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SW_CROP program and its potential for mapping water deficit and relative yield potential of rainfed wheat in GIS environment*

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ABSTRACT

A SW-CROP program for irrigation management was designed and used for spatial mapping of water deficit and relative yield potential in rainfed wheat using GIS. SW-CROP constitutes both soil water balance according to criterian expressed by Thornthwaite and Mather (1955) and multiplicative form of Stewart's formula (Stewart and Haggam, 1973). A case study using SW-CROP and geographic information system (GIS) is well demonstrated for mapping water deficit and water limited yield potential of rainfed wheat in Suarna watershed of Doon Valley, India.

Key Words: Modeling, wheat GIS, software

The challenges of ever increasing food demand could at least be met partially by restoring judicious agronomic management and crop intensification on rainfed lands. Rainfed agriculture in Northern hilly region has enormous potential, but exploitation of the same is even less than 50% of available production potential (Swaminathan, 1980), owing to lack water control and complete absence of selective cropping pattern and agronomic strategy. Thus, the system approach to analyze vast yield gaps between actual and potential yields on rainfed lands are not only imminent but also urgent.

The biophysical crop production potential differs between years, in response to differences in available solar radiation and temperature. But in situation of scanty rainfall, calculated production potential may be high, whereas actual production might be sharply depressed by severe drought. For this and other reason the (reference) biophysical production potential is often replaced by the "water-limited production potential", i.e. the production potential of a system in which nutrient supply and plant protection are optimized, and production and yield are entirely conditioned by the sunshine, temperature and actual water availability over the crop growing period. Calculation of water- limited production potential must keep track of the actual quantity of soil moisture stored in the crop root zone at any moment in the crop life cycle, and match "water availability' with "demand for water by crop".

Many researchers have shown that

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soil-water-crop modelling provides improved accounting of soil water in order to quantify water deficit and to identify sensitive growth stages in field crop (Hanks, 1974; Rasmussen and Hanks, 1978 and Ramachandrappa and Nanjappa, 1994). Improvements to water bugeting models may be possible through availability of digital maps and remotely sensed information supplying data in high spatial resolution. GIS provides the opportunity for efficient and improved processing and analysis of geographical information. Spatially varied information, such as precipitation, evaporation, land use, soil properties and soil moisture contents, etc. opens the door to more physically based approaches to simulate the water balance of watersheds. The GIS program is used to analyze the spatial information and provides model input data such as effective rainfall, maximum evapotranspiration, soil properties and soil moisture content, etc. for the water balance model. However, the formats of the data are usually not compatible with those in the soil-water-crop model. Therefore the data needs to be rearranged, with the assistance of spreadsheet programs or other third party data interchange programs. The results of the water balance model will also need to be re-ordered for import back into GIS format. The results can then be interpreted, manipulated, analyzed, displayed and mapped. This paper illustrates the application of soil-water-crop modelling to quantify water deficit and to assess water limited yield potential in rainfed crops and their spatial representation using Geographical Information System (GIS).

MATERIALS AND METHODS

SW_CROP - an irrigation scheduling software

SW-CROP program has been designed keeping in view the need of regional agrometeorological Information System to help farmer's decision on irrigation. SW-CROP is developed using C++ as back end and Visual Basic (V. 5.0) as front end language. This program is mainly based on soil water balance (Thornthwaite and Mather, 1955) and crop yield estimation (Stewart's formula) routines and computes reference evapotranspiration, maximal crop evapotranspitration, available water capacity, soil water balance components and water limited yield.

Soil-water-balance model

The soil-water balance routine in SW-CROP is based on the soil-water-balance according to the criteria expressed by Thorthwaite and Mather (1955).The soil-water balance provides output time series estimates of soil water content (Sw_t, in mm) actual evapotranspiration (ETa_t, in mm) water surplus (WS_t, in mm) and crop water deficit (WD_t, in mm). While the input series are decadal effective rainfall, maximum crop evapotranspiration and crop coefficient derived from various sub routines of SW-CROP.

Effective rainfall (ERF_t, in mm) based on FAO-AGLW method (FAO, 1995).

