A two layer soil moisture model for estimating crop evapotranspiration and runoff

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सार — इस अध्ययन में वाष्प-वाष्पोत्सर्जन, मृदा आर्द्रता संचयन और जल प्रवाह के आंकलन के लिए एक दो स्तरीय निदर्श पर विचार किया गया है । इस कार्य के लिए मृदा को दो परतों वाली माना गया है - 100 मि.मी. तक की गहराई की निश्चित कृषि क्षमता वाली ऊपरी परत तथा मृदा की ऊपरी परत की संरचना पर आधारित कृषि क्षमता वाली निचली परत । इस अध्ययन में साप्ताहिक वर्षा के सामान्य मानों और संभावित वाष्पन-वाष्पोत्सर्जन का उपयोग किया गया है ।

खरीफ और रबी की फसलों के मौसम में उपयोग में लाए गए इस निदर्श से दो परतों वाली मिट्टी में फसल के दौरान मृदा शुष्क बिंदु अैर जल प्रवाह तथा फसल वाष्पन वाष्पोत्सर्जन की अवधि का पता चलता है ।

भारत में 41 स्थानों पर पाई जाने वाली मृदा की अधिकांश किस्मों के लिए विकसित निदर्श का प्रयोग किया गया है । इस विश्लेषण से खरीफ और रबी के मौसमों में उप हिमालय के क्षेत्रों और उत्तरी पूर्वी भारत में न्यूनतम ई टी का पता चला है । उत्तरी पूर्वी भारत में खरीफ के मौसम की समाप्ति पर फसलों को पर्याप्त अवशिष्टों वाली मृदा की नमी मिलती है जो अधिकांशतः ऊपरी परत पर रहती है । पूर्वी भारत में अधिकतम 800-1000 मि.मी. जल प्रवाह का पता चला है किन्तु उत्तरी पश्चिमी भारत में शुष्क से अर्द्ध-शुष्क क्षेत्रों में जल प्रवाह बहुत अधिक नहीं है ।

ABSTRACT. In the present study, a two layer model has been proposed to estimate evapotranspiration, soil moisture storage and runoff. For this purpose soil profile has been assumed to be composed of two layers: the top layer having a fixed field capacity of 100 mm and the underlying layer having field capacity depending on the soil texture. Normal values of weekly rainfall and potential evapotranspiration have been used in the study.

The model, applied to kharif and rabi seasons furnishes crop evapotranspiration period when soil in two layers reach wilting point and surface runoff and its duration.

The model developed has been applied to 41 locations representing most of the soil types found in India. The analysis revealed that lowest ET is seen over Himalayan foothills and northeast India in kharif and rabi seasons. Enough residual soil moisture is available to the crops at the end of kharif season over NE India; most of it being in the top layer. Eastern India record largest runoff of 800-1000 mm. Arid to semi-arid region in NW India does not seem to experience much runoff.

Key words—Soil moisture model, Evapotranspiration, Runoff, Kharif & Rabi crops.

1. Introduction

For objective and effective crop planning and operations like preparatory tillage, sowing/transplanting, application of fertilizers, irrigation etc. a prior knowledge of available moisture in the crop root zone is essential. A soil profile generally consists of different layers with distinct physical characteristics and root activity. Distribution of soil water content in a particular soil layer in the field determine the amount of water available to the crops through the root system. Normally soil moisture is measured through conventional equipments which, though a laborious and time consuming process, nevertheless is reasonably accurate. Dependent as it is on soil texture, structure, slope, hydraulic conductivity etc., the soil moisture is, like rainfall, highly variable in space. A fairly accurate and comparatively quicker method for estimating soil moisture is through water balance. A knowledge of various components of water

