International Journal of Agriculture Sciences
ISSN: 0975-3710 & E-ISSN: 0975-9107, Volume 11, Issue 21, 2019, pp.-9177-9181.
Available online at https://www.bioinfopublication.org/jouarchive.php?opt=&jouid=BPJ0000217

Research Article

SIMULATION OF SOIL MOISTURE CONTENT FOR ESTIMATION OF CROP YIELD AND NET BENEFITS

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Received: October 30, 2019; Revised: November 11, 2019; Accepted: November 12, 2019; Published: November 15, 2019

Abstract: Simulation model developed in this study is based on Soil Water Balance Crop Yield and Net Benefits (SWAB-CRYB) model. The simulation model considers the heterogeneity with respect to crop, soil, climate and irrigation strategies and found useful for evaluation of net benefits. The simulation model provides the detailed output of daily values of reference crop evapotranspiration, maximum crop evapotranspiration, actual crop evapotranspiration, crop coefficient, root zone depth, moisture content in soil root zone by simulating the different processes responsible for soil water balance in the root zone. After application of developed simulation model, it was observed that the soil moisture content in the root zone always remains above the allowable soil moisture content for all the combinations of deficit factors when irrigation interval was small. There was no stress and no reduction in yields. Therefore, the developed model enables the user to take decisions on selecting suitable irrigation strategy for maximum yield and net benefits by screening several irrigation strategies.

Keywords: Farm level, Irrigation water management, Decision support, Soil water balance module, Crop evapotranspiration

Citation: Jadhav P.B., *et al*., (2019) Simulation of Soil Moisture Content for Estimation of Crop Yield and Net Benefits. International Journal of Agriculture Sciences, ISSN: 0975-3710 & E-ISSN: 0975-9107, Volume 11, Issue 21, pp.- 9177-9181.

Academic Editor / Reviewer: Dr Ajay Haldar, Dr H. V. Pandya, Darshan Dharajiya, Kishor Dhanpal Gharde

Introduction

Irrigation scheduling studies need the knowledge of soil moisture status at various instances of time during the crop growth period to know how much and when to irrigate. Similarly, irrigation water management studies use the information on irrigation water requirement and corresponding crop yield (net bene Arial Narrow fits) as influenced by different crop, soil and climatic parameters. This information can be known either by conducting experiments or estimated by simulating individual processes in the crop-soil-climate system. Experiments may produce accurate results but have severe limitations. The important limitations are that the results are not transferable between locations and years, conducting experiments is time consuming and expensive, and it is almost impossible to generate information on numerous alternatives available in the optimization process by experiments. On the other hand, in a simulation technique, all the intricate processes involved in the crop-soil-climate system can be modelled mathematically using known principles, empirical relations and basic data. It is, therefore, possible to quantify different physical aspects of the system for different alternatives. The estimation can be approximated to accuracy by calibrating the simulation model with a test set of experimental data. The solutions can be obtained quickly for different locations, time and alternatives; therefore, the simulation technique has gained enormous popularity in irrigation water management. The study was aimed to develop the simulation model for irrigation water management. By considering above aspects the study was aimed to develop the simulation model for irrigation water management. The review of simulation models to estimate crop yield shows that some models (IRMOS, CROSOWAT numerical model) are complex and need high amount of data while other models (SWAB-CRYB, SWABGRAPH) are simple, require less data, but at the expense of accuracy. According to Gorantiwar and Smout (2006), simulation model that needs less data have more applicability in obtaining optimum water deliveries at command area level [1]. Therefore, in this study the model based on the concept of soil water balance as explained by Gorantiwar (1995) and Gorantiwar and Smout (2003) was developed [2,3].

Methodology for model development

The simulation model is developed by using Visual Basic.NET in the framework of Microsoft Visual Studio 2012 [4]. The procedure and methodology followed for the development of the simulation model is given by Gorantiwar (1995) [2] and included in Kadam *et al*, 2016 [4]. While developing the simulation model, the assumptions made to simplify the system are as follows;

1. The input of water to soil root zone is from effective rainfall and irrigation and output of water from the soil root zone is in the form of evaporation and transpiration (evapotranspiration) and deep percolation.
2. The contribution of moisture to the soil root zone from the groundwater through capillary rise is considered as negligible.
3. The flow is vertical and one-directional.
4. The water added or removed by the process such as precipitation, irrigation, evapotranspiration, percolation, *etc.* are assumed to occur in the lumped manner at the end of time period.
5. The soil root zone and irrigation water are free from salinity.