Monthly reference evapotranspiration estimation routine developed based on FAO-Penman method. Decadal reference evapotranspiration time series (ETo_i, mm), from which it is possible to estimate maximum crop evapotranspiration time series (Etm_i, in mm) as input to soil water balance by means of crop coefficients (related to different generic crop growth stages) according to Doorenbos and Pruitt (1977).

Soil – crop unit characteristics, synthesized as single parameter U (available soil water capacity zone).

The last input U, is based on the hypothesis that the soil water zone is considered to be like a reservoir from which the crops can take in a part of the stored water through their root system. It represents maximum available water capacity to plants, which is evaluated for unit soil – crop characteristics using following relations,

$$U = [D \times f_1 \text{ (texture)}] - f_2 \text{ (stones)} \quad \ldots. (1)$$

Where,

f_1 = Function supplying the available water as difference of field capacity (FC) and permanent wilting point (PWP) depending upon the textural class of physiographic-soil unit.

f_2 = Reduction of available reserve by percentage of coarse material such as stones or gravel in each physiographic – soil unit.

D = Effective rooting depth (RD), soil depth is considered if soil depth < RD.

During dry periods ($ERF_i < ETm_i$), soil transfers water to crop and dries itself. While in wet periods ($ERF_i \geq ETM_i$), the soil stores water and get recharged. The soil – water balance model uses Thornthwaite and Mather (1955) law for the simulation of drying process, based on the hypothesis that the way in which soil dries depends on actual moisture status and climatic conditions. During drying process ($ERF_i \geq ETM_i$), the soil water content at particular interval was simulated by the following expressions Thornthwaite and Mather (1955),

$$\frac{Sw_i}{U} = \text{Exp}\left[\frac{ERF_i \geq ETM_i}{U} + \ln \frac{Sw_{i-1}}{U}\right] \quad \ldots\ldots (2)$$

and the actual evapotranspiration (ETa_i) calculated as,

$$ETa_i = (SW_{i-1} - SW_i) + ERF_i \quad \ldots.. (3)$$

Where,

ERF_i = Effective rainfall during i^{th} interval

ETm_i = Crop maximum evapotranspiration during i^{th} interval.

Sw_i = Soil water content during i^{th} interval.

Sw_{i-1} = Soil water content during $(i-1)^{th}$ interval.

U = Available water capacity

ETa_i = Actual evapotranspiration during i^{th} interval.

While, the recharge phase has been

simulated by following equation,

$$SW_t = SW_{t-1} + (ERF_t - ETm_t)$$

$$0 \leq Sw_t \leq U \quad .... (4)$$

$$ETa_t = ETm_t \quad ...... (5)$$

If a value of Swt > U is obtained by equation (4), the difference SWt – U = WS_t (water surplus). The crop water deficit (WD_t) is obtained as a difference of ETm_t – ETa_t.

Crop production function

This model is based on the hypothesis that considering all other factors of production at their optimum level, it is the water scarcity factor (estimated as a ratio of actual to maximum evapotranspiration, Et_a/Et_m) that limits final yield. The varying sensitivity of crops to water deficit has been expressed by means of multiplicative differential coefficient called yield response factor, Ky (Doorenbos and Kassam, 1979). This formula takes into account the productivity related to end of a growth stage in order to estimate reduction of yield in the subsequent growth stage.

$$Ya/Ym = \prod_{i=1}^{n} [1 - Ky_i (1-ETa_i/ETm_i)] \quad ..... (6)$$

where,

i = generic growth stage

n = number of growth stages considered

Ya = actual crop yield (kg ha^{-1})

Ym = maximum crop yield (kg ha^{-1})

ETa = actual evapotranspiration

ETm = maximum evapotranspiration

Ky_i = yield response factor

If observed data on maximum crop yield was not available, actual crop yield or water limited yield potential has been expressed as percentage of maximum production potential of crop assuming Y_m = 100.

A case study using SW-CROP and GIS

The study area is a part of Swarna watershed which falls between 30°20'00" to 30°28'25" N latitudes and 77°47'10" to 78°0'00" E latitudes. The climate of this area is humid sub-tropical with an annual rainfall of 1516 mm. The soil-physiography of the area includes piedmont plains and flood plains with maize, sugarcane, paddy and winter wheat as major cultivated crops.