TABLE 1
Weeks when the two layers reach their wilting points

Climatic zones	General soil type	Top layer	Underlying layer
Arid zone	Red and yellow soil	45th to 46th week	After 49th week
Semi-arid zone	Alluvial soil	45th to 46th week	50th week
NE monsoon region	Red loamy soil	23rd to 24th week	*
Dry sub humid zone	Medium black soil	45th to 46th week	50th week
Moist sub humid zone	Red and yellow soil	50th week	*
Humid zone	Alluvial soil	50th - 51st week	*
Per humid of NE India	Red and yellow soil	3rd week	*

Note: * means the underlying layer does not reach wilting point.

balance enables to find the duration and quantum of moisture availability. A meaningful water budget procedure could help determining distribution of plant available water within the soil profile in relation to root proliferation during developing stages of the crop. Such an information enables identification of crop water stress period so that necessary irrigation could be provided to save the crop in case of stress. In the earlier studies of water balance (Thornthwaite, 1948; Thornthwaite and Mather, 1955; Slatyer, 1968; Keig and McAlpine, 1974), the soil was considered as a single layer with soil and plant as one system. Water was assumed equally available to plants for transmission uniformly almost throughout the range from field capacity to wilting point. From experiments on transpiration loss for different crops, Denmead and Shaw (1969) concluded that the root zone should be divided into two layers. This concept of two soil layers in soil water balance was adopted by many research workers (Kohler, 1963; Palmer, 1958; Baier and Robertson, 1966; Ligon *et al.*, 1967; Place and Brown, 1987, etc.). In the present paper, an attempt has been made to determine soil water balance related to plant rooting characteristics to arrive at a reasonable estimate of plant available water. This has been achieved by dividing the soil profile roughly into two moisture zones.

2. Material

The study utilizes the data of 41 locations representing nearly most of the soil types (Fig. 1) and agroclimatic zones in India. The soil profile has been divided into two layers, the top layer of 0.80 m depth, having uniform field capacity of 100 mm and an underlying layer of 1 m or more depth whose field capacity and wilting point depend on soil texture and other physical and chemical properties. For a few selected stations, field capacity and wilting points for each of the two layers are given in Table 1. The first layer, it is believed, can serve purpose of shallow rooted crops like rice, groundnut, etc., while the second layer would take care of

deep rooted crops like sorghum, maize, etc. Rainfall data used in the study were taken from "Agroclimatic observations of India", India Met. Department (1991), while weekly potential evapotranspiration (PET) has been computed by using the Penman's formula as refined by Doorenbas and Pruitt (1977). Values of field capacity have been collected from agricultural institutes at these locations. The time interval chosen in the study is a week. The analysis was carried out for 22nd to 15th standard week of the next year (*i.e.*, 1st June to 15th April) which constitute both kharif and rabi crop seasons.

3. The model

The proposed model bifurcates the crop root zone into two soil moisture availability zones and each is considered to be homogeneous in all respects. The upper layer has many roots and has soil depth of 0.80 m (approx. 3 ft) and a field capacity of 100 mm. The amount of water during the dry phase within this rooting zone is extractable from the soil for transpiration at potential rate uniformly in proportion to the remaining moisture in the soil in that zone from field capacity to wilting point (Mavi, 1994) as given below:

$$ET = PET \frac{SM_1}{FC_1} \tag{1}$$

where ET and PET are the actual and potential evapotranspiration, SM_1 is the available soil moisture in the top or first layer during a week, FC_1 is the field capacity of the first layer. When the surface layer dries up and reaches its wilting point the pattern of water extraction drifts downwards (Mayer and Ritchie, 1983; Kar *et al.*, 1992, etc.).

