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An assessment of water footprint for irrigated rice in Punjab

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ABSTRACT

Water scarcity has become one of the highest risks for environmental and economic security worldwide. The water footprint for rice production, i.e., the total volume of freshwater consumed to produce a unit quantity rice has been estimated for three different agroclimatic zones of Punjab for the years 2000 to 2017. The results revealed that effective rainfall (P_{eff}) improved in later years due to a change in crop calendar,legally enforced by an Act prohibiting the transplanting of paddy before a specified date. During the period of study, minimum crop evapotranspiration (ET_c) was 4645 and maximum was ET_c of 9511 m^3ha^{-1} during 2014 and 2011, respectively. The green water footprint (WF_{green}) for rice varied from 646litreskg^{-1}of rice during low rainfall years (2012) to 1149 litre kg^{-1} of rice during heavy rainfall (1192 mm) during 2011.Out of a total water footprint (WF_{total}) of 2650 litre kg^{-1}, the share of blue water footprint (WF_{blue}) was higher 1804 litre kg^{-1} (68%), indicating a need to improve on-farm irrigation management to conserve water resources.

Keywords: Weather parameters, evapotranspiration, water footprint, crop calendar

The water footprint of a product is the total volume of freshwater that is used or polluted during the production of the product (Hoekstra *et al.,* 2009). The total water footprint (WF_{total}) of the growing crops is the sum of the *green*, *blue,* and *grey* components of its production process. *Green* water footprint (WF_{green}) describes the amount of water used from precipitation (*green* water resources), and *blue* water footprint (WF_{blue}) stands for the surface and groundwater used for irrigation (*blue* water resources). The *grey* water footprint (WF_{gray}) is the share of freshwater resources needed to assimilate aload of pollutants to the environment with regards to the existing ambient water quality standards (Hoekstra *et al.* 2011). The consumptive water footprint of the production of rice indicates the consumption of freshwater resources in different practices carried out during the entire cultivation process. Mekonnen and Hoekstra (2010) reported that between 1996 and 2005, the global water footprint for crop production was 7404 billion cubic meters per year (78% green, 12% blue, 10% grey). Total water footprint was very high for wheat (1087 billion cubic meters, Gm^3year^{-1}), rice (992 Gm^3year^{-1}), and maize (770 Gm^3year^{-1})(Mekonnen and Hoekstra (2011).

In India, rice is anessential food crop as it feeds more than 60% of its population. The area under rice has increased 143%, *i.e.*, from 30.8 million hectares in 1950-51 to 43.8 million hectares during 2017-18, and its production has increased from 20.6 million tonnes in 1950-51 to 112.8 million tonnes during 2017-18, an increase of about 5.5 times (http://drdpat.bih.nic.in/). Similarly, area under rice in Punjab has increased tremendously from 390 thousand hectares in 1970-71 to 3065 thousand hectares in 2017-18, andproductivity in Punjab increased from 2,774 kgha^{-1} in 1970-71 to 4344 kgha^{-1} in 2017-18. Thus, there is positive growth in the area, productivity, and production of rice in the state over the years. The Punjab state, having only 1.5% of the total geographical area of the country, contributes more than one-fourth of rice to the central pool for the last four decades.

Rice, a water-guzzling crop, occupies about three-fourth of the cultivated area in Punjab during the summer season. The water requirement of rice is about 120 to 150 cm (Brar *et al.,* 2015). More than 71% of its irrigation water requirement is met through groundwater, resulting in a declining underground water table at an alarming rate. Consequently, the Central Ground Water Board (CGWB)has estimated that the overall stage of groundwater development of the state is 165%, and 79% area is over-exploited. The CGWBhas warned that "if the exploitation of state underground water resources continues at the current rate, renders Punjab into a desert within 25 years" (CGWB, 2018).

During April-June in Punjab, there is high atmospheric demand for water as the weather is hot and dry, relative humidity is low, wind speed is high, and the temperature is also high. There is hardly any rainfall during May-June, except for some pre-monsoon showers in some years. Thus, crops grown in this period have very high evapotranspiration (ET) and irrigation needs. The present study is an attempt to quantify the total water footprint of transplanted rice, considering a large amount of surface and groundwater use in rice production. This assessment may, in turn, guide the policymakers and other stakeholders to plan the optimal use of available freshwater in the production of rice and thereby control the declining water table and conserve the already limited natural resources in the state.