The input meteorological data sets are daily rainfall, mean temperature, humidity, sunshine and wind speed to compute effective rainfall and reference evapotranspiration (Penman method) for 10 days interval obtained from nearby agrometeorological observatory located in Central Soil Water Conservation Research and Training Institute, Dehradun. The satellite data used is IRS 1C LISS III imageries acquired during October 1998 to derive crop cover and physiographic – soil information through visual interpretation supplemented with ground survey and systematic soil profile observations. The Geographical Information System (GIS) was used for inputing, storing, analyzing and display of spatial and non-spatial data on crops, soils, and identification aids such

Table 1 : Physiographic -soil and their characteristics

Mapping Unit	Texture	Soil depth cm	Course Fragment (%)	AWC(%)	Soil type
P11	Loam	120	10	13.0	Loamy skeletal typic udortthents
P112	Loam	80	25	13.0	L.S.Dystric Euterochrepts
P121	L, CL	>100	50	15.0	L.S. Typic Udorthents
P122	L, CL	>100	40	15.0	L.S.Dystric Euterochrepts
P123	SL	90	60	11.0	C. L. Typic Euterochrepts
P13	SL	70	50	11.0	C. L. Typic Euterochrepts
P211	SL, L	120	15	12.0	C.L.Typic Euterochrepts
P212	SL, L	120	15	12.0	C.L. Dystric Euterochrepts
P213	L	120	20	13.01	L.S. Typic Euterochrepts
P221	L	110	20	13.0	C.L.Typic Euterochrepts
					L.S. Typic Euterochrepts
P222	L	120	20	13.0	C.L.Typic Euterochrepts
P23	SCL, CL	120	10	16.0	F. L. Typic Euterochrepts
P311	SL, L	150	5	12.0	C.L.Typic Hapluudalf
P312	SL,L	150	5	12.0	C. L. Typic Euterochrepts
					Molic Euterochrepts
P321	SL, L	150	15	12.0	C.L. Typic Euterochrepts
P322	L	150	10	13.0	C.L. Molic Euterochrepts
P323	SL, L	150	20	12.0	C.L. Typic Euterochrepts
P33	CL	150	5	17.0	F.L. Typic Euterochrepts
FP1	CL	150-160	5	17.0	F.L. Typic Udifluvents
FP2	L	150-160	10	13.0	C.L. Typic Udifluvents

as roads, settlement and study area boundary. A GIS Software – Integrated Land and Water Information System version 2.2 was used to integrate spatial data on crops and soils along with their characteristics for generating soil-crop unit characteristics synthesized as available soil water capacity .

In the present study to use SW-CROP for quantifying water deficit and water limited yield potential in rainfed wheat, the soil – water balance and crop yield estimation routine of SW-CROP program was run for each soil – crop unit characteristics, inputting time series of effective rainfall and maximum crop evapotranspiration. The initial soil water content in this case study is assumed 75 % of total available water reserve, however, SW-CROP allows users to specify actual intial soil water content measured in crop root zone at sowing time. A general outline of methodology is presented in Fig. 1.

RESULTS AND DISCUSSION

Available water capacity regimes

The soil scape units (Fig. 2a) of the study area were characterized as upper piedmont (P1), middle piedmont (P2), lower piedmont plains (P3) and flood plain (FP). The soil characteristics used for determining available water content are presented in Table 1. The percentage of coarse fragments (>2 mm) were found in the range of 5 to 60% and the same was taken in to account to reduce available soil water content obtained as a function of texture. This is due to the fact that gravels and stones reduce the amount of soil moisture held per unit of soil surface area. The dominant soils found in the study area were loamy skeletal Typic Udorthents, Coarse loamy Typic Euterochrepts, Coarse loamy Dystric Uterochrepts, Coarse loamy Typic Hapludalfs and fine loamy Typic Udifluvents.

