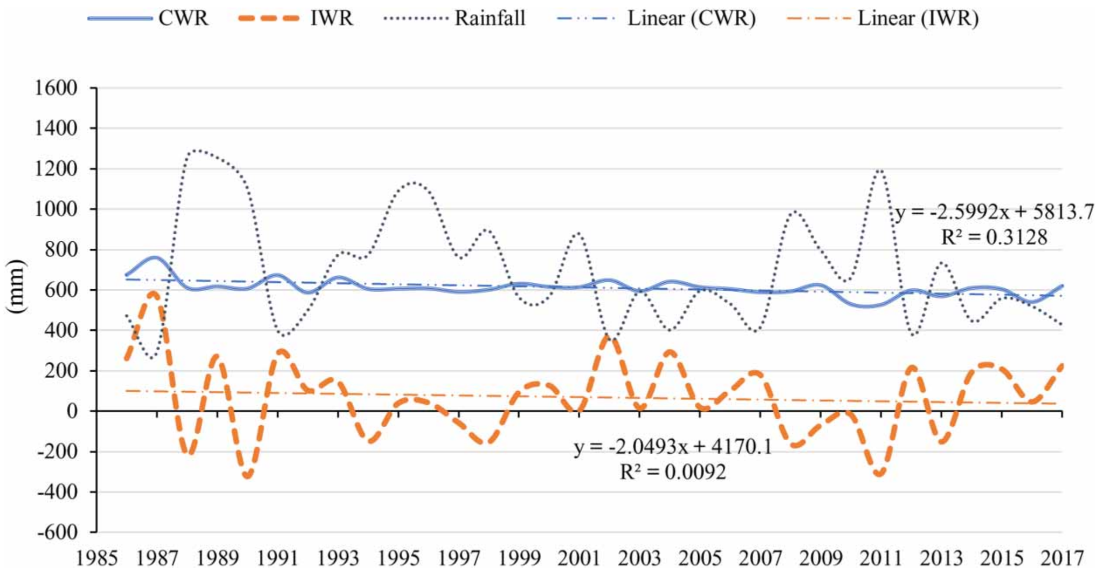


Figure 5 | Interannual variability in CWR, IWR and total rainfall (May–October) in the rice-growing season during 1986–2017.

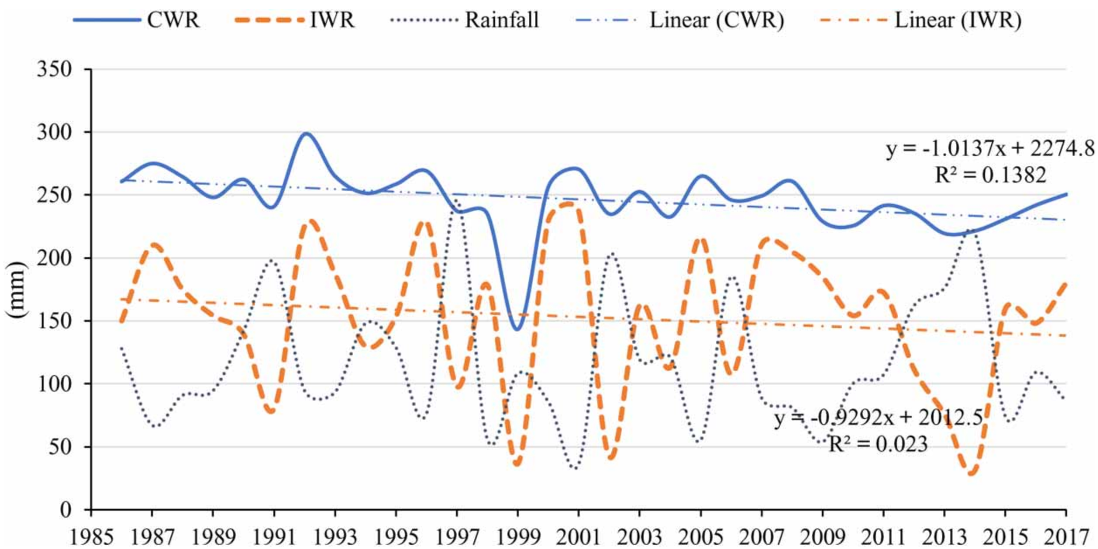


Figure 6 | Interannual variability in CWR, IWR and total rainfall (November–April) in the wheat growing season during 1986–2017.

