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Agricultural Development in Punjab: An Empirical Analysis of Sustainability of Water Resources

Chhabilendra Roul[1]*, SK Chaudhury[2], Sheelabhadra Mohanty[3], Balvinder Sukla[1] and Naleeni Ramawat[4]

[1]*Amity University, Noida-201313, Uttar Pradesh, India*
[2]*NRM Division, Indian Council of Agricultural Research, KAB-II, New Delhi-110012, India*
[3]*ICAR-Indian Institute for Water Management, Bhubaneswar-751023, Odisha, India*
[4]*Amity Institute of Organic Agriculture, Amity University, Noida, Uttar Pradesh, India*
**Corresponding author E-mail: c_roul@hotmail.com*

Abstract

Sustainable management of water resources for agriculture and non-agricultural purposes warrants thorough analysis of the issues relating to depletion of ground water, irrigation water use efficiency, smart irrigation management, waterlogging due to poor drainage and flood irrigation, and suitable cropping patterns. Overexploitation of groundwater resources for use in agriculture has caused serious groundwater depletion in north-western states of India. In states of Punjab, Haryana, Rajasthan, Delhi and Western UP, the depletion of groundwater resources has increased the cost of pumping and has raised questions about sustainable groundwater supply in the long run. In the present study, effort has been made to develop composite water sustainability index (CWSI) for the state of Punjab to quantify the status of sustainability water resources in the state. Seventeen indicators crucial for sustainability of agriculture and water resources were identified for the analysis. The CWSI for the state of Punjab was calculated as 0.519, with the district-wise value varying from a minimum of 0.409 in Mansa to a maximum of 0.606 in Muktasar district. The reason for such low to moderate water sustainability in the state of Punjab was attributed to overexploitation of groundwater and improper cropping system.

Key words: Water sustainability index, Overexploitation of groundwater, Water use efficiency, Sustainability indicators

Introduction

Irrigated agriculture plays a crucial role in in meeting the food requirement of ever-increasing worldwide population. At the same time, it is also the largest exploiter of water resources, since about 70% of the freshwater is withdrawn to produce food (FAO, 2012). At the same time due to the water resource-energy linkage, high amounts of energy consumption are associated with freshwater supply (Sishodia *et al*., 2016). In this context, water resources experience increasing pressures due to the combined actions of socio-economic challenges and climate change impacts. Therefore, there is an urgent need to preserve the ecosystem from further damages, with sustainable agriculture and water resources management (Pretty, 2008; Godfray *et al*., 2010).

The National Research Council (NRC) of USA (NRC, 2010) envisaged four sustainable goals for 21st Century agriculture. Sustainable agriculture should (1) satisfy human food, feed, and fibre needs, and contribute to biofuel needs, (2) enhance environmental quality and the resource base, (3) sustain the economic viability of agriculture, and (4) enhance the quality of life for farmers, farm workers, and society as a whole. The imperative of the above sustainable agricultural development debate is that, enhancing the natural resource base (soil, water, biodiversity, ecosystem services) is one of the prime objective of sustainable agriculture.

The biological and physical scientists have tended to focus on biophysical measures of agricultural sustainability, such as crop yields, quality of soil and water, and input use efficiency. The narrow focus only on agricultural productivity without allowance to environmental impact has serious repercussions for the long-term sustainability of the farming system. Despite these difficulties, a considerable body of work has been developed by crop and soil scientists to define and measure indicators of resource quality as a basis for tracking the sustainability of agricultural systems (Barnett *et al.*, 1995; Pieri *et al.*, 1995). The agro-ecological dimensions consider the extent of depletion of nutrients, extent of land degradation, water management issues, water foot-print per person, water use efficiency (WUE), agro-biodiversity, microbial mass, sustainability of agriculture, effects of intensive agriculture on environment and climate change, and greenhouse gas emission from major crops, etc.

There are several attempts to construct sustainable agricultural index by many scholars. Several agricultural sustainability assessment methods have been developed over the last decades (Binder *et al.*, 2010). Assessment methodologies are being developed for the purpose of research and policy, farm monitoring, farm extension, certification, self-assessment, landscape planning and consumer information (Schader *et al.*, 2014). Talukder *et al.* (2017) have summarised eight such methodologies which attempt to capture the holistic nature of agricultural sustain-ability. Environmental and economic and social aspects of sustainability need to be considered in agricultural sustainability assessment, and so holistic approaches that address different dimensions and objectives of sustainability are important (Gafsi *et al.,* 2006; Van de Fliert and Braun, 2002).