Crop evapotranspiration is estimated using Penman-Monteith method. The crop water requirement is calculated using crop evapotranspiration and crop coefficient. In simulation model, crop evapotranspiration values were estimated using polynomial equation and FAO tabulated Kc. Soil water balance was carried out to obtain actual crop evapotranspiration (ETa), using linear root growth model. Actual crop yield was estimated with Stewart, *et al.* (1976) crop growth model incorporating crop growth stages and response of water stress to each crop growth stage [5]. The net benefits from farms was estimated using economic model. The developed simulation model enables the estimation of soil moisture in the root zone, actual evapotranspiration and return flow to the groundwater due to irrigation in terms of deep percolation, crop yield and net benefits. The model needs four input data files related to crop, soil, climate and irrigation strategies. The model provides the detailed output of daily values of different parameters such as reference evapotranspiration, maximum crop evapotranspiration, crop coefficient, root zone depth, moisture content in soil root zone *etc.* and yield and net benefits.

Main function

Simulation model is designed for crops to provide a practical decision tool for irrigation management. The main functions include: (1) To evaluate crop water requirements, and to make the real-time irrigation plans based on the historical weather data and weather forecast information. (2) To simulate daily change of soil moisture content in the root zone. (3) To evaluate a given irrigation schedule. (4) Database management capability.

Main Function Models

The developed simulation model is the combination of soil water balance model, crop phenology model, root growth model, crop water production function, and irrigation decision-making model.

Soil water balance module

The soil moisture balance is performed on daily basis. The inflow parameters comprise of rainfall and irrigation and outflow parameters are evapotranspiration and deep percolation. The general soil water balance equation is given by following equation,

$$RFe_{t-1} + ID_t = ETa_{t-1} + DP_t \pm \Delta\theta_t$$

Where,

RFe_t = effective Rainfall in mm for t[th] day (mm)

ID_t = depth of irrigation on t[th] day (mm)

ETa_t = actual evapotranspiration on t[th] day (mm/day)

DP_t = deep percolation losses on t[th] day (mm)

$\Delta\theta_t$ = change in soil moisture storage from (t-1)[th] day (mm)

Output from the soil water balance equation

The outputs from the soil water balance model are daily values of maximum actual evapotranspiration (ET_{mt} and ET_{at}), soil moisture content (θ_{lt}) and deep percolation (DP_t).

Reference crop evapotranspiration (ET_r)

The Penman-Monteith method has been recommended as the sole standard method for estimation of ET_r. It needs daily values of maximum and minimum temperature, maximum and minimum relative humidity, actual sunshine hours and wind speed. Therefore, Penman-Monteith Method [6] was used in this study to compute ET_r [1], and presented by equation below,

$$ETrt = \frac{0.408\Delta_t(R_{nt} - G_t) + \gamma_t \frac{900}{T_t + 273} u_t(e_{st} - e_{at})}{\Delta_t + \gamma_t(1 + 0.34u_{2t})}$$

Where,

ET_{rt} = potential evapotranspiration on t[th] day (mm day^{-1})

R_{nt} = net radiation at the crop surface on t[th] day (MJ m^{-2} day^{-1})

G_t = soil heat flux density on t[th] day (MJ m^{-2} day^{-1})

T_t = mean daily air temperature at 2 m height on t[th] day (°C)

u_{2t} = wind speed at 2 m height on t[th] day (m s^{-1})

e_{st} = saturation vapour pressure on t[th] day (kPa)

e_{at} = actual vapour pressure on t[th] day (kPa)

$e_{st} - e_{at}$ = saturation vapour pressure deficit on t[th] day (kPa)

Δ_t = slope vapour pressure curve on t[th] day (kPa °C^{-1})

γ_t = psychrometric constant on t[th] day (kPa °C^{-1})

Maximum crop evapotranspiration

The maximum crop evapotranspiration (ETm) is the ET when water is not limited and is different from ETr due to effect of crop characteristics and a weather condition. It is computed by equation,

$$ETm_t = Kc_t \times ETr_t$$

Where,

ET_{mt} = maximum crop evapotranspiration on t[th] day (mm)

K_{ct} = crop coefficient on t[th] day

ET_{rt} = reference crop evapotranspiration on t[th] day (mm)

Crop coefficient (kc)

The daily kc values are obtained by using polynomial equation. In case of stage wise kc, the daily kc values are estimated by interpolation method [7].