METHOD AND MATERIALS

The study area

Punjab is located in northern India between 29° 30' N to 32° 32' N latitude and 73° 55' E to 76° 50' E longitude, at an altitude ranging from 230 m to 700 m above mean sea level. It has a geographical area of 50362 km^{2}of which about 41250 km^{2}is under the plough, and the rice-wheat cropping system occupies more than 80% of this area. Climatically, it has three major seasons – summer season from April to June, rainy season from July to September, and winter season from December to February. The average temperature varies from 34°C in June to 13°C in January but the highest being as high as 48°C in summer and lowest near to freezing point in winter. The average annual rainfall varies from 1250 mm in the north to 350 mm in the southwest, and more than 70 percent of it occurs from July to September, i.e., during the monsoon season. The climatic variations have resulted in a variety of soils in Punjab -the north-western part mainly dominated by calcareous soil, the eastern part by loamy to clayey soil, and central part by sandy loam to clayey soils, with the pH ranging from 7.8 to 8.5. Nowonder, due to the massive production of food grains (31.67 million tonnes in 2017-18),Punjab has been rightly named as the bread-basket of India, but the prevailing soil and climate conditions in the state culminate into a wide range of crops and vegetation.

For this study, daily meteorological parameters of representing stations of each zone (Table 1) have been used for the study period (2000-2017) to work out the water footprint of irrigated rice for Punjab. The weather parameters used for the study have been sourced from Punjab Agricultural University, Ludhiana. The soil type has been taken as clay loam for the sub-mountainous zone (SMZ), loamy sand for south-western zone (SWZ), and sandy loam for the central plain zone (CPZ), for as these classes dominate the main rice-growing area in these zones of the state. The data regarding the area of rice transplanted on different dates in different zones and different years has been collected from the Department of Agriculture and Farmers Welfare, Punjab.

Methodology

The methodology for 'water footprint assessment' explained in 'the water footprint assessment manual' (Hoekstra, 2011) followed to work out the water footprint of the production of rice in Punjab. The FAO-56-PM model (Allen *et al.,* 1998) used to estimate the reference evapotranspiration (ET_o) using CROPWAT 8.0 software. For working out the crop evapotranspiration (ET_c), the following equation was employed

$$ET_c = K_c \times ET_o \qquad (1)$$

The K_c value represents crop-specific water use and required for accurate estimation of the irrigation requirement of the crop. For the present study, adopted the $K_c$values for initial, mid, and end phases (1.15, 1.36 and 0.86, respectively) from Kaur *et al.* (2017) who have estimated the K_c values for different stages of rice crop grown under different transplanting dates for Ludhiana. ET_o expresses the evaporating power of the weather at a given location and a specific time of the year and does not reflect the soil and crop characteristics.

Effective precipitation (P_{eff}) is that part of the total rainfall which is retained by the soil and is potentially available for meeting the crop water requirement. Generally,it is less than the total amount of rainfall as,in reality, the crop cannot appropriately use the whole of the rain owing to the surface run-off or deep percolation losses (Dastane, 1978). The $P_{eff}$for rice crop was also computed by CROPWAT 8.0. $ET_o$was determined using weather parameters for the year 2000 to 2017for different zones (Table 1). The average surface runoff factor for Punjab is 13% through rainfall in *Kharif,* and deep percolation losses from rice fields are about 60 % (Prihar *et al.,* 1993).

To calculate the irrigation requirement(*IR*) took the difference between crop water requirement (CWR) and P_{eff}. The irrigation requirement is zero if P_{eff} is larger than the CWR. Therefore,

$$IR = \max (0, CWR - P_{eff}) \qquad (2)$$

Green water evapotranspiration (ET_{green}) is the ET of

Table 1: Geographical coordinates of selected agroclimatic zones of Punjab

Sl. no.	Agroclimatic zone	Representing station	Latitude	Longitude	Altitude
1.	South – western zone (SWZ)	Bathinda	30° 17' N	74° 58' E	211 m amsl
2.	Central plain zone (CPZ)	Ludhiana	30° 55' N	75° 54' E	247 m amsl
3.	Sub-mountainous zone (SMZ)	BallowalSaunkhari	31° 65' N	76° 23' E	357 m amsl

the rainfall. It is the minimum of total ET_c and P_{eff}. Blue water evapotranspiration (ET_{blue}), in other words, field ET of irrigation water, is equal to the total ET_c minus P_{eff}, but zero when P_{eff} exceeds ET_c:

$$ET_{green} = \min(ET_c, P_{eff}) \quad (3)$$

$$ET_{blue} = \max(0, ET_c - P_{eff}) \quad (4)$$

Both the WF_{blue} and WF_{green} are indicators of the consumptive amount of water by the rice crop. In contrast, the WF_{grey} indicates water quality.