Sustainable management of water resources is one of the sub-goals of sustainable agriculture every society should thrive for. However, indiscriminate groundwater withdrawal for agriculture in some parts of the country has affected the sustainability of groundwater resources. Excessive groundwater exploitation has led to alarming decrease in groundwater levels mostly in north-western states of the country (CGWB, 2019). In recent studies, the analysis of GRACE satellite data revealed that the groundwater reserves in the states of Punjab, Haryana and Rajasthan are being depleted at a rate of 17.7±4.5 $km^3 yr^{-1}$ (Rodell *et al.*, 2009). It was also found that between August 2002 to December 2008, the above mentioned north-western states of India lost 109 km^3 of groundwater which is double the capacity of India's largest reservoir Wainganga and almost triple the capacity of 'Lake Mead', the largest man-made reservoir in the United States (Rodell *et al.*, 2009). In the present study, an attempt has been made to develop composite water sustainability index (CWSI) for the state of Punjab considering different indicators crucial for sustainability of agriculture and water resources.

Materials and Methods

The study was carried out for the state of Punjab which covers as area of 50,362 square kilometres, 1.53% of India's total geographical area. It is the 20th largest Indian state by area and 16th largest state by population comprising 22 districts. However, Punjab is one of the progressive and advanced state in India from economic and agriculture point of view. The region is ideal for wheat growing with rice, sugarcane, fruits and vegetables being other major crops in the state. The state is called as India's bread basket. It produces 19.5% of India's wheat, 11% of India's rice and 10.26% of India's cotton. However, excessive use of fertilisers and indiscriminate withdrawal of water for agriculture has raised questions about sustainability of land and water resources.

The Composite Water Sustainability Index (CWSI) for the state of Punjab was computed using the stepwise procedure prescribed in the OECD Handbook on constructing composite Indicators (OECD, 2008). The steps for construction of composite indicators include theoretical framework for selection of indicators, identification of data source and data collection, multivariate analysis, normalisation, weighting and aggregation, sensitivity analysis and validation of results. Seventeen indicators belonging to (1) climate and weather related indicators, (2) water stress indicators, and (3) water management related indicators were identified for computation of CWSI for the state of Punjab.

Climate and weather-related indicators

DAR (Deviation from long-term average rainfall): This indicator furnishes the drought and heavy precipitation frequency. A total of 41 years rainfall data from 1971 to 2011 was considered. Number of years in which the deviation from normal rainfall is more than 25%.

HCW (Heat and cold waves): Number of episodes of extreme weather conditions (heat and cold waves). The heat wave events are defined as the number of days with maximum temperature above 32°C and cold wave events are number of days with minimum temperature below 4°C. This is taking into consideration the major wheat crop sown in the region. A total of 41 years temperature data from 1971 to 2011 was considered.

CDD (Consecutive dry days): Number of dry spells of consecutive 14 dry days (June to Oct) were considered. Consecutive dry days can serve as an effective measure of seasonal drought. Consecutive dry days is defined as number of episodes with rainfall below 2.5 mm for consecutively 14 days during the monsoon days (June to September).

GDD (Growing degree days): Growing degree days is a weather-based indicator for assessing crop development. It is defined as the mean daily temperature (average of daily maximum and minimum) above a certain threshold temperature. GDD is calculated using the formula, CDD = (Tmax+Tmin)/2 - base temperature (5°C). In the present study, GDD was computed for wheat crop considering duration from 16th November to 15th March.

SPI (Standardized precipitation index): SPI is a probability index that gives a representation of abnormal wetness and dryness. SPI < -0.99 is considered as undesirable for agricultural sustainability.

Water stress indicators

GDI (Groundwater development index): Ground water development index is an index estimated by the Central Ground Water Board (CGWB, 2019) for the year 2017.

GWTD (Groundwater table depletion): The change in groundwater level in meters during the period 1996-2018 based on the data accessed from the Department of Water Resources, Punjab.

GWTD7 (Groundwater table depletion below 7m): Number of tube wells having water table at a depth of more than 7 meters. This is based on data accessed from Department of Water Resources, Punjab.

WQI (Water quality index): It is calculated based on pH and EC values. This is based on data accessed from the Central Ground Water Board. Lesser the value of the index, poorer is the quality of water.

TWD (Tube well density): It is the number of tube wells per 100 ha of area.

ROF (Runoff potential): It is defined as runoff potential as percentage of water demand in agriculture measures. Runoff potential is taken from the ICAR-Indian Institute of Soil and Water Conservation, Dehradun and crop wise area (ha) from the Directorate of Economics and Statistics, Department of Agriculture, Cooperation and Farmers Welfare, GOI.

RWS (Relative water supply): Water supply as percent of demand. This is calculated based on water availability (MCM), crop wise area (ha) and crop water requirement estimated as suggested by Chand *et al.* (2019).

Water management related indicators

WUE (Water use efficiency): This is calculated by taking irrigated area by source and dam-wise irrigation efficiency as per the methodology adopted by the Central Water Commission, Government of India and reported as percentage.