The root density in the lower soil zone is assumed to follow exponential function (Feddes *et al.*, 1974). The depletion of water from this zone is at an exponential rate and follows Gompertz type of curve. Moisture extraction from this zone takes place only when moisture in the first layer
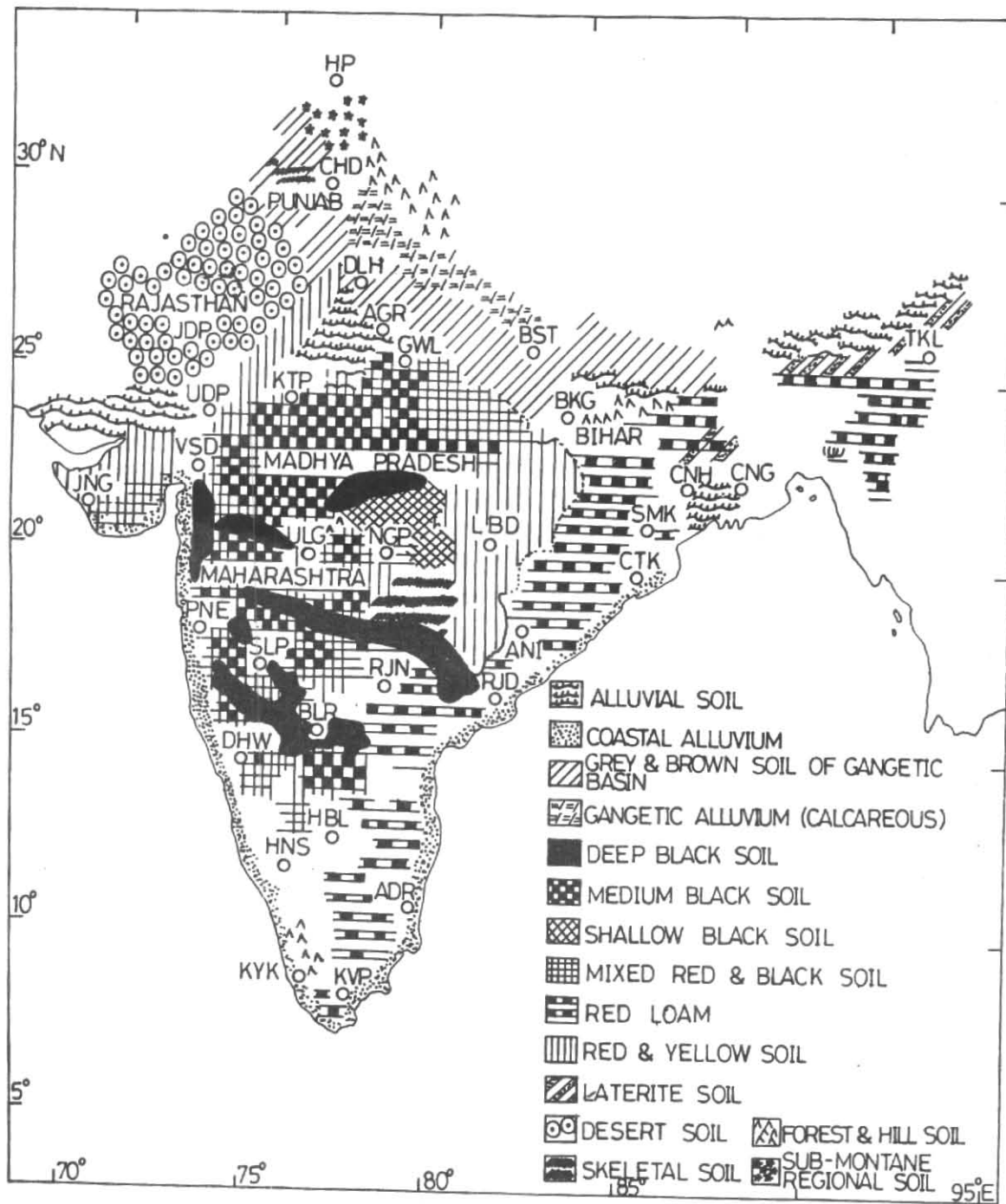
Fig.1. Soil types

reaches its wilting point. Depletion of moisture given by Gompertz curve is at much lower rate and is given by

$$ET = PET\, e^{-be - k\frac{SM_2}{FC_2}} \qquad (2)$$

where SM_2 is the available soil moisture in the second layer, FC_2 the field capacity of the second layer and b and k are constants.