K_{ct} equation

The equation form of crop coefficient values is represented by polynomial equation as given in below equation and the daily values of crop coefficient can be obtained using this equation.

$$Kc_t = a_0\left(\frac{t}{T}\right)^n + a_1\left(\frac{t}{T}\right)^{n-1} + \cdots\cdots\cdots a_n$$

Where,

K_{ct} = crop coefficient on t[th] day

T = total crop period (days)

T = days since sowing or planting

N = order of equation

a0, a1, a2,………, an = coefficients of the equation

Actual evapotranspiration

Doorenbos and Kassam (1986) proposed that actual evapotranspiration equals to maximum evapotranspiration until the readily available soil water (fraction of available soil water) has been depleted [8]. The mathematical representation is given by following equations,

$$ETa_t = ETm_t$$
$$if\ (\theta_t^R - \theta_w^R)Z_t \geq (1 - p_t)(\theta_f^R - \theta_w^R)Z_t$$
$$ETa_t = [(\theta_t^R - \theta_w^R)Z_t ETm_t]/[(1 - p_t)(\theta_f^R - \theta_w^R)Z_t]$$
$$if\ (\theta_t^R - \theta_w^R)Z_t < (1 - p_t)(\theta_f^R - \theta_w^R)Z_t$$

Where,

θ_t^R = volumetric soil moisture content in root zone depth on t[th] day (mm/m)

θ_w^R = volumetric soil moisture content in root zone depth on t[th] day at wilting point (mm/m)

θ_f^R = volumetric soil moisture content in the root zone depth on tth day at field capacity (mm/m)

Z_t = depth of root zone on t[th] day (mm)

p_t = soil water depletion factor on t[th] day

Soil water depletion factor (pt)

The value of soil water depletion factor (pt) depends upon crop, magnitude of maximum crop evapotranspiration and soil. The pt values for different crops and ETm are adapted from Doorenbos and Kassam (1986), [8]. The pt values can also be computed by the function given by equation,

$$p_t = p_2 - [(p_2 - p_1)/(ETm_1 - ETm_2)](ETm_1 - ETm_t)$$

Where,

ET_{m1} = maximum value of ETm (mm/day)

ET_{m2} = minimum value of ETm (mm/day)

p_1 = p value corresponding to ET_{m1}

p_2 = p value corresponding to ET_{m2}

Effective rainfall

In present study, the effective rainfall is considered as certain fraction of total rainfall. The effective rainfall is computed by using following equation given by Dastane (1974), [9],

$$RFe_t = (1 - \alpha)RF_t$$

Where,

RF_{et} = effective rainfall on t[th] day (mm)

RF_t = total rainfall on t[th] day (mm)

α = runoff coefficient

Deep percolation

The water in excess of field capacity of the soil is considered as deep percolation.

Crop phenology module

The crop phenology module contains the information crop name, sowing date, harvesting date, crop period, root growth model, crop coefficient model and yield response models required to simulate the soil moisture content in the root zone, computation of crop water requirement and estimation of the yield and net benefits.