PUC (Percentage utilisation of potential irrigation): This is based on district-wise irrigated area and irrigation potential utilized as per information accessed from the Directorate of Economics and Statistics, and Ministry of Water Resources, GOI.

IDS (Investment on drainage system): This is calculated as investment on drainage system for degraded land based on the data accessed from the ICAR-Central Soil Salinity Research Institute, Karnal and the State Irrigation Departments of Punjab.

IWS (Investment on watershed): Investment on watershed/ rainwater management based on area under degraded lands (Source: ICAR-Central Soil Salinity Research Institute) and investment in watershed management during the period 2009-15 accessed from the Department of Land Resources, Ministry of Rural Development, GOI.

MI (micro-irrigation): This is the area under micro-irrigation based on the proxy indicator of groundwater utilisation.

Normalization

Data of different indicators can be aggregated into a composite index without being normalized if all the variables are measured with the same unit. But in many situations, the variables to be aggregated have different units. Therefore, normalization is a crucial process in developing sustainability indices as it makes indicators comparable with each other on a common basis. Normalization is, therefore, the process of reducing the measurements to a standard scale which helps to avoid the dominance of extreme values in a data set and partially corrects data quality problems. Normalization of indicators is required to make the indicators mathematically operational in aggregation (Talukder *et al.,* 2017). In this study, the benchmark method of normalization has been followed. Benchmarking function assigns a normalized value to each indicator based on its level of sustainability, determined by reliable and authentic literature and international legislation sources.

Assigning weights to indicators

Assigning weights to individual indicators is an important step in construction of composite indicators. Various scholars have suggested three possible ways of assigning weights to individual indicators. These are equal weights, expert opinion and principal component analysis (PCA). Each system of assigning weights has its own advantages and disadvantages. Equal weights may undermine some variables which largely influences the index; expert opinion will be subjective and limited to availability of experts, number of variables and research time to get the response; and PCA works with the assumption that linear relationship exist among variables. In the present study, a comparison has been made among the three approaches.

Results and Discussion

Table 1 shows the district-wise weather and climate related indicators in the state of Punjab. The DAR index values shows that highest drought years is observed in the district of Mansa (36.59%) followed by Bhatinda district (31.71%). Lowest drought years is observed in the districts of sub-mountain districts of Gurdaspur, Hoshiarpur, Rupnagar and Shahid Bhagat Singh Nagar apart from Jalandhar (9.76). The average frequency of drought years in the state of Punjab is observed 20.09%. The HCW index values suggest that the frequency of extreme weather events are maximum in Ferozpur (4359) followed by Sangrur district (4270). On the other hand, the districts like Hoshiarpur (1167) and SBS Nagar (1382) have the least frequencies of such extreme episodes. The average number of such episodes in the state of Punjab is 2299. It is observed from the CDD index values that, events of consecutive 14-days dry spell has occurred maximum times in the Muktasar (92) district followed by Faridkot (90) and Mansa (70) district. The least frequency is

Table 1. District-wise weather and climate related indicators

District	DAR	HCW	CDD	GDD	SPI
Amritsar	19.51	3632	37	1546	17.07
Bhatinda	31.71	2147	54	1616	14.63
Faridkot	26.83	2062	90	1614	19.51
Fatehgarh Sahib	19.51	1515	56	1460	9.76
Ferozpur	24.39	4359	56	1601	19.51
Gurdaspur	9.76	2542	24	1351	14.63
Hoshiarpur	9.76	1167	22	1329	9.76
Jalandhar	9.76	1545	38	1474	9.76
Kapurthala	12.20	1850	38	1566	9.76
Ludhiana	14.63	1545	51	1474	12.20
Mansa	36.59	2160	70	1631	19.51
Moga	29.27	1920	61	1582	17.07
Patiala	21.95	1887	57	1585	14.63
Rupnagar	9.76	2960	28	1387	9.76
Sangrur	29.27	4270	53	1608	14.63
Muktasar	26.83	2137	92	1606	19.51
SBS Nagar	9.76	1382	16	1427	12.20
State Average	20.09	2299	49.59	1521	14.35

Abbreviations as defined in Materials and Methods

observed in SBS Nagar (16) followed by Hoshiarpur district (22). The average value for the state of Punjab is 49.59 times.

The parameter growing degree days in wheat (GDD) is crucial as the wheat growing state of Punjab depend on favorable weather conditions for healthy growth of the wheat crop. The state average GDD (from November 15 to March) is observed as 1521 (Table 1). Highest GDD is observed in Mansa district (1631) closely followed by Bhatinda, Ferozepr, Faridkot, Muktasar, and Sangrur districts. The least GDD during this period is observed in Hoshiarpur (1329) followed by Gurdaspur district. Standardized precipitation index quantifies observed precipitation as a standardized departure from a selected probability distribution function that models the raw precipitation data. From Table 1, it is observed that probability of occurrence of standardized precipitation index (SPI) < -0.99, is 14.35 in the state. The highest probability of occurrence of such events (19.51%) is in Faridkot, Ferozpur, Mansa and Muktasar districts. The lowest probability of occurrence (9.76%) is observed in Fatehgarh Sahib, Hoshiarpur, Jalandhar, Kapurthala, and Rupnagar districts.