The WF_{grey} accounts for a load of pollutants added during the crop season to the freshwater resources. This pollution happens due to the application of the chemical fertilizers and plant protection chemicals in the field. There is no consideration of WF_{grey} in the present investigation following Zhuo *et al.* (2016); Bosire *et al.* (2017) and Civit *et al.* (2018), and the calculated WF_{total} of the rice cultivation as the sum of the *green* and blue components.

The accumulation of daily *ET* (mm day^{-1}) over the entire growing period was used to calculate the *green* and *blue* components in crop water use (*CWU*, m^{3}ha^{-1}).

$$CWUgreen = 10 \times \sum_{d=1}^{lgp} ETgreen \quad (5)$$

$$CWUblue = 10 \times \sum_{d=1}^{lgp} ETblue \quad (6)$$

Where ET_{green} and ET_{blue} represent *green* water evapotranspiration, and the blue water evapotranspiration respectively. Factor 10 is for the conversion of water depths in millimetres into water volumes per land surface in m^{3}ha^{-1}, *lgp* stands for the length of the growing period in days. The summation is done over the entire growing period, *i.e.,* from the day of planting (day 1) to the day of harvest.

RESULTS AND DISCUSSION

Variation in the weather conditions

In Punjab, the average minimum and maximum temperature during the rice crop season (May-October) ranged between 23.2-24.5 °C and 34.3-36.1 °C. The south-western zone (SWZ) is relatively warmer than the central plain zone (CPZ) conversely, the sub-mountainous zone (SMZ) in the northern region of the state was coolest among the selected locations

The lowest mean temperature recorded at Ballowal Saunkhari(SMZ) was 28.6 °C,followed by 29.6 °C at CPZ and 30.2 °C at Bathinda (SWZ) (Fig. 1). The maximum and minimum temperatures at different zones of Punjab increased linearly with the varying rate at different locations, except for the maximum temperature, which showed a slightly decreasing trend at SWZ (@ -0.014 °Cyear^{-1}). Observed a high variation in the rainfall during cropping season at different locations. The mean (2000-2017) rainfall was 369.9 mm at SWZ, 781.8 mm at SMZ and 610.4 mm at CPZ. The lowest rainfall only 162.6 mm was recorded during the year 2000 in SWZ that was 355.4 mm during 2002 at CPZ and 500.0 mm during 2012 at SMZ. The entire Punjab state received, the least crop season rainfall amount of 367.4 and 432.8 mm during 2012 and 2002, respectively. Contrarily, the highest rainfall of 558.4 mm (during 2016), 1133.5 mm (during 2008) and 1192.0 mm (during 2011), in respective zones.

Reference evapotranspiration (ET_o)

The rate of ET_o was too high during the May-June due to higher environmental temperatures and almost dry weather conditions. The month of May and June recorded a maximum rate of ET_o followed by July and August, and subsequently, it declined during September, October, and November. The gradual decrease in the mean ETo has been recorded from crop initiation (May) until its maturation phase (October) at different regions owing to the temperature and rainfall variations. In different years the range of the ETo was 4004 to 1954 mm at SWZ, 3824 to 1822 mm at SMZ and 3634 to 1673 mm at CPZ. Higher environmental temperatures accelerated the seasonal ET rainfall played the inhibitory role in this acceleration. Therefore, the heavy rainfall periods experienced lower ET than low rainfall years and *vice-versa*.In different years, with 1003.1 mm mean EToSWZ experienced the highest rate of ET followed by