Crop growth module

Actual crop yield is estimated by crop growth model using actual and maximum evapotranspiration and maximum crop yield. Therefore, the purpose of crop growth model is to estimate the crop yield from the output such as actual evapotranspiration obtained from the soil water balance equation as influenced by the different amount of irrigation water applied at different instants of time. Crop production function in additive form (Stewart, *et al*. (1976) is used in developed simulation model [5], and presented by equation,

$$\frac{Y_a}{Y_m} = 1 - \sum_{s=1}^{ns} ky_s \left(\frac{ETm_s - ETa_s}{ETm_s}\right)$$

Where,

Y_a = actual crop yield, kg/ha
Y_m = potential crop yield, kg/ha
s = subscript for crop growth stage
ky_s = yield response factor of s^{th} stage
ns = number of stages
ETm_s = maximum crop ET of s^{th} stage (mm)
ETa_s = actual crop ET of s^{th} stage (mm)
ET_m = maximum crop ET of entire crop growth period (mm)

Root growth module

The root growth is dependent on crop, soil type and management strategies. In this DSS the root growth is assumed to be dependent on crop only. According to literature, linear model is most widely used which is the function of maximum rooting depth and the time at which the crop attains the maximum rooting depth. The linear root growth function is used in this study [10] and described as follows; Linear root growth function [11],

$$Z_t = Z_0 + (Z_m - Z_0)(t/t_m)$$

Where,

Z_t = depth of root zone on t^{th} day (mm)
Z_m = maximum depth of root zone during crop growth period (mm)
Z_0 = initial depth of root zone (depth of sowing) (mm)
t_m = the day at which crop attains Z_m since sowing
T = the day on which root growth is to be calculated (day)

The specific information on root growth with time from other types of root growth functions can be used in the model by directly giving the input of daily root zone depth.

Initial soil moisture content

Either initial soil moisture is considered as known and its input is given or it is assumed. When pre-sowing irrigation is not performed, the initial soil moisture is assumed at field capacity, 50 % available moisture and wilting point for the planting in rainy (*kharif*), winter (*rabi*) and summer (hot weather) seasons, respectively. The depth of presowing irrigation is either given or computed in the model so that soil moisture content at the presowing irrigation is brought to field capacity.

Irrigation module

The irrigation module contains the information about number of stages, stage length and strategy name. The application efficiency was considered as 75 %. The runoff coefficient of 0.70 was considered for computation of effective rainfall. The irrigation depth was assumed 150 mm as maximum value and 50 mm as minimum value for all crop-soil combinations. Variable date variable depth strategy was used to simulate moisture content in root zone. In this irrigation strategy the date of irrigation is not fixed or predecided however it is variable and based on moisture content in the root zone. The date of irrigation is decided when the moisture content in the root zone is just reached to allowable depletion (no deficit) or some degree below the allow depletion (deficit). The irrigation depth per irrigation is decided on the basis of moisture content. The irrigations are provided per irrigation such that moisture content is reached to field capacity (*i.e.,* adequate irrigation) or some proportion less than field capacity (*i.e*., deficit irrigation).

Estimation of net benefits

The net benefits are estimated by calculating total cost and total benefits. The total cost is summation of the cost of cultivation including all resources and operations and water related costs which include cost of water and cost of water application. The yield obtained from actual crop and fodder for particular irrigation strategy and market price of produce was used for computation of total benefits. Net benefit (NB) is estimated as total benefit minus total cost and given in following equation,

$NB=B-C$

Where, NB = net benefits (unit/ha)

Graphical representation of soil water in the root zone

The results of the simulation model can be represented as graphical plots of variations in moisture content of root zone (moisture content at field capacity, wilting point and allowable depletion level) over crop growth period.

Case study for wheat crop

The developed simulation model was applied to *rabi* wheat cultivated on clay soil considering variable date variable depth (Irrigation strategy wise date of irrigation and depth of irrigation per irrigation are variable. The date of irrigation is decided when the moisture content in the root zone is just reached to allowable depletion (no deficit) or some degree below the allow depletion (deficit). This depth is the depth required to take moisture content to field capacity (adequate irrigation) or some proportion of field capacity (deficit irrigation) with application efficiency). The maximum and minimum possible values of irrigation depth were assumed as 150 and 50 mm respectively. The model was used to simulate the daily soil moisture content in root zone and to evaluate the different irrigation strategies of varying the deficit factor for irrigation depth from 1.0 to 0.7 and the deficit factor for irrigation interval of 1.0 based on yield reduction and net benefits. It is considered that the wheat crop is sown on 15 November 2015 and harvested on 13 March 2016. The total crop growth period is 120 days. The depth of soil is 2500 mm. Field capacity and wilting point of soils are 43 % and 17 %, respectively. The weather parameters data for the year 2015 and 2016 were collected from the daily records of the Meteorological Observatory of Indian Meteorology Department located at AICRP on Irrigation Water Management, Mahatma Phule Krishi Vidyapeeth, Rahuri. The weather data is considered for the calculation of reference crop evapotranspiration during the crop growth period. Linear root growth model is used to simulate daily root zone depth considering minimum rooting depth as 150 mm, maximum rooting depth as 900 mm and days to attain maximum rooting depth as 50. The Stewart yield response model is used for the estimation of crop yield and net benefits. The values of stage wise yield response factors for wheat are adopted from Doorenbos and Kassam (1986), [4]. The simulation model was run by varying the deficit factor for irrigation depth from 1.0 to 0.7 and the deficit factor for irrigation interval of 1.0 for wheat crop. The results of crop yields and net benefits obtained for the combinations of these deficit factors is presented in [Table-1].