Table 2 shows the district-wise water stress indicators in the state of Punjab. The runoff potential as percentage of water demand in agriculture (ROF) is highest in Rupnagar (8.47%) followed by Amritsar district (5.73%). It is as low as 0.94% in Moga district, and the average value for the state is only 2.27%. The average groundwater development index (GDI) for the state is very high at 165.77% which is a matter of concern. The value is very high (>200%) for the districts of Sangrur, Jalandhar, Moga and Kapurthala districts, whereas it is somewhat reasonable (<100%) in the districts of Muktasar, Bhatinda, Rupnagar and Hoshiarpur districts.

The GWTD index values show that average groundwater depletion in the state during the period 1996-2018 is 9.67 m. Highest depletion of groundwater level during the period has occurred the Sangrur district (25.17 m) followed by Patiala district (21.68 m). Lowest groundwater depletion has occurred in Muktasar district (1.18 m) followed by Gurdaspur (2.37 m) and Faridkot district (2.46 m). In general, there has been more depletion of groundwater level in the districts with high groundwater development index (GWTD7) values suggest that in 77.32% tube wells in the state, groundwater level is below 7 m.

In Jalandhar, Sangrur and Moga districts, 100% of tubewells have groundwater level below 7 m, whereas in Amritsar, Fatehgarh Sahib,

Table 2. District-wise water stress indicators

District	ROF	GDI	GWTD	GWTD7	WQI	TWD	RWS
Amritsar	5.73	126	8.11	98.81	0.45	34	96
Bhatinda	1.24	93	8.04	80.00	0.27	23	87
Faridkot	0.99	160	2.46	48.57	0.22	37	74
Fatehgarh Sahib	2.07	191	16.41	96.43	0.37	40	79
Ferozpur	2.38	144	3.65	46.67	0.17	31	108
Gurdaspur	5.58	124	2.37	48.19	0.48	33	80
Hoshiarpur	4.75	99	5.76	72.00	0.51	31	78
Jalandhar	2.52	209	13.38	100.00	0.59	39	57
Kapurthala	1.83	205	11.48	94.29	0.65	48	48
Ludhiana	2.42	162	7.01	90.16	0.28	39	79
Mansa	1.36	138	8.42	83.87	0.14	26	83
Moga	0.94	207	15.64	100.00	0.38	33	77
Patiala	2.65	189	21.68	93.02	0.34	38	73
Rupnagar	8.47	98	4.99	61.90	0.27	28	120
Sangrur	2.50	211	25.17	100.00	0.27	36	75
Muktasar	1.18	70	1.18	3.70	0.27	32	114
SBS Nagar	2.88	107	8.67	96.00	0.56	36	76
State Average	2.27	165.77	9.67	77.32	0.40	34	84

Abbreviations as defined in Materials and Methods

Kapurthala, Ludhiana, Patiala and SBS Nagar districts, it is for more than 90% of the tubewells. The average WQI index value for the state is 0.40. The districts Kapurthala, Jalandhar and Hoshiarpur have better groundwater quality with higher WQI index. The TWD index shows that on an average, there are 34 tubewells per 100 ha area in the state. The tubewell density is highest in the Kapurthala district (TWD = 48) followed by Fatehgarh Sahib district (TWD = 40). The average water supply in the state as percentage of demand (represented by RWS index) is 84%. The RWS index is highest in Rupnangar district (120) followed by Muktasar district (114), whereas it is lowest in Kapurthala (48) followed by Jalandhar district (57).

Table 3 shows the district wise water management related indicators for the state. The average water use efficiency (WUE) for the state is 62.61%. It is highest for the districts of Jalandhar, Moga, Fatehgarh Sahib, Kapurthala, SBS Nagar and Patiala (about 70%). It is lowest in the district of Muktasar (35%) followed by Bhatinda (41.74%).

The PUC index values show that the average percentage of irrigation water utilised for the state is 79%. Highest value of 90% has been reached in several districts. The lowest PUC value of 60% is observed in the districts of Bhatinda, Faridkot, Mansa and Muktasar. The investment in drainage system (IDS) is uniform INR 0.27 lakh ha^{-1} in the state of Punjab in the absence of district wise data. The IWS index values show that the investment in watershed management programmes in the state is INR 32213 ha^{-1}. The value is high in districts like Hoshiarpur, Jalandhar and SBS Nagar, whereas the lower per hectare investment is observed in districts like Ferozepur and Mansa. The average value of MI indicator representing the area under micro-irrigation for the state is 2.98%. The value is highest in the districts of Gurdaspur (6.44%) and Faridkot (6.12%). The value is lowest in the districts of Mansa (1.34%) and Bhatinda (1.66%).

