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A critical study on parameters controlling water requirement of wheat (*Triticum aestivum* L.) at various growth stages in ten different agroclimatic zones

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सार—गेहूं की जल आवश्यकता को नियंत्रित करने वाले प्राचलों तथा फसल की बढ़ोतरी की विभिन्न महत्वपूर्ण अवस्थाओं से संबंधित दस भिन्न कृषिजलवायविक क्षेत्रों के पांच वर्षों के फसल आंकड़ों को एकत्रित किया गया और उनका विश्लेषण किया गया है। अध्ययन से ज्ञात हुआ कि गेहूं की पैदावार के विभिन्न क्षेत्रों में गेहूं के लिए कुल सी.यू. मांग में 160 से 465 मि.मी. तक जल की मात्रा में अंतर रहता है। अधिकांश क्षेत्रों में चरम सी.यू. मांग या तो गेहूं के दाने में दूध पड़ने के समय (कुल सी.यू. मांग का 21.0%) या जोताई अवस्था (बाले आने के समय) की अवस्था में (कुल सी.यू. मांग का 19.5%) रही है। बढ़ोतरी की विभिन्न अवस्थाओं में फसल की जल आवश्यकता की सी.यू. मांग पूरी करने के लिए रबी की फसल के समय की वर्षा पर्याप्त नहीं पाई गई है। मृदा नमी के अध्ययन से ज्ञात हुआ कि जोताई अवस्था के आस-पास मृदा में नमी की कमी आरम्भ हुई है जिससे पता चलता है कि इस अवस्था के उपरांत सिंचाई की आवश्यकता है। विभिन्न कृषिजलवायविक क्षेत्रों में आकलित औसत फसल के के.सी. मान में (फसल की बढ़ोतरी की सम्पूर्ण अवधि में) 0.36 से 1.05 तक भिन्नता पाई गई। फसल की वृद्धि के अनुसार के.सी. मान पौधों की लम्बाई बढ़ने की अवस्था में अथवा उसके उपरांत भी एक से अधिक रहा है। विभिन्न कृषिजलवायविक क्षेत्रों में गेहूं की 17 से 26 किग्रा/हेक्टेयर/दिन औसत उत्पादकता के साथ इसकी पैदावार में 1900 से 4800 किग्रा/हेक्टेयर तक का अंतर रहा है। विभिन्न क्षेत्रों में फसल की जल उपयोग क्षमता (डब्ल्यू यू ई) 5 से 17 किग्रा ग्रेन/हेक्टेयर/मि.मी. के बीच रही। इस अध्ययन के आधार पर गेहूं की उपज वाले भागों को छः क्षेत्रों में विभाजित किया गया है।

ABSTRACT. The parameters controlling water requirement of wheat and its crop data, at various critical growth stages, from ten different agroclimatic zones, for five years, were collected and analysed. The study revealed that the total CU-demand for wheat crop in different wheat growing zones varied from 160 to 465 mm of water. In most of the zones, peak CU-demand were either at milk stage (21.0% of the total CU-demand) or at tillering stage (19.5% of the total CU-demand). Rabi season rainfall was not sufficient to meet the crop CU-demand at different growth stages. The soil moisture study revealed that its depletion started around tillering stage indicating, thereby, need for irrigation water beyond that stage. Computed average K_c values (throughout the crop growth period) varied from 0.36 to 1.05 in different agroclimatic zones. Growth stage-wise K_c values at or after elongation stage even exceeded one. Wheat yield in various agroclimatic zones varied from 1900 to 4800 kg/ha with the average productivity of 17 to 26 kg/ha/day. The WUE of the crop in different zones lay between 5 to 17 kg of grain/ha/mm of water. Depending upon this study wheat growing areas were divided into six zones.

Key words — Agroclimatic zones, Critical growth stages, CU (Consumptive use)-demand, Rabi, K_c (Crop coefficient), WUE (Water use efficiency), Productivity, CRI (Crown root initiation).

1. Introduction

Wheat is one of the most important cereal crops in regard to its antiquity and its use as human food. It is grown in summer season in temperate region and winter or rabi season in the subtropics. In India, it is grown on an area of about 20 million hectares of which nearly 54% is irrigated (Michael 1990). Uttar Pradesh, Madhya Pradesh, Punjab, Bihar, Rajasthan, Haryana are the major wheat producing states.

