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Application of SPAW model parameters – optimum sowing date and water stress to explain wheat yield variability

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सार – वाराणसी ज़िले में गेहूँ की पैदावार के 1991-92 से 1993-94 तक की अवधि के क्षेत्रीय प्रयोग के आँकड़ों का उपयोग करते हुए मृदा-पादप-वायुमंडल-जल (एस.पी.ए.डब्ल्यू) निदर्श अंशसंशोधित एवं प्रमाणित किया गया है। 23 वर्षो के लिए दैनिक जल बजट उपलब्ध कराने हेतु दीर्घ अवधि (1973-74 से 1995-96) दैनिक मौसम आँकड़ों को गेहूँ की बढ़वार और मिट्टी की क़िस्मों की सामान्य जाँच के साथ समन्वित किया गया है। इस निदर्श को एक वर्ष की विस्तृत फ़सल बढ़वार की विशेषताओं और मृदा जल की जाँच के साथ अंशसंशोधित किया गया और अन्य वर्ष के मृदा जल की जाँच के साथ प्रमाणित किया गया है। फ़सल के मौसम के अंत में दैनिक समन्वित जल प्रतिबल इंडैक्स मानों के इस क्षेत्र में हुई अनाज की पैदावार के साथ अच्छे संबंधों का पता चला है।

जल बजट के विश्लेषण से यह ज्ञात हुआ है कि न्यूनतम जल प्रतिबल इंडैक्स के साथ 5 से 25 नवंबर तक की अवधि गेहूँ की बुवाई के लिए सर्वोत्तम है जिसमें 15 नवंबर की तिथि विशेष रूप से उत्तम है। इन परिणामों से इस क्षेत्र में गेहूँ की फ़सल के लिए सिंचाई की योजना और जल प्रबंधन की योजना तैयार करने के लिए मृदा-पादप-वायुमंडल-जल के निदर्श के प्रयोग की अच्छी संभावनाओं का पता चलता है।

ABSTRACT. The Soil-Plant-Atmosphere-Water (SPAW) model has been calibrated and validated using field experiment data from 1991-92 to 1993-94 for wheat crop at Varanasi district. Long-term (1973-74 to 1995-96) daily weather data were combined with general observation of wheat growth and soils to provide daily water budgets for 23 years. The model was calibrated with one year detailed crop growth characteristics and soil water observations and validated with another year soil water observations. The daily-integrated water stress index (WSI) values at the end of crop season correlated quite well with observed grain yield in this region.

The water budget analysis shows a distinct optimum sowing period from 5th to 25th November and an optimum sowing date on 15th November with minimal water stress index. These results demonstrate the potential of SPAW model for planning irrigation scheduling and water management for wheat crop in this region.

Key words – Simulation, Calibration, Water stress index and Water budget.

1. Introduction

In recent years numerous models (Ritchie, 1972; Baier *et al.*, 1972; Gardner, 1974; Saxton *et al.*, 1974; Ritchie and Otter, 1985; Aggrawal *et al.*, 1994) have been developed for movement of soil water and its extraction by plants. Very few studies report the interrelationships between soil water crop growth and grain yields (Omar *et al.*, 1988). However, recent reports tend to conclude that soil water or water stress alone can not provide adequate information on the effect of water supply on crop growth and grain yields. This can only be achieved if atmospheric conditions, type of crops, stage of growth and soil characteristics are all taken into account in addition to the above parameters (Major *et al.*, 1988; Reginato *et al.*, 1988; Siddique *et al.*, 1990).

Therefore in the present study SPAW model has been studied keeping in view to (a) calibrate and validate the

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SPAW model for wheat crop under sandy loam to sandy clay loam soil of Varanasi district, (b) identify the threshold soil moisture level for irrigation scheduling, and (c) quantify the response of wheat crop to various sowing dates considering climatic variability.

2. Material and methods

2.1. *Study site and climate description*

Varanasi district is situated in the Indo-gangetic plain of India at an elevation of 75 meters above mean sea level and 25° 20′ N latitude and 83° 03′ E longitude having semiarid and subtropical climate. The wheat growing season rainfall is 86 ($\pm$ 60 mm) and the potential evapotranspiration (PET) is approximately 521 ($\pm$ 60 mm). The seasonal solar radiation, maximum and minimum temperature were 18.9 MJ m^{-2}, 26.4° C and 11.9° C respectively.