Table 3. District-wise water management related indicators

District	WUE	PUC	IDS	IWS	MI
Amritsar	66.91	90	0.27	7784	3.37
Bhatinda	41.74	60	0.27	32213	1.66
Faridkot	54.36	60	0.27	5919	6.12
Fatehgarh Sahib	69.99	90	0.27	32213	3.72
Ferozpur	67.72	80	0.27	1668	3.69
Gurdaspur	66.51	81	0.27	56601	6.44
Hoshiarpur	68.26	80	0.27	84929	3.38
Jalandhar	70.00	90	0.27	74327	2.51
Kapurthala	69.99	90	0.27	30377	4.67
Ludhiana	68.82	90	0.27	26081	4.10
Mansa	44.49	60	0.27	4613	1.34
Moga	70.00	90	0.27	36735	5.47
Patiala	69.81	90	0.27	32213	6.00
Rupnagar	68.59	90	0.27	22183	2.25
Sangrur	62.17	64	0.27	32213	3.64
Muktasar	35.00	60	0.27	32213	1.81
SBS Nagar	69.95	90	0.27	74246	2.16
State Average	62.61	79	0.27	32213	2.98

Abbreviations as defined in Materials and Methods

Table 4 shows the normalized water indicators for all the districts of the state using benchmark method of normalization. Some of the indices like DAR, HCW, CDD, GDI, GWTD and GWTD7 having higher index value for a particular district have been assigned lower values after normalization. This is due to the fact that the higher value of the indices imply lower sustainability. Table 5 shows the assigned relative weights to different indicators by the Equal weight, PCA weight and Expert weight method. The summation of the weights of all the indicators is equal to unity.

Table 6 presents the CWSIs for all districts of Punjab using the Equal weight, PCA weight and Expert weight approach along with ranking of the districts. In case of Equal weights, Muktasar has highest CWSI (0.610) followed by Gurudaspur (0.576). Mansa has the lowest CWSI (0.407) followed by Sangrur (0.449). In case of PCA weights, the first position is again occupied by Muktasar (0.597) closely followed by Gurudaspur district (0. 577). Mansa (0.414) and Sangrur district (0.454) occupy the last two positions. CWSIs with Expert weights also gave nearly similar results. Muktasar (0.611) occupies the highest rank followed by Gurudaspur district (0.586). The last two positions are occupied by and Mansa (0.407) and Sangrur districts (0.463). The average CWSI for the state is 0.514, 0.52 and 0.524 in Equal weight, PCA weight and Expert weight method respectively.

Table 4. Normalized water indicators using benchmark method

District	DAR	HCW	CDD	GDD	ROF	SPI	WUE	PUC	RWS	IDS	IWS	MI	GDI	GWTD	GWTD7	TWD	WQI
Amritsar	0.80	0.27	0.91	1.00	0.00	0.83	0.71	0.90	0.96	0.35	0.31	0.00	0.60	0.76	0.01	0.16	0.45
Bhatinda	0.68	0.57	0.87	0.92	0.00	0.85	0.15	0.60	0.87	0.35	1.00	0.00	0.84	0.76	0.20	0.44	0.27
Faridkot	0.73	0.59	0.78	0.93	0.00	0.80	0.43	0.60	0.74	0.35	0.24	0.00	0.36	0.93	0.51	0.08	0.22
Fatehgarh Sahib	0.80	0.70	0.86	1.00	0.00	0.90	0.78	0.90	0.79	0.35	1.00	0.00	0.14	0.52	0.04	0.00	0.37
Ferozpur	0.76	0.13	0.86	0.99	0.00	0.80	0.73	0.80	1.00	0.35	0.07	0.00	0.48	0.89	0.53	0.24	0.17
Gurdaspur	0.90	0.49	0.94	1.00	0.00	0.85	0.70	0.81	0.80	0.35	1.00	0.00	0.62	0.93	0.52	0.17	0.48
Hoshiarpur	0.90	0.77	0.95	1.00	0.00	0.90	0.74	0.80	0.78	0.35	1.00	0.00	0.79	0.83	0.28	0.22	0.51
Jalandhar	0.90	0.69	0.91	1.00	0.00	0.90	0.78	0.90	0.57	0.35	1.00	0.00	0.01	0.60	0.00	0.02	0.59
Kapurthala	0.88	0.63	0.91	1.00	0.00	0.90	0.78	0.90	0.48	0.35	1.00	0.00	0.04	0.66	0.06	0.00	0.65
Ludhiana	0.85	0.69	0.88	1.00	0.00	0.88	0.75	0.90	0.79	0.35	1.00	0.00	0.35	0.79	0.10	0.03	0.28
Mansa	0.63	0.57	0.83	0.84	0.00	0.80	0.21	0.60	0.83	0.35	0.18	0.00	0.52	0.75	0.16	0.35	0.14
Moga	0.71	0.62	0.85	1.00	0.00	0.83	0.78	0.90	0.77	0.35	1.00	0.00	0.03	0.54	0.00	0.19	0.38
Patiala	0.78	0.62	0.86	1.00	0.00	0.85	0.77	0.90	0.73	0.35	1.00	0.00	0.16	0.36	0.07	0.05	0.34
Rupnagar	0.90	0.41	0.93	1.00	0.00	0.90	0.75	0.90	1.00	0.35	1.00	0.00	0.80	0.85	0.38	0.31	0.27
Sangrur	0.71	0.15	0.87	0.96	0.00	0.85	0.60	0.64	0.75	0.35	1.00	0.00	0.00	0.26	0.00	0.10	0.27
Muktasar	0.73	0.57	0.78	0.97	0.00	0.80	0.00	0.60	1.00	0.35	1.00	0.00	1.00	0.97	0.96	0.21	0.27
SBS Nagar	0.90	0.72	0.96	1.00	0.00	0.88	0.78	0.90	0.76	0.35	1.00	0.00	0.74	0.74	0.04	0.09	0.56
State Average	0.799	0.54	0.88	1.00	0.08	0.86	0.61	0.96	0.84	0.35	1.00	0.03	0.00	0.00	0.23	0.16	0.40