The critical growth stages for wheat are germination, crown root initiation (CRI), tillering, elongation (*i.e.*, jointing), flowering, milk stage, dough stage and harvest maturity which are critical in their demand for water. Water deficiency at any of these growth stages affects the wheat yield severely. The duration of these growth stages varies according to variety, soil type and climatic factors prevalent in a particular locality. Though wheat shows considerable resistance to drought, it is highly sensitive to moisture stress during the period from shooting (*i.e.*, internode elongation) to advanced grain formation stage (*i.e.*, dough stage).

In India, the rainfall distribution is not very favourable for the wheat crop. However, the residual moisture stored in the soil profile is used

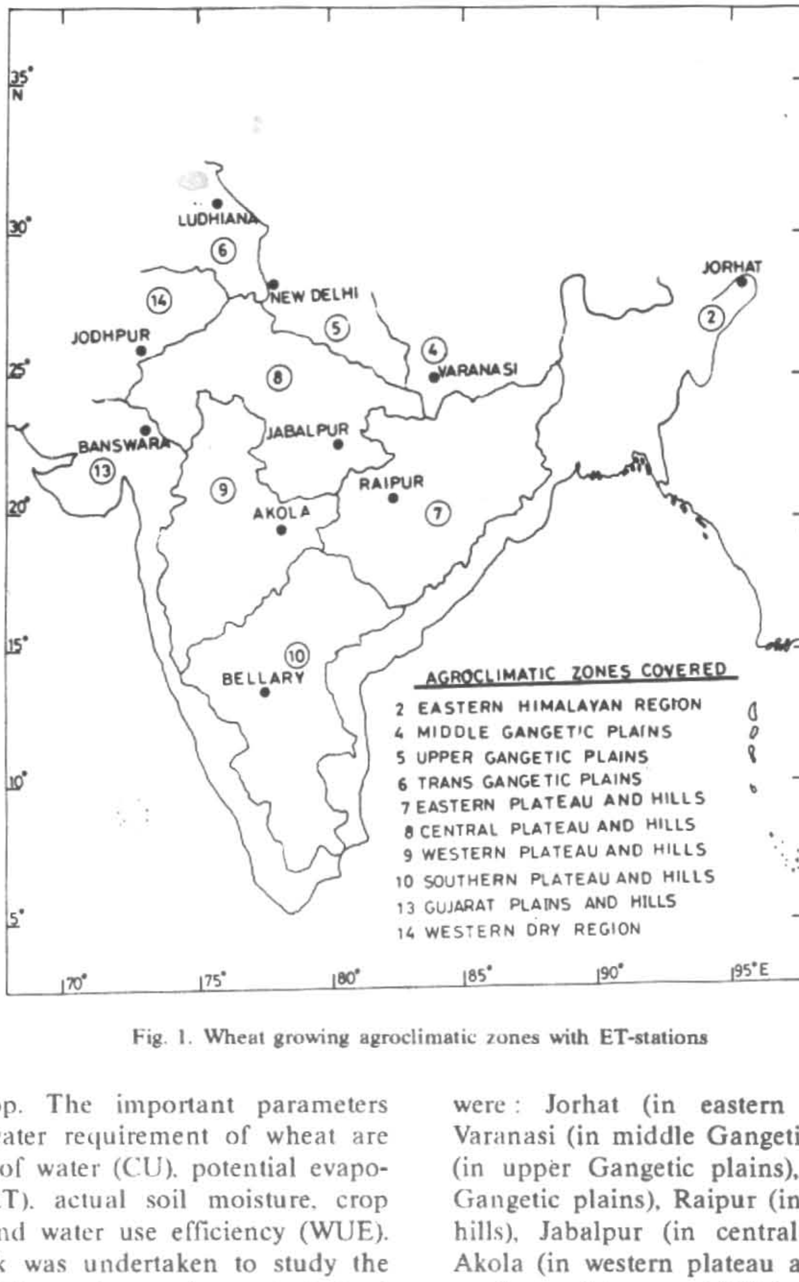

Fig. 1. Wheat growing agroclimatic zones with ET-stations

to raise the crop. The important parameters controlling the water requirement of wheat are consumptive use of water (CU), potential evapotranspiration (PET), actual soil moisture, crop coefficient (K_c) and water use efficiency (WUE). The present work was undertaken to study the parameters controlling water requirement of wheat at various critical growth stages in different wheat growing agroclimatic zones.

