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551.579.5:551.573:633

Soil-moisture and evapotranspiration simulations for irrigated wheat using Soil-Plant-Atmosphere-Water (SPAW) model

L. S. RATHORE, G. SRINIVASAN* and K. K. SINGH

NCMRWF, Department of Science & Technology, New Delhi

(*Received 23May 1991,Modified 1 September 1993*)

सार – दिल्ली में गेहूं के लिए मृदा-आर्द्रता की रूपरेखा बनाने के लिए मृदा-वनस्पति-वायुमंडल-जल (एस पी ए डब्ल्यू) मॉडल का अनुप्रयोग किया गया है। दिल्ली के एक स्थान पर मृदा-आर्द्रता का आकलन करने के लिए वाष्पीकरण और वर्षा के दैनिक मौसम आंकडों सहित 11 वर्षों के लिए गेहूं की उपज के अभिलक्षण एवं मृदा की निर्धारित सूचना का उपयोग किया गया। मॉडल में 1979–80 से 1989–90 के वर्षों की लगातार फसल ऋतुओं की मृदा-आर्द्रता अनुरूपता का ग्रेविमीटर पद्धति से मापे गए प्रेक्षित आंकड़ों के साथ अनुकूल संबंध पाया गया। मॉडल से उत्पन्न वाष्पोत्सर्जन मानों की भी तुलना की गई। 11 वर्ष की अवधि के दौरान विभिन्न परतों में प्रेक्षित और अनुरूपी मृदा आर्द्रता के बीच 0.7 से 0.85 तक सहसंबंध पाए गए। इसी प्रकार फसल की विभिन्न अवस्थाओं में समाकलित कॉलमों के आर्द्रता परिमाण में भी 0.4 से 0.8 तक सार्थक सहसंबंध पाया गया। फसल की अंतिम अवस्थाओं के दौरान मॉडल ने योजनाबद्ध ढंग से वास्तविकता से बहुत अधिक मृदा-आर्द्रता का आकलन करने की प्रवृत्ति दिखाई। यह प्रवृत्ति संभवत: निवेश की त्रुटि, मॉडल के कृत्रिम रूप और प्रेक्षणात्मक अपर्याप्तता के कारण पाई गई। तथापि, भारतीय परिस्थितियों में गेहूं की फसल की सक्रिय उपज के लिए मृदा-आर्द्रता में देखे गए परिवर्तनों को उत्पन्न करने हेतु मॉडल सर्वथा उपयोगी है।

ABSTRACT. Soil-Plant-Atmosphere-Water (SPAW) model has been applied to simulate soil-moisture profiles for wheat in Delhi. Prescribed information on wheat growth characteristics and soils alongwith daily meteorological data on evaporation and rainfall were used to estimate soil-moisture at a location in Delhi for 11 years. Soil moisture simulations from model runs of consecutive crop seasons from 1979-80 to 1989-90 were in favourable agreement with the gravimetrically measured observed data. Comparisons were also made for the model generated evapotranspiration values. Correlations between observed and simulated soil-moisture in the different layers ranged from 0.7 to 0.85 for the 11-year period. Similarly, integrated column moisture amounts during different stages of the crop also showed significant correlations ranging from 0.4 to 0.8. The model exhibits a tendency to systematically over estimate soil-moisture during the final stages of crop, possibly due to imperfections in input, model artifacts and observational inadequacies. However, the overall ability of the model to reproduce observed changes in soil-moisture for actively growing wheat crop in Indian conditions, underlines its utility.

Key words — Soil-moisture, Evapotranspiration, Simulation.

1. Introduction

Knowledge of the soil moisture profile dynamics during the crop life-span enables optimal utilization of available water resources. However, monitoring this parameter on a real time basis is not always possible, necessitating the adoption of soil moisture estimation techniques based on readily available meteorological data. Modelling techniques developed in recent years have been extensively applied for this purpose (Baier & Robertson 1966, Ritchie 1972, Saxton & Bluhm 1982 and Ritchie 1985). These techniques adopt a holistic approach and comprehensively integrate the dynamics of sub-processes to provide clearer understanding of the underlying biophysical mechanisms, which makes them suitable for a broad range of applications.