In the case of rice, a significant positive relationship was found between CWR and sunshine hours ($\rho = 0.68$) (Table 2); CWR and RH shared a significant negative relation ($\rho = -0.37$). For wheat, significant positive relationship was found between CWR and sunshine duration ($\rho = 0.62$), followed by CWR and wind speed ($\rho = 0.43$). CWR, IWR and yield data for each year are presented in supplementary Table A4. Yield for both rice and wheat showed a significant increasing trend over the period 1986–2017. Rice and wheat yield were found to increase at the rate of 35 and 31 kg/ha/a, respectively (Figure 4).

Interannual variability in WF of rice and wheat

Interannual variability in green WF

Figure 7 shows the interannual variability of green WF of rice and wheat during 1986–2017. The green WF of both

Table 2 | Correlation matrix of CWR, WF and climatic factors

Factors	Temperature	Relative humidity	Wind speed	Sunshine duration	Rainfall
Rice					
$CWR_{(R)}$	−0.097	**−0.374***	0.186	**0.680***	−0.262
$WF_{green\ (R)}$	**−0.368***	**0.355***	−0.314	0.256	**0.714***
$WF_{blue\ (R)}$	0.223	**−0.491***	0.319	0.290	**−0.720***
$WF_{(R)}$	−0.341	−0.127	0.208	**0.796***	0.063
Wheat					
$CWR_{(W)}$	−0.161	−0.084	**0.431***	**0.623***	−0.103
$WF_{green\ (W)}$	**−0.439***	**0.490***	0.347	0.025	**0.907***
$WF_{blue\ (W)}$	0.296	**−0.613***	0.152	**0.461***	**−0.786***
$WF_{(W)}$	−0.196	−0.285	**0.608***	**0.733***	−0.066

*Values in bold are different from 0 with a significance level alpha = 0.05. R: rice; W: wheat; ETc: crop evapotranspiration; WF: water footprint.

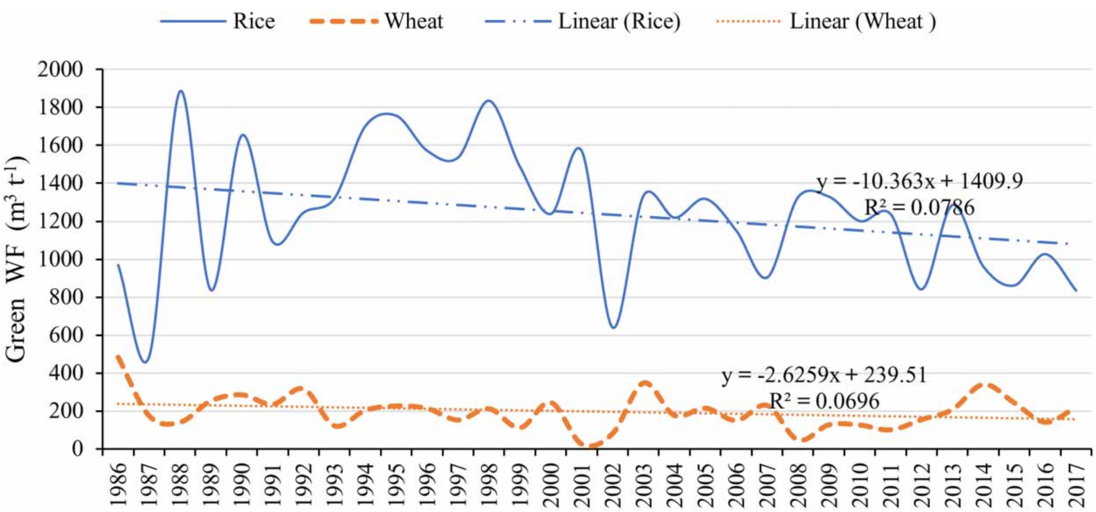


Figure 7 | Interannual variability in green WF of rice and wheat during 1986–2017.

rice and wheat does not show a statistically significant trend with time. This implies no change in the green WF of rice and wheat over the past 32 years. The average green WF of rice and wheat was found to be 1,239 and 206 m^3/t, respectively (Table A6). Correlation analysis indicated a significant positive effect between WF_{green} of rice and rainfall ($\rho = 0.71$) followed by WF_{green} of rice and RH ($\rho = 0.36$). There was a negative correlation of temperature ($\rho = -0.37$) with the WF_{green} of rice ($p < 0.05$) (Table 2). This was consistent with the results of path analysis that showed that rainfall and RH significantly influenced WF_{green} during the rice-growing season ($p < 0.05$) (Table 3). Additionally, sunshine duration was also found to significantly influence WF_{green}. Similar to the WF_{green} of rice, the correlation analysis of WF_{green} of wheat revealed a significant positive effect of rainfall ($\rho = 0.91$) followed by RH ($\rho = 0.49$) and a negative effect of temperature ($\rho = -0.44$) ($p < 0.05$). According to path analysis results, the WF_{green} of wheat in the *Rabi* (winter) season was significantly influenced ($p < 0.05$) by rainfall only.