2. Methodology

2.1. *Selection of zones*

Agroclimatic classification of India, as proposed by Planning Commission, Govt. of India, 1989, divided it into 15 zones out of which 10 zones were selected where wheat is grown. From each of the wheat growing zones, one ET-station had been selected (Fig. 1). The selected ET-stations were: Jorhat (in eastern Himalayan region), Varanasi (in middle Gangetic plains), New Delhi (in upper Gangetic plains), Ludhiana (in trans Gangetic plains), Raipur (in eastern plateau and hills), Jabalpur (in central plateau and hills), Akola (in western plateau and hills), Bellary (in southern plateau and hills), Banswara (in Gujarat plains and hills) and Jodhpur (in western dry region). The ET-stations, alongwith their respective zone numbers, locations (latitude, longitude) and soil types were presented in Table 1. The numbering of the zones were according to the Planning Commission, Govt. of India, 1989.

2.2. *Data collection*

2.2.1. *Crop data*

The crop data were collected for five years (Table 1) from the ET-stations. The mean values of

TABLE 1

Details of selected ET-stations

Items	ET-Stations									
	Jorhat	Varanasi	New Delhi	Ludhiana	Raipur	Jabalpur	Akola	Bellary	Banswara	Jodhpur
Agroclimatic Zone nos.*	2	4	5	6	7	8	9	10	13	14
Data studied (5 years)	1981-82 to 1985-86	1985-86 to 1989-90	1985-86 to 1989-90	1984-85 to 1986-87, 1988-89, 1989-90	1983-84, 1984-85, 1986-87, 1990-91, 1991-92	1985-86 to 1989-90	1985-86 to 1989-90	1985-86 to 1989-90	1985-86 to 1989-90	1975-76 to 1979-80 †
Soil types	Sandy loam	Sandy clay loam	Loam	Loamy sand	Silty loam	Sandy clay	Clay	Clay	Loamy clay	Loamy fine sand
Location (Lat./Long.)	26°47'N 94°12'E	25°18'N 83°03'E	28°40'N 77°10'E	30°56'N 75°52'E	21°16'N 81°36'E	23°09'N 79°58'E	20°42'N 77°02'E	15°09'N 76°51'E	23°33'N 74°27'E	26°18'N 73°01'E

* Numbering of agroclimatic zones was according to the Planning Commission, Govt. of India, 1989.

† Recent data for the wheat crop was not available.

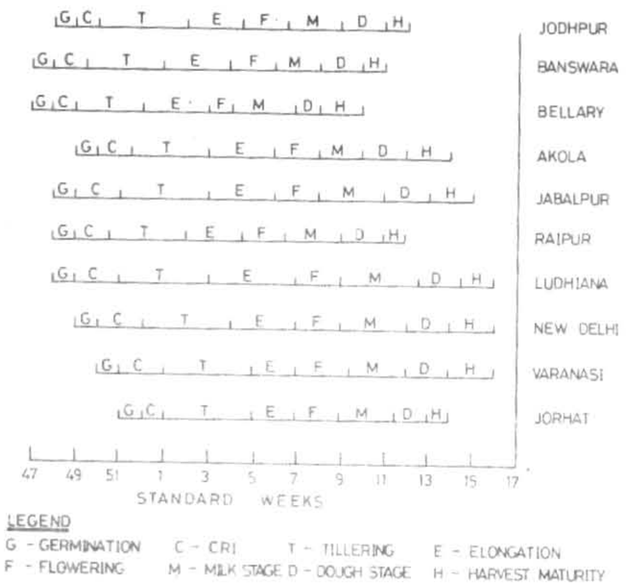

Fig. 2. Durationwise growth stages at different ET-stations

the five years data were obtained. The wheat variety predominantly grown, its mean sowing date, mean harvesting date, mean duration of the crop (in days) for each of the ten stations are presented in Table 2. The mean crop yield (in kg/ha) and mean crop productivity (in kg/ha/day) for the 5 years are presented in Table 6.

2.2.2. *Parameters controlling water requirement of wheat crop*

The main parameters controlling water requirement of wheat crop may be taken as rainfall, potential evapotranspiration, consumptive use of water, actual soil moisture, crop coefficient and water use efficiency. Eight critical growth stages were germination (G), crown root initiation (C), tillering (T), elongation (E), flowering (F), milk stage (M), dough stage (D) and harvest maturity (H). The mean span for each of the eight critical growth stages of wheat crop were identified in each of the stations and shown in Fig. 2.

Rainfall data were collected from all the ten stations for five years and the mean values were obtained and summarized in tabular form. From daily rainfall data, growth stage-wise values were obtained (Table 3) for each of the stations.

Modified Penman method was used for computation of weekly PET. Mean daily PET values for 52 weeks using weekly meteorological normals were obtained (Khambete and Biswas 1992) and growth stage-wise PET were derived and presented in Table 4.