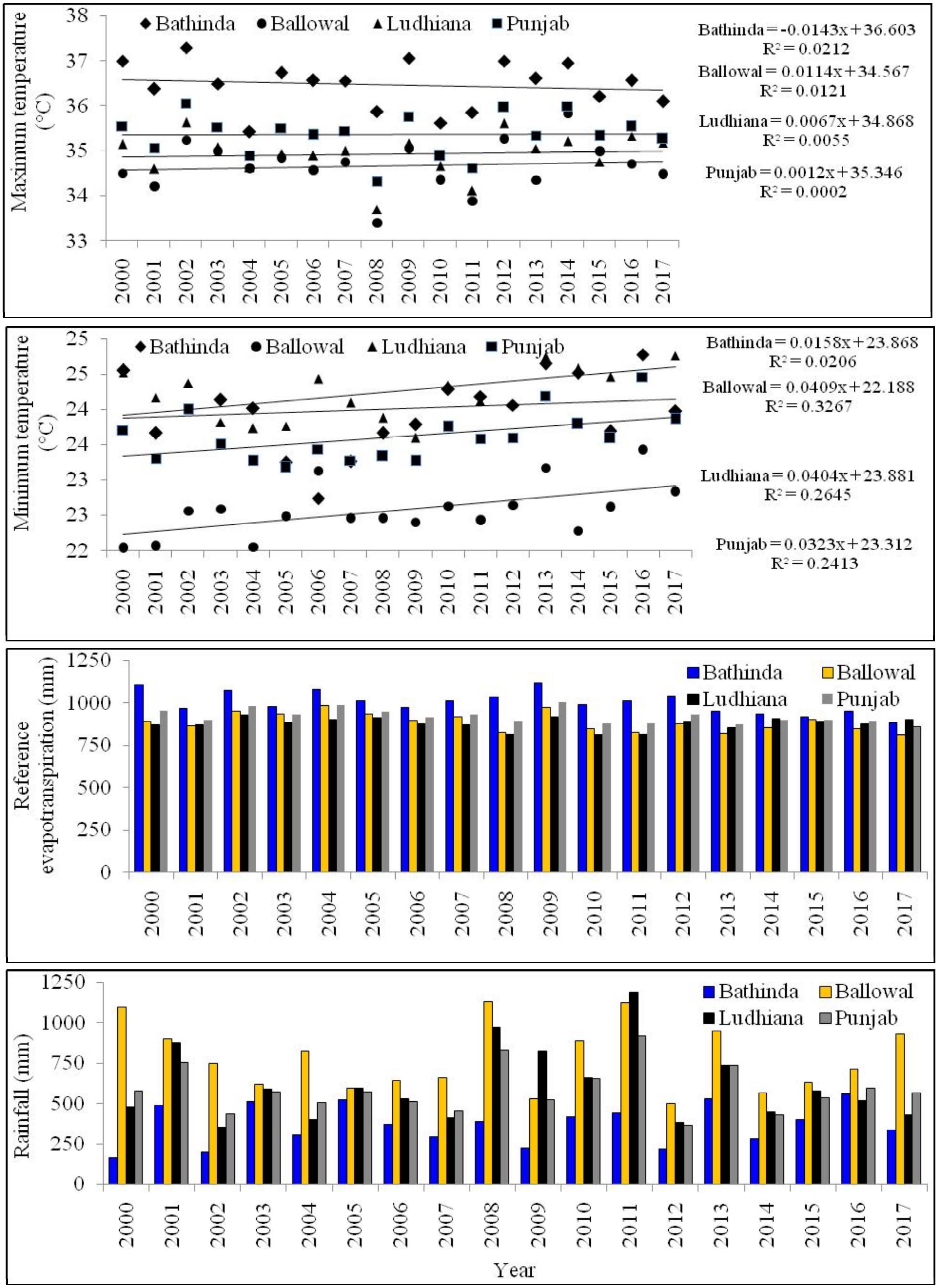

Fig. 1: Variation in weather conditions in different zones

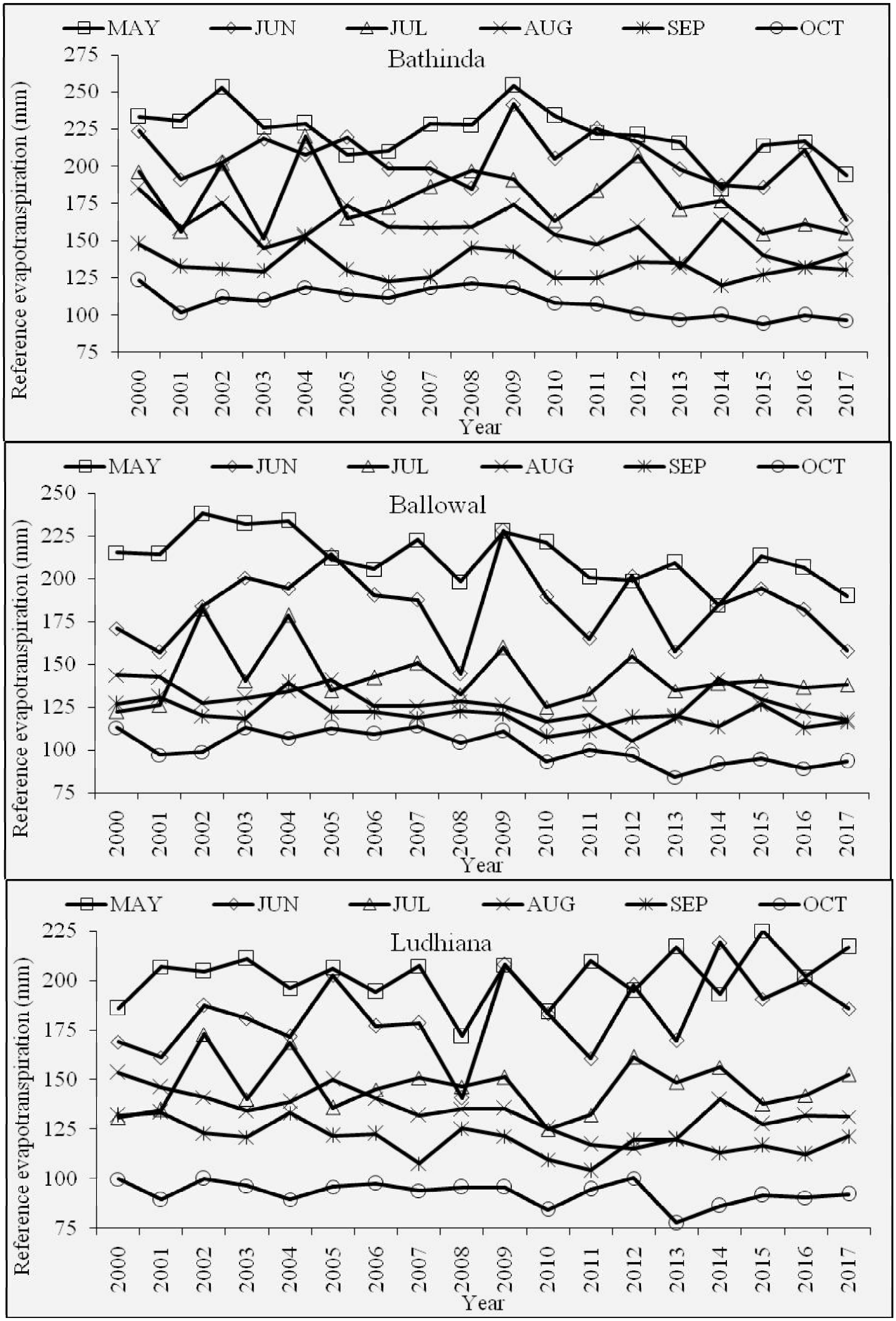

Fig.2: Reference evapotranspiration (ETo) in different zones of Punjab

Table 3: Water footprint of rice in different zones of Punjab

Year	South-western zone					Central plain zone					Sub-mountainous zone				
	Area	yield	WFP (liters kg^{-1})			Area	Yield	WFP (liters kg^{-1})			Area	Yield	WFP (liters kg^{-1})		
	(000 ha)	(kg ha^{-1})	Green	Blue	Total	(000 ha)	(kg ha^{-1})	Green	Blue	Total	(000 ha)	(kg ha^{-1})	Green	Blue	Total
2000	610	3526	328	2670	2999	1651	3616	769	1889	2658	350	3161	1463	1910	3373
2001	517	3688	846	2117	2963	1622	3615	1098	1904	3002	350	3024	1503	2075	3578
2002	598	3260	453	2550	3003	1600	3687	552	1998	2550	332	3096	1199	2214	3414
2003	598	3777	814	1962	2775	1667	3790	938	1794	2732	349	3259	1145	2026	3171
2004	589	3947	392	2176	2568	1697	4084	610	1799	2410	361	3372	1077	2065	3143
2005	563	3994	762	2059	2821	1736	3961	890	1811	2701	355	3241	1110	2066	3176
2006	537	4041	537	1937	2474	1708	3825	781	1793	2573	376	3257	1011	1933	2944
2007	545	4132	472	1905	2377	1706	4073	732	1600	2332	358	3520	1061	1796	2858