Some models may be theoretically superior due to their detailed procedures, but have limited operational utility due to intensive input needs. The SPAW model developed by Saxton (1980), provides a suitable compromise between the level of details and inputs required thus making it ideal for field applicability. It has been widely applied to various crops like corn, soybeans, bromegrass, wheat and sorghum (Sudar *et al.* 1981, Saxton *et al.* 1974, Saxton 1983 and Omer *et al.* 1988) for estimating soil moisture, predicting yields and other crop management aspects. The model has also been successfully used in a tropical, semi-arid region (Omer *et al.* 1988).

The main objective of the study was to calibrate the model for wheat crop using data available for sandy loam soils of Delhi and to evaluate its capability to simulate soil moisture profile and daily evapotranspiration. This objective was expected to satisfy our broader aim to examine the performance of the model with generalized input information.

*Affiliation : Meteorological Office, New Delhi.

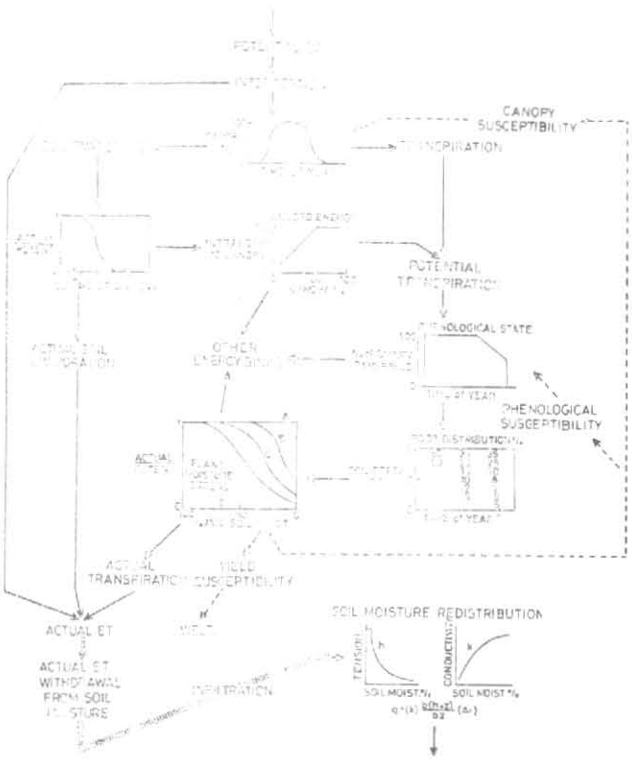

Fig. 1. Schematic representation of the Soil-Plant Atmosphere-Water model (*Source* : Saxton, 1989)

2. Model

The SPAW model was chosen because of its relatively simple, physically based technique which incorporates sufficient degree of detail with minimal requirements of daily inputs consisting of routinely measured meteorological data. It has been described by Saxton (1989) as a predictive procedure for the daily accounting of soil water within soil layers which is governed by the major effects of weather, plants and soil. The initialized soil moisture status at day-one of the crop season is forced in the model by precipitation and atmospheric evaporative demand through the plant-soil system.

Potential evapotranspiration (PET) fixed as a upper boundary of energy available for water loss is partitioned, using the percent ground shading, into soil evaporation and plant transpiration. Actual evaporation and transpiration are determined taking into consideration the availability of soil moisture and agglomerates of roots which can actively extract water from different layers of the soil column. A fixed amount of water is intercepted by the canopy and the soil surface and is allowed to evaporate without any resistance at a potential rate as interception-evaporation. From these values the actual ET is then computed. Subsequently, the model carries out a budget calculation of input-output components to estimate layerwise soil-moisture status. Free water input at the soil surface through rainfall or irrigation is reduced by runoff amounts (computed by SCS-CN method) before being allowed to infiltrate. After augmenting the soil moisture status of each layer excess infiltrated water is lost as deep percolation. Layerwise soil moisture status, thus calculated, is redistributed using a simplified Darcy's equation for water flow in saturated conditions to arrive at final soil moisture levels. Details flow diagram is given in Fig. 1.