The term CU is almost equal to actual evapotranspiration (ET), the direct measurement of which was done by using gravimetric lysimeter.

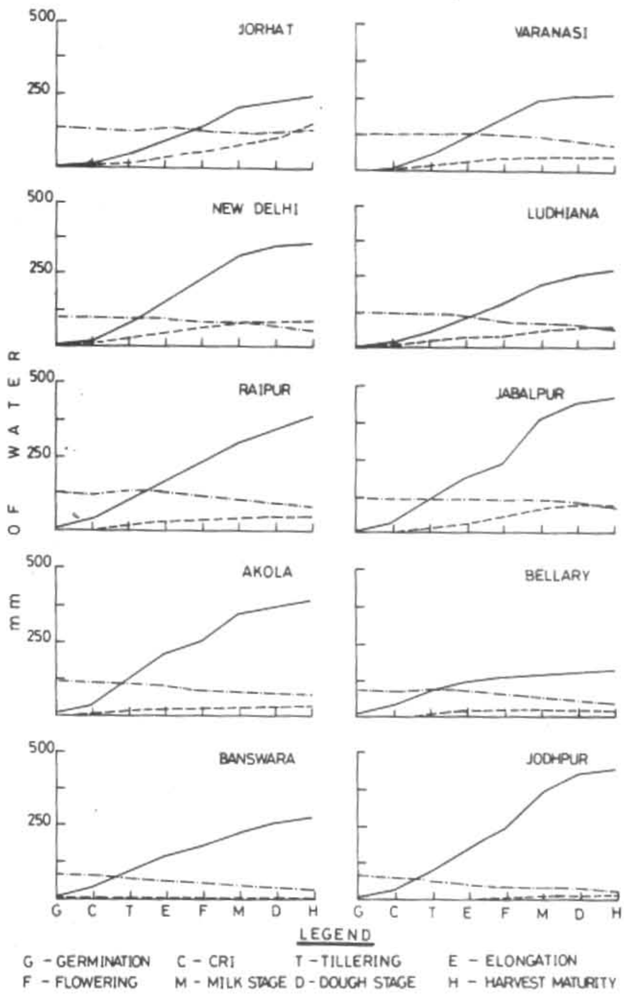

Fig. 3. Cumulative CU (——), cumulative rainfall (.....) and actual soil moisture (—.—) at various growth stages

The lysimeter data from each of the ten stations were collected for five years. For each year growth stage-wise cumulation was made to obtain CU at different growth stages and the mean CU values are obtained (Table 5).

The weekly mean of five years' actual soil moisture (in percentage) measured by gravimetric method, were calculated for each of the ten stations. The actual soil moisture (in percentage) for each of the growth stages were derived and converted into the actual soil moisture in mm (Todorov 1982) by using the formula,

$$W = \frac{a \times b \times c}{10} \tag{1}$$

where, W = actual soil moisture in mm,
a = soil moisture in percentage of the weight of the dry soil,
b = bulk density of the soil in gm/cc and
c = thickness (height) of the soil layer in cm.

The cumulative CU, cumulative rainfall and the actual soil moisture (mm) at various growth stages are presented in Fig. 3.

The crop coefficient (K_c) for all the five years was obtained by the formula,

$$K_c = \frac{\text{AET}}{\text{PET}} \tag{2}$$

The ~~mean~~ K_c values, growth stage-wise for each of the ten stations are presented in Fig. 4.

TABLE 2

Details of wheat crop

Items	ET-Stations									
	Jorhat	Varanasi	New Delhi	Ludhiana	Raipur	Jabalpur	Akola	Bellary	Banswara	Jodhpur
Variety	Sonalika	*Variable	HD-2285	HD-2329	Narmada-4 C-306	WH-147	HD-2278, HD-2189	HD-2181	Lok-1	Kalyan-sona
Mean sowing date	22 Dec	16 Dec	5 Dec	28 Nov	1 Dec	1 Dec	6 Dec	22 Nov	24 Nov	29 Nov
Mean harvesting date	7 Apr	17 Apr	19 Apr	22 Apr	23 Mar	12 Apr	2 Apr	5 Mar	17 Mar	24 Mar
Duration (days)	107	123	136	146	113	133	118	104	114	116

*Varieties were HD-1553, HUW-213, K-65, HD-2285, Malviya-206

TABLE 3

Rainfall (in mm of water) in different agroclimatic zones during wheat growing season

