Mausam, (1993), **44**, 4, 343-346

551.579 : 633.1

Soil moisture balance and its application to yield monitoring of rainfed paddy at Raipur

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(Received 10 September 1990, Modified 22 November 1992)

सार—इस अध्ययन में, कृषि-मौसम वेधशाला, रायपुर के 1977 से 1988 तक दस वर्षों (1984 और 1987 को छोड़कर) के आंकड़ों से, चावल की फसल के मृदानमी संतुलन के परिकलन की तकनीक प्रस्तुत की गई है। मृदानमी संतुलन के विभिन्न घटकों के मान ज्ञात किये गए हैं और उन पर चर्चा की गई है। एक परिकलित उपज सूचकांक के आधार पर, उपज में संभावित कमी का पता लगाने के लिये, प्रतिबल मानों का प्रयोग किया गया है।

अध्ययन से ज्ञात हुआ है कि पौधों को जल की आवश्यकता तल शाखन और प्रजनन दशाओं में सर्वाधिक होती है; शुष्क पदार्थ के उत्पादन और जल के खपत-उपयोग के बीच सीधा सम्बन्ध प्रतीत होता है। उपज सूचकांक और चावल की वास्तविक उपज के मध्य उल्लेखनीय सम्बन्ध दृष्टिगोचर होता है।

ABSTRACT. The study presents a technique for computing soil moisture balance of paddy crop based on 10 years data from 1977-1988 except 1984 and 1987, from agrometeorological observatory, Raipur. Values of different components of the moisture balance have been determined and discussed. The stress values have been used to estimate possible yield reduction by devising an yield index.

The study revealed that water demand of the plant is largest between tillering and reproductive stages. Dry matter production appears directly related to the consumptive water use. A significant association is observed between the yield index and the actual rice yield.

Key words – Water balance, Bund, Potential rate, Transplantation, Crop coefficient.

1. Introduction

Crop production and cropping pattern in tropics depends mainly on the water availability, in contrast to temperate regions where temperature governs the type of crop and length of growing season. In view of availability of abundant water in brief spells during monsoon season, with longer periods experiencing dry weather, it becomes imperative to synchronise the crop growth to this period. Rice is a staple food for millions of people in India and has been cultivated for thousands of years. Yield though moderate, widely fluctuates from year to year due to variations in the rainfall. Water shortage is a serious constraint often drastically bringing down the yield.

Rapid progress in recent years in soil moisture and evapotranspiration studies has confirmed utility and usefulness of water balance technique. Water balance depend not only on the climatic variables that regulate the water supply to the crop, but also on water use by the crop (or transpiration), and water evaporating from the ground surface (*i.e.*, evaporation), on the physical and chemical characteristics of the soil like, water holding capacity, the crop specie (leaf area of the crop, distribution of stomata on the leaf) etc. Determination of the balance between amount of water entering the system and the quantity that leaves it at a given time and location, help to indentify periods when a crop should be transplanted or when it could experience stress. In short, accumulative water balance method can be used in monitoring the crop growth and estimating the yield.

In the present analysis, water requirements of rainfed paddy crop has been computed from water balance technique. This has been used to monitor crop response to soil water availability and the yield.

2. Data

The study pertains to Raipur (21° 14′ E, 81° 39′ N) located at an elevation of 248 m in Chhatisgarh region the traditional rice bowl of Madhya Pradesh. Paddy is grown in this region on mostly rainfed culture during the kharif season. Weather data for the years 1977 to 1988 of agrometeorological observatory at the station has been used. Data for 1984 and 1987 was not used as it was not found reliable. From the daily observations weekly totals of the various agrometeorological parameters were worked out from the date of transplanting to harvest. The rice yield data pertains to the observatory farm at Raipur.

The soil texture around that observatory is silty loam containing 45% silt, 30% sand and 25% day. The bulk density of the profile was found 1.6 gm/cm^3. The effective root zone of the crop was taken as 30 cm. As such the soil moisture at saturation, at field capacity and wilting point were found 141, 98 and 53 mm respectively. The available water, taken as the difference between the soil moisture at field capacity and wilting point worked out as 45 mm.