Abbreviations as defined in Materials and Methods

Table 5. Assigned relative weights for water indicators using different methods

Variable	Equal weight	PCA weight	Expert weight
DAR	0.063	0.066	0.060
HCW	0.063	0.067	0.048
CDD	0.063	0.064	0.063
GDD	0.063	0.046	0.063
ROF	0.063	0.067	0.056
SPI	0.063	0.064	0.055
WUE	0.063	0.069	0.085
RWS	0.063	0.072	0.088
IDS	0.063	0.064	0.052
IWS	0.063	0.065	0.065
MI	0.063	0.068	0.057
GDI	0.063	0.054	0.065
GWTD	0.063	0.052	0.063
GWTAB7	0.063	0.059	0.058
TWD	0.063	0.066	0.055
WQI	0.063	0.054	0.062
Total weights	1	1	1

Abbreviations as defined in Materials and Methods

The rank correlations between $CWSI_{EW}$ and $CWSI_{PCA,}$ $CWSI_{EW}$ and $CWSI_{EXW}$, $CWSI_{PCA}$ and $CWSI_{EXW}$ are 0.991, 0.985 and 0.996, respectively. These correlations are highly significant. In other words, the ranking of districts with respect to CWSI remains consistent irrespective of the change in methodology of assigning weights to individual indicators. The reasons for inter-district variation in CWSIs in Punjab is due to difference in agro-ecology of the districts and cropping pattern adopted. The dry regions with less annual rainfall like the districts of Sangrur, Mansa and Faridkot are having consistently low CWSIs and the districts bordering Lower Siwalik Hills having diversified cropping patterns are having consistently higher CWSIs. Fig. 1 shows the CWSIs of different districts in graphical form. Table 7 presents the t-statics for different CWSIs calculated based on the three weighting methods. It is evident that the t-ratios are not significant at any level of significance. Hence, it can be safely concluded that the weighting methodologies are not making significant difference in the calculation of CWSIs for various districts as well for the entire state of Punjab.

As the methodological variations do not have significant impact on the outcome (estimated value of CWSIs), it would not be inappropriate to take the average of the estimated CSWIs by three different approaches, to arrive at a single measure of water sustainability. Table 8 presents such average CWSIs for all districts for the state of Punjab. From Table 8, it is evident that the state has a lower moderate water sustainability at 0.512, just marginally above the 0.500 benchmark. The

Table 6. Combined Water Sustainability Indices (CWSI) for the state of Punjab

District	Equal weights	Rank	PCA Weight	Rank	Expert Weight	Rank
Amritsar	0.462	14	0.467	13	0.480	13
Bhatinda	0.496	12	0.501	12	0.496	12
Faridkot	0.462	13	0.461	14	0.464	15
FatehgarhSahib	0.509	9	0.517	8	0.521	8
Ferozpur	0.457	15	0.461	15	0.476	14
Gurdaspur	0.576	2	0.577	2	0.586	2
Hoshiarpur	0.564	3	0.571	3	0.571	3
Jalandhar	0.516	6	0.520	6	0.522	6
Kapurthala	0.512	7	0.514	9	0.517	9
Ludhiana	0.511	8	0.519	7	0.522	7
Mansa	0.407	17	0.414	17	0.407	17
Moga	0.501	11	0.508	11	0.514	10
Patiala	0.502	10	0.509	10	0.514	11
Rupnagar	0.551	4	0.560	4	0.566	4
Sangrur	0.449	16	0.454	16	0.463	16
Muktasar	0.610	1	0.597	1	0.611	1
SBS Nagar	0.536	5	0.543	5	0.546	5
Punjab	0.514		0.520		0.524	

