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A simple new crop model based on water balance for agrometeorological crop monitoring

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सार – जल संतुलन की अवधारणा के आधार पर फसल की मोनीटरिंग करने के लिए एक नए सरल फसल निदर्श को विकसित किया गया है। दो स्तरीय मृदा जल संतुलन, वृष्टि की प्रभावोत्पादकता, फसल की जलपूर्ति का साप्ताहिक मूल्यांकन, मौसम के दौरान इकट्ठे किए गए फसल का निष्पादन बताने वाले सूचकांक मान इस निदर्श की प्रमुख विशिष्टताएँ हैं। फसल की वृद्धि को पूरा होने के लिए आवश्यक 100 के अधिकतम संचयी मौसमी सूचकांक मानों को दो बराबर भागों में बाँटा गया है। वास्तविक समय योगदान का मूल्यॉंकन फसल द्वारा ज्ञात की गई कमियों और अधिकता तथा मौसम के दौरान एकत्र किए गए मान के आधार पर किया गया है। इस निदर्श का परीक्षण, मानसून की स्थितियों के समय नागपुर के वर्टिसॉल के शोरघम पर बुआई की तारीख के प्रयोग को बदलते हुए वास्तविक प्रेक्षणों के साथ किया गया है। यह निदर्श उपज और मौसमी कुल सूचकॉंक मान के बीच सर्वश्रेष्ठ सहसंबंध दिखाता है। इन दोनों के बीच रैखिक संबंधों का उपयोग उपज का पूर्वानुमान करने के लिए किया जा सकता है। ये निदर्श मानसून के अंर्तगत आने वाले वर्षा पर निर्भर कृषि में शुष्क, अर्द्धशुष्क और उपनमी वाले सूखे क्षेत्रों में अच्छे परिणाम दे सकते हैं।

ABSTRACT. A simple new crop model based on water balance concept for crop monitoring is developed. The main distinctive features of the model are use of two layer soil water balance, effectivity of precipitation, weekly assessment of water fulfillment of the crop and an index value in percentage accumulated during a season expressing performance of the crop. The maximum cumulative seasonal index value of 100 is apportioned equally into weeks required by a crop to complete the growth. Actual weekly contribution is evaluated on the basis of deficits and surplus experienced by a crop and value accumulated during a season is reached. The model is tested against actual observations in shifting sowing date experiment conducted on sorghum on the vertisols of Nagpur under monsoon conditions. The model has exhibited excellent correlation ship between yield and the total seasonal index value. The linear relationship between the two can be used to predict yields. The model can give better results in arid, semi-arid, and dry sub humid regions in rainfed agriculture under monsoon.

Key words – Crop water balance, Crop model, Crop monitoring , Yield prediction etc.

1. Introduction

Crop yield is the integrated effect of a number of interacting physical and physiological processes that occur during the crop growing period. These processes are influenced by the characteristics of the crop, weather, soil and management factors. Quantitative knowledge of these factors on crop production is important. Several models have been developed and categorized (Sirotenko, 1994). Models in various fields like breeding, soil science, plant physiology, fertilizer response, insect damage and regional crop planning are used. A simplified model useful for operational purpose and able to asses the crop condition at any growth stage working on minimum agrometeorological, soil and crop data is always desired. Such model should be useful for research workers, workers connected with crop monitoring and agromet advisory department. A model with a view to incorporate these features is attempted here below.

2. Material and methods

In tropics and subtropics thermal, photoperiodic and radiation regimes are most satisfactory but the rainfall is a major limiting factor in crop production. In such regions simple models based on water balance concept seems to be more adequate (Ghadekar 2001). Some of the models using water balance concept and rainfall as input (Ghadekar and Thakre, 1991) and various monsoon characteristics have been worked out by these authors

(Ghadekar and Thakre, 1991). Improvements in these models alongwith some past experiences compelled the need to develop a more refined version of a crop water balance model.