Crop growth stages	ET-Stations									
	Jorhat	Varanasi	New Delhi	Ludhiana	Raipur	Jabalpur	Akola	Bellary	Banswara	Jodhpur
Germination	4.8	1.5	0.9	1.4	0.0	0.0	0.3	0.0	0.0	0.0
Crown root initiation	2.3	8.4	8.3	2.1	2.5	1.6	2.9	0.0	0.0	0.0
Tillering	9.6	9.6	19.3	26.9	20.5	21.3	15.4	14.3	2.0	0.0
Elongation	30.6	17.4	17.2	7.4	10.0	7.8	0.7	5.7	0.6	1.6
Flowering	12.4	9.7	18.4	8.0	4.3	30.6	5.1	3.9	0.0	0.9
Milk stage	27.7	5.0	17.6	21.8	7.4	27.3	4.0	0.3	0.0	8.7
Dough stage	18.4	0.1	6.8	6.5	5.8	4.8	2.0	0.5	0.1	0.0
Harvest maturity	66.9	0.0	1.2	3.0	0.2	0.0	4.6	0.0	0.0	0.0
Total	172.7	51.7	89.7	77.1	50.7	93.4	35.0	24.7	2.7	11.2

The water use efficiency (WUE) was computed by the formula.

$$WUE = \text{yield/total ET}. \quad (3)$$

For each station, WUE for the five years were obtained and the mean values are presented in Table 6.

3. Results and discussions

3.1. *The spatial and temporal variations of different parameters*

The parameters are discussed in the following sub-sections :

3.1.1. *Rainfall*

Table 3 shows that mean rainfall was the highest at Jorhat (more than 170.0 mm), rainfall between 50.0 and 95.0 mm were obtained at Jabalpur, New Delhi, Ludhiana, Varanasi and Raipur, while Banswara and Jodhpur received very negligible rainfall during the wheat growing season, closely followed by Bellary and Akola (Fig. 3). So, raising wheat crop at Banswara, Jodhpur, Bellary, Akola depended mainly on irrigation and soil profile stored moisture. In Jorhat, high rainfall during harvest maturity period was not congenial for obtaining good product. Rainfall distribution in Jabalpur, New Delhi, Ludhiana was good enough. In India during rabi season, rainfall and its distribution was not favourable for growing wheat (Gill 1979) though the crop showed considerable resistance to drought (Kakde 1985).

3.1.2. *Potential evapotranspiration*

All the stations except Jorhat showed high values of potential evapotranspiration (PET). In Jorhat the PET value was the lowest (around 250 mm). while Bellary showed the highest PET (around 510 mm). This implied that the rate of PET was governed by evaporative power of air as determined by radiation, humidity, wind (Mukammal and Bruce 1960) and also by state of the soil, its structure, moisture content, colour as varied in different agroclimatic zones (Vitkevich 1968). Among various growth stages, PET demand was the peak at milk stage. A secondary peak was found at tillering stage. PET demand increased after CRI stage and dropped after milk stage (Table 4).

3.1.3. *Consumptive use*

Bellary recorded the lowest total CU (around 160 mm) closely followed by Jorhat, Varanasi, Banswara and Ludhiana, while the highest total

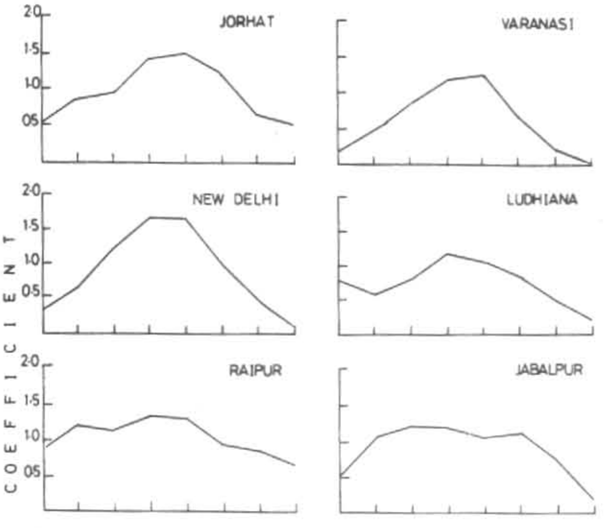

Fig. 4. Computed crop coefficient (K_c) at various growth stages at different ET-stations

CU was recorded at Jabalpur (around 465 mm) closely followed by Jodhpur, Akola, Raipur, New Delhi (Table 5). The CU demand at different growth stages varied widely. Initially the CU demand was low at germination and CRI stages. Gradually the value increased from elongation to milk stage and then again decreased (Fig. 3). The growth stage-wise general pattern of CU values for different stations were obtained due to similar pattern of change in leaf area index (Gaastra 1958). For cereal crops, optimum leaf area was the largest at tillering stage and the smallest during the ripening stage (Takeda 1961). Most of the stations recorded peak CU demand at milk stage, closely followed by tillering, elongation and flowering stages. Other important stages were CRI and dough stages. Considering the CU demand at various growth stages in different agroclimatic zones, scheduling of irrigation is possible. The results showed that milk stage was the most critical from point of water need, very closely followed by tillering and elongation.