Due to its one-dimensional approximation the model assumes horizontally homogeneous condition and neglects lateral fluxes of moisture. To simplify the representation of infiltration, it is assumed to be instantaneous. Parameterised water extraction patterns, although varying seasonally are not influenced by water stress. Diurnal fluctuations are also not considered.

3. Data set

The model requires generalized information on crop and soil characteristics and specific information of weather during each day of the crop season. The input data set pertains to the research farms of Indian Agricultural Research Institute (IARI), New Delhi.

3.1. *Crop parameters*

Crop characteristics during the different phenophases have to be specified for setting the model to a particular crop. Data on crop canopy (soil shading percentage), crop phenology : describing canopy's ability to transpire, susceptibility curves representing water stress effects on growth and phenology, plant water extraction pattern by root distribution values throughout the soil profile at selected time intervals and plants' ability to extract soil moisture are required as general inputs. The water uptake by roots is parameterized in the model by specifying a water abstraction pattern (Table 1). Since the redistribution of the soil moisture in the profile is done using Darcy's equation, boundary conditions are

TABLE 1

Distribution of water extraction from the soil layers (representing water uptake by roots)

Depth of soil layer (cm)	Day after sowing (Extraction %)												
	0	10	20	30	40	50	60	70	80	90	100	110	120
0-2.5 (Evaporative layer)	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5-15	95	90	80	70	62	56	50	45	45	45	45	45	45
15-30	4	8	10	14	18	20	20	22	22	22	22	22	22
30-45	1	2	6	11	13	15	16	17	15	15	15	15	15
45-60	0	0	4	5	7	8	11	10	10	9	9	9	9
60-90	0	0	0	0	0	1	2	3	3	4	4	4	4
90-120	0	0	0	0	0	0	1	2	3	3	3	3	3
120-150	0	0	0	0	0	0	0	1	2	2	2	2	2
150-195 (Image layer)	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 2

Textural and moisture characteristics of soil layers

Layer	Depth (cm)	% Moisture (volumetric at) Satu-ration	Field capacity	Wilting point	Sand %	Silt %	Clay %	Bulk density
1*	0-2.5							
2	2.5-15	41.0	18.9	7.6	74	10	16	1.56
3	15-30	41.0	16.0	7.3	74	10	16	1.57
4	30-45	43.0	17.2	8.6	73	11	16	1.52
5	45-60	43.0	16.0	7.6	73	11	17	1.52
6	60-90	43.0	19.5	9.5	72	12	18	1.52
7	90-120	42.0	27.2	14.2	68	12	20	1.55
8	120-150	42.0	25.2	13.2	68	12	20	1.54
9*	150-195	42.0	25.2	13.2	68	12	20	1.54

*The first one is "evaporative layer" & the ninth one is "image layer" both without roots. Second through eighth are referred in the sequel as "real layers."