In GIS environment, Spatial data on physiographic - soil and spatial distribution of crops (Fig. 2b) alongwith attribute characteristics such as texture, coarse fragments, soil depth and effective rooting depth of wheat crop were integrated to derive soil - crop unit characteristics synthesised as available soil water capacity in the crop root zone. Soil depth is considered in the area wherever it was found limiting root penetration. Fig. 2c depicts the spatial distribution of various available soil water capacity zones for applying soil water balance model inputing time series (10 days interval) of maximum crop evapotranspiration and effective rainfall corresponding to spatial extent of each growing period of wheat.

Evapontranspiration and water deficit

A time series of actual evapotranspiration (ETa) and crop water deficit (WD) has been computed through running soil water balance model for each soil-crop unit characteristics (U) and data sets were summed over different wheat growing periods to obtain seasonal ETa and WD for each soil-crop unit characteristics in the study area. These annual ETa and WD for rainfed wheat are regrouped to obtain various ranges of ETa and WD

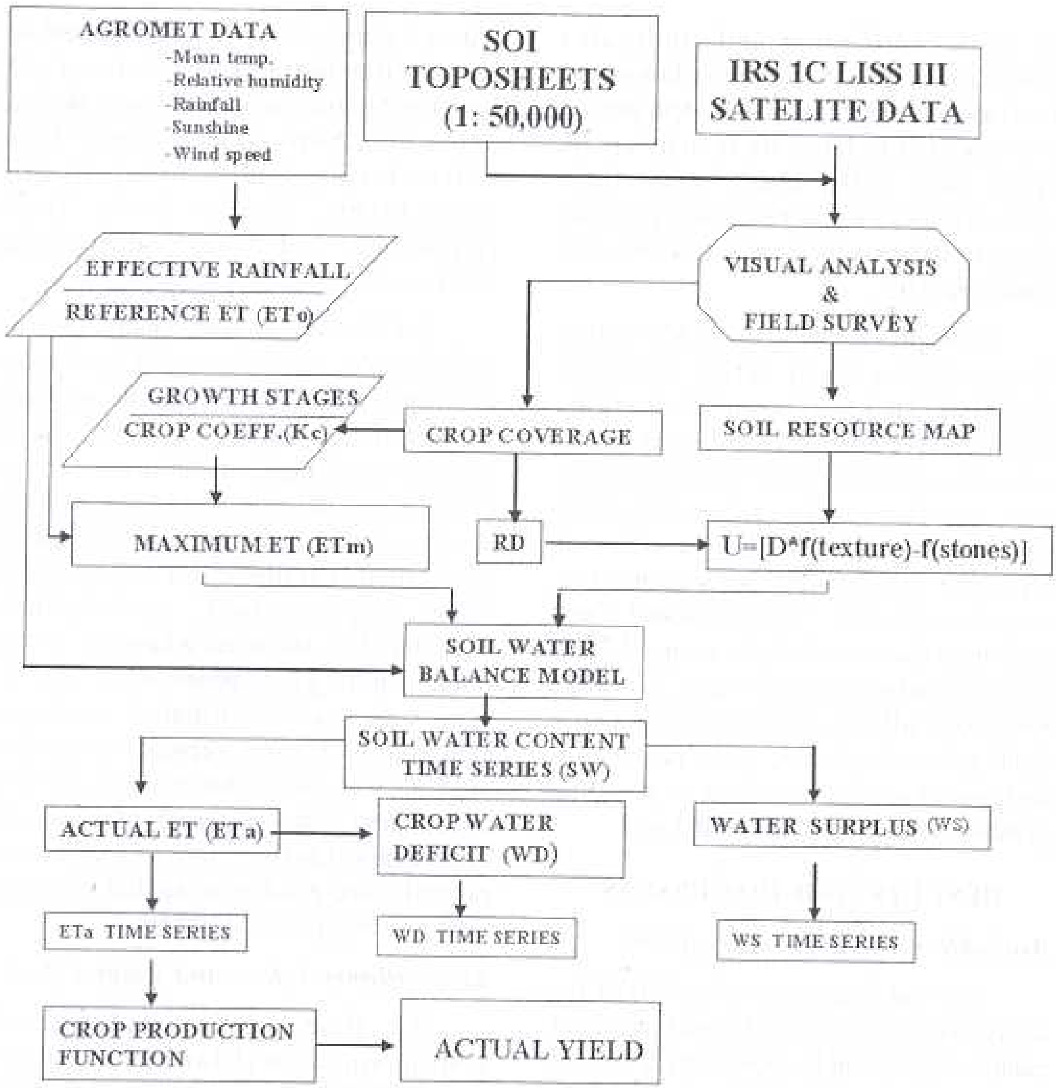

Fig. 1 : General methodological outline

classes. The spatial distribution and areal extent under different ETa and WD classes are presented in Fig. 2d & Fig. 2e and Table 2 & 3 , respectively. Results reveals that actual evapotranspiration of rainfed wheat in Suarna watershed was ranges from 91.2 to 246 mm falling and maximum aréa was falling under ETa class (150 – 200 mm). Whereas, higher area falls under water deficit class (70 – 90 mm) followed by 50 –