When the CU falls short of the PET, the actual yield will also be less than the maximum, though the relationship between ET and yield may or may not be linear (Chang 1968). In the present study, the balance between cumulative CU and cumulative rainfall (Fig. 3) showed wide gap at Raipur, Jabalpur, Akola, Banswara and Jodhpur. The balance was quite narrow at Jorhat, New Delhi, Varanasi, Ludhiana and Bellary. So, it is very clear that the profile stored soil moisture at the end of kharif season plays important role for growth and development of wheat crop. If rainfall and profile stored soil moisture together are insufficient to meet the crop CU-demand, the only alternate remains is to apply irrigation water. Many scientists (Lal 1974, Michael and Pandey 1975) pointed that CRI was one of the most critical stages because from this stage CU value started increasing abruptly (Fig. 3).

3.1.4. *Actual soil moisture*

The general pattern of variation in soil moisture with growth stages at different stations were depicted in Fig. 3. Its values were more or less constant upto tillering or elongation stage and then gradually decreased. Jorhat maintained high moisture status (around 125 mm of water) throughout its growth period. Stations like Varanasi, New Delhi, Ludhiana, Raipur, Jabalpur, Akola maintained medium soil moisture status, while Bellary, Banswara and Jodhpur recorded very poor soil moisture status.

The crossing point of cumulative CU and actual soil moisture curves has got immense significance in determining irrigation need of the crop. Beyond tillering or elongation stage the balance between actual soil moisture and cumulative CU was negative, indicating thereby, the necessity of irrigation water. Jorhat recorded the point of crossing at flowering stage, Varanasi, Ludhiana recorded the same at elongation stage while for the other stations, crossing point was observed at around tillering stage. Therefore, as the balance between actual soil moisture and cumulative CU was negative after the crossing point, application of irrigation water would be useful upto dough stage (Michael 1990).

TABLE 4

Potential evapotranspiration (in mm of water) of wheat during various growth stages

Crop growth stages	ET-Stations									
	Jorhat	Varanasi	New Delhi	Ludhiana	Raipur	Jabalpur	Akola	Bellary	Banswara	Jodhpur
Germination	8.7	15.1	13.7	12.3	15.9	16.8	16.8	24.6	24.3	20.1
Crown root initiation	14.5	23.6	25.7	21.9	24.5	32.2	32.4	36.5	38.5	35.2
Tillering	37.3	59.4	52.2	47.4	61.9	66.6	80.6	89.7	91.7	84.8
Elongation	36.0	48.6	46.7	46.1	48.0	58.8	64.8	80.1	65.3	58.2
Flowering	29.2	51.0	44.0	45.0	45.5	47.1	60.2	57.6	56.9	52.5
Milk stage	52.8	90.7	83.5	74.8	73.2	88.7	90.6	92.7	83.4	82.2
Dough stage	34.5	66.4	68.6	68.6	53.2	70.0	68.8	61.5	59.0	66.4
Harvest maturity	35.5	77.6	84.9	84.0	59.4	81.2	78.0	67.0	64.4	65.5
Total	248.5	432.4	419.3	400.1	381.6	461.4	492.2	509.7	483.5	464.9

TABLE 5

Consumptive use (in mm of water) of wheat during various growth stages

Crop growth stages	ET-Stations									
	Jorhat	Varanasi	New Delhi	Ludhiana	Raipur	Jabalpur	Akola	Bellary	Banswara	Jodhpur
Germination	4.5	3.0	4.1	9.8	14.1	9.2	9.4	16.8	13.3	12.7
Crown root initiation	12.3	11.3	16.4	12.9	29.4	35.2	28.1	25.9	23.4	22.1
Tillering	34.0	50.5	62.8	38.2	71.1	81.7	92.4	53.8	65.5	65.4
Elongation	50.9	56.0	78.5	55.0	63.7	70.9	89.8	31.1	46.3	74.5
Flowering	44.0	62.4	74.0	48.3	59.1	51.2	65.5	12.9	35.7	73.1
Milk stage	65.5	59.1	81.6	63.7	69.2	146.7	64.5	12.7	45.7	118.2
Dough stage	23.3	13.9	32.9	34.2	46.8	53.7	26.2	5.0	31.6	60.3
Harvest maturity	18.9	4.1	9.4	20.0	39.0	15.7	16.6	3.6	15.7	15.6
Total	253.4	260.3	359.7	282.1	392.4	464.3	392.5	161.8	277.2	441.9