The soil of this area is alluvial in origin and belongs to Ustochrepts and Ustifluvents groups (Singh *et al*., 1989). Soils were sandy clay loam texture upto 1.2 m soil depth. (Jha, 1994).

2.2. *Field experiment*

Field experiments was conducted at Agricultural Research Farm during 1991-92 to 1993-94 in a randomised block design with three replications under irrigated. The crop growth characteristics and phenological data at different phenophses were recorded. The soil profile was divided into six layer's *i.e.* 15 cm, 30 cm, 45 cm, 60 cm, 90 cm and 120 cm below the soil surface. Soil water measurements were made by the gravimetric method for depth of 0 to 15 cm, and by the neutran probe method for depths from 15 to 120 cm. Weekly water losses (AET) were recorded by gravimetric lysimeter.

2.3. *The model and methods*

The Soil-Plant-Atmosphere-Water (SPAW) model (Saxton *et al*., 1974; Sudar *et al*., 1981; Saxton and Bluhm, 1982; Saxton, 1994) code were updated to estimate runoff, crop-water stress and water stress effects on crop growth and yield.

The SPAW model has been found to adequately describe, integrate and relate the plant-soil-atmosphere process as demonstrated by several research applications (De Jong and Zentner, 1985; Saxton *et al*., 1992; and Rathore *et al*., 1994). The model computes a daily soil water profile budget by considering climatic input, crop growth characteristics, and soil profile water-holding characteristics. Daily potential evapotranspiration (PET) values were estimated by daily pan evaporation data reduced by pan coefficient is sequentially applied to relationships to separately consider intercepted water evaporation, soil water evaporation and plant transpiration. These components were added to estimate daily actual evapotranspiration (AET), infiltration (daily precipitation minus runoff) wets the soil profile layer's and soil water in all layers is redistributed according to tension and conductivity relationships uniquely specified for each layer.

Plant transpiration calculations include time distribution of canopy development, plant phenology and root density. The ability of the plant to meet the daily atmospheric transpiration requirements indicates whether it is stressed or not.(Hiller and clark 1971) in the form of

$$\text{Crop water stress} = 1 - (\text{AET} / \text{PET})$$

Where, AET and PET are the actual and potential transpiration respectively.

In order to account for impact of soil water stress on yield reduction, daily stress values were multiplied by a yield susceptibility (YS) factor based on stage of growth so that an end of growing season water stress index (WSI) is computed by the experiments (Sudar *et al*, 1981; Hiller and clark 1971)

$$\text{WSI} = \text{YS} * (1 - (\text{AET} / \text{PET})$$

The computed WSI values are the seasonally integrated results of daily soil water profile, root profiles, climatic demand and crop stage. Lewis *et al*., 1974 defined Yield Susceptibility (YS) as a fractional reduction in yield caused by a certain water deficit at a particular growth stage compared with a well-watered control treatment as

$$\text{YS} = (X - X_s) / X$$

Where, X is yield from the control and X_s yield from the stressed treatment.

2.4. *Input data*

The model requires input data on soil, crop and weather for its calibration in different environments. Weather (rainfall and evaporation) and soil (USDA Soil Conservation Service Curve Number for runoff and layerwise information and saturation, field capacity, wilting point, texture and hydraulic conductivity) and crop management data (Dates of sowing, plant and row spacing, irrigation, etc.) were collected for the location under study. Observed district wheat grain yield (1973-74 to 1995-96) for the study site was obtained from statistical magazine of the concerning year, from Varanasi and Krishi Bhawan, Lucknow, Uttar Pradesh, India. The