2008	617	4219	586	1671	2257	1741	4032	1095	1571	2667	376	3579	1259	1589	2848
2009	641	4091	410	1744	2154	1763	4114	880	1655	2536	398	3510	915	1779	2694
2010	655	3935	762	1674	2436	1766	3838	915	1549	2464	409	3641	1294	1536	2831
2011	646	3678	679	1728	2407	1768	3789	1107	1488	2595	406	3466	1245	1594	2839
2012	672	4074	392	1803	2195	1780	4079	653	1625	2278	397	3546	894	1756	2650
2013	686	4050	589	1703	2292	1771	4041	904	1542	2447	392	3306	1293	1728	3021
2014	728	3778	337	1818	2155	1771	3974	675	1690	2365	396	3210	1010	1860	2870
2015	788	3884	651	1767	2418	1783	4065	765	1545	2311	399	3650	982	1769	2751
2016	841	4093	665	1629	2294	1801	4231	656	1483	2140	405	3698	1094	1584	2678
2017	849	4239	531	1564	2095	1805	4474	641	1429	2069	410	3824	1222	1515	2737

Table 2: Effective precipitation, crop evapotranspiration and precipitation deficit in rice season in Punjab

Year	SWZ			CPZ			SMZ			Punjab		
	P_{eff}	ETc	Deficit rain (%)	P_{eff}	ETc	Deficit rain (%)	P_{eff}	ETc	Deficit rain (%)	P_{eff}	ETc	Deficit rain (%)
2000	1530	2060	-34.6	4409	5770	-30.9	8681	11504	-32.5	4873	6445	-32.2
2001	4379	5712	-30.5	6882	9058	-31.6	8414	11093	-31.8	6558	8621	-31.5
2002	1212	1515	-25.0	3199	4151	-29.8	6950	9020	-29.8	3787	4895	-29.3