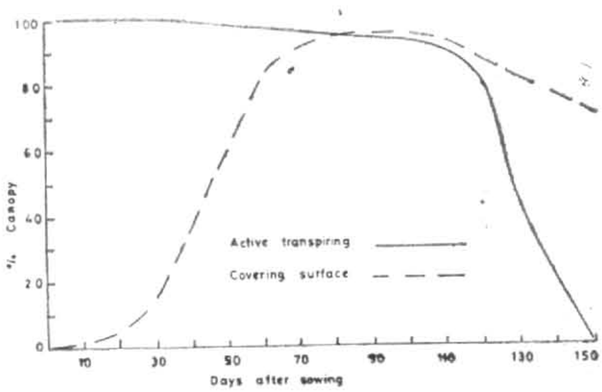

Fig. 2. Canopy and transpirability (non-stressed) curves

required to be specified which is done by providing an upper "evaporative" layer and a lower most "image" layer in the model profile. The "evaporative" layer is a very thin layer which offers no resistance to evaporation and dries out quickly similar to a stage 1 soil water evaporative process. The "image" layer functions as a reservoir controlling deep percolation or upward flow of water, back to the active profile. Only when the field capacity of the image layer is exceeded, water is lost as deep percolation from the model profile. Similarly, if the penultimate layer becomes drier than the image layer, water is taken up from it.

Curves for crop canopy and transpirability (Fig. 2) and stress susceptibility were composited based on data collected at IARI on wheat varieties (Sonalika, HD-2009 and HD-2285) and from published studies (Gajri & Prihar 1985 and Doorenbose & Pruitt 1977). These data were also supplimented by regular observations made on the wheat crop at the evapotranspiration station of the India Meteorological Department located at the Water Technology Centre, IARI, New Delhi. Each model run also requires (WTC) data on sowing and harvesting for the concerned crop season.

3.2. *Soil parameter*

Keeping in view the rooting pattern of wheat and soil profile characteristics, a soil column of 195 cm depth was assumed for the study. This was divided into nine unequal layers for which textural details and moisture constants are listed in Table 2. Textural information on each layer was used to define moisture-tension and conductivity properties based on moisture characteristics curves (Kalra 1986). Observed values of soil-moisture obtained from WTC, IARI, New Delhi were used to initialize the model. Additionally, for soil moisture redistribution calculations control values of maximum pressure change (cm) allowed per time step and, maximum and minimum time step (hrs) were also fixed.

The daily estimates of runoff were made by a modified version of the Soil Conservation Service (SCS) Curve