The soil profile at Raipur has been found homogeneous up to the root zone (*i.e.*, 30 cm). Such homogeneous soil profile with uniform texture would have little distinct horizonation (Baver *et al.* 1972) and little lateral movement of water. The bund height in the computations was taken as 100 mm.

3. The soil water balance

The salient features of the technique are as follows :

(*i*) The paddy field is bunded on all sides up to a certain height.

(*ii*) At the time of transplanting soil is at saturation and the field contains water up to the bund height.

(*iii*) Transpiration proceeds throughout the crop growth period at the potential rate.

(*iv*) Excess rainfall after meeting the plant requirement is deemed to go as seepage, percolation and run-off.

(*v*) Crop experience stress when the crop water requirement exceed available soil moisture.

The basic equation is :

$$S_i = S_{i-1} + P_i - WR_i - SP_i - RO_i \qquad (1)$$

where, the suffix i stands for value at the beginning of the ith week and (i—1), the end of previous week.

Here, S represents soil moisture, P the rainfall, WR the water requirement, SP, seepage and percolation losses and RO, the run-off.

In the methodology, the soil moisture S_i in the ith week is compared with soil moisture in the previous week S_{i-1}, rainfall P_i, water need WR_i and seepage/percolation loss SP_i. It is further assumed that in the beginning of the crop season, soil profile is saturated which is generally the case at the time of transplanting and subsequent 2/3 weeks.

The plant water requirement is computed by multiplying potential evapotranspiration PET by crop coefficient K_c for the week. The PET values were computed from Penman-Monteith formula. The K_c values were taken from Tomar and O'Toole (1979) for wetland rice in Asian countries and given phasewise in Table 1.

The weekly seepage/percolation loss is calculated as below :

$$SP_i = 0 \quad \text{for } S_i < S_f \qquad (2)$$

$$SP_i = 0.5\ SPA_i\ (S_i - S_f)/(S_o - S_f) \quad \text{for } S_f < S_i < S_o \qquad (3)$$

$$SP_i = 0.5\ SPA_i + 1.5\ SPA\ (S_i - S_o)/H \quad \text{for } S_i < 0 \qquad (4)$$

where, S_o is the soil moisture at saturation, S_f is the soil moisture at field capacity, and SPA_i seepage and percolation index for the ith week. SPA is assumed as 1 in the computation.

The available soil moisture, S_a is taken as the difference between the soil moisture at the field capacity S_f and the wilting point, S_w.

Flooding RO_i is presumed to occur above the bund height when soil moisture in the ith week exceed the sum of S_o, the soil moisture at saturation and H, the bund height.

i.e., if $S_i > S_o + 100$

then, $RO_i = S_i - (S_o + 100)$

The method described above is a modified form of that propounded by Olderman and Frere (1982).

4. Critical values of soil moisture

Concept of critical soil moisture has been introduced in the study. The critical soil moisture value in the ith week, S_{cri} is the lower limit of soil moisture content appropriate for the phenological growth stage of the crop.

In the first three weeks of transplantation the critical value of soil water content is assumed as (S_o+25) mm. This value enables the plant to avoid competition from the weeds. During the period of maximum vegetative growth till full heading, S_{cri} is assumed equal to S_o. During the last 4 weeks of the phenological cycle, *i.e.*, grain formation and ripening, the critical values are calculated from the moisture at the wilting point and the available soil moisture as shown below :

$$S_{cri} = S_w + 0.7\ S_a \qquad (5)$$

since $S_a = S_f - S_w$

Eqn. (5), therefore, becomes :

$$S_{cri} = 0.3\ S_w + 0.7\ S_f \qquad (6)$$

The values of critical soil moisture content for different phenological phases are also given in Table 1.

TABLE 1

Characteristic values of water balance parameters

Development stages	K_c	S_{cri}	F
Transplanting	1.1	166	0.2
Tillering	1.2	141	0.5
Vegetative growth	1.4	141	1.0
Reproduction	1.3	85	0.7

For a typical crop season, the water balance is shown in Table 2.