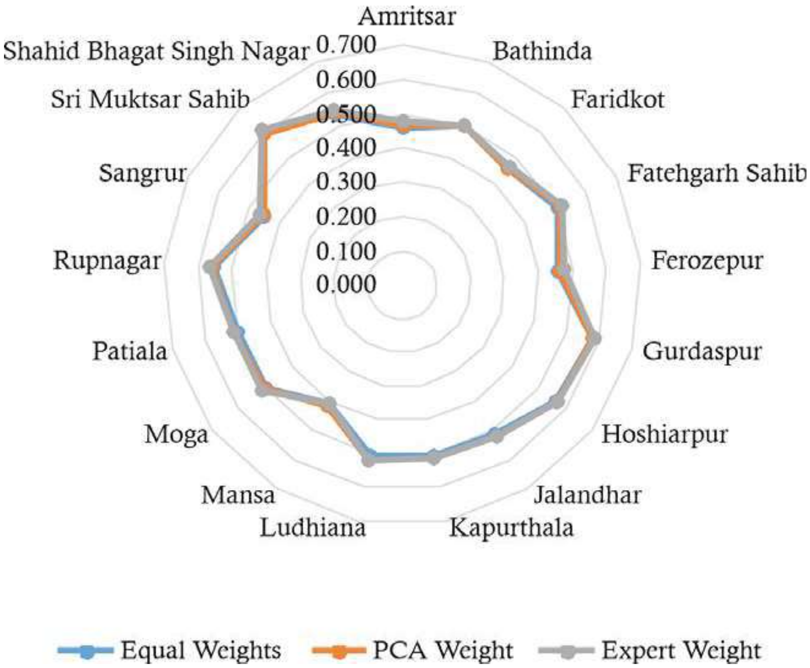

Fig. 1 CSWIs for different districts of Punjab

Table 7. Difference between CWSI values among different weighting methodologies

Punjab	BM_Equal	BM_PCA	BM_Expert
BM_Equal	0		
BM_PCA	0.006 (t -0.246, P 0.403)	0	
BM_Expert	0.010 (t -0.515, P 0.304)	0.004 (t -0.277, P 0.391)	0

Table 8. Reconstructed CWSI value for the state

District	CWSI
Amritsar	0.470
Bhatinda	0.498
Faridkot	0.462
Fatehgarh Sahib	0.516
Ferozpur	0.465
Gurdaspur	0.580
Hoshiarpur	0.569
Jalandhar	0.519
Kapurthala	0.514
Ludhiana	0.517
Mansa	0.409
Moga	0.508
Patiala	0.508
Rupnagar	0.559
Sangrur	0.455
Muktasar	0.606
SBS Nagar	0.542
Punjab	0.519

CWSI stands for composite water sustainability index

reasons for such moderate water sustainability can be attributed to two reasons. They are (a) low sustainability of sub-spatial CWSIs (district CWSIs) add up to low aggregate CWSI for the state; and (b) low values of individual indicators pertaining to the larger spatial dimension.

(a) Low values of District CWSIs

As Table 8 shows, the state's CWSI at 0.519 is reflective of the district CWSIs which vary between 0.409 in Mansa to 0.606 in Muktasar district. Six out of 17 districts, namely Mansa, Sangrur, Ferozepur, Faridkot, Bathinda and Amritsar, a contiguous belt of Malwa region of the state plus Amritsar and Ferozepur of the Majha region have CWSIs lower than 0.500, dragging the state average. In addition to the specific agro-ecological factors, management of water resources are much to be desired.

(b) The low values of individual Parameters for the states

The normalised data for the state has been presented in Table 4. From Table 4, it can be seen that the normalised values with respect to 7 out of 17 indicators are pretty low. For instance, the normalised values of indicators like for Micro irrigation, Groundwater development index, Groundwater table depletion, Tubewell density, Groundwater table at more than 7 meters depth, Ground water quality and Investment on watershed management have dragged down the overall CWSI for the state.

The natural factors (indicators) have performed better than the manmade factors. Hence, it warrants better management practices in the state. Overexploitation of groundwater in the state has also contributed to the low to moderate CWSI. The Groundwater development index for the state is 165.7%. Central Ground Water Board puts a benchmark of 70% as most sustainable exploitation of groundwater. Such huge deviation from the benchmark GDI impacts the ultimate CWSI of the state. Improper crop and cropping systems in Punjab contributes to low CSWI. Rice cultivation requires minimum annual rainfall of 650 mm to demand less irrigation. Many districts in the state of Punjab have annual rainfall less than 650 mm. The area under rice cultivation in Punjab is 3.2 Mha per annum. The cropping pattern in groundwater overexploited regions of the state requires to be diversified to low duty crops like maize, pulses and oilseeds. However, the present marketing (MSP and public procurement), comparative yield and per hectare income from these crops, the risk of getting better quality seed and managing disease and pests in these alternative crops need to be established to lure away farmers from water guzzling rice cultivation.