Frere and Popov (1979) developed a model based on cumulative ten days or weekly crop water balance which gives an Index expressing the degree of water requirement satisfaction (WRSI). Use of different components of water balance *viz*, water requirement of the crop, soil characteristics etc. have been made in this FAO model and described elsewhere (Frere and Popov 1979). FAO model makes an assumption that the Water Requirement Satisfaction Index [WRSI] in the beginning is 100 as the sowing is carried out only when the rainfall is adequate and subsequently reduces for surpluses and deficits of rains. This "preset" value of 100 needs reconsideration as 'early – season 'or 'mid – season' total crop failures under severe drought will show higher index value with less or no yields. FAO model does not consider effectivity of rains which is more essential. FAO model considers only single layer moisture balance allowing moisture extraction from deeper layers at full rate which is contradictory to the fact that the moisture extraction for a crop becomes increasingly difficult with deeper depths as the moisture depletes in upper layers decreasing extraction rates.

3. Details of the new model

The new improved model so as to eliminate some of the above mentioned deficiencies has the following features. The improved version, instead of using a "preset" seasonal value of 100 only at the sowing instances uses a week by week contribution to the water balance index on the basis of water regimes actually enjoyed by the crop considering surplus and deficit and then accumulated over a growing period of the crop considered.

3.1. *Time scale*

A weekly period is considered as appropriate time scale, being most common in agriculture.

3.2. *Cumulative crop specific weekly contributing index*

Meteorological parameters affect the crop and the integrated result such as dry matter production, growth and development are cumulative in nature in response to the weather experienced. Therefore, a weekly index (Iw) is designed to get extent to which water requirement of the crop can be satisfied and makes highest possible weekly contribution to the total seasonal index (Is) . This highest value is considered as normal value that crop can accumulate and actual value never exceeds this value. The maximum weekly contribution is decided as follows :

$$\text{Maximum weekly normal contribution} = \frac{\text{Days in a week } (7) \times 100}{\text{Duration of a crop in days}}$$

Thus, the maximum weekly contribution for the sorghum crop maturing in 117 days is 5.98 (nearly 6). The actual weekly contribution (Iw) is decided on the basis of surplus and water deficit experienced by the crop from sowing till harvest in a growing season and added to get seasonal index (Is). Water surplus causes water logging but still it enriches soil moisture which can be used subsequently and therefore its contribution is taken as 75% of maximum weekly contribution (for sorghum, 6 × 75% = 4.50). During water deficit, the crop experiences water stress and therefore, maximum weekly contribution is reduced proportionately to get actual value (Iw) as follows :

$$\text{Actual weekly contribution, Iw} = \left\{\begin{array}{l}\text{Maximum}\\ \text{weekly}\\ \text{contribution}\end{array}\right\} - \left\{\frac{\text{Actual water used by crop in a week}}{\text{Weekly water requirement of the crop}} \times \begin{array}{l}\text{Maximum}\\ \text{weekly}\\ \text{contribution}\end{array}\right\}$$

The total cumulative sum of the actual weekly contributions made in each week during the whole growing season serves as an index giving the degree of suitable or unsuitable regimes enjoyed by the crop and hence performance of the crop during that season, thus enabling the assessment of crop growth.

3.3. *Normal precipitation (Pn)*

The long term average of weekly rainfall to give idea about normal weekly quantum of rainfall and enable comparison with the actual value in the week.

3.4. *Actual precipitation (Pa)*

The actual precipitation in a week represent total rainfall in a given week .

3.5. *The number of rainy days (da)*

The number of rainy days to give an idea of the distribution of rain fall in a week is given.

3.6. *Potential evapotranspiration (ETo)*

Potential evapotranspiration is computed from actual weather data or from any suitable equation valid in a region or by FAO method from class – A open pan evaporimeter multiplying by pan coefficient (Kp)

3.7. *Crop coefficient (Kc)*

To compute crop water requirement in a week, crop coefficient suitable to the crop stage needs to be selected. For initial growth stages it is 0.3 and progressively reaches to 1.0 to 1.2 for the fully grown crop and slowly decreases to o.4 to 0.5 during maturing stage. Doorenbos and Pruitt (1977) have given a method of selecting crop coefficients. For simplicity and to allow soil evaporation, we are taking the value of Kc as unity throughout the season.

3.8. *Crop water requirement (WR)*

The crop water requirement is computed by multiplying total weekly ETo with Kc. As stated earlier, the value of Kc selected in the model is unity and therefore ETo directly expresses the water requirement of the crop. Seasonal water requirement is arrived at by adding weekly values for the whole season.