2003	4318	5868	-35.9	5455	7290	-33.6	5491	7246	-31.9	5088	6801	-33.7
2004	2492	3026	-21.4	3810	4804	-26.1	6675	8058	-20.7	4325	5296	-22.4
2005	4787	6286	-31.3	5148	6903	-34.1	5591	7464	-33.5	5175	6884	-33.0
2006	3360	4188	-24.6	4189	5545	-32.4	5381	7146	-32.8	4310	5626	-30.5
2007	2615	3331	-27.4	3781	4950	-30.9	5788	7586	-31.1	4062	5289	-30.2
2008	3023	3798	-25.6	8477	10681	-26.0	9855	12410	-25.9	7119	8963	-25.9
2009	1859	2479	-33.3	6422	8521	-32.7	4667	6231	-33.5	4316	5744	-33.1
2010	3897	5183	-33.0	6154	8251	-34.1	8157	10663	-30.7	6070	8032	-32.3
2011	3968	5367	-35.3	8434	10810	-28.2	9522	12356	-29.8	7308	9511	-30.1
2012	2020	2694	-33.4	3509	4757	-35.6	4794	6486	-35.3	3441	4646	-35.0
2013	4750	6072	-27.8	6399	7977	-24.7	8674	11071	-27.6	6607	8374	-26.7
2014	2665	3481	-30.6	3799	4986	-31.2	4084	5470	-33.9	3516	4645	-32.1
2015	3721	4912	-32.0	5181	6892	-33.0	5811	7730	-33.0	4904	6511	-32.8
2016	5062	6749	-33.3	4075	5324	-30.7	6091	7961	-30.7	5076	6678	-31.6
2017	2984	3731	-25.0	3135	3951	-26.0	7937	10424	-31.3	4686	6035	-28.8
Mean	3258	4247	-30.4	5137	6701	-30.5	6809	8884	-30.5	5068	6611	-30.4

SMZ (888.0 mm) and CPZ (329 mm). The mean ETo for the rice crop period for whole Punjab state was 923.0 mm (Fig. 2).

