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Development of Irrigation Requirements and Water Scheduling Model for West Africa

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Abstract: Irrigation requirements and water scheduling model that takes into consideration the uniqueness of West African weather, soil and crops has been attempted and developed. The West African Irrigation Requirements and Water Scheduling (WIRWAS) model like other forecasting models in the developed countries in which the end users may not necessary be computer literates was developed using an Object Oriented-Programming language (OOP) with good Graphical User Interface (GUI) for easy interaction with the end users. WIRWAS model was designed to run in Windows, the programming language used is Microsoft Visual Basic (version 6.0) as front view while Microsoft Access was used as the back view for storing and updating the database. The model was designed using the common and generally acceptable Food and Agriculture Organisation (FAO) standard equations for computing all the needed parameters such as evapotranspiration, estimating crop water, soil water deficit, irrigation amount and water scheduling requirements. It was designed in such a way that each page of the model presents to users all the methods for estimating a particular parameter and options for the users to select one of them depending on the data availability. It gives the user opportunity to edit or update some local factors such as weather, crop type/specie, growing stage/length. The model alerts the user when there is need to irrigate and depending on the irrigation equipment (efficiency), the total amount of water to be used as well as the time it will take for the irrigation application is given by the model.

Key words: Irrigation requirment, water scheduling, development, GUI, OOP, WIRWAS, West Africa

INTRODUCTION

Like most parts of the world, agricultural practices in West Africa are rainfall dependents. Water scarcity, the need for energy savings as well as the optimization of crop yield both in quality and quantity require that irrigation practices and systems are able to achieve high level of performance and efficiency. Managers and administrators of large scale farming have to take daily decisions on how best they can allocate and meet the demands for water by crops/plants. About 60-95% part of the physiological active plant is water. Water is required for plant processes such as: Digestion, photosynthesis, transportation of minerals, structural support, growth and transpiration but plant uses water primarily for transpiration because it usually accounts for about 99% of the water used by the plant (Monteith, 1977; Doorenbos and Pruitt, 1977; Allen and Scott, 1980).

There exists a strong relationship between plants, soil and atmosphere, the linkage factor is water. The relationship can be summarized as follows: The plants need water for transpiration and transportation of minerals, the soil stores the water needed by the plants and the atmosphere provides the energy needed by the plants to withdraw the water from the soil while the plants lose most of the water through transpiration back to the atmosphere. The cyclic relationship must be kept intact and flowing during the growing season in order to avoid uninterrupted growth of the plants. Therefore, water must be made readily available in the soil for the plants (Yin Xinyou *et al*., 2003).

The primary aim of irrigation is to complement the water available from natural sources such as rainfall, dew, flood and ground water which seeps into root zone. It is needed in most parts of West Africa where there may be a prolonged drought period and mostly where water from natural sources is inadequate for effective crop germination and production.

In the past, processing of large amount of information and data that irrigation systems require was costly, time consuming and sometimes inaccurate, but with recent development in computer technology by producing models, processing of information quickly, cheaply and more accurately can easily be achieved. Therefore, there is a need for considerable research in the development of software/model for improved irrigation systems and water management particularly for West African farmers and water managers. There exists an irrigation model such as

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CROPWAT developed by Food and Agricultural Organisation (FAO) in 1992, but this model has some shortcomings most especially over West Africa. Firstly, it did not really take into consideration the uniqueness of the West African weather and most especially the varieties and different species of crops grown in this sub-region with the non-uniformity/homogeneity in soil conditions. Another major general disadvantage of this software is that it was not presented in a user-friendly manner thereby it can not be easily used or understood by end users in West Africa whose most of the time may not be computer literates or agrometeorologists. Most developed countries have modified this to be user-friendly for their respective countries. This present research attempts to solve the above mentioned shortcomings over West African sub-region.