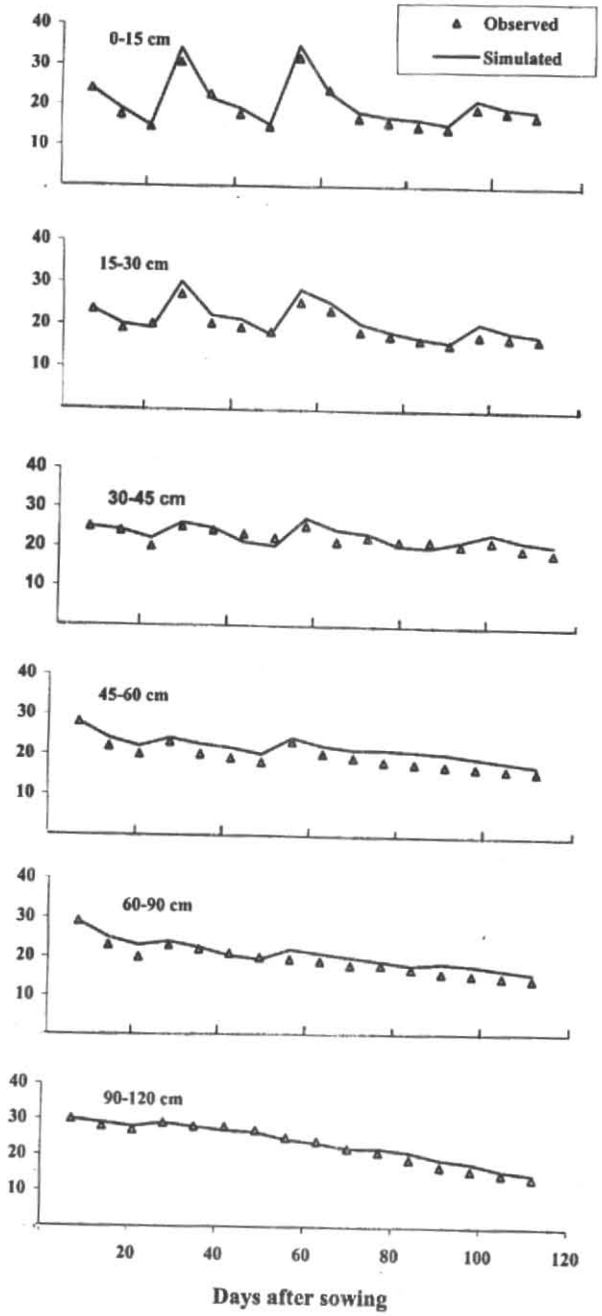

Fig. 1. Layer wise observed and estimated soil moisture for 1993-94 crop season

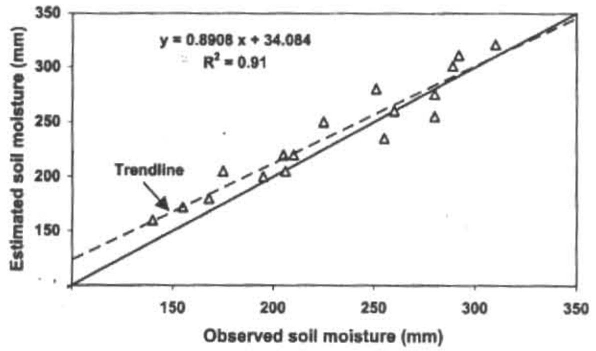

Fig. 2. Simulated soil moisture compared with observed soil moisture for 1.2 m soil profile

experimental wheat yield data at different sowing dates are collected from annual reports of AICWIP on Dryland Agriculture for the study years.

The model was calibrated using the observed field experiment data of 1991-92 season experiment. Model was validated using the daily-observed soil moisture data of 1992-93 and 1993-94 wheat-growing season.

3. Results and discussion

Daily values of soil moisture for six layers were computed during the growing season of wheat and compared with observed data for 18 observation dates. Fig. 1 shows typical example of the prediction accuracy of soil moisture contents. The estimated soil moisture values (solid line) were set equal to observed at the first measurement date only to simulated moisture states at later stages. The correlation between observed and estimated soil moisture for different soil layers 0-15, 15-30, 30-45, 45-60, 60-90 and 90-120 cm were 0.96, 0.92, 0.88, 0.95, 0.91 and 0.97 respectively with t -test values significant at 1% level of significance. The model simulated soil moisture through the vegetative phases upto the flowering periods but after this stage model overestimated the soil moisture. The moisture changes in the upper soil layers were related to actual evapotranspiration and infiltration, whereas soil water redistribution and percolation mostly caused changes in the lower layers. Model did not represent the poorly drained lower boundary condition, so more percolation's occurred. Model over estimated the soil moisture changes in dry period explaining more direct soil water evaporation than observed values.