The deficit factor for irrigation interval was kept same for all the irrigations, meaning that the application of irrigation water in relation to irrigation water needed for full irrigation is the same for all the irrigations but the irrigation depth is different as per the deficit factor for irrigation depth. It seen that the maximum yields are obtained though the deficit factor increases because the total depth of water applied is same during all the strategies as minimum depth of application is considered as 50 mm and the irrigation interval remains constant. The number of irrigations varies according to the deficit factor for irrigation depth.

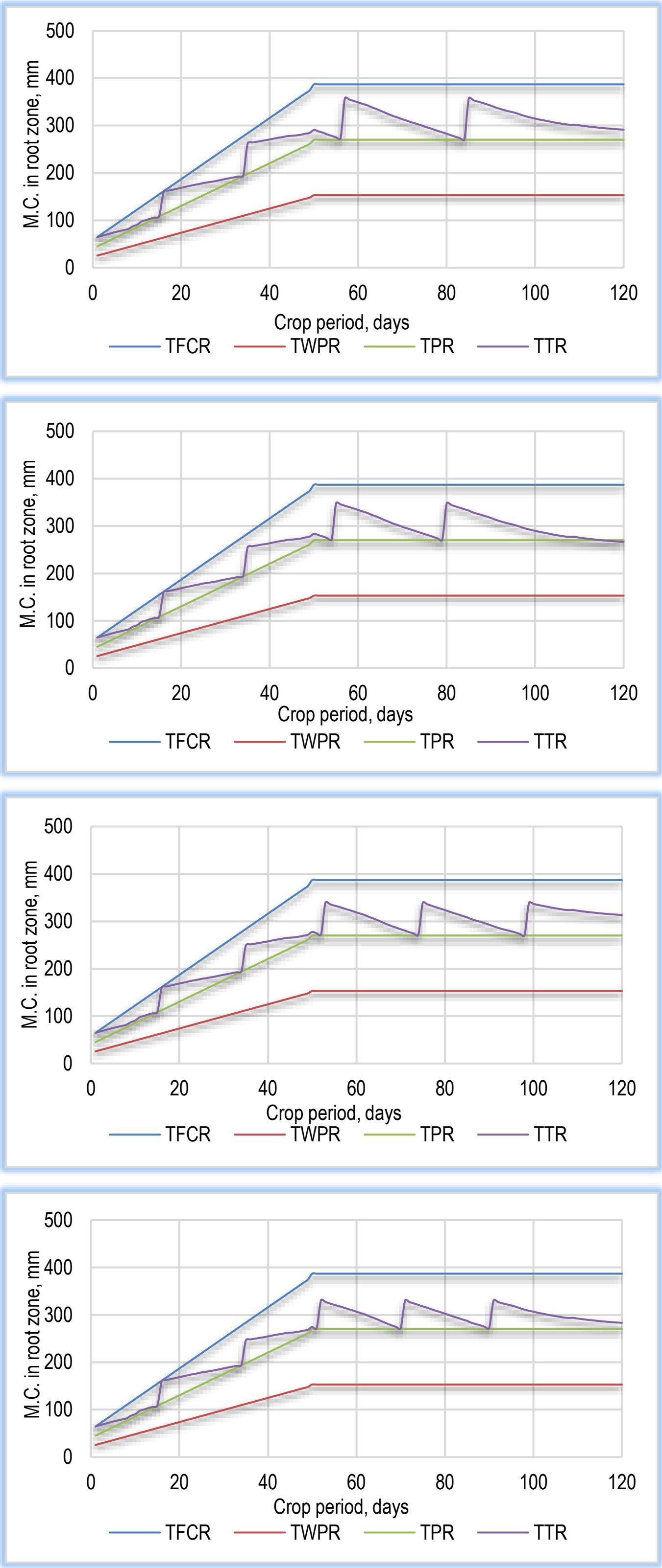

Fig-1 Variations in moisture content of root zone of wheat in clay soil with deficit factor for irrigation interval (dfii) as 1.0 and deficit factor for irrigation depth (dfid) as 1.0, 0.9, 0.8 and 0.7 respectively, (TFCR, TWPR, TTR,TPR =Soil moisture content in the root zone at field capacity, wilting point, at depletion level and actual moisture content, mm respectively)

The graphs showing variations of soil moisture content in the root zone over the crop growth period is presented in [Fig-1]. It is seen from figures that the soil moisture content in the root zone always remains above the allowable soil moisture content for all the combinations of deficit factors. Therefore, there is no stress and no reduction in yields. This unstressed condition is depicted [Table-1] *i.e.*, actual yield (Ya) and potential yield (Ym) are equal (the actual ET is equal to maximum ET over the crop growth period). Thus, with simulation model it is possible to take decision of the deficit factor for adequate irrigation where there is a maximum irrigation depth or deficit ratio up to which deficit irrigation is not caused.

Table-1 Seasonal irrigation depth (TDI, mm), potential yield (Ym, kg/ha), actual crop yield (Ya, kg/ha), net benefits (NB, Rs.) and reduction in yield (RY, %) of wheat for deficit irrigation with deficit factor for irrigation interval (dfii) as 1.0 and deficit factor for irrigation depth (dfid) as 1.0, 0.9, 0.8 and 0.7

Irrigation strategy	Ym	Ya	NB	TDI	RY
Deficit irrigation with dfii =1.0 and dfid = 1.0	4500	4500	39688	344	0