After series of trials, the values of $b = 0.6$ and $k = 0.8$ were found to give reasonably accurate estimates of the soil moisture depletion.
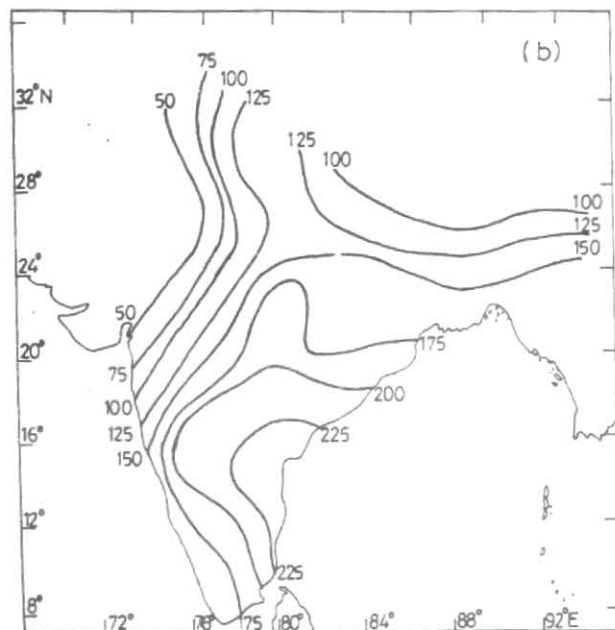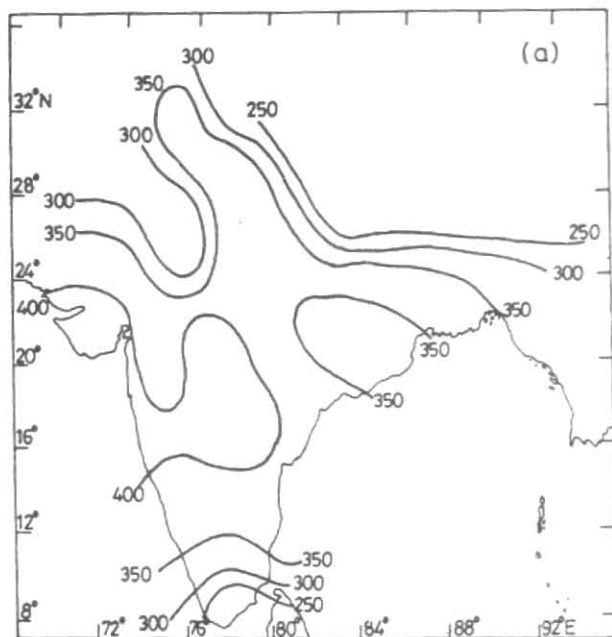
Figs 2(a&b). Spatial distribution of evapotranspiration (mm) (a) kharif
season and (b) rabi season

In those cases where $SM_1 \leq WP_1$, $SM_2 \leq WP_2$, we expect
no ET loss to take place where WP_1 and WP_2 are the wilting
points of the first and second layers respectively. This may
be true for transpiration but not so for evaporation. So in
such case

$$ET = P, \quad P < 20 \text{ mm} \qquad (3)$$

Such ET is termed in the study as "unproductive ET
loss" since it is not useful to vegetation.

As mentioned above, eqns. (1) and (2) are applicable
during dry spell. For this purpose a week is assumed dry
when the weekly rainfall P<20 mm. When P≥ 20mm, eva-
potranspiration is given by

$$ET = 0.6 \text{ PET} \qquad (4)$$

Change in the moisture status ΔM in any week is given
by

$$\Delta M = P - ET \qquad (5)$$

A negative value of ΔM would mean that the rainfall is
unable to meet the ET demand and the crop must extract
adequate moisture either from first layer or the second layer
depending upon the availability. A positive value of ΔM
simply would suggest that after meeting the ET demands
there is enough water for recharging the soil layers and
runoff (RO). In such a case, first the top soil is recharged till
it attains its field capacity (FC), then the second layer gets
recharged. Runoff takes place only when both the layers
have attained their field capacities.