Most packages in which the end users may not necessary be computer literates such as AVALOC- "a simulation model for design and evaluation of micro-irrigation systems" by Pedras and Pereira (2001) DAILYET-a computer program for calculating evapotranspiration by Hess (1996) AWSET-computing potential evapotranspiration from automatic weather station by Hess (1995) and AFSIRS-agricultural field scale irrigation requirements simulation were all designed using a user-friendly program. For example AVALOC was designed using a Microsoft Visual Basic (Version 4.0). In a similar manner, this model WIRWAS was designed in Windows environment using Microsoft Visual Basic (Version 6.0) as front view while Microsoft Access was used as the back view for storing and updating the database.

THE WIRWAS MODEL

There are 4 major components to the model. These are:

- Calculation of a daily reference crop evapotranspiration from local meteorological data,
- Adjustment of the reference crop evapotranspiration to an actual evapotranspiration, taking into consideration the soil characteristics, crop stage and some crop specifics,
- Calculation of the soil water deficit and
- Extrapolation of the water balance to predict the timing of the next irrigation and the amount of water to be used for irrigation, given the type of irrigation equipment to be used.

Figure 1 shows the general page (which comes after the welcoming and login pages) of WIRWAS model and the above listed four components. Each of these components is described briefly.

Reference crop evapotranspiration (Et_o) part: Reference crop Evapotranspiration (ET_o) is calculated on a daily basis and stored in a file for use in the calculation of actual evapotranspiration. The WIRWAS program allows three methods to calculate, or estimate, the daily ET_o.

- Long-term average rates of ET_o can be used according to the month.