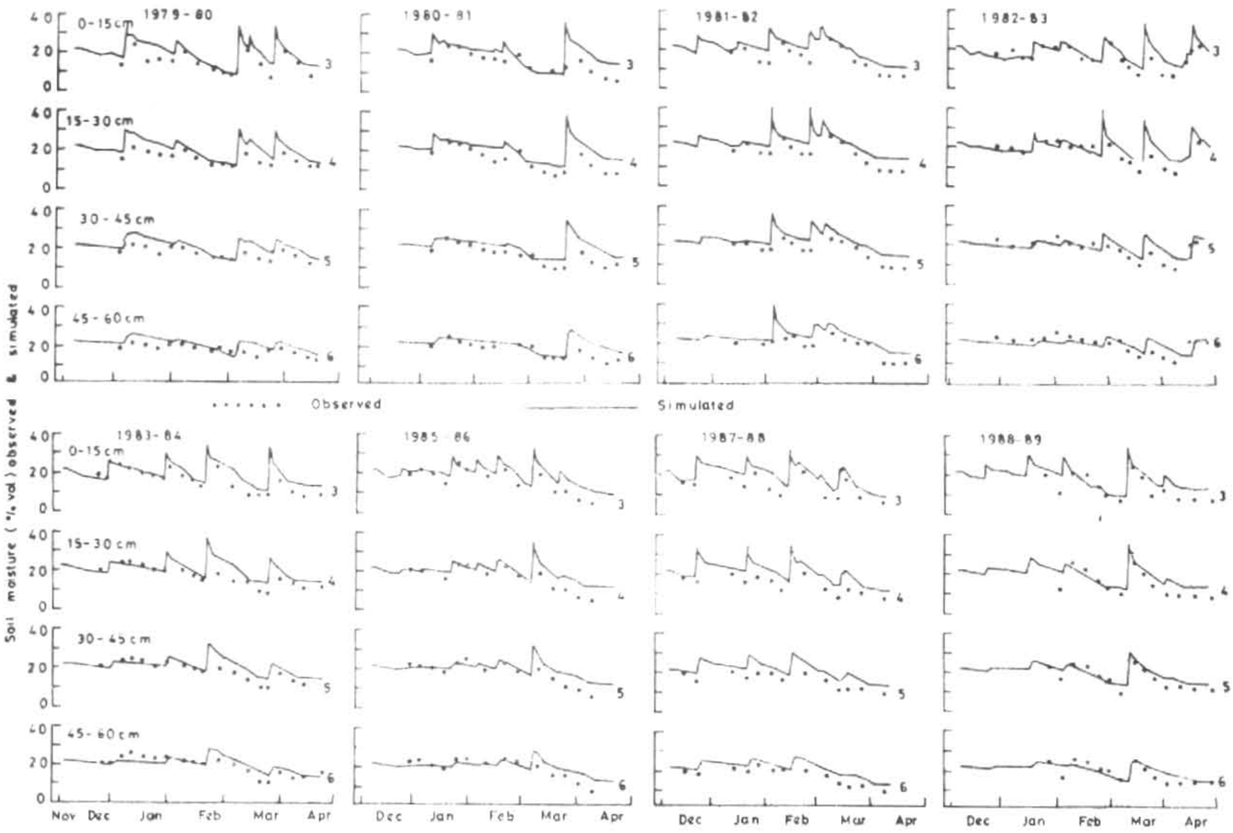

Fig. 3. Layerwise observed and simulated soil moisture under wheat at Delhi

Number (CN) method. Based on a series of curves, the method estimates the amount of daily precipitation which is lost as runoff. The curve numbers are selected from tabulated CN values for soil-crop combinations and antecedent soil moisture conditions. As crop canopy and moisture are dynamic variables computed in the SPAW model, their estimates are used instead of conventional average annual values.

3.3. *Meteorological parameters*

Daily rainfall and pan evaporation data for 11 wheat crop seasons (1979-80 to 1988-89)recorded at IARI, New Delhi observatory were used to run the model. Monthly values of pan-coefficients as given by Arora *et al.* (1988), Chakravarty and Sastry (1984) were used. Input data on irrigation type, date and amount were obtained from WTC, IARI, New Delhi.

4. Soil moisture profiles : Observed and simulated

Simulated soil-moisture values are compared with gravimetrically observed data (weekly) for four levels. Fig. 3 shows daily, layerwise soil-moisture distribution for different years alongwith observed values at discrete points. Output from the eleven runs were used to make comparisons at more than 150 points for each layer. The agreement between simulated and measured soil moisture content is good from germination through reproductive phase. But as the crop enters senescence, the model tends to overestimate the soil moisture. This could be attributed to reduction in actual evapotranspiration rate during this phase. This data was subjected to statistical analysis, results of which indicate reasonably good agreement between the observed and simulated values. The scatter plots for each layer (Fig. 4), correlations and Root Mean Square Errors (RMSE) (Table 3) illustrate the performance of the model. Deeper soil layers exhibit better agreement between simulated and measured soil moisture content as compared to upper layers of the profile. However, in general, the comparisons with 1 : 1 line shows the model's tendency to overestimate.

For a more comprehensive analysis of the performance of the model for estimating soil moisture, a comparison of observed and simulated values between irrigations events were made. Observed volumetric soil moisture content, integrated up to 60 cm depth, in between irrigations and different phenophases (based on days after sowing) were compared with the model estimated values for the same dates. Correlation coefficients and RMSEs obtained are presented in Table 4. It is apparent from this analysis that the model performance, based on correlation coefficients, is better during the periods, between 2nd - 3rd and 3rd - 4th irrigations. Similarly, from phenological point of view the correlations between observed and simulated soil moisture values are higher during vegetative/reproductive and ripening phases of the crop. However, during these periods the standard errors are comparatively higher than those during initial/between Ist & 2nd irrigation period. This may be due to systematic errors arising from deficiency in runoff estimation in the model. This is also supported by the lower intercept values during the later phases.