TABLE 6

Yield (kg/ha), productivity (kg/ha/day) and water use efficiency (WUE in kg/ha/mm) of wheat in different agroclimatic zones

Parameters	ET-Stations									
	Jorhat	Varanasi	New Delhi	Ludhiana	Raipur	Jabalpur	Akola	Bellary	Banswara	Jodhpur
Yield (kg/ha)	2350	2446	3551	4823	2644	3180	3001	2490	1924	2185
Productivity (kg/ha/day)	21.963	19.886	26.110	33.034	23.398	23.910	25.432	23.942	16.877	18.836
Consumptive use (mm)	253.4	260.3	359.7	282.1	392.4	464.3	392.5	161.8	277.2	441.9
WUE (kg/ha/mm)	9.27	9.40	9.87	17.10	6.74	6.85	7.65	15.39	6.94	4.94

3.1.5. *Crop coefficient*

Computed K_c values showed wide fluctuations among various growth stages as well as among various stations (Fig. 4), though the general trend tallies with the table values of K_c of wheat at various growth stages as published by FAO (Doorenbos and Pruitt 1975). On an average K_c value was the highest at Raipur, closely followed by Jabalpur, Jorhat, Jodhpur, New Delhi indicating that these stations have almost equal demand of AET and PET. Bellary, on the other hand, showed the lowest K_c value, closely followed by Banswara, Varanasi indicating that for these stations, AET was lower than PET, while Ludhiana, Akola showed medium range of K_c value. These values act as a tool for comparing relationship between water and crop yield obtained in different areas (Chang *et al.* 1963). Among various growth stages as shown in Fig. 4, the peak was mainly recorded at or after elongation stage. In all the stations (except Bellary) the K_c values for wheat were initially low, reached a peak and then gradually decreased. K_c values in some particular growth stages even exceeded one for some stations. Kakde (1985), reported that at some advanced plant growth stages under favourable moisture conditions actual ET rate was even greater than potential ET. In the present study Jabalpur showed K_c value more than one from CRI to milk stage, Raipur showed more than one from CRI to flowering stage, New Delhi and Akola showed higher value (more than one) from tillering to flowering stage, Jorhat and Jodhpur recorded greater than one K_c values in between elongation and flowering stage. Varanasi and Ludhiana recorded higher values between elongation and flowering stage, while Bellary and Banswara never recorded K_c value more than one (Fig. 4). In wheat, the maximum leaf area index occurred at the time of rapid shoot elongation which resulted in the highest crop coefficient values and as leaf area lowered after milk stage, the crop coefficient values were also reduced (Watson 1947).

3.2. *Spatial variation of yield, productivity and WUE of wheat*

Yield, productivity and water use efficiency data for all the 10 stations are summarized in Table 6. Yield varied from 1924 kg/ha in Banswara to 4823 kg/ha in Ludhiana. Ludhiana, New Delhi, Jabalpur and Akola yielded very high, while Banswara, Jodhpur, Jorhat and Varanasi yielded low. Productivity (*i.e.,* grain yield/day) of the wheat crop in different stations followed the same pattern as that of yield. While WUE pattern for different stations showed some variation from the yield and productivity pattern. Ludhiana, Bellary recorded very high WUE, New Delhi, Varanasi, Jorhat, Akola recorded medium values of WUE, while Jodhpur, Raipur, Jabalpur, Banswara recorded low WUE. However, Michael (1990) suggested that WUE increased with the increase in crop yield.

3.3. *Grouping of agroclimatic zones based on water requirement and yield parameters of wheat*

Based on the water requirement and yield parameters of wheat we can make six groups : (*i*) New Delhi, Ludhiana with similar tune of rainfall, PET, average K_c and peak CU at milk stage formed the first group, (*ii*) Jorhat with its high winter rainfall and low PET value formed a separate group, (*iii*) Jodhpur, Banswara because of their same pattern of rainfall, PET, yield and productivity formed the third group, (*iv*) Raipur, Akola showed peak CU during tillering stage with similar range of rainfall, average CU, WUE and productivity values, (*v*) Varanasi, Jabalpur together came under group five owing to their same fashion of PET, productivity and WUE, (*vi*) Bellary alone formed the sixth group considering its location as well as its typically low rainfall, average CU and K_c values, at the same time with high PET and WUE values.