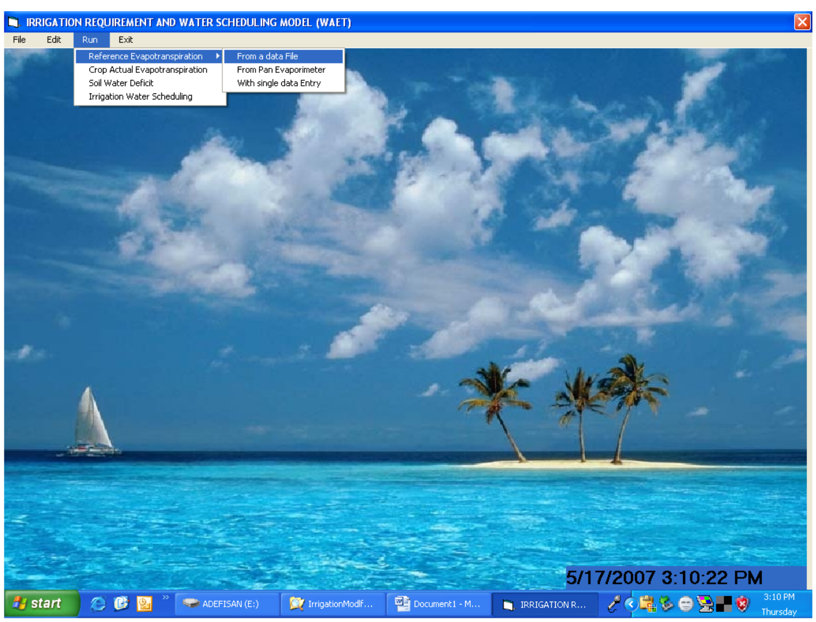


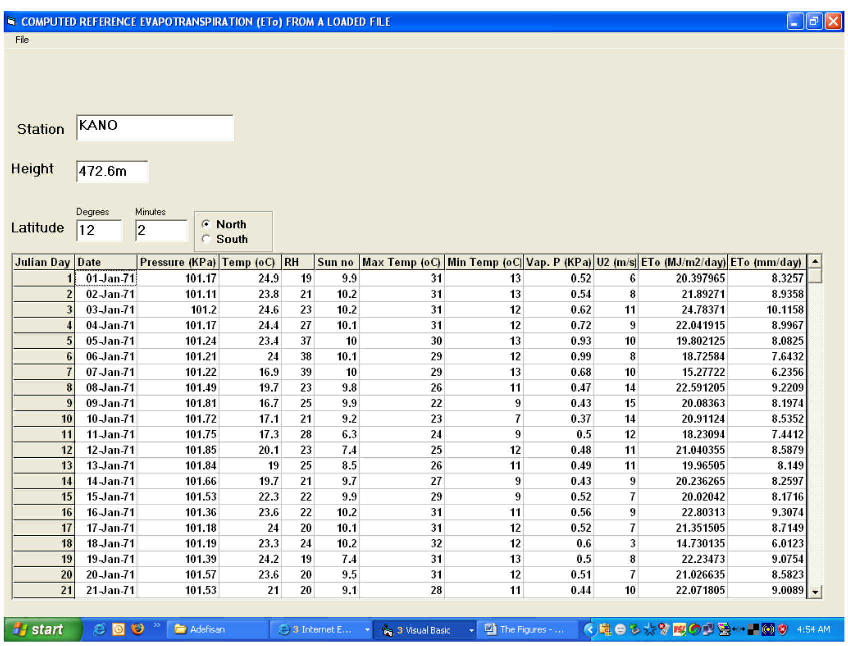
Fig. 1: The general page of the WIRWAS model, displaying its four major components

- Daily ET_o may be entered directly if it is available from an external source (e.g., modified pan evaporation or subscription to a weather data service).
- ET_o is computed on daily basis (or any user specified time interval) using meteorological data from a nearby meteorological station with the generally accepted FAO Penman-Monteith combination method to estimate ET_o. The equation is as follows

$$ET_o = \frac{0.408\Delta(Rn - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where : ET_0 is the reference evapotranspiration [mm day^{-1}],
R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}],
G is the soil heat flux density [MJ m^{-2} day^{-1}],
T is the air temperature at 2 m height [°C],
u_2 is the wind speed at 2 m height [m s^{-1}],
e_s is the saturation vapour pressure [kPa],
e_a is the actual vapour pressure [kPa],
e_s-e_a is the saturation vapour pressure deficit [kPa],
Δ is the slope vapour pressure curve [kPa °C^{-1}],
γ is the psychrometric constant [kPa °C^{-1}].

Each of the parameters in the above equations can be estimated through many methods. The vapour pressure deficit is calculated from a wet and dry bulb psychrometer or mean relative humidity and the saturated vapour pressure at the mean air temperature. Allen *et al.* (1998) in the FAO reports on the guidelines for computing crop water requirements gives the detailed step to step in computing the ET_o. WIRWAS model uses the recommendations of this report either with normal or minimum meteorological data requirements. The normal meteorological data requirement comprises of maximum and minimum temperature and relative humidity, pressure, wind speed at 2 m height, net radiation and ground heat flux. But most meteorological stations do not measure net radiation directly, therefore, net radiation is estimated by using maximum daylight hours and extra-terrestrial radiation are calculated as functions of latitude and date and received shortwave radiation is then estimated from the sunshine duration. The detail of missing data and the appropriate equations to be used as extensively discussed in Allen *et al.* (1998) and Kevin (2000) is used for WIRWAS. This first component involves a lot of methods, so there is this high interaction between the model and the user. The user selects the data type available so that the model picks the appropriate set of equation for computing the ETo. Figure 2 displays a sample daily weather data loaded from a Microsoft excel file and the corresponding computed ET_o.