Effective rainfall (P_{eff}) and crop evapotranspiration (ET_c)

P_{eff} in Punjab state ranged from 3411 to 7308 $m^3 ha^{-1}$ for ETc range of 4645 - 9511 m^3 ha^{-1}. There was g deficit rainfall from 74.1% (2004) - 76.8% (2012) in rice crop. The high P_{eff} was able to meet the high ETc demand at various temporal and spatial environments (Table 2). The maximum P_{eff} was 5062, 9855 and 8477 $m^3 ha^{-1}$ while, the highest ETc of rice was 6749, 12410 and 10810 m^3 ha^{-1}, at SWZ, SMZ and CPZ, respectively. The ETc simultaneously increased with P_{eff} and *vice-versa*. Hence for low rainfall years, a large part of the ETcrequirement was met by applying irrigation from surface and groundwater. Therefore, under low rainfall (arid/semi-arid) zones, a higher portion of the precipitation may be converted as the P_{eff} by reducing the surface run-off and deep percolation losses through improved crop management practices. The results (Table 2) revealed that during the early years, the P_{eff} was lower (4873 $m^3 ha^{-1}$ during 2000 and 3747 $m^3 ha^{-1}$ during 2002) that was insufficient to fulfil the crop water requirement. The consequent notification of "The Punjab Preservation of Subsoil Water Act" (referred as Act-2009) made it mandatory for all farmers "not to sow paddy nursery before 10th day of May" and not to go for transplanting "before such date, as may be notified in this regard by the State Government" (Sharma *et al.,* 2010). The adoption of improved water management practices, particularly the change in crop calendar enforced through notification of Act-2009, has considerably improved P_{eff} in later years (7119 $m^3 ha^{-1}$ during 2008 and 7308 $m^3 ha^{-1}$ during 2011). The date of transplanting was notified as 10th June in 2009 and shifted to June 15th by notification in 2014. This change of the date of transplanting has shifted the crop growing season to a period of low ET and to coincide it better with the onset of monsoon. Further, the evaporation losses are more than the transpiration losses during the early phases of crop growth because of the exposure of the large land surface to the sunlight. As the crop grows, the

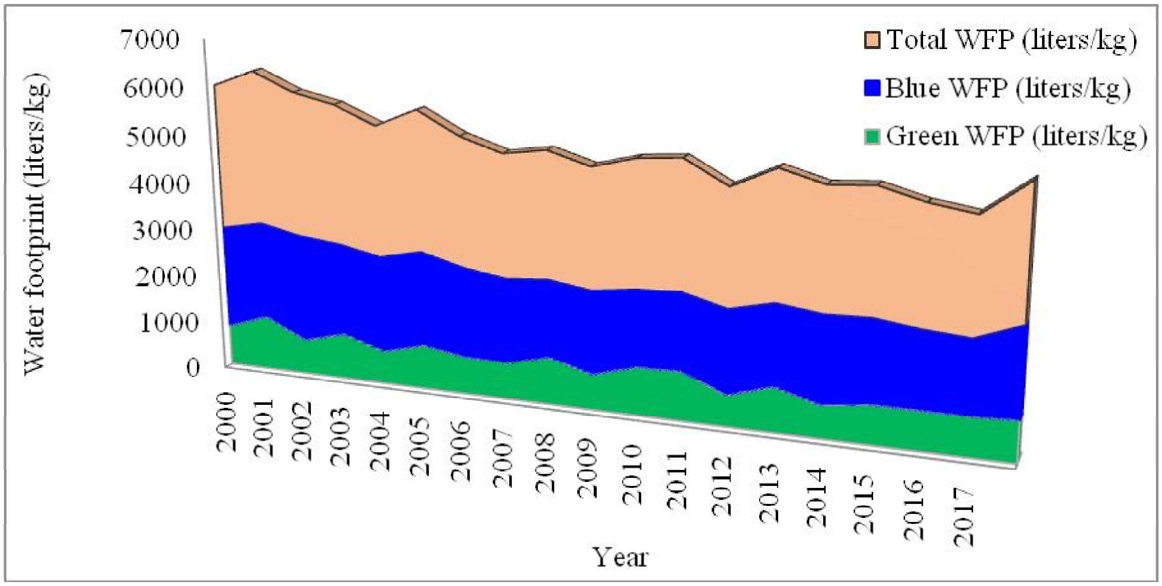

Fig. 3: Green, blue and total water footprints of rice in Punjab

transpiration exceeds the evaporation due to a fully developed crop canopy.