Table 3 | Path coefficient analysis of green WF, blue WF and total WF of rice and wheat

	Rice			Wheat		
	Green WF	Blue WF	Total WF	Green WF	Blue WF	Total WF
Temperature	0.03	0.108	0.188	0.116	0.001	0.137
RH	**0.512***	**−0.328***	0.232	0.015	−0.161	−0.215
Rainfall	**0.479***	**−0.4***	0.088	**0.926***	**−0.678***	0.097
Wind speed	**−0.326***	**0.351***	0.049	0.125	0.195	**0.428***
Sunshine duration	**0.482***	0.169	**0.879***	0.115	0.154	0.357

*Significance at $\alpha = 0.05$ level.

Interannual variability in blue WF

Similar to the trend of WF_{green}, the blue WF of both rice and wheat did not show a significant trend over the duration 1986–2017 (Figure 8). The average blue WF for rice and wheat, respectively, for 32 years was found to be 296 and 334 m^3/t (Table A6). Similar to the IWR of rice, the blue WF of rice was found to be highly fluctuating varying from 0 m^3/t (in several years) to as high as 1,448 m^3/t in 1987 (Table A5). This is because of variability in rainfall. In the case of rice, correlation analysis indicated a significant negative effect of rainfall ($\rho = -0.72$) and RH ($\rho = -0.49$) on the WF_{blue} of rice (Table 2), thus indicating high rainfall led to low blue WF. Path analysis showed that RH, rainfall and wind speed influenced WF_{blue} during the rice-growing season ($p < 0.05$) (Table 3). Deficit of rainfall is compensated by irrigation, i.e. the blue WF. A high rainfall year translates to less IWR (WF_{blue}). Therefore, a negative correlation exists between WF_{blue} and rainfall. The correlation analysis of WF_{blue} of wheat revealed a significant positive effect of sunshine duration ($\rho = 0.461$) and a negative effect of rainfall ($\rho = -0.786$) and RH ($\rho = -0.613$) ($p < 0.05$). Similar to WF_{green} of wheat, the WF_{blue} of wheat was also found to be significantly influenced ($p < 0.05$) by rainfall according to the results of path coefficient analysis (Table 3).

Interannual variability in total WF

Annual variability of WF for rice and wheat is presented in Figure 9. The total WF of both rice and wheat showed a significant decrease over the past 32 years ($p < 0.05$) declining at the rate of 19 and 6 $m^3/t/a$, respectively. The average total WF of rice and wheat for the period 1986–2017 was found to be 1,535 and 540 m^3/t, respectively. If the 32-year period is divided into three periods, period I (1986–1995),

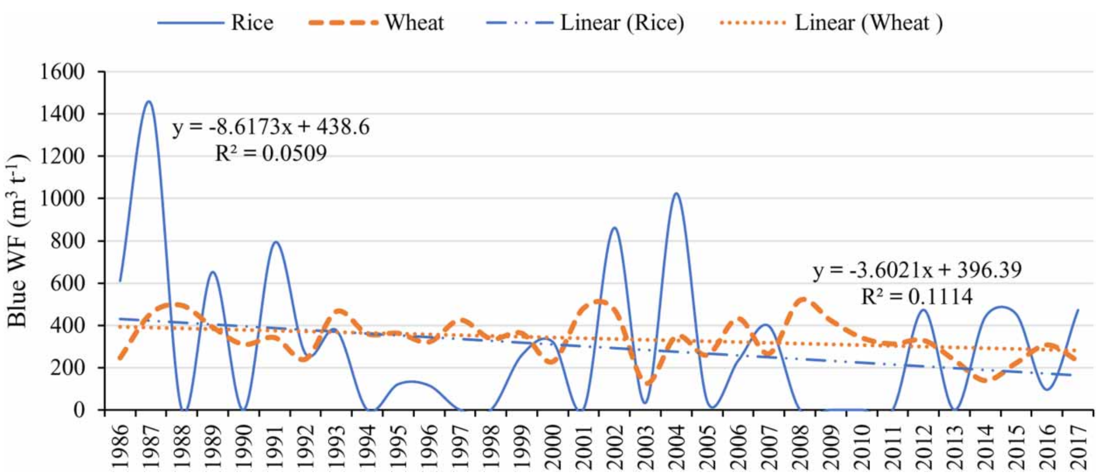


Figure 8 | Interannual variability in blue WF of rice and wheat during 1986–2017.