Julian Day	Date	Pressure (KPa)	Temp (oC)	RH	Sun no	Max Temp (oC)	Min Temp (oC)	Vap. P (KPa)	U2 (m/s)	ETo (MJ/m2/day)	ETo (mm/day)
1	01-Jan-71	101.17	24.9	19	9.9	31	13	0.52	6	20.397965	8.3257
2	02-Jan-71	101.11	23.8	21	10.2	31	13	0.54	8	21.89271	8.9358
3	03-Jan-71	101.2	24.6	23	10.2	31	12	0.62	11	24.78371	10.1158
4	04-Jan-71	101.17	24.4	27	10.1	31	12	0.72	9	22.041915	8.9967
5	05-Jan-71	101.24	23.4	37	10	30	13	0.93	10	19.802125	8.0825
6	06-Jan-71	101.21	24	38	10.1	29	12	0.99	8	18.72584	7.6432
7	07-Jan-71	101.22	16.9	39	10	29	13	0.68	10	15.27722	6.2356
8	08-Jan-71	101.49	19.7	23	9.8	26	11	0.47	14	22.591205	9.2209
9	09-Jan-71	101.81	16.7	25	9.9	22	9	0.43	15	20.08363	8.1974
10	10-Jan-71	101.72	17.1	21	9.2	23	7	0.37	14	20.91124	8.5352
11	11-Jan-71	101.75	17.3	28	6.3	24	9	0.5	12	18.23094	7.4412
12	12-Jan-71	101.85	20.1	23	7.4	25	12	0.48	11	21.040355	8.5879
13	13-Jan-71	101.84	19	25	8.5	26	11	0.49	11	19.96505	8.149
14	14-Jan-71	101.66	19.7	21	9.7	27	9	0.43	9	20.236265	8.2597
15	15-Jan-71	101.53	22.3	22	9.9	29	9	0.52	7	20.02042	8.1716
16	16-Jan-71	101.36	23.6	22	10.2	31	11	0.56	9	22.80313	9.3074
17	17-Jan-71	101.18	24	20	10.1	31	12	0.52	7	21.351505	8.7149
18	18-Jan-71	101.19	23.3	24	10.2	32	12	0.6	3	14.730135	6.0123
19	19-Jan-71	101.39	24.2	19	7.4	31	13	0.5	8	22.23473	9.0754
20	20-Jan-71	101.57	23.6	20	9.5	31	12	0.51	7	21.026635	8.5823
21	21-Jan-71	101.53	21	20	9.1	28	11	0.44	10	22.071805	9.0089

Fig. 2: Sample of daily weather data (loaded from a MS excel file) and their corresponding reference Evapotranspiration (ETo) values

Actual crop evapotranspiration (ET_a) part: Actual crop evapotranspiration, ET_a is calculated by using a one-dimensional empirical model. The date, length of growing stage and crop type are the necessary inputs in the estimation of actual crop evaporation.

$$ET_a = K_c ET_0 \tag{2}$$

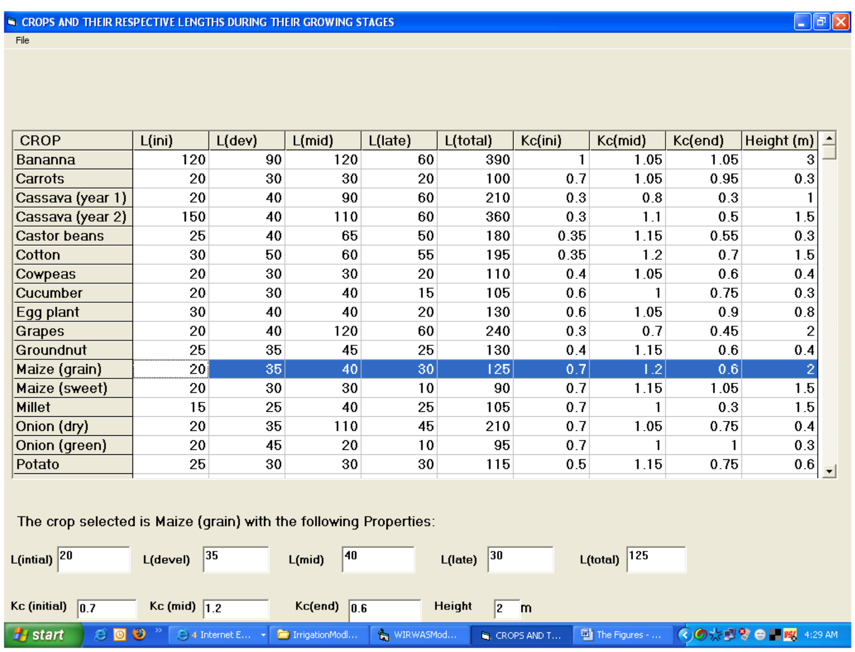
Where K_c is the crop coefficient
The procedures for computing the ET_a are as follows