Estimated and observed soil moisture content in 1.2 m profile are shown in Fig 2. The correlation between the estimated and observed soil moisture was in close agreement with t-test value is significant at 1 % level of significance. Soil water budgets were simulated for the 23 years study period to explain the variability in district wheat grain yields (30 November sowing date). The seasonal climatic data and estimated soil water budgets components (November to April) values shows that calculated actual evapotranspiration (AET) is the sum of direct soil water evaporation, plant transpiration and interception evaporation (Table 1). Similar

TABLE 1

Seasonal total of observed precipitation and estimated water balance component for the study site representing continuous wheat for 30 November sowing date (mm)

Sowing Year	PET	AET	Rain fall	Soil evaporation	Transpiration	Interception	Runoff	Percolation	WSI*
1973	553	206	57	80	111	15	14	-15	6.3
1974	579	250	47	108	117	25	0	-18	4.2
1975	631	256	84	111	120	25	12	-17	3.9
1976	554	230	42	94	122	14	4	-17	2.8
1977	468	287	313	99	145	43	119	-4	0.2
1978	514	290	96	119	141	30	5	-12	0.5
1979	562	201	61	74	106	21	14	-14	5.9
1980	396	231	88	78	121	22	16	3	3.1
1981	525	262	133	83	152	27	10	-11	1.2
1982	536	223	63	84	126	13	20	17	3.5
1983	454	288	132	113	141	34	19	-11	1.2
1984	588	224	38	99	106	19	2	-18	3.7
1985	534	246	88	83	128	35	3	-13	1.4
1986	551	216	33	86	110	20	0	-16	2.7
1987	553	292	129	136	127	29	23	-16	1.1
1988	597	209	54	92	105	12	20	-13	1.3
1989	506	234	106	70	142	22	20	-10	1.5
1990	472	237	56	97	117	23	2	-14	1.9
1991	507	239	35	105	120	14	1	-17	0.8
1992	409	214	61	87	113	14	8	-15	2.8
1993	473	222	90	86	126	10	7	-9	2.4
1994	541	240	62	101	131	8	5	-4	2.9
1995	496	246	107	89	143	14	12	-7	2.1
Mean	521	0	86	95	125	21	14		2.4
SE	60	29	60	17	14	8	25	-	1.4

* Dimensionless

results were observed on weekly and seasonal AET values using SPAW model and observed lysimetric data values in different years during wheat growing season (Mall, 1996). The interception amount includes the evaporation from water captured on soil and leaf surfaces (2.5 mm per rainfall). On a seasonal basis the simulation predicted an average transpiration of 125 ± 14 mm, a soil evaporation of 95 ± 17mm and as interception evaporation of 21 ± 8 mm. Deep percolation is the estimated end of the year net water movement up (negative) or down across the lower soil profile boundary.

The accumulated WSI values at the end of growing season ranged from 0.16 in 1977-78 to 6.29 in 1973-74. Fig. 3 presents that WSI values explained wheat grain yield variability to 61 percent.

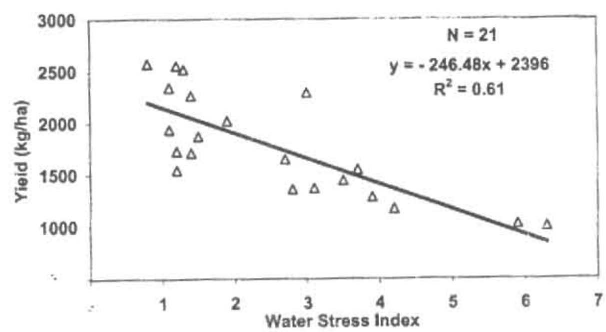

Fig. 3. Water stress index (WSI) from end-of-the-season water budgets *vs.* grain yields of the Varanasi district

TABLE 2

Estimated seasonal plant transpiration (mm) for different sowing dates for all study years