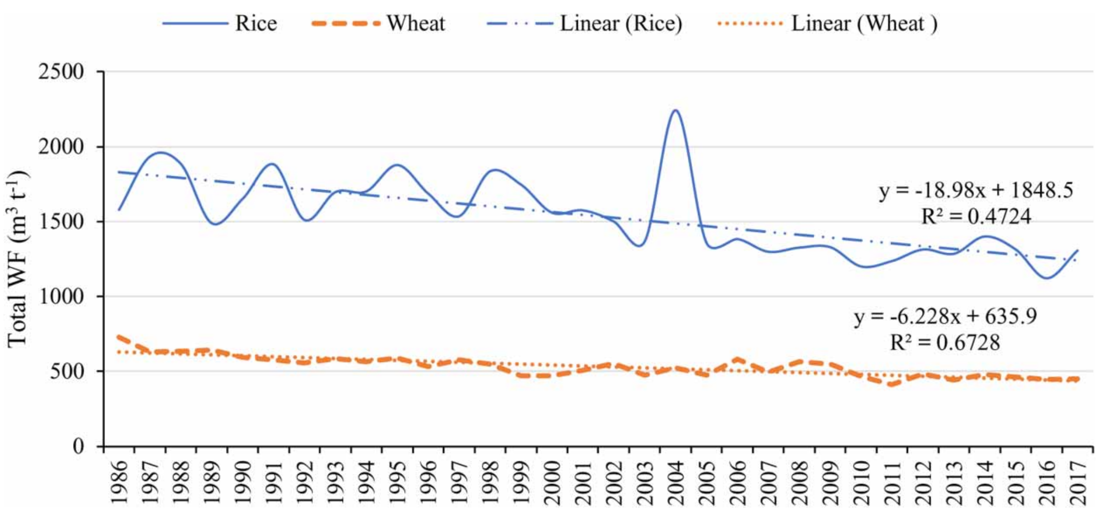


Figure 9 | Interannual variability in total WF of rice and wheat during 1986–2017.

period II (1996–2005) and period III (2006–2017): the average WF of rice for each period was 1,721, 1,641 and 1,293 m^3/t, respectively, with a percentage decrease of 5% between period I and II and 21% between period III and II. The average WF for wheat was 629, 507, 493 m^3/t, respectively, for the corresponding periods. In terms of percentage, the wheat WF decreased by 19% between the periods I and II, and 3% between the periods II and III. The contribution of the WF_{green} and WF_{blue}, respectively, to the total WF was 80.7 and 19.3% for rice, and 38.2 and 61.8% for wheat. The annual total WF of rice was found to be positively correlated with sunshine duration ($\rho = 0.79$) ($p < 0.05$). The WF_{total} of wheat was found to be positively correlated with sunshine duration ($\rho = 0.73$) followed by wind speed ($\rho = 0.61$) ($p < 0.05$). Results of path analysis indicated that the total WF of rice grown in *Kharif* (monsoon/autumn) season in Ludhiana was mainly influenced by sunshine duration ($p < 0.05$), while wind speed influenced the WF of wheat. The details of regression weights for the relationship between WF of rice and wheat and climatic factors are presented in supplementary Table A9.