3.9. *Effective rains (Pe)*

To account for partial loss of rains by surface runoff, deep percolation and soil evaporation, the effective rainfall has been considered in this model and computed simply by taking 80% of actual rainfall. This accounts for losses of rainwater when the soil surface is dry and the rains are received at the start of the monsoon after the end of long dry spells. Deep percolation losses or surface runoff during heavy wet spells especially in monsoon regions are well accounted for through this.

3.10. *Difference between effective precipitation and potential evapotranspiration (Pe – ETo)*

This difference gives us the amount of water left after fulfilling the water requirement of the crop from rains without utilizing any moisture from the soil. The difference is positive when rainfall is more than ETo and will be stored into the first layer of the soil and then into the second layer. If the difference is negative, the water requirement (ETo) will be met firstly from the rains and the remainder from the first layer at full rate and if required, at half rate from the second layer.

3.11. *Two layer soil moisture reserve (Rs_1 and Rs_2)*

Two layer soil moisture model has been propounded first by Palmer (1965). Later, the concept was expanded and used by many authors including (Baier and Robertson 1966, Smith 1975). The moisture extraction by a crop from the first few centimeters is easier but becomes increasingly difficult with depletion of moisture from the upper layers there being exponential relationship between the two. Therefore for simplicity the depth of first soil layer was fixed as equivalent to 50 mm moisture level which is 27.7cm. Depth of soil layer was calculated as follows :

$$\text{Depth of soil layer, d(cm)} = \frac{\text{Depth of moisture (5cm)} \times 100}{\text{FC(30\%)} - \text{PWP(15\%)} \times \text{BD(1.2g/cc)}}$$
$$= 27.7 \text{ cm}$$

Thus this layer (Rs_1) stores 50mm of moisture from the positive charge Pe-ETo. From the total depth of 1 m soil, the available water content (AWC) between field capacity (FC, 30%) and permanent wilting point (PWP, 15%) for the bulk density (B.D., 1.2 g / cc) was calculated as follows :

$$\left[\text{AWC}(\text{cm}) = \frac{(\text{FC} - \text{PWP}) \times \text{depth}\,(100\text{cm}) \times \text{B.D.}}{100} = 18\text{cm or } 180\text{mm}\right]$$

Out of this Rs_1 contains 50 mm, therefore the second layer Rs_2 is fixed at 130 mm. Thus after filling the first layer Rs_1, the positive charge Pe–ETo will be directed and stored into Rs_2 upto 130 mm, excess, if any, will be converted into surplus.

3.12. *Surplus and deficit (S /D)*

The water more than the storage in both the layers appears as surplus in the S/D column. Surplus causes water logging and the growth is hampered still the moisture can be used latter, being stored into the soil. Therefore, the weekly contribution from the background experiences is taken to be 75% of the normal weekly value. When both the layers are exhausted, soil moisture falls to the level of permanent wilting point (PWP) and crop cannot grow and therefore the weekly contribution becomes zero.

3.13. *Stress (St)*

When the water from the first layer (Rs_1) is exhausted, water from the second layer is utilized at half rate to fulfill ETo and therefore the crop experiences stress. For only stress, the weekly contribution in proportion to stress is reduced. Suppose for a week, ETo has a value of 40 mm . After exhausting first layer (Rs_1), from second layer (Rs_2) only 20 mm are available, therefore the stress experienced is equal to [40 – 20] = 20 mm. If the water requirement of the crop is 40mm / week