Policy imperatives for water productivity and water management

Though in the water sustainability index of these states falls in the lower moderate zone, there are poor performance with respect to important individual parameters. Water productivity in wheat as state indicator gives poor value of 0.21 for Punjab. This compares poorly with international benchmarks. Similarly, the score regarding water use efficiency is 0.56 for Punjab, again showing very poor standards compared to internationally best practices. Punjab does not perform in any reasonable manner in adapting smart management of water resources like adaptation of micro irrigation and sensor based irrigation. The factors behind the above poor water sustainability parametric scores emanates from the distorted policies of not pricing water and energy use for agricultural use (mainly for power to extract ground water). Such policies lead to poor water related parametric values. Both the states need to focus on policy changes regarding pricing water and power, and incentivizing adaptation of micro irrigation and other modern irrigation practices to improve water related agricultural sustainability.

The Indian National policy objectives are enshrined in the National Water Policy, 2012 (MOWR, 2012) complement the international commitments towards attaining Sustainable Development Goals (DSG 2.4 and SDG 13, SDG 15.3).

Water is a state subject as per entry no 17 in the State List of the Constitution of India.. Attempts have been made with limited efficacy to regulate ground water management by invoking the Central enactment, namely the Environment Protection Act, 1956. The state of Punjab has recently enacted the Punjab Ground Water (Control and Regulation) Act, 2020 for establishment of the Punjab ground Water Authority to regulate ground water uses in the state. However, the efficacy of the legislation depends on the actual implementations of the provisions of the enactment.

Exclusive focus areas for Punjab

The following points are relevant to Punjab:

(i) ***Regulation and pricing***: Punjab should proactively legislate enactments for regulating water use, water pricing and related matters. There is need to estimate the national / regional cost of capping agricultural water withdrawals to protect natural water aquifers.

There should be proper water allocation policy by the regulatory bodies to determine the optimum proportion between irrigated agriculture, non-agriculture and leaving appropriate amount for environmental functions. There is need to strike a balance between the competing uses and healthy functions of natural ecosystems (Pretty *et al.*, 2010).

The National Water Policy, 2012 (MOWR, 2012) advocates that the Water Users Associations should be given statutory powers to collect and retain a portion of water charges, mange the volumetric quantum of water allotted to them and maintain the distribution system in their jurisdiction. Historically, the state of Punjab was charging water user fee (*abiana*) since pre-independence period for use of canal water. However, *abiana* has been abolished with effect from 2014 and water-cess has been introduce for maintenance of distribution channels for irrigation.

(ii) Another corollary to inadequate pricing of water is the recovery of the cost of energy used for extracting ground water. Punjab provides free electricity for agricultural purposes including energy used for extracting ground water through submersible pumps.

(iii) On-farm management of water and water storage facilities would enhance water use efficiency in the four sub-mountain districts in Punjab. The involvement of FPOs could be encouraged by introducing differential rates of subsidy to these groups compared to individual beneficiaries.

(iv) Most of the sustainable practices require wholehearted participation and adaptation by various stakeholders, particularly the farming communities. A lot depend on the behavioural aspects of the farming community. Price incentives and public spending on projects and schemes may not be adequate to usher in adaptation of sustainable practices like balanced use of water saving methods, construction of ground water recharge systems, adaptation of micro irrigation practices, proper crop planning, land use and land augmenting methods by the farming community. This is more so in absence of strong regulatory measures prohibiting certain practices detrimental to agricultural sustainability. Tweaking the existing MSP and other incentive structure to change the cropping pattern for less water consuming crops, adaptation of micro-irrigation practices and water harvesting structures.

Conclusions

In view of extensive cultivation of water guzzling crops and overexploitation of groundwater for this purpose in the state of Punjab, a composite water sustainability index (CWSI) for the state was developed. The indicators crucial for sustainability of agriculture and water resources for the state were identified. In total, there were 17 indicators under weather and climate related indicators, water stress indicators, and water management related indicators. Normalisation and weight assignment to the indicators was done in order to develop the composite water sustainability index (CWSI). The average CWSI for the state was calculated as 0.519 with a minimum value of 0.409 in Mansa district and a maximum value of 0.606 in Muktasar district. The improper cropping system and overexploitation of groundwater are the main reason for the low to moderate sustainability of agriculture and water resources in the Punjab state. There is a need to diversify to low duty crops like maize, pulses and oilseeds in place of high water consuming crops like rice in order to have a better sustainability of water resources.

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