TABLE 2

Calculation of soil moisture balance and yield index

Week after transplanting	Soil moisture parameter (mm)						Crop yield parameter		
	S_{i-1}	P_i	WR_i	SP_i	RO_i	S_i	Y_{i-1}	Y_{ri}	Y_i
1	141.0	18.2	47.0	3.5	0.0	108.7	100	0	100
2	108.7	69.6	37.0	0.9	0.0	140.7	100	0	100
3	140.7	231.9	35.3	3.5	93.1	241.0	100	0	100
4	241.0	85.5	31.9	11.6	42.0	241.0	100	0	100
5	241.0	66.3	37.0	11.6	17.7	241.0	100	0	100
6	241.0	33.3	33.6	11.6	0.0	229.1	100	0	100
7	229.1	27.1	45.5	10.7	0.0	199.9	100	0	100
8	199.9	45.9	40.9	8.3	0.0	196.7	100	0	100
9	196.7	0.0	50.1	8.1	0.0	138.8	100	0	100
10	138.8	17.0	47.1	3.3	0.0	105.7	100	0	100
11	105.7	0.0	51.0	0.7	0.0	54.3	100	0	100
12	54.3	0.0	48.0	0.0	0.0	6.0	100	0	100
13	6.0	3.4	47.0	0.0	0.0	0.0	100	7.3	92.7
14	0.0	36.6	37.3	0.0	0.0	0.0	92.7	7.1	86·3
15	0.0	0.0	37.0	0.0	0.0	0.0	86.3	5.7	81.6
16	0.0	0.0	33.1	0.0	0.0	0.0	81.6	1.1	80.5
							80.5	1.8	79.2

5. Results and discussion

5.1. *Water balance parameters*

The evapotranspiration of paddy at Raipur has been observed to increase consistently up to heading stage and then follow a declining trend. The transpiration loss during transplanting is found equal to 5-5.5 mm per day. The demand gradually goes up to 6-7 mm per day (sometimes as high as 8 mm) during vegetative growth and flowering. While reviewing literature on rice evapotranspiration, Tomar and O' Toole (1979) found that the crop attains highest values of 4-7 mm per day at the heading time. During the last phase of the crop growth the evapotranspiration diminishes to 5 mm or less. Transpiration follows a trend similar to that of evapotranspiration.

Seepage and percolation rates are generally much higher on initiation of rains after the dry season than those that prevail after the soil is recharged. Wickman and Sen (1978) observed it to increase 10 times after a paddy field was dried. In this study, the seepage and percolation losses worked out as 1-2 mm/day. It compared favourably with the values given by Guerra *et al.* (1990) for rice fields in Phillipines.

Other things remaining constant, run-off is directly related to rainfall. Run-off was mostly observed during transplanting, tillering or initial vegetative growth stage when normally heavy rainfall occurs over southeast Madhya Pradesh in association with monsoon depressions. The weekly amount of run-off varied from 5-10 mm to as large as 40 mm per day. Nearly 10% of the total water loss (evapotranspirative, seepage and run-off) is accounted for by the seepage and percolation losses in the study. On the other hand the run-off, when observed, contributed to nearly 50% of the soil water loss; in some cases it was as large as 80% of the water loss.

A comparison of water lost due to seepage *plus* run-off with rainfall revealed that the former account for nearly half of the total rainfall during the crop season.

5.2. *Crop response factor*

In order to find out how the crop responds to the water balance, the following relationship between the actual yield Y_a in a year and the maximum yield Y_m observed in the sample, was adopted:

$$Y_a/Y_m = K_y\,(1-W_d)/W_m \qquad (7)$$

where, W_d are the number of weeks of stress, W_m the duration of crop growth in weeks (from transplanting to physiological maturity) and K_y the crop response factor (*cf.* Doorenbos and Kassam 1979). Accordingly, if the crop did not experience any stress in any of the weeks, the yield could be K_y times the maximum yield produced or in other words this would be the potential yield.