TABLE 1

Computation of cumulative index (Is) from new model for Nagpur

Met week	Normal rainfall Pn (mm)	Rainfall Pa (mm)	Rainy days da	Effective rain [Pe]	E To (mm)	Pe-ETo (mm)	RS_1 I Layer 50 mm	RS_2 II Layer 130 mm	S /D	St Stress	Weekly Index Iw
24	36.8	41.6	3	33.3	51.1	-17.8	-	-	-	-	-
25	58.9	0.2	1	0.16	42	-41.8	-	-	-	-	-
26	58.3	179.4	7	143.5	35.7	+107.8	50	57.8	-	-	6.0
27	64.0	90.6	3	72.5	31.5	+41	50	98.8	-	-	6.0
28	73.3	59.8	6	47.8	30.5	+17.3	50	116.1	-	-	6.0
29	63.7	134.9	5	107.9	28.7	+79.2	50	130	65.3	-	4.5
30	66.8	35.8	2	28.6	28.7	-0.1	49.9	130	-	-	6.0
31	67.1	18.8	4	15.0	28	-12.9	37	130	-	-	6.0
32	66.0	52.6	5	42	27.3	+14.8	50	130	+1.8	-	4.5
33	55.0	71.0	5	56.8	27.3	+29.5	50	130	+29.5	-	.5
34	45.7	62.4	2	49.9	28	+21.9	50	130	21.9	-	4.5
35	63.4	77.4	3	61.9	28	+33.9	50	130	33.9	-	4.5
36	50.8	83.4	7	66.7	27.3	+39.4	50	130	39.4	-	4.5
37	30.9	8.8	4	7.0	28.7	-21.7	28.3	130	-	-	6.0
38	44.3	81.8	5	65.44	31.5	+33.9	50	130	12.2	-	4.5
39	23.7	30.6	5	24.5	32.9	-8.4	41.6	130	-	-	4.5
40	16.0	50.6	4	40.5	30.1	+10.4	50	130	2	-	4.5
41	13.2	2.0	1	2.0	30.0	-28	12	120.6	-	-	6.0
42*	3.5	-	-	-	30.6	-3.8	0	105.9	-	-9.4	6- 1.8 = 4.2
43	-	-	-	-	29.4	-29.4	0	93.0	-	-14.7	6 –3=3
44	-	-	-	-	25.9	-25.9	0	50.9	-	-13.0	6 –3 =3
45	-	-	-	-	23.8	-23.8	0	81	-	-12.0	6 –3=3

the reduction in normal value (say, 6) will be $\left(\frac{20}{40} \times 6\right)$ equal to 3. Thus, for each stress week contributions are decided.

3.14. *Cumulative seasonal index (Is)*

Thus considering surpluses and deficits the actual weekly contributions (Iw) are computed and added to get the total cumulative seasonal value (Is) for the crop considered. The index Is thus expresses the extent to which the water regimes were favourable and therefore also indicates the performance of the crop in a season.

3.15. *Yield prediction*

For any specific crop, computations of Is for some season with corresponding yields or by conducting shifting sowing date experiments in the same season giving various Is and yield values, it is possible to build a relationship between Is and yield (Y). Such an equation forms a simple model capable of predicting yield on the basis of Is value accumulated in a season.

TABLE 2

Computation of Index from FAO model based on water balance for Nagpur

Met. week	Period	Rainfall Pa (mm)	Rainy days (da)	Evapotran. (ETo) (mm)	Crop. Coeff (Kcr)	Water requirement (mm)	Pa-WR	Rs. (180mm)	S/D (mm)	Iw
24	11-17 Jun	41.6	3	51.1	-	-	-	-	-	-
25	18-24 Jun	0.2	1	42.0	-	-	-	-	-	-
26	25-1 Jul	179.4	7	35.7	0.4	14.3	165.1	165.1	0	100
27	2-8 Jul	90.6	3	31.5	0.5	15.8	74.8	180	+59.9	*97.9
28	9-15 Jul	59.8	6	30.5	0.7	18.3	41.5	180	+41.5	95.8
29	16-22 Jul	134.9	5	28.7	0.8	20.0	114.9	180	+114.9	93.7
30	23-29 Jul	35.8	2	28.7	0.9	23.0	12.8	180	+12.8	91.6
31	30-5 Aug	18.8	4	28	0.9	25.2	–6.4	173.6	-	91.6
32	6-12 Aug	52.6	5	27.3	1.0	24.6	28	180	+21.6	89.5
33	13-19 Aug	71.0	5	27.3	1.0	27.3	43.7	180	+43.7	87.4
34	20-26 Aug	62.4	2	28.0	1.0	28.0	34.4	180	+34.4	85.3
35	27-2 Sep	77.4	3	28.0	1.0	28.0	49.4	180	+49.4	83.2
36	3-9 Sep	83.4	7	27.3	1.0	27.3	56.1	180	+56.1	81.1
37	10-16 Sep	8.8	4	28.7	1.0	28.7	–19.9	160.1	-	81.1
38	17-23 Sep	81.8	5	31.5	0.8	25.2	56.6	180	+36.6	79.0
39	24-30 Sep	30.6	5	32.9	0.7	23.0	7.6	180	+7.6	76.9
40	1-7 Oct	50.6	4	30.1	0.6	18.0	32.6	180	+32.6	74.8
41	8-14 Oct	2.0	1	30.1	0.5	15.0	–13.1	166.9	-	74.8
42	15-21 Oct	-	-	30.8	0.5	15.4	–15.4	151.5	-	74.8
43	22-28 Oct	-	-	29.4	0.5	14.7	–14.7	136.8	-	74.8
44	29-4 Nov	-	-	25.9	0.5	12.9	–12.9	123.9	-	74.8
45	5-11Nov	-	-	23.8	0.5	12.9	–11.9	112.0	-	74.8

* FAO index decreases by 2.1 per week when surplus occurs and for deficit in proportion to stress (more details in the text).