The following points must be borne in mind while
working the soil moisture budget enunciated above:

(a) When during some week, say $(t-1)^{th}$ week, P≥20
mm and the first soil layer is already at its FC and
in the tth week P <20 mm, the ET during the tth
week as per eqn. (1) will be equal to PET, the ratio
(SM_1/FC_1) being equal to unity. There would
therefore be sudden rise in ET in the tth week
compared to $(t-1)^{th}$ week.

Weather in tropics during monsoon being persist-
ent in nature, it is assumed that cloudiness, hu-
midity etc. persist atleast during first half of the
t^{th} week. As such ET in first half of tth week
would be governed by eqn. (4), while in the
second half of the week eqn.(1) should give rate
of ET loss. As the unit of time considered is a
week and not its fraction, the multiplying term
has been taken as the average of 0.6 and 1.0, i.e.,
0.8. The equation governing ET loss in such a
case is

$$ET = 0.8 \text{ PET} \qquad (6)$$

From the $(t+1)^{th}$ week onwards if P<20 mm, eqn.(1)
will continue to give transpiration loss.

(b) While drawing moisture from first layer during a
week it is possible that ET> (SM_1-WP_1). Such
situations generally occur only during with-
drawal of moisture in the transition from the first
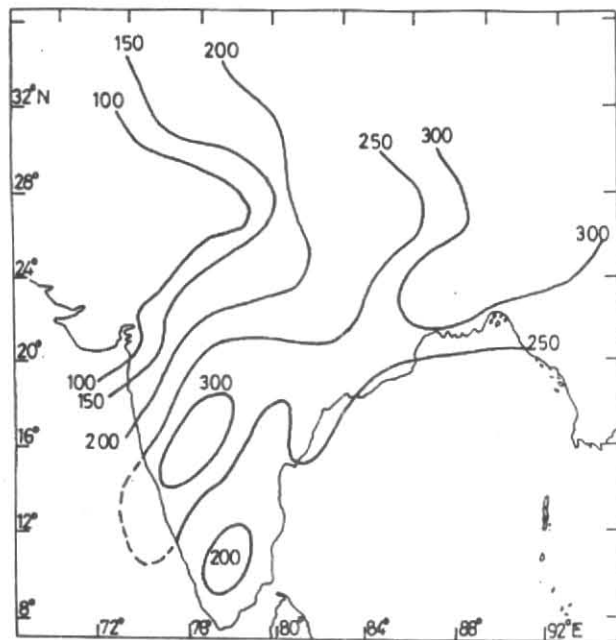to second layer.

Fig. 3. Soil moisture (mm) at the end of the kharif season (46th standard week)

$$\Delta M = P - ET = P - (SM_1 - WP_1) \qquad (7)$$

If ΔM is negative, the excess of moisture over and above SM_1 will be simply linearly drawn from the second layer for the week as per eqn. (2).

(c) During the dry period when moisture extraction is taking place from second layer, if for a week $P \geq 20$, eqn.(4) will come in force. ΔM, if positive in such a case, the excess will go to the first layer to recharge it, while if negative, the extraction of moisture will be from second layer. In case ΔM is positive and during subsequent week, if $P < 20$, eqn.(1) will become operative subject to the condition given in (a) above.

4.   Results and discussion

Spatial distribution of evapotranspiration (ET) during kharif and rabi seasons is shown in Fig. 2. The foothills of Himalayas and the northeast India, with humid climate, is a zone of lowest ET. The evapotranspiration during kharif crop season here hardly exceeds 250 mm. The southern parts of Tamil Nadu which receives most of its rainfall during the northeast monsoon season, also have ET less than 250 mm. Over north Rajasthan the ET is between 300-350 mm. Peak ET, exceeding 400 mm is observed over the predominant drought prone areas of Telengana, west Vidarbha and north interior Karnataka. The ET values for the kharif season

compares favourably with PET values over northwest India computed by Rao *et al.* (1971).