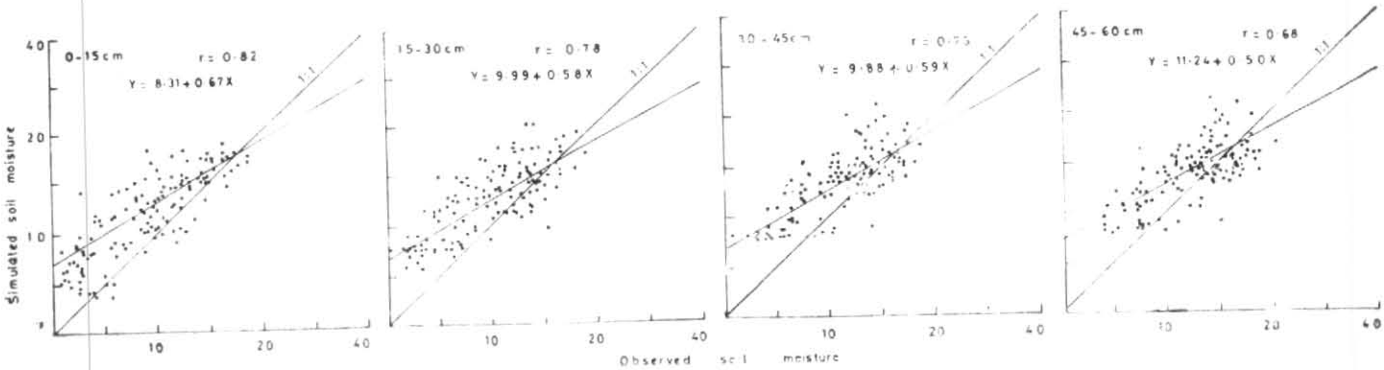

Fig. 4. Scatter plots of observed and simulated soil moisture for different layers based on ten years data set

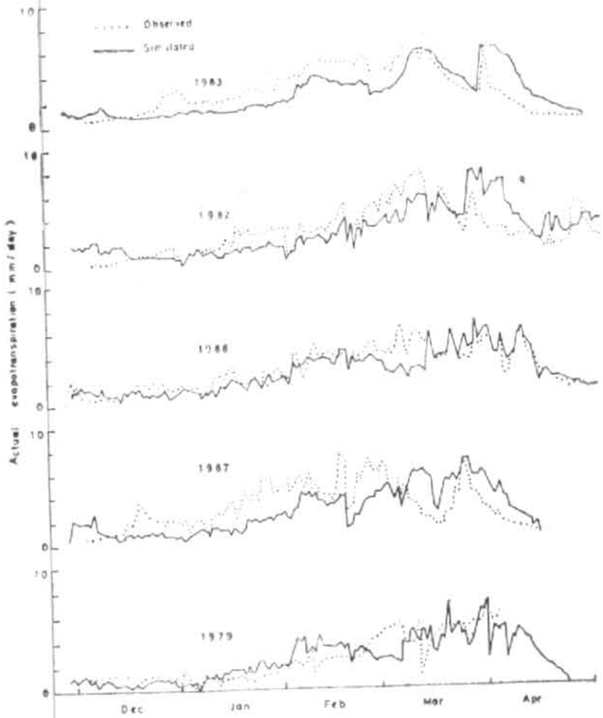

Fig. 5. Plots of observed and simulated AET for five years

Keeping in view the limited input data set and the degree of complexity of the model the results are considered satisfactory.