When the dry matter yield of the paddy crop was considered, the mean values of K_y was found as 1.22. This means when the crop is raised in unstressed conditions, the highest yield could be nearly 1/4 more than the maximum yield observed in the past.

5.3. *Dry matter-water requirement relationship*

The water requirement paddy crop vary according to variety, soil type, percolation and seepage losses, length of growing season etc. The water use is a function of prevailing meteorological conditions.

The total moisture need ($X = \Sigma\, WR_i$), WR_i being water requirement in the *i*th week worked out in the water balance from transplanting to maturity was correlated with the yield of total dry matter produce, (Y, q/hec). The following relationship could be established :

$$Y = 0.15\,X + 1.0, \quad (r = 0.51) \qquad (8)$$

The correlation was found statistically significant.

On the basis of the Eqn. (8) the expected yield for selected values of water need has been calculated. It was observed that when the water need is 500 mm, the dry matter production is 76 q/hec. The production goes up by 15 q/hec for every 100 mm of water need above 500 mm.

The water need thus appears low and could be attributed to :

(*i*) the short growth period considered in the study.

(*ii*) the maximum water need does not necessarily mean high dry matter produce, and

(*iii*) different strains of rice used in different years in the study.

Another factor which must be borne in mind in this connection is the fundamental defect in the regression approach that the dependence of crop yield on climatic factors is usually far too complex to be described adequately by a linear regression on a few gross measures of climatic variation (IRRI 1976).

5.4. *Yield response in relation to stress*

One of the advantages of the soil moisture balance described above is that it enables to estimate the extent to which the water needs of a crop is met at any stage of its development and growth. It can then be expressed as a yield index. The crop is assumed to experience stress when the soil moisture content in any week S_i is less than S_{cri}. This would imply that the development of the crop is retarded in some way to a degree depending upon its growth stage and the extent of the stress, resulting in reduced yield.

In the study the yield reduction Y_{ri} due to stress in the *i*th week is calculated from the moisture deficit (which is taken as the difference between the actual available soil moisture and the water requirement) divided by the total water requirement and expressed as a percentage, as shown below :

$$Y_{ri} = \frac{S_{cri} - S_i}{WR_i} \times F_i \times 100$$

where, F_i is the dimensionless weighing factor for the *i*th week taken as per Olderman and Frere (1982). Values for F_i for different phenological phases are given in Table 1.

The yield index Y_i in the first week is taken as 100. This gets progressively reduced as the critical soil moisture becomes less than S_i.

The yield index is cumulative, *i.e.*, reduction in yield in a week is subtracted from the index of the previous week to get the yield index for the week, *i.e.*,

$$Y_i = Y_{i-1} - Y_{ri}$$

The method is similar to the one used by Frere and Popov (1979). Computaton of the yield index is illustrated in Table 2.

In order to find if the index proposed in the study really represents conditions during growth and the final yield, the actual yield from the observatory farm was regressed with the value of the index observed at the end of the crop season. The following relationship could be obtained :

$$Y = 350.1\ X - 29671.3,\ (r = 0.67) \tag{9}$$

where, Y is the grain yield in kg/hec and X is the yield index.

The correlation was found statistically significant at 5% level.

Thus, it appears possible to progressively monitor the crop growth as the season progresses and estimate the yield immediately at the end of the crop season from the yield index.

6. Conclusions

Using soil moisture budget technique, the study furnishes weekly soil moisture balance parameters and also brings out the crop response to moisture stress. It also provides a method to estimate yield from yield reduction due to moisture stress. This approach could be useful in monitoring crop growth and the yield as the crop develops to physiological maturity.

The following results also emerge from the study :

(*i*) Maximum moisture demand, about 6-7 mm per day is noticed during the vegetative growth stage of the paddy plant.

(*ii*) Seepage and percolation losses occur generally during transplanting and early tillering phases.

(*iii*) Seepage and run-off together, could be as high as half of the total rainfall during the paddy crop season.

(*iv*) Potential for increasing paddy output by at least 25% exists in the region.

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