DISCUSSION

Among the climatic factors, temperature showed an increasing trend, which is in agreement with the global trend. The increase in temperature despite an observed decrease in sunshine duration indicates an increased warming due to heat trapping by greenhouse gases. Additionally, an increase in temperature did not translate to an increase in ET_o and CWR, thus indicating the role of other climatic factors in determining WF. The declining trend of sunshine duration and solar radiation found in this study is in agreement with the reduction in solar radiation, also known as 'solar dimming', observed globally (Stanhill & Cohen 2001). Increase in the amount of aerosols and other air pollutants was found to be the major reason behind this phenomenon (Stanhill & Cohen 2001), while in South Asia, it was found to be primarily driven by cloud cover (Kambezidis *et al.* 2012). Wind speed is another factor that has been shown to affect aerosol concentration (Moorthy *et al.* 1998). According to the findings of our study, wind speed shows a declining trend, which could have affected the aerosol concentrations and cloud cover that are less likely to be blown away with decreasing wind speed. Rainfall showed an insignificant decreasing trend. Similarly, global mean precipitation trends between 1901 and 2005 were found to be statistically non-significant (Bates *et al.* 2008). But, the decreasing trend is in agreement with the observed decrease in rainfall over the tropic and subtropic zone in the past 30–40 years (Bates *et al.* 2008). Among all climate variables, rainfall was found to have the highest CV both annually (34%) and seasonally (41% in Kharif season and 44% in *Rabi* season). CV indicates the deviation of rainfall from the mean value and illustrates the erratic nature of rainfall in

Ludhiana during the study period. A CV > 30% for rainfall indicates high variability in rainfall amount and distribution patterns (Kisaka *et al.* 2015). Rainfall is projected to become more erratic and unpredictable in the future (IPCC 2013). The predicted increase in precipitation intensity due to a decrease in even spread of precipitation interspersed with longer dry spells in the subtropical region (Bates *et al.* 2008) might do more harm to the crop even if the total amount of precipitation matches the crop water requirements. This would have significant implications for agriculture. Water availability in such long dry spells can be ensured through rain harvesting and storage during the wet spells.

Consistent with the findings of this study, ET_o was found to show a decreasing trend in most of the studies worldwide (Dinpashoh *et al.* 2011; Fan & Thomas 2013; Wang *et al.* 2015; Gao *et al.* 2017). Decrease in net radiation (Wang *et al.* 2015) or sunshine duration (Fan & Thomas 2013) was found to be the major cause of decreasing ET_o. In this study, sunshine duration, the dominant factor influencing ET_o, also showed a significant decreasing trend. This could be a possible reason for the downward trend of ET_o. Similarly, crop evapotranspiration (ET_c) was also found to decrease significantly along with a decrease in total WF of both rice and wheat. Therefore, both the factors, i.e. increase in yields and decrease in (ET_c) or CWR contributed to the decrease in total WF across the years. This is in agreement with the reported decrease in WF of wheat due to both yield increase and decline in ET_c in China over 1980–2009 (Sun *et al.* 2012). Likewise, a reduction in WF of cereals over 2005–2014 in India is reported to be primarily driven by an increase in yields along with decreased evapotranspiration (Kayatz *et al.* 2019). Several studies have reported a decline in long-term WF. A decreasing trend in WF was reported for winter wheat and summer maize over 35 years in North China (Lu *et al.* 2016), spring wheat and maize in Hetao irrigation district, China between 1960 and 2008 (Sun *et al.* 2013), barley and spring wheat in Canada between 1965 and 2014 (Zhao *et al.* 2019) and all cereals in India for the period 2005–2014 (Kayatz *et al.* 2019). On the contrary, an increasing trend in WF for various crops in Lake Dianchi Basin, China (1981–2011) (Zhang *et al.* 2015) was reported.