Sowing Year	Sowing dates								
	15 Oct	25 Oct	05 Nov	15 Nov	25 Nov	5 Dec	15 Dec	25 Dec	5 Jan
1973	101	109	119	123	116	110	106	101	90
1974	106	110	119	129	120	117	110	108	102
1975	113	120	126	139	122	120	115	110	107
1976	115	130	144	137	125	121	114	108	96
1977	106	112	126	150	153	140	138	130	119
1978	110	113	130	145	156	135	123	119	109
1979	106	109	128	118	110	105	98	94	82
1980	115	123	148	149	134	129	123	111	101
1981	113	132	145	158	160	151	139	130	120
1982	115	120	134	138	128	125	108	100	93
1983	98	102	118	137	140	146	139	125	115
1984	103	106	116	118	113	105	103	99	91
1985	125	137	143	155	138	125	120	111	102
1986	101	105	112	119	120	108	105	101	95
1987	118	126	139	148	132	129	121	118	109
1988	96	100	123	110	106	105	99	93	86
1989	101	120	138	146	148	140	130	121	111
1990	97	112	119	128	120	116	109	102	96
1991	103	116	123	139	130	114	107	101	91
1992	101	114	121	129	118	111	108	102	94
1993	110	121	130	139	130	122	115	109	101
1994	115	124	131	135	141	126	114	109	99
1995	113	129	136	146	151	138	116	101	91
Mean	108	117	130	136	131	123	116	109	101
SE	8	10	11	14	16	14	13	11	11

* Underscore indicates maximum values for all sowing dates.

Two years 1977-78 and 1978-79 were not included in developing the regression expression of Fig. 3 to test the validity of the relationships of WSI and wheat yield levels. When higher rainfall occurred in the region there was excessive runoff leading to poor farming conditions, however 1281 mm and 1206 mm rainfall events resulted in water logging.

In this region early maturing wheat provided better yield. Therefore the impact of sowing time on water stress index and other model parameters were also studied by simulating yearly water budget for the growing season of 23 consecutive years with nine different sowing dates starting from 15 October with 10 days interval upto 5 January. The water-budget simulations provided parameters such as PET, AET, and WSI, which were related to the crop response to different sowing dates.

The annual cycle of PET is strongly influenced by the cold and hot seasons. Due to significant increase of air temperature, PET ranges from a minimum during November-December to a maximum in March-April (Fig. 4). Because 30 years are a minimal for statistical analysis, it is useful to show the probability of occurrence of higher than average value of PET. The probability curves were obtained by integrating the areas under the ET-frequency histogram at 50, 75, 90 and 99 percent levels for the 15 November sowing date.

AET is a composite function of PET, plant growth, soil water availability and the prevailing environment (Fig. 4). AET is much below than the potentiality level in early season before the sowing of crops. During flowering to grain formation, when the crops are rapidly growing in favourable conditions, AET nearly equals PET for a few weeks.

TABLE 3

Water Stress Index (WSI) for different sowing dates for all study years

Sowing Year	Sowing dates									
	15 Oct	25 Oct	05 Nov	15 Nov	25 Nov	5 Dec	15 Dec	25 Dec	5 Jan	Mean
1973	5.3	5.0	4.6	4.5*	5.0	6.8	7.7	8.5	9.4	6.3
1974	3.8	3.6	3.4	3.2	3.1	4.8	5.5	6.4	8.0	4.6
1975	4.4	3.9	3.6	3.5	3.8	4.5	5.1	5.9	6.3	4.5
1976	3.8	3.4	2.7	2.8	2.9	3.7	4.4	5.2	5.6	3.8
1977	1.0	0.8	0.4	0.2	0.2	0.5	1.6	3.8	6.3	1.6
1978	1.1	0.7	0.2	0.4	0.5	1.1	1.9	3.1	4.3	1.4
1979	4.9	4.5	4.0	3.5	4.9	5.6	6.2	6.9	7.5	5.3
1980	3.4	2.8	2.2	2.5	2.8	2.4	2.9	4.5	7.7	3.4
1981	2.3	1.9	1.4	1.3	1.2	1.5	3.5	3.3	3.6	2.2
1982	3.4	2.9	2.6	2.5	3.5	4	4.6	5.1	5.3	3.7
1983	2.3	1.6	1.3	1.2	1.4	1.3	2.3	3.5	4.5	2.2
1984	4.9	4.4	3.8	3.7	3.8	4.7	4.9	5.4	6.0	4.6
1985	2.6	2.0	1.5	1.2	1.6	2.0	2.8	3.7	4.6	2.4
1986	3.3	3.0	2.4	2.2	2.6	3.4	4.0	5.0	5.7	3.5
1987	1.5	1.0	1.1	1.2	1.3	1.6	2.9	4.0	4.7	2.1
1988	4.2	3.7	2.9	2.5	2.6	4.7	5.3	5.9	6.6	4.2
1989	1.0	1.2	0.5	0.9	0.5	0.9	1.8	4.0	4.9	1.7
1990	2.5	2.0	1.4	1.3	2.0	3.4	4.0	4.6	5.4	2.9
1991	3.0	2.3	2.0	2.5	2.7	3.1	3.8	4.8	5.9	3.3
1992	3.6	3.4	2.9	2.0	2.6	3.0	4.0	5.2	5.7	3.6
1993	3.4	3.2	2.8	2.1	2.3	2.7	3.1	4.2	5.2	3.2
1994	3.2	2.9	2.5	2.4	2.8	3.1	3.5	3.9	4.7	3.2
1995	3.5	2.6	2.4	2.2	2.1	2.7	2.9	3.8	4.9	3
Mean	3.1	2.7	2.2	2.1	2.4	3.2	3.9	4.8	5.8	3.3
SE	1.4	1.3	1.3	1.2	1.4	1.7	1.6	1.3	1.4	1.4