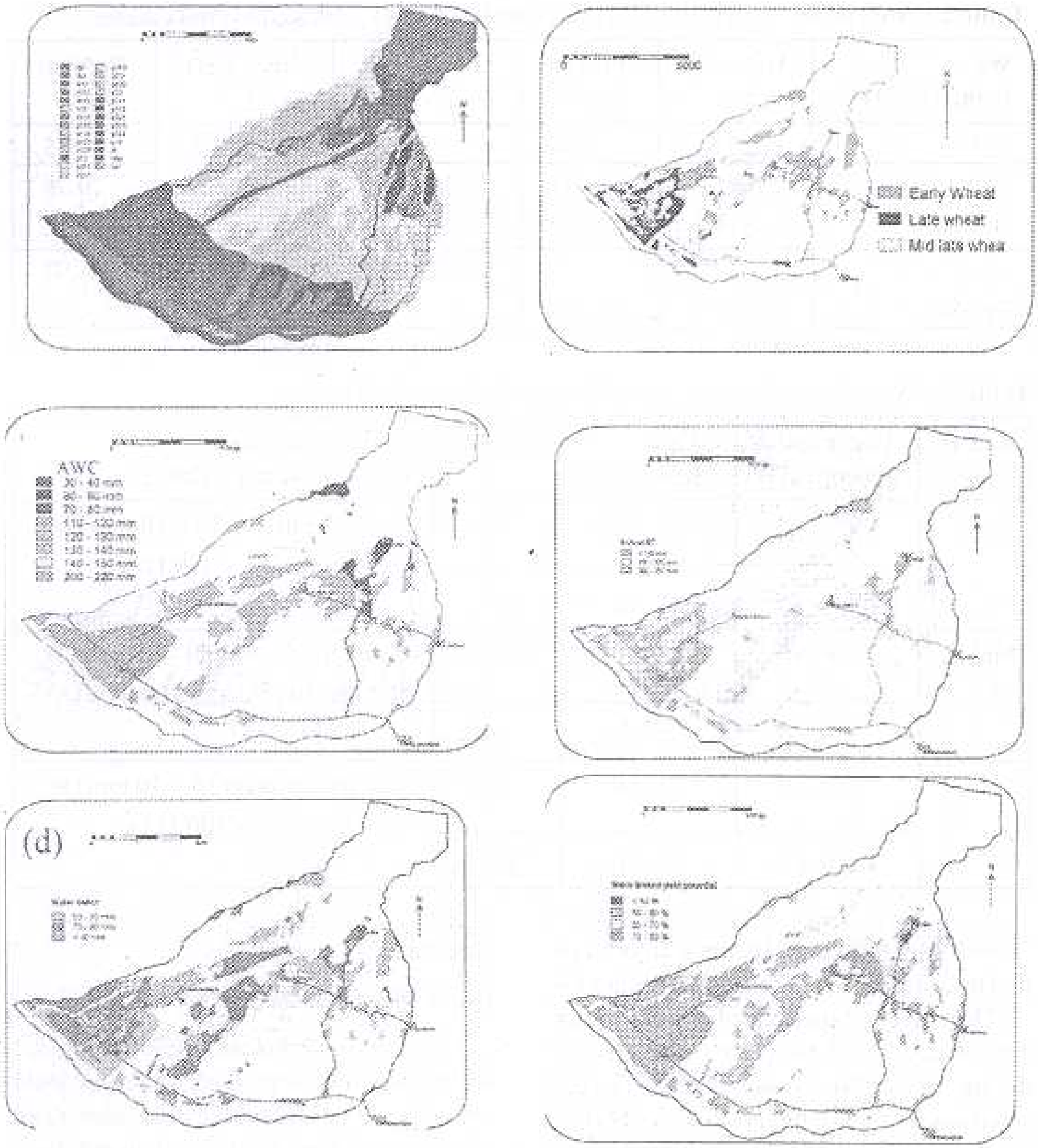

Fig. 2 : (a) Physiographic-soil map, (b) Crop distribution, (c) soil-crop unit characteristics (AWC), (d) actual evapotranspiration (e) water deficil and (f) Water limited yield potential of wheat in Suarna watershed

Table 2 : Area under water limited yield potential and evapotranspiration classes

Water limited yield (%)	Area (ha) area	Percent area	ETa (mm)	Area (ha)	Percent
< 50	22.81	0.57	< 150	292.5	7.25
50 – 60	1764.16	43.71	150 - 200	2856.6	70.78
60 - 70	529.5	13.12			
70 - 80	1719.2	42.60	200 - 250	886.6	21.97

Table 3 : Water limited yield potential, water deficit and irrigation

Wheat season	Water limited potential (%)	Water deficit (mm)	Area (ha)	Irrigation decision based on water balance
Early	60 – 70	79 - 90	476.7	Two irrigation (30 – 40 mm) at 70 – 80 & 100 – 110 DAS
	70 – 80	50 - 70	885.3	
Mid late	50 - 60	70 - 90	1764.1	Three irrigation (30 – 40 mm) at 50 - 60, 80 - 90 and 100-110 DAS
	< 50	> 90	22.8	
Late	60 - 70	70 - 90	52.7	Two irrigations (30 – 40 mm) at 70 – 80 & 90 – 100 DAS
	70 - 80	50 - 70	833.8	

70 mm and > 90 mm. It was also noticed that mid late wheat (wheat sown during 5 – 15 December) experienced greater water deficit compared to early (wheat sown during 10 – 15 November) and late (wheat sown on 5 – 15 January) wheat. This is attributed to more residual soil moisture during crown root initiation and winter rain showers during anthesis in early and late wheat, respectively has favoured to curtail effect of water stress on production potential.

Water limited yield potential