During the rabi season (Fig. 2b) in arid west Rajasthan and adjoining Saurashtra and Kutch, ET is less than 50 mm. In fact, in the core of the Thar desert, the ET loss is 10 mm or less. Areas close to the foothills continue to have lower ET values. In the traditional rabi growing areas in the peninsular India, the ET loss exceeds 200 mm, the largest values confined to coastal areas of Tamil Nadu and Andhra Pradesh. A sharp gradient in the ET isopleths over south Gujarat, west Madhya Pradesh and adjoining Maharashtra perhaps demarcate the predominant kharif growing zone in northern India from rabi growing zone in the south.

The methodology enunciated in the paper enables to determine the fraction of precipitation (P) which goes to meet ET demand. In eastern India, by and large, the ET/P ratio during kharif is 30% or less (Fig. not shown). This is not surprising, as the monsoon rainfall over this region is normally large enough to meet evaporative demand, provided it is evenly distributed during the crop season. On the other hand, if the total ET is compared with the total quantum of rainfall, the ratio over peninsula and northwest India comes out as 60%. This is mostly the dry farming zone of the country where even if the rainfall is well distributed does not meet water needs of the plant in full. Thus, irrigation to the tune of about 40% of ET, can perhaps help the kharif season crops to attain their genetic potential.

Similar analysis for rabi season did not reveal any regular pattern except that over northeast India, the ET demand is met in fully by the rainfall.

Rainfall over most parts of the country barring Jammu and Kashmir, Tamil Nadu and south coastal Andhra Pradesh practically ceases after the monsoon. Subsequent rainfall, if any, is erratic and undependable (Das and Chowdhury, 1992). With irrigation facilities hardly exceeding 30%, the rabi crops for their sustenance and growth have to rely, besides dew deposits (Chowdhury *et al.*, 1990), on the residual soil moisture storage at the end of kharif season. In view of the assumption made in the study, that kharif season ends on 46th week, *i.e.*, middle of November, spatial distribution of soil moisture at the end of 46th week is depicted in Fig. 3. A high value of over 300 mm over northeast India is prominently seen. Most of this is available on the top 100 cm depth. Surprisingly equally high value is observed in parts of north interior Karnataka which is rather hard to explain. Over northwest India, the soil moisture is less than 100 mm and is invariably present below 100 cm from the surface. Thus, this is not readily available when the root system of rabi crop plants is just developing. A comparative lower value of 200 mm soil moisture storage is seen over interior Tamil Nadu.
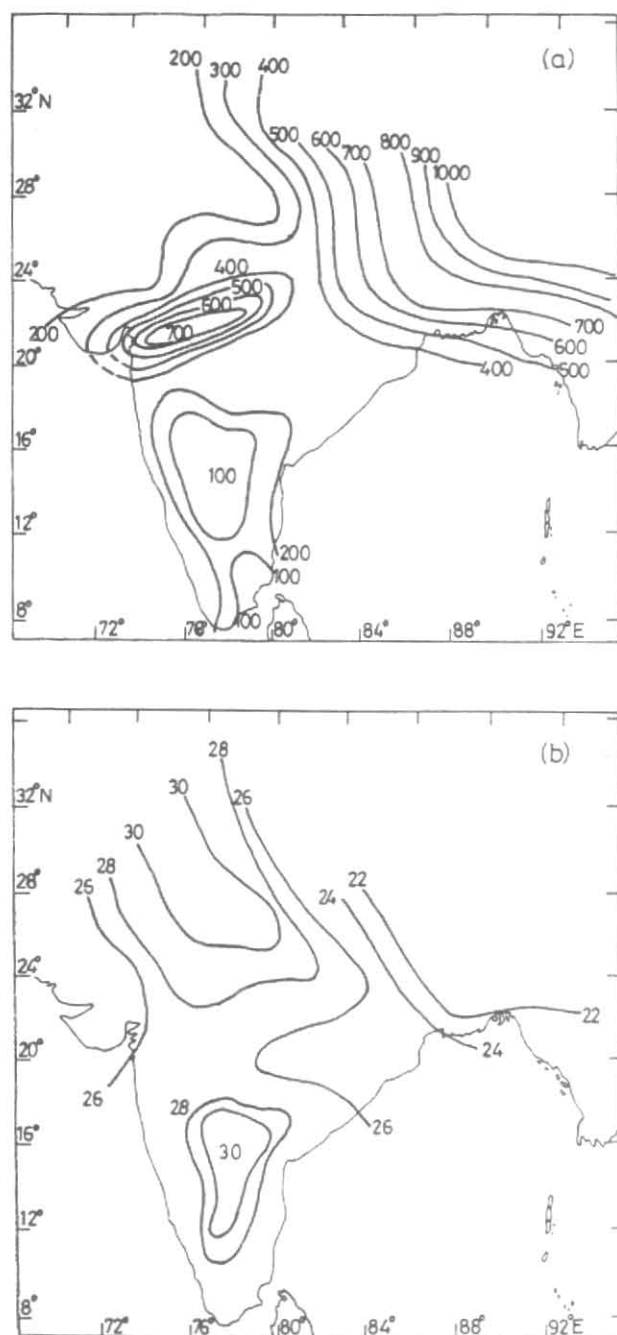
Figs.4(a&b). Spatial distribution of (a) total runoff and (b) commencement (week No.) of runoff