The proportion of green WF (81%) in total water consumption for rice was relatively high as compared to blue WF as rice is grown in the monsoon season. On the other hand, blue WF contributed a higher proportion (61%) to the total WF of wheat which largely depends on irrigation water as the winter (*Rabi*) season in the study area receives less rainfall. Under climate change, future irrigation water demand is projected to exceed water availability (Wada *et al.* 2013). The study region, where 98.5% of the gross sown area is irrigated, is heavily dependent on groundwater for irrigation, and the situation is made worse due to groundwater abstractions. The net volume of groundwater available for irrigation use in 2025 was projected to be greater than 4318 ha m in the majority of the blocks in the state of Punjab, indicating the negative availability of groundwater for irrigation in the future (Shiao *et al.* 2015). Further, the normalized deficit index (NDI) in Punjab falls in the category '2–5' and '> 5', indicating extreme overdraft (Shiao *et al.* 2015). The NDI denotes the amount of water that needs to be drawn from external storage to meet current demand annually. An NDI value >1 indicates storage required to meet deficit is less than average annual rainfall (Shiao *et al.* 2015). This is strong evidence of the fact that the study area is lacking in water storage practices and infrastructure, despite the severe water crisis. Previously, studies have focused more on the reduction of blue and grey WF, since green WF is completely dependent on climatic conditions. In agreement, the findings of this study highlight the importance of rainfall and its erratic nature, and therefore, the need for better management of green water in the face of the climate crisis. Green water can be converted to blue water and used for irrigation through storage. Rainfall was also found to be the most significant and common climatic factor influencing the blue–green WF of rice and wheat. The WF components taken separately, i.e. green and blue WF of both rice and wheat, did not show a significant trend despite the tremendous increase in yields over the years, which was due to the high variation in CWR and IWR as a result of variation in rainfall. Such variability in IWR leads to the vulnerability of regions that have deficit water reserves but still grow crops that have a high WF like rice. Thus, green water or rain water must be stored to compensate for the variability in rainfall and IWR. The impact of the high variability in rainfall is expected to increase by 50% if groundwater depletion continues in India (Fishman 2018). Moreover, it has been found that sustainable use of irrigation water in India could only mitigate less than 10% of the climate change impact (Fishman 2018). Water storage is a recommended key strategy in climate change adaptation to ensure water availability throughout the year (McCartney & Smakhtin 2010). Water-saving technologies, collection and storage of rainwater have been suggested as an active adaptation measure to the spatiotemporal variations in the distributions of precipitation (Zhao *et al.* 2019). Therefore, it is imperative that steps should be taken in the direction of developing water storage infrastructure for agriculture in the state. This is a generalized conclusion for any region facing similar crisis.

In the study area, it was also observed that even though farmers were facing water issues, they were not driven or aware about rain water conservation. Therefore, apart from institutional investments in water harvesting infrastructure, it is also crucial that awareness and capacity building for green water conservation are simultaneously implemented. In addition, for decentralized rainwater harvesting, investments in local institutions and small credit schemes are important so that the initial costs can be made affordable for small-scale water harvesting by farm households (Fox *et al.* 2005).

CONCLUSION

The present study analysed temporal trends in climatic factors, ET_o and WF of rice and wheat for the period 1986–2017 in Ludhiana, Punjab, along with impacts of changes in climatic factors on WF. Sunshine duration had a declining trend, and consequently, ET_o also showed a downward trend, which in turn led to a decline in CWR. However, IWR was found to be highly fluctuating because of high variability in rainfall over the study period. Temperature showed an increasing trend, thus establishing 'evaporation paradox' in the study region. The total WF of both rice and wheat, influenced mainly by sunshine duration, was found to decrease over the years because of significant increase in yields and a decline in CWR. However, green and blue WF of rice and wheat, which were most significantly influenced by rainfall, showed no significant trend. This study demonstrated the implications of varying rainfall on WF. Therefore, long-term trends in WF in relation to climatic factors, particularly variability in precipitation, should be accounted for while strategizing future cropping patterns.

Most importantly, the study area is facing a water crisis with decreasing and fluctuating levels of rainfall and already depleting groundwater resources. Even though the model estimates of CWR (ET_c) for rice and wheat showed a declining trend in Punjab, water availability for agriculture could be a tough challenge in the future, considering climate change. Apart from mitigation measures to reduce water use, adaptive measures like water storage could prove to be useful to fight the challenge of water availability for agriculture in the future. This is true for all regions facing a similar crisis. Awareness building and investments in rain water harvesting infrastructure are particularly important measures that need to be urgently implemented.

This study was limited to understanding the role of climatic factors in WF variation, which was computed theoretically based on climate data. It is certain that the trend of WF based on actual irrigation water use (including water loses during transmission) would be different and more accurate than the findings of this study. Furthermore, the computation of WF in CROPWAT was also undermined by the use of constant planting dates and growing period (irrespective of variety) over the years since data for crop planting dates for each year was not available. Particularly for rice, a crop transplanting date of 25 June was taken as per recent government regulations. Therefore, rice WF calculated in this study reflects the best possible scenario, as ET reduces by ~75 mm when the transplantation date is shifted from late May to late June (Humphreys *et al.* 2010).

ACKNOWLEDGEMENT

One of the authors acknowledges the fellowship received from the host institute.

DECLARATION OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56, p. 300. Food and Agriculture Organization, Rome, Italy.

Bates, B. C., Kundzewicz, Z. W., Wu, S. & Palutikof, J. P. 2008 *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. IPCC Secretariat, Geneva, Switzerland.