- Identifying the crop growth stages, determining their lengths and selecting the corresponding K_c.
- Adjusting the selected K_c for frequency of wetting or climatic conditions during the stage.
- Cconstructing the K_c curve (allowing one to determine K_c value for any period during the growing period. This is done numerically in this model by using equation).
- Calculating ET_a as the product of ET_0 and K_c.

Crop coefficient is subdivided into three: K_{cini}, K_{cmid} and K_{cend}, they refer to the initial, middle and end of the growing season respectively, the fourth stage is the developmental stage and it is between the initial and middle stages. Figure 3 lists part of one of the tables in the model's database, containing: The crops, average length of crop developmental stages and their total length of growing periods as well as the Kc at these stages and the average height of the crop as presented by WIRWAS model. It was designed in such a way that after the user had selected a crop, the crop and its various developmental stages and the Kc with the corresponding number of days will be listed below the table so that the user sees the selected crop, this is shown at the bottom of the table for maize in Fig. 3. After the user had selected the stage, the model goes into the table to determine the corresponding crop coefficient $K_{c(ini/mid/end)}$ and this is adjusted for the frequency of wetting with the following equation.

$$K_{Ci} = K_{Cprev} + \left(\frac{i - \sum(L_{prev})}{L_{stage}}\right)(K_{cnext} - K_{cprev}) \tag{3}$$

Where: K_{ci} is the adjusted K_c of the day i
K_{cprev} is the K_c of the previous stage (e.g K_{cini} is the previous K_c for development stage).
i is day number within the growing season (1 … length of growing season).
$\sum L_{prev}$ is sum of the lengths of all previous stages (days).
L_{stage} is the length of stage under consideration (days).
K_{cnext} is the K_c of the next stage (e.g K_{cmid} is next K_c for developmental stage).



CROP	L(ini)	L(dev)	L(mid)	L(late)	L(total)	Kc(ini)	Kc(mid)	Kc(end)	Height (m)
Bananna	120	90	120	60	390	1	1.05	1.05	3
Carrots	20	30	30	20	100	0.7	1.05	0.95	0.3
Cassava (year 1)	20	40	90	60	210	0.3	0.8	0.3	1
Cassava (year 2)	150	40	110	60	360	0.3	1.1	0.5	1.5
Castor beans	25	40	65	50	180	0.35	1.15	0.55	0.3
Cotton	30	50	60	55	195	0.35	1.2	0.7	1.5
Cowpeas	20	30	30	20	110	0.4	1.05	0.6	0.4
Cucumber	20	30	40	15	105	0.6	1	0.75	0.3
Egg plant	30	40	40	20	130	0.6	1.05	0.9	0.8
Grapes	20	40	120	60	240	0.3	0.7	0.45	2
Groundnut	25	35	45	25	130	0.4	1.15	0.6	0.4
Maize (grain)	20	35	40	30	125	0.7	1.2	0.6	2
Maize (sweet)	20	30	30	10	90	0.7	1.15	1.05	1.5
Millet	15	25	40	25	105	0.7	1	0.3	1.5
Onion (dry)	20	35	110	45	210	0.7	1.05	0.75	0.4
Onion (green)	20	45	20	10	95	0.7	1	1	0.3
Potato	25	30	30	30	115	0.5	1.15	0.75	0.6

Fig. 3: Lengths of crops and their various growing stages with their respective crop coefficients (Maize grain is selected)