Among other valuable parameters, the methodology provides information about the period when the soil in the two layers likely to reach its wilting point. For rainfed culture, which constitutes nearly 70% of the available land in the country, this type of information is useful for crop planning. For different climatic and soil zones for selected locations in different agroclimatic zones, this is already

given in Table 1. It is seen that except areas like Tamil Nadu and south coastal Andhra Pradesh receiving major rainfall in northeast monsoon season, by and large, moisture is retained in the top soil up to 45th week and a small pocket in south Tamil Nadu where the excess amount hardly exceeds 100 mm. In the rest of the area of the run off generally varies between 200 to 600 mm.

It may be mentioned that the values of RO obtained in the study are theoretical values which inspite of different approaches agree with values of some of the stations computed by Rao *et al.* (1972). Unfortunately the authors could not get the actual values of RO for any location/area to substantiate efficacy of the proposed technique.

Spatial distribution of commencement of runoff is shown in Fig. 4(b). Runoff normally starts early in the eastern region by 24th week (11-17 June). In fact, over Assam and neighborhood it is in the 22nd week (*i.e.*, 28th May - 3rd June) and can be attributed to norwester activities.

In Telengana and eastern Karnataka the runoff is delayed till 30th week. Over north Rajasthan and adjoining areas of Punjab, Haryana and Uttar Pradesh, RO also occurs quite late (*i.e*, 30th week) as monsoon onset itself there is often delayed. Over most parts of the country, 26th - 28th week (*i.e.*, late June to mid July) appears to be favourable for surface RO.

The duration in which runoff is observed (Fig. not shown) exceeds 20 weeks in northeast India. Over northwest India the excess occurs hardly for 10 weeks. While over southern peninsular India, it lasts for 6 weeks.

The analysis has large potential use since, wherever the runoff occurs even in smaller magnitude, can with proper water management, be used for growing short duration vegetables in the subsequent comparatively dry period.

5. Conclusion

During the kharif crop season ET loss over northeast India is about 250-300 mm, accounting for nearly 30% of the total rainfall. Over the peninsula, the same exceeds 400 mm though rainfall in these areas is moderate.

As the rainfall belt shifts over south peninsula during rabi season, it records 200-225 mm of evapotranspiration. The lowest amount is observed in northwest India ranging from 50-100 mm. It is believed that plant extracts considerable amount of moisture from the soil during the lean rainfall period.