5. Actual evapotranspiration : Observed and simulated

Daily integration of water losses through evaporation and transpiration from the system gives the actual evapotranspiration amounts which is another output parameter available for comparisons. This parameter was compared with lysimetrically measured evapotranspiration data (Source : IMD station at WTC, IARI) for the 11 years period (Fig. 5). It is apparent from the figure that the observed evapotranspiration values differ from the model computed values during many occasions especially during the latter half of the crop season. These variations could be attributed to various aspects ranging from insufficiencies in model representations to fluctuations in microclimatic

TABLE 3

Comparisons between observed and simulated soil-moisture

Layer**	RMSE (cm)	CC	Reg. Equation
1(0-15)	0.62	0.85	$y=9.86+0.75x$
2(15-30)	0.64	0.80	$y=13.20+0.63x$
3(30-45)	0.58	0.78	$y=13.05+0.64x$
4(45-60)	0.54	0.70	$y=16.08+0.52x$

**Based on comparisons at more than 150 points

TABLE 4 (a)

Comparison of observed and simulated soil moisture in 60 cm soil profile between two irrigation

Irrigation sequence between	RMSE (cm)	CC	Reg. Equation
First & second	1.6	0.48	$y=90.12+0.32x$
Second & third	1.9	0.82	$y=33.39+0.79x$
Third & fourth	3.2	0.89	$y=40.68+0.89x$

TABLE 4 (b)

Comparison of observed and simulated soil moisture in 60 cm soil profile between phenophases

Phenophase* (Day after sowing)	RMSE (cm)	CC	Reg. Equation
30	1.0	0.82	$y=60.67+0.5x$
31–70	1.8	0.48	$y=87.86+0.35x$
71–120	2.5	0.79	$y=37.83+0.79x$

*In absence of phenophase observations, average period of occurrence of three phenophases, *i.e.*, (*i*) 30 days for initial phase;

(*ii*) 31-70 days for vegetative/reproductive phase; and

(*iii*) 71-120 days for ripening phase have been assumed.

controls and inherent problems of lysimetric measurements of evapotranspiration. However, the curves do reproduce the general pattern of water loss through the canopy during the different phenological phases.

6. Discussion

The model is able to simulate the observed fluctuations in moisture content of different layers of soil profile reasonably well, as evidenced by the correlations. In case of actual evapotranspiration estimates, the model could only bring out the general pattern of the observed variations.

It would be unreasonable to expect very close agreement between simulated and observed values keeping in view the assumptions made and the general nature of the input information. Significant improvements are possible by perfecting the input information through more comprehensive compilation of available data and field experimentation.

The practical applicability of the soil moisture estimates in agricultural operations and irrigation management need no emphasis. The SPAW model could be used for determining the time and amounts of irrigation based on the soil-moisture status. At a regional scale it may be used for determining water losses and resultant stress on crops (Saxton and Bluhm 1982). When coupled with climatological information for a region, it can be used to decide the best period for raising a particular crop (Omer *et al.* 1988).

Apart from the uses listed above the chief advantage of the model is that it can be used to obtain comprehensive soil-moisture status at different depths from past, present or forecasted meteorological data (rainfall & pan evaporation), once the calibration has been done.

7. Conclusions

The study establishes that the SPAW model could be successfully used for simulating the moisture content of the soil profile under wheat crop.

Although existing inadequacies could be reduced significantly by making improvements certain latitude has to be allowed for errors arising due to inherent problems in methods of observations. This investigation demonstrates the extent of applicability of the model in operational agricultural meteorology at farm and regional levels under Indian conditions.

Acknowledgements

The authors are thankful to Dr. Keith Saxton, USDA-ARS Washington for providing the model and his valuable guidance. They are grateful to Dr. R. K. Datta, Dr. J. Bahadur, Shri S. R. Puri and Dr. Naveen Kalra for their encouragement and suggestions. They wish to thank Shri J. M. Sharma for preparing the diagrams, Ms. Lamba for typing and Shri D. N. Ram for providing graphics packages. The data generated at WTC, IARI, New Delhi in collaboration with Agrimet Division of India Meteorological Department were made available freely. This help is gratefully acknowledged.

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