Area and productivity of rice

Both area and productivity of rice have considerably increased in Punjab. During 2000,the total area under rice cultivation was 610, 1651 and 310 thousand hectares at SWZ, CPZ and SMZ which was subsequently increased up to 849, 1805 and 410 thousand hectares until 2017, in respective zones. Similarly, the corresponding yield of the rice has also increased in Punjab over the years. In 2017, rice productivity of 4239, 4474 and 3824 $kgha^{-1}$ had been increased by 16.8, 19.2 and 17.3 % from 3526, 3616 and 3161 $kgha^{-1}$ (2000), respectively in southwestern, central plain and sub-mountainous zones (Table 3).

Water footprint assessment

The edapho-climatic-management factors and inherent geno-morphological characters of the selected cultivar influenced the WFP of the cultivation process. Minimum WF_{green} of rice production was 328 litre kg^{-1} (during 2000) in south western zone 552 litre kg^{-1} (during 2002) under central plain, and 894 litre kg^{-1} (during 2012) under sub-mountainous regions (Table 3) due to low rainfall of 162.6 mm (in SWZ) 500 mm (in SMZ) and 355.4 mm (in CPZ), respectively. On the other hand, heavy rainfall 558.4 mm (at SWZ during 2016), 1133.4 mm (at SMZ during 2008) and 1192 mm (at CPZ during 2011) correspondingly responded to maximum WF_{green} of 2670, 1998 and 2214 litre kg^{-1} rice. An increase in the WF_{blue} reveals the high irrigation water input applied for crop production. Mekonnen and Hoekstra (2010) also reported that the most significant WF_{blue} among the cereals is for rice and wheat crops, and both of these together accounts for 45% of the blue water footprint globally.

The total water footprint (WF_{total}) is the summation of the water consumed as evaporation and transpiration from precipitation (WF_{green}) and through irrigation (WF_{blue}) over the entire crop growth season at a given location. Thus, it largely depends upon the climatic and water management factors. Our results described that in the study period, WF_{total} was 2095-3003, 2069-3002 and 2650-3578 litre kg^{-1} rice in south western, central plain and sub-mountainous regions. The average WFP in the respective regions was 2482, 2490 and 2976 litre kg^{-1}. Distribution of WF_{total} between the WF_{green} and WF_{blue} was22.8 and 77.2% in south-western zone, 32.7 and 67.3% in central plains, and 38.8 and 61.2% in sub-mountainous zones. These results revealed the values of $WF_{total,}$ and the WF_{green} of rice increased from south-western zone towards the central and sub-mountainous regions of the state, whereas, the WF_{blue} followed the opposite fashion (Table3). For whole Punjab state, the minimum and maximum WF_{green} was 646 (2012) and 1149 litre kg^{-1} (during 2001), WF_{blue} was in the range of 150 (during 2017) and 2254 litre kg^{-1} of rice (during 2002). Hence, the highest WF_{total} of rice production 3010 and 3181 litre kg^{-1} rice during 2000 and 2001, which considerably reduced up to 2300 litre kg^{-1} rice during the year 2017. Share of WF_{green} and WF_{blue} in the WF_{total} was 32 and 68%, respectively (Fig. 3).

CONCLUSION

The WFP of a product is the sum of the WF of various activities involved in the entire production process. The WF_{green} is particularly relevant for agricultural produce as a higher WF_{green} means effective use of rainwater for meeting the ETneed of crops and thereby reducing the amount of irrigation water required for its cultivation (WF_{blue}). Thus, the WF_{blue} is highly dependent on the amount and temporal distribution of rainfall during the crop season as more the P_{eff}, lesser the irrigation requirement. The WF_{green} during the study period improved with synchronization of date of transplanting of rice with the onset of monsoon through the implementation of Act of 2009, and it varied from328 (SWZ) to 1503 liter kg^{-1} (SMZ) while, $WF_{blue,}$ varied from 1429 (CPZ) to 1954 liter kg^{-1} (SMZ). During the study period, irrigated transplanted rice on an average consumed about 2650 liters of water per kilogram of production (WF_{total}), and out of this, about 1804 liters of water (68%) was applied as irrigation. The change in crop calendar by legally prohibiting the early transplanting of rice up to mid-June, coupled with theimprovement in rice productivity, has primarily contributed to the reduction in the consumptive water footprint of rice production in the state.

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