Considerable amount of runoff, 800-1000 mm is observed over northeast India *i.e.*, Arunachal Pradesh, Assam and adjoining states, West Bengal and Sikkim and parts of Bihar and Orissa. This mostly occurs between 22-26 and 46th week. Over moist and humid zones in northeast India,

TABLE 2

Runoff (mm) during the monsoon season at selected stations

Station	Climatic type	Soil type	RO (mm)
Kayamkulam (kerala)	Per humid	Coastal alluvial soil	1045.3
Solapur (Maharashtra)	Semi-arid	Medium black soil	0079.2
Surat (Gujarat)	Semi-arid	Coastal alluvial soil	0710.0
Sillicoorie (Assam)	Per humid	Red and yellow soil	1145.5
Basti (UP)	Dry sub humid	Alluvial soil	0750.7
Kota (Rajasthan)	Semi-arid	Alluvial soil	0433.5
Dharwar (Karnataka)	Humid	Red loamy soil	0137.4
Rajahmundry (Andhra Pradesh)	Dry sub humid	Alluvial Soil	0427.1
Jallunder (Punjab)	Semi-arid	Alluvial soil	0212.7

the wilting point in top 100 cm profile is reached towards end of December to middle of January. Over Tamil Nadu and adjoining areas top layer gets depleted of moisture up to wilting point, by the beginning of June *i.e.*, 23rd - 24th standard week.

In the underlying layer too, the moisture reaches wilting level over arid zone by 49th week *i.e.*, beginning of December and over semi arid and dry sub-humid areas, by the succeeding week or middle of December. Over remaining areas the underlying layer generally retains moisture above wilting point throughout the year.

In any watershed RO depends on (*i*) amount of rainfall (*ii*) intensity of rainfall (*iii*) area of the catchment (Schwab *et al.*, 1981 (*iv*) slope of the surface (*v*) available soil moisture and (*vi*) depth of aeration zone (Anonymous, 1972). Hydrological based statistical models to estimate RO from rainfall have been observed by Adhikari *et al.*, (1989) to be best suited to dry farming zone in Karnataka. Assuming that RO occurs only when the soil reaches its field capacity, the model developed in the study also furnishes rough estimate of the surface runoff (RO). This is obtained as the positive difference between the precipitation and ET *i.e.*

$$RO = \Delta M = P - ET$$

The commencement, duration and the total RO has been computed. Spatial distribution of total amount of run off is shown in Fig. 4(a). For selected stations in different agroclimatic zones, the same is shown in Table 2.

In the north-eastern states of India (*i.e.*, Bihar, Orissa, West Bengal and Sikkim, Assam, etc.), the rainfall available for runoff is substantial (*i.e.*, more than 600 mm) particularly in Assam, Arunachal Pradesh, Nagaland and Meghalaya etc. where it exceeds 1000 mm. This is but natural as this is the area which receives highest rainfall (250 cm or more) during monsoon. A zone of comparative large RO is observed on the northern side of Satpura range over Surat district and

Nimar regions of Madhya Pradesh. Like Assam, this region is also prone to floods and has been corroborated by Nootan Das *et al.*, (1987). Contrary to general belief, the rain starved region of the northwest India, a zone of subnormal rainfall, also experiences, though comparatively small run off *i.e.*, less than 200 mm in the entire monsoon season. Another zone of lower run off is on the side of the Western Ghats standard weeks *i.e.*, beginning of June to middle July. Substantial runoff also occurs over northern periphery of Satpura range during early July.

Towards the end of kharif season large amount of moisture (about 300 mm) is retained by the soil over humid per-humid states of Arunachal Pradesh, Assam, West Bengal, Nagaland, etc. During the same period over arid to semi-arid states of Rajasthan, Gujarat, Haryana and parts of west Uttar Pradesh, the top soil layer has hardly any moisture and whatever moisture is available it is in the underlying layer.

Acknowledgement

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