4. Conclusions

The present study revealed the following conclusions :

(*i*) Total CU-demand of wheat crop varied widely from 160 to 465 mm of water.

(*ii*) Most of the stations recorded peak CU-demand either at milk stage (21.0% of the total CU-demand) or at tillering stage (19.5% of the total CU-demand) indicating, thereby, that these two stages were the most critical for scheduling irrigation.

(*iii*) Rabi season rainfall was not at all sufficient to meet the specific crop CU-demand at various growth stages of wheat. The soil moisture depleted around tillering stage indicating, thereby, need of irrigation water beyond that stage.

(*iv*) Computed average K_c values showed wide variation ranging from 0.36 to 1.05.

(*v*) In all the stations (excluding Bellary) the K_c values were initially low, reached a peak at or after elongation stage (the value even exceeded one) and then it gradually decreased after milk stage.

(*vi*) Wheat yield varied from 1900 to 4800 kg/ha. The productivity of wheat crop varied from 17 to 26 kg/ha/day.

(*vii*) WUE were ranged between 5 to 17 kg of grain/ha/mm of water.

(*viii*) Depending upon parameters of water requirement and yield of wheat, ET-stations in different agroclimatic zones can be clubbed into six groups which are : (a) New Delhi, Ludhiana, (b) Jorhat, (c) Jodhpur, Banswara, (d) Raipur, Akola, (e) Varanasi, Jabalpur and (f) Bellary.

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References

Chang, J. H., 1968, *Climate and Agriculture : An ecological survey,* Aldine publishing company, Chicago, First edn. (1968), pp. 1-296.

Chang, J. H., Cambell, R. B. and Robinson, F. E., 1963, "On the relationship between water and sugarcane yield in Hawaii", *Agronomy J.,* **55**, pp. 450-453.

Doorenbos, J. and Pruitt, W. O., 1975, "A guideline for predicting crop water requirements", Irrigation and drainage, Paper No. 24, FAO, Rome.

Gaastra, P., 1958, "Light energy conversion in field crops in comparison with the photosynthetic efficiency under laboratory conditions", *Mededelingen van de Landbouwhogeschool te Wageningen,* **58**, 4, pp. 1-12.

Gill, K. S., 1979, Research on dwarf wheats, I.C.A.R., New Delhi, pp. 1-180.

Kakde, J. R., 1985, Agricultural Climatology, Metropolitan Book Company (P) Ltd., New Delhi, First edn. (1985), pp. 1-387.

Khambete, N. N. and Biswas, B. C., 1992, Weekly potential evapotranspiration over India, Meteorological Monograph, Agrimet No. 14, India Meteorological Department.

Lal, R. B., 1974, "Studies on the relative performance of dwarf *durum* and *aestivum* varieties of wheat at limited as well as adequate moisture condition" Proc. 13th I.C.A.R. All India Wheat Worker's Workshop. PAU, Ludhiana, Punjab.

Michael, A. M., 1990, Irrigation — Theory and Practice, Vikas Publishing House Pvt. Ltd., New Delhi, pp. 1-801.

Michael, A. M. and Pandey, S. L., 1975, "Efficient utilization of available water for getting optimum wheat yields", 14th I.C.A.R. All India Wheat Worker's Workshop, Kalyani, West Bengal.

Mukammal, E. I. and Bruce, J. P., 1960, "Evaporation measurements by pan and atmometer", International Union of Geodesy and Geo-physics, Association of Scientific Hydrology, No. 53, pp. 408-420.

Takeda, T., 1961, "Studies on the photosynthesis and production of dry matter in the community of rice plants", *Japanese J. Botany*, **17**, pp. 403-437.

Todorov, A. V., 1982, "Determination of the agrohydrological properties of the soil", Lecture notes for training class IV agricultural meteorological personnel, W.M.O. No. 593, W.M.O., Geneva, Switzerland, pp. 129-140.

Vitkevich, V. I., 1968, Agricultural Meteorology, Translated from Russian. Israel program for scientific translations, Jerusalem, Second impression, pp. 1-320.

Watson, D. J., 1947, Comparative physiological studies on the growth of field crops, I. Variation in net assimilation rate and leaf area between species and varieties and within and between years, *Annals Botany* (*N.S.*), **11**, pp. 41-76.