Cisneros, J. B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T. & Mwakalila, S. S. 2014 Freshwater resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea & L. L. White, eds.) Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 229–269.

Department of food civil supplies and consumer affairs, Government of Punjab 2019 Available from: http://foodsuppb.gov.in/?q=node/88 (accessed 8 July 2019).

Dewey, R. & Lu, K. H. 1959 A correlation and path-coefficient analysis of components of crested wheatgrass seed production. *Agron. J.* **51**, 515–518.

Dhawan, V. 2017 *Water and Agriculture in India Background Paper for the South Asia Expert Panel During the Global Forum for Food and Agriculture*. Federal Ministry of Food and Agriculture, Berlin, Germany. Available at https://www.oav.de/fileadmin/user_upload/5_Publikationen/5_Studien/170118_Study_Water_Agriculture_India.pdf (accessed 5 July 2019).

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V. P. & Kahya, E. 2011 Trends in reference crop evapotranspiration over Iran. *J. Hydrol.* **399**, 422–433.

Fader, M., Rost, S., Müller, C., Bondeau, A. & Gerten, D. 2010 Virtual water content of temperate cereals and maize: present and potential future patterns. *J. Hydrol.* **384** (3–4), 218–231.

Fan, Z. & Thomas, A. 2013 Spatiotemporal variability of reference evapotranspiration and its contributing climatic factors in Yunnan Province. *Clim. Change* **116**, 309–325.

Fox, P., Rockstrom, J. & Barron, J. 2005 Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. *Agric. Syst.* **83** (3), 231–250.

Fishman, R. 2018 Groundwater depletion limits the scope for adaptation to increased rainfall variability in India. *Clim. Change* **147**, 195–209.

Gao, Z., He, J., Dong, K. & Li, X. 2017 Trends in reference evapotranspiration and their causative factors in the West Liao River basin, China. *Agric. For. Meteorol.* **232**, 106–117.

Gulati, A., Roy, R. & Hussain, S. 2017 *Getting Punjab Agriculture Back on High Growth Path: Sources, Drivers and Policy Lessons*. Indian Council for Research on International Economic Relations (ICRIER), New Delhi.

Hamed, K. H. & Rao, A. R. 1998 A modified Mann–Kendall trend test for autocorrelated data. *J. Hydrol.* **204**, 182–196.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M. & Mekonnen, M. M. 2011 *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, London.

Humphreys, E., Kukal, S. S., Christen, E. W., Hira, G. S., Singh, B., Yadav, S. & Sharma, R. K. 2010 Halting the groundwater decline in north-west India – Which crop technologies will be winners? *Adv. Agron.* **109**, 155–217.

IPCC 2007 In: *Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson, eds). Cambridge University Press, Cambridge, UK, pp. 976.

IPCC 2013 *IPCC Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, p. 1535.

Kambezidis, H., Kaskaoutis, D., Kharol, S. K., Moorthy, K. K., Satheesh, S. K., Kalapureddy, M. C. R., Badarinath, K. V. S., Sharma, A. R. & Wild, M. 2012 Multi-decadal variation of the net downward shortwave radiation over south Asia: the solar dimming effect. *Atmos. Environ.* **50**, 360–372.

Kaur, J., Gill, K. K., Kaur, S. & Aggarwal, R. 2017 Estimation of crop coefficient for rice and wheat crops at Ludhiana Estimation of crop coefficient for rice and wheat crops at Ludhiana. *J. Agrometeorology* **19** (2), 170–171.

Kayatz, B., Harris, F., Hillier, J., Adhya, T., Dalin, C., Nayak, D., Green, R. F., Smith, P. & Dangour, A. D. 2019 More crop per drop': Exploring India's cereal water use since 2005. *Sci. Total Environ.* **673**, 207–217.

Kendall, M. G. 1948 *Rank Correlation Methods*. Hafner, New York.

Kisaka, M. O., Mucheru-Muna, M., Ngetich, F., Mugwe, J., Mugendi, D. & Mairura, F. 2015 Seasonal rainfall variability and drought characterization: case of eastern Arid Region, Kenya. In: *Adapting African Agriculture to Climate Change*. (W. L. Filho, A. O. Esilaba, K. P. C. Rao & G. Sridha, eds). Springer, New York, pp. 53–71.

Lu, Y., Zhang, X., Chen, S., Shao, L. & Sun, H. 2016 Changes in water use efficiency and water footprint in grain production over the past 35 years: a case study in the North China Plain. *J. Clean. Prod.* **116**, 71–79.