Water limited yield potential (Fig. 2f) can be quantified as possible attainable yield under varying water scarcity considering all other factors of production at their optimum level. A crop production function in the form of multiplicative Stewart's formula was used to assess relative yield potential assuming maximum production potential as

100. The crop specific parameters such as generic growth stages and its duration as well as yield response factor (Ky) were obtained from agronomic literature (Doorenbos & Kassam, 1979). The ranges of water limited yield potentials and areal extent corresponding to early, midlate and late wheat crop are presented in Table 2 & 3. It is inferred that maximum acreage of rainfed wheat crop in the Suarna watershed has water limited yield potential in the range of 50-60% followed by 70 – 80% and 60 – 70%, respectively, while yield of maize seems to be not affected by in-season soil water availability. Mid late wheat had less water limited yield potential compared to both early and late wheat. Depending upon the differential sensitivity of crops and varying crop water deficit conditions in various growth stages, critical decision on irrigations are formulated to use available water resourcese more efficiently in the region for improving and stabilizing yields of rainfed wheat.

CONCLUSIONS

SW-CROP, thus developed can be effectively utilized for assssing crop water requirement, water deficit and water limited proction potential . Use of SW-CROP In GIS environment would enables mapping of water deficit and water limited yield potential on a spatial scale which inturn would helps better planning of supplemental irrigation applications in rainfed wheat and to support regional agrometeorological information to help farmers decision on irrigation.

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