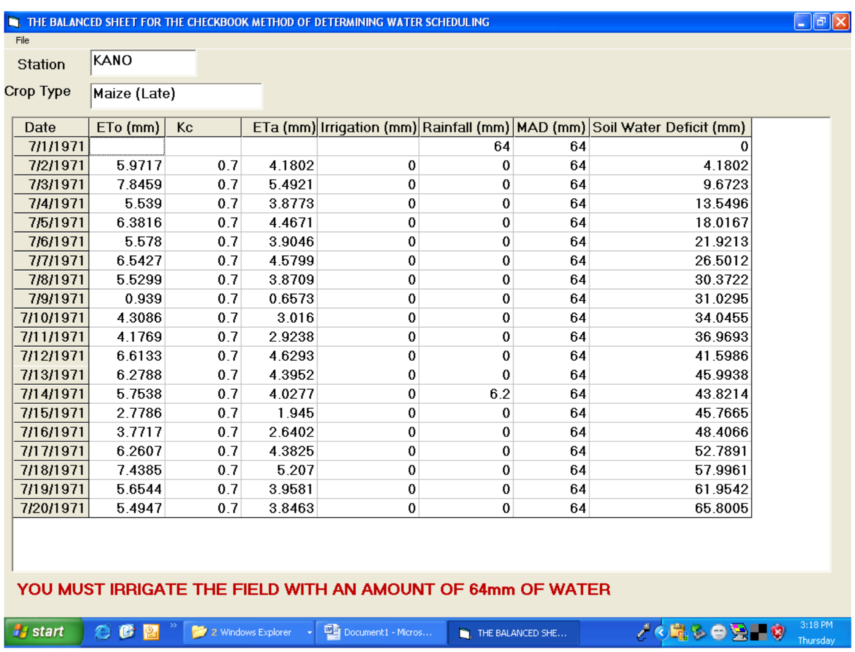
Then the value obtained here is multiplied by the ET_o to give the ET_a using the Eq. 2 above. The beauty of this model is that the length of each growing stage and the total growing period of any of the crops and if there is any new specie(s) of any of these crops can easily be modified by the user, if there is more recent research work on such crop.

Soil water deficit part: During irrigation, water infiltrates (penetrates) the soil surface. It is then distributed in the soil by gravity and soil capillary forces. As the soil becomes wetter, gravitational forces dominate and water drains downward through the soil. At this time, soil moisture in the root zone may be considered to be in storage. This upper limit of water storage in the soil is called "Field Capacity" (FC). A practical lower limit of soil water may be defined as the soil-water content below which severe crop water stress and permanent wilting occurs. This lower limit is called the Permanent Wilting Point (PWP). The difference between FC and PWP is called the Available Water Capacity (AWC). One of the tables in the software's database consists of typical values of AWC for various soil types, the user clicks the exact type of the soil used for cultivation and the corresponding soil's AWC will be automatically loaded and used for subsequent computing. Soil water deficit is the amount of water that is removed (depleted) by plant from the soil for evapotranspiration purposes, several methods can be used to estimate soil water deficit, but each has its shortcomings. The best, recent and commonest method used in developed countries is the water budget approach which is also used in this model to estimate soil water deficit. In this method, a farmer manages the water budget like a bank account. Irrigation and rainfall are deposits to the account and daily crop water use is a withdrawal from the account. Available soil moisture stored in the root zone is then like the balance in the account. Recent research works on this method are Steel *et al.* (2000), Laboski *et al.* (2001), Smajstrla and Zazueta (2002) and Smajstrla *et al.* (2006). The equation is given as

$$WC_t = WC_{t-1} + IRR + RAIN - ET_a - DP \qquad (4)$$

Where: WC_t and WC_{t-1} are the water content today and yesterday, respectively (mm).
IRR and RAIN are respectively the irrigation depth and Rainfall amount since yesterday DP is the deep percolation (Runoff and Drainage in mm).

The model computes and saves the water content on daily basis and compares the present water content with half (50%) of the Available Water-holding Capacity (AWC), this 50% of the AWC is called the Maximum Allowable Deficit (MAD). If the water content of any day is just less than or equal to half (50%) of the AWC then the model advises the farmer that it is time to irrigate.