Mann, H. B. 1945 Non-parametric test against trend. *Econometrica* **13**, 245–259.

McCartney, M. & Smakhtin, V. 2010 *Water Storage in an era of Climate Change: Addressing the Challenges of Increasing*

Rainfall Variability, IWMI Blue Paper. International Water Management Institute, Colombo.

Mekonnen, M. M. & Hoekstra, A. Y. 2011 The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **15**, 1577–1600.

Moorthy, K. K., Satheesh, S. & Murthy, B. V. K. 1998 Characteristics of spectral optical depths and size distributions of aerosols over tropical ocean regions. *J. Atmos. Sol. Terr. Phys.* **60**, 981–992.

OECD 2012 *OECD Environmental Outlook to 2050*. OECD Publishing. Available from: http://dx.doi.org/10.1787/9789264122246-en (accessed 24 June 2019).

Rang, A., Mangat, G. & Kaur, R. 2011 *Status Paper on Rice in Punjab. Rice Knowledge Management Portal (RKMP)*. Directorate of Rice Research, Hyderabad. Available at http://www.rkmp.co.in/sites/default/files/ris/rice-state- wise/Status%20Paper%20on%20Rice%20in%20Punjab.pdf (accessed 13 January 2020).

Sarkar, A., Sen, S. & Kumar, A. 2009 Rice–wheat cropping cycle in Punjab: a comparative analysis of sustainability status in different irrigation systems. *Environ. Dev. Sustain.* **11**, 751–763.

Singh, K. & Kalra, S. 2002 Rice production in Punjab: systems, varietal diversity, growth and sustainability. *Econ. Polit. Wkly* **37**, 3139–3148.

Singh, K. B., Jalota, S. K. & Sharma, B. D. 2009 Effect of continuous rice–Wheat rotation on soil properties from four agro-ecosystems of Indian Punjab. *Commun. Soil Sci. Plant Anal.* **40** (17–18), 2945–2958.

Smit, B. & Skinner, M. W. 2002 Adaptation options in agriculture to climate change: a typology. *Mitig. Adapt. Strateg. Glob. Change* **7**, 85–114.

Stanhill, G. & Cohen, S. 2001 Global dimming: a review of the evidence for a widespread and significant reduction in global radiation. *Agric. For. Meteorol.* **107**, 255–278.

Statistical Abstracts of Punjab 2018 Available from: https://www.esopb.gov.in/Static/Publications.html (accessed 10 July 2019).

Shiao, T., Luo, T., Maggo, D., Loizeaux, E., Carson, C. & Nischal, S. 2015 *'India Water Tool.' Technical Note*. World Resources Institute, Washington, DC. Available from: www.wri.org/publication/india-water-tool.

Sun, S. K., Wu, P. T., Wang, Y. B. & Zhao, X. N. 2012 Impacts of climate change on water footprint of spring wheat production: the case of an irrigation district in China. *Span. J. Agric. Res.* **10** (4), 1176–1187.

Sun, S. K., Wu, P. T., Wang, Y. B. & Zhao, X. N. 2013 Temporal variability of water footprint for maize production: the case of Beijing from 1978 to 2008. *Water Resour. Manag.* **27** (7), 2447–2463.

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F. T., Stacke, T., Tessler, Z. & Schewe, J. 2013 Multi-model projections and uncertainties of irrigation water demand under climate change. *Geophys. Res. Lett.* **40** (17), 4626–4632.

Wang, Q., Wang, J., Zhao, Y., Li, H. & Zhai, J. 2015 Reference evapotranspiration trends from 1980 to 2012 and their attribution to meteorological drivers in the three-river source region, China. *Int. J. Climatol.* doi:10.1002/joc.4589.

Wright, S. 1921 Correlation and causation. *J. Agric. Res.* **20**, 557–585.

Zhang, Y., Huang, K., Yu, Y., Hu, T. & Wei, J. 2015 Impact of climate change and drought regime on water footprint of crop production : the case of Lake Dianchi. *Nat. Hazards* **79** (1), 549–566.

Zhao, Y., Ding, D., Si, B., Zhang, Z., Hu, W. & Schoenau, J. 2019 Temporal variability of water footprint for cereal production and its controls in Saskatchewan, Canada. *Sci. Total Environ.* **660**, 1306–1316.

First received 18 April 2020; accepted in revised form 5 June 2020. Available online 8 July 2020