4. Testing the model

The new crop water balance model proposed was tested on the basis of shifting sowing date experiment that we conducted in the year 1983 (Ghadekar *et al.* 1985) on sorghum. Five sowing dates generally, with a week interval *viz.* 28 Jun, 5 Jul, 12 Jul, 19 Jul, 26 Jul (1983) were used for sorghum and the crop was harvested after maturity on 23 Oct, 29 Oct, 3 Nov, 6 Nov and 9 Nov respectively. The yields (Y) recorded for these sowings were 46.65, 45.93, 40.23, 37.02 and 30.75 q/ha respectively. Table 1 shows the computation of actual weekly values of index Iw for various weeks according to the proposed crop water balance model along with various other components. For reference in the Table 2 similar calculations using FAO model are also shown. The soils of the station (Nagpur 21° 9' N, 79° 81' E, 321 masl) are vertisols with AWC 180 mm/m . The cumulative index Is for 5 different sowing dates for sorghum alongwith harvesting dates, yields are given in the Table 3.

TABLE 3

Seasonal index value (Is) according to new model for five different sowing dates of sorghum with harvesting dates and yield. FAO value for reference is also shown

Sowing and harvesting dates	FAO Index (FAO)	New model	Yield (q/ha)
28 Jun - 23 Oct	74.8	88.2	46.65
5 Jul - 29 Oct	74.8	85.2	45.93
12 Jul - 3 Nov	74.8	82.2	40.23
19 Jul - 6 Nov	74.8	79.2	37.02
26 Jul - 9 Nov	74.8	74.7	30.75

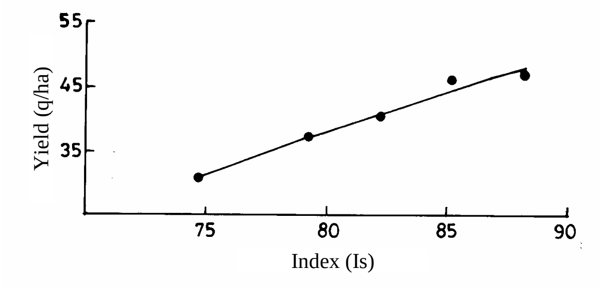

Fig. 1. The linear relationship between Is & yield

From the Table 1, it is seen that the two layer model shows that the crop undergoes stress from the 42nd meteorological week (MW) (15-21 Oct) till harvest. The stress quantum increases for delayed sowing dates under monsoon, a most commonly experienced situation in the Vidarbha region. The reduction in the yield being due to water stress coinciding with grain filling stage in the delayed sowings. Such stresses are responded in the new model and therefore different but reducing cumulative index Is is recorded with delay. A glance at Table 2, shows that single layer FAO model (AWC, 180 mm) shows constant value of 74.8 for all sowing dates maturing between 41th MW to 45 MW. The graphical representation between the cumulative index Is for the five different sowing dates of sorghum and the corresponding yield (q/ha) is exhibited in the Fig. 1 which is a straight line. The correlation between Is and yield (Y) was found to be very excellent with correlation coefficient r = 0.99. The R^2 value was found to be equal to 0.97. Regression between yield (Y) and index value (Is) was

$$Y = 1.24 \text{ Is} - 61.12 \text{ (q /ha)} \qquad (1)$$

5. Conclusion

The two layer crop water balance model with various components was developed. The model when tested under shifting date experiments for sorghum crop on the vertisols of Nagpur has exhibited excellent correlation between the yield (Y) and the seasonal index (Is) derived from the model with r = 0.99. The regression equation between the two , Y = 1.24 Is – 61.12 (q / ha) can be used to predict mid season crop yield for subsequent normal condition while Is value can be used to exhibit crop performance or crop condition in a season.

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