Date	ETo (mm)	Kc	ETa (mm)	Irrigation (mm)	Rainfall (mm)	MAD (mm)	Soil Water Deficit (mm)
7/1/1971					64	64	0
7/2/1971	5.9717	0.7	4.1802	0	0	64	4.1802
7/3/1971	7.8459	0.7	5.4921	0	0	64	9.6723
7/4/1971	5.539	0.7	3.8773	0	0	64	13.5496
7/5/1971	6.3816	0.7	4.4671	0	0	64	18.0167
7/6/1971	5.578	0.7	3.9046	0	0	64	21.9213
7/7/1971	6.5427	0.7	4.5799	0	0	64	26.5012
7/8/1971	5.5299	0.7	3.8709	0	0	64	30.3722
7/9/1971	0.939	0.7	0.6573	0	0	64	31.0295
7/10/1971	4.3086	0.7	3.016	0	0	64	34.0455
7/11/1971	4.1769	0.7	2.9238	0	0	64	36.9693
7/12/1971	6.6133	0.7	4.6293	0	0	64	41.5986
7/13/1971	6.2788	0.7	4.3952	0	0	64	45.9938
7/14/1971	5.7538	0.7	4.0277	0	6.2	64	43.8214
7/15/1971	2.7786	0.7	1.945	0	0	64	45.7665
7/16/1971	3.7717	0.7	2.6402	0	0	64	48.4066
7/17/1971	6.2607	0.7	4.3825	0	0	64	52.7891
7/18/1971	7.4385	0.7	5.207	0	0	64	57.9961
7/19/1971	5.6544	0.7	3.9581	0	0	64	61.9542
7/20/1971	5.4947	0.7	3.8463	0	0	64	65.8005

Fig. 4: Typical result (in a balanced sheet form) of the model over a corn plantation

Irrigation water scheduling part: If the soil water content is less than 50% of the allowable soil water content, the model advises that irrigation is required. The next thing to determine is the correct amount of water to be judiciously and economically used for irrigation. This is determined using the following equation:

$$I_a = (AWC - WC_i) / I_e \quad (5)$$

Where: I_a is the amount of water to be used for irrigation (mm).
I_e is the efficiency of the irrigation equipment (a decimal fraction).

It should be noted that the above definition for irrigation requirement does not include water applied for leaching of salts, crop cooling, or other purposes, even though water for these purposes is required for crop production and is applied through an irrigation system. The irrigation time is

$$I_t - I_a / A_r \quad (6)$$

Where I_t and A_r are the irrigation time (hr) and application rate (mm/hr), respectively.

Figure 4 presents a typical result page in form of statement of bank account, the model will generate for Maize (corn) in 21 days, if the user follows the step to step computing of all the aforementioned parameters.

CONCLUSION AND RECOMMENDATIONS

An irrigation requirements and water scheduling model that addresses the weather, types of soil and the crops grown in West Africa has been developed. This model gives the user opportunity to select one from a wide range of methods of computing a particular parameter depending on data availability. It also gives the user ability to edit or update as the case may be, the local factors such as: crop, soil and weather factors therefore, the ability of the end-user to incorporate new findings by the researchers. It was presented in a user-friendly manner therefore people with virtually no computer knowledge will find it interesting to use.

The model will go a long way in solving the problems of ETo calculation using any of the available methods and also helps in determining the onset, cessation and therefore length of growing season of any crop. The model's database serves as archive for storing and updating the individual crop lengths and stages cultivate with different planting dates in West African sub-Region.

It is hereby recommended that, this model can be improved upon to take into consideration the case of dual-cropping. Seminars should be organized at regular interval for the researchers in agriculture to present their latest findings to the agriculturists (farmers) and also for the researchers to have the feedback from the agriculturists (end users) after using some of these findings, most especially in this West African sub-region.

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