* Underscore indicates minimum values for all sowing dates.

However, at maturity soil water is depleted rapidly AET rapidly reduces to lowest value. The simulated 23 growing seasons were again analyzed for probability of occurrence and AET amounts greater than normal (50%) is shown in Fig. 4.

Optimum plant transpiration rate is essential for better plant growth, development and grain yield. Table 2 show estimated seasonal plant transpiration values for all sowing dates for each of the 23 years period. The plant transpiration values and grain yield (All India Coordinated Project on Dryland Agriculture) at different sowing dates (15 to 30 December) are positively correlated (R^2 = 0.66). The detailed water budget studies suggests that this is caused by the better plant growth when precipitation is most probable with minimal non-productive losses due to evaporation and interception.

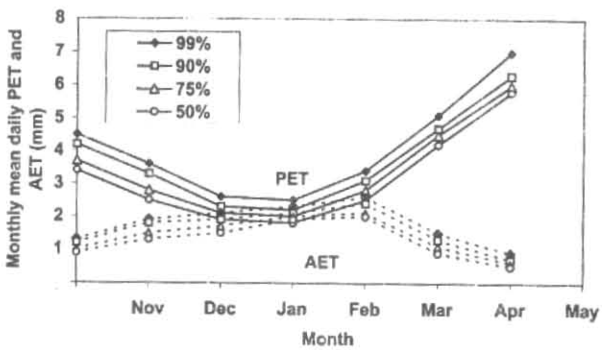

Fig. 4. Probability distribution of monthly mean daily potential and actual evapotranspiration for 15 November sowing date

While vegetative crop growth can be limited through water stress and reduced transpiration, grain yields are also quite susceptible at the phenologic stage due to the water stress. By summation of daily estimated crop water stress weighted by phenologic development throughout the growing season, end of-season WSI values were obtained for each season for all sowing dates. These are shown in Table 3. The WSI values and grain yield (All India Coordinated Project on Dryland Agriculture) at different sowing dates (15 to 30 December) are well correlated ($R^2 = -0.58$). The optimum sowing date for minimum WSI was around 15 November. Results suggest a wide range sowing period of 20 days, from 5 November to 25 November.

On shifting of the sowing dates, similar results were also obtained by O'leary *et al.*(1985) and French *et al.*(1979). With delayed sowing dates, higher water stress index was obtained is obvious. The climatic pattern of this region also confirms this to be true, as the evaporative demand rapidly increases with the start of the spring month when soil water storage may not be sufficient to meet the demand.

4. Conclusions

The estimates of yearly crop-water stress values show a good relationship with average Varanasi district wheat grain yields. 15 November was the optimum sowing date for wheat at Varanasi. The frequencies of occurrences depicted the nature and variability of the interaction of climatic patterns and water budget parameters under the semi-arid conditions. The water budget results show a distinct optimum sowing period of 5 November to 25 November for wheat in this region. Maximum transpiration and minimum water stress index are main indices for deciding the optimum sowing time for wheat.

The simulated SPAW model results, combined with cropping pattern of winter wheat in Varanasi, provide valuable information for future research in the area of soil water management, yield prediction and irrigation scheduling. However, the study has lot of potentialities and could be extended over other crops and regions where relevant data are available.

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