Deficit irrigation with dfii =1.0 and dfid = 0.9	4500	4500	39688	319	0
Deficit irrigation with dfii =1.0 and dfid = 0.8	4500	4500	39688	366	0
Deficit irrigation with dfii =1.0 and dfid = 0.7	4500	4500	39688	336	0

Conclusion

The simulation model was developed based on crop phenology model, root growth model, crop yield response model and different irrigation strategies and database management. The model could be used for simulation of soil moisture content in the root zone on daily basis and evaluation of the effect of certain irrigation strategy on crop yield and yield reduction. It was observed that the soil moisture content in the root zone always remains above the allowable soil moisture content for all the combinations of deficit factors when irrigation interval was small. Therefore, there was no stress and no reduction in yields. In general, the results of the developed simulation model would provide guidelines to select the appropriate irrigation strategy depending on the land and water availability.

Application of research

The developed simulation model can be used for screening several irrigation strategies and would provide guidelines to select the appropriate irrigation strategy depending on the land and water availability.

Research Category: Irrigation Water Management

Acknowledgement / Funding: Authors are thankful to Department of Irrigation and Drainage Engineering, Mahatma Phule Krishi Vidyapeeth, Rahuri, 413 722, Maharashtra, India

***Research Guide or Chairperson of research: Dr S. D. Gorantiwar**
University: Mahatma Phule Krishi Vidyapeeth, Rahuri, 413 722, Maharashtra
Research project name or number: PhD Thesis

Author Contributions: All authors equally contributed

Author statement: All authors read, reviewed, agreed and approved the final manuscript. Note-All authors agreed that- Written informed consent was obtained from all participants prior to publish / enrolment

Study area / Sample Collection: Mahatma Phule Krishi Vidyapeeth, Rahuri, 413 722, Maharashtra, India

Cultivar / Variety / Breed name: Nil

Conflict of Interest: None declared

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.
Ethical Committee Approval Number: Nil

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