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Mathematical Models and Comparative Analysis for Rice and Soya Bean Irrigation Crop Water Needs: A Case Study of Bida Basin Niger State, Nigeria

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Abstract

In this manuscript, mathematical models for cropping water need (C.W.N) and the size of land for irrigation (S.L.I) were formulated. The solutions of the models for Crop water need for Soya beans and Rice, and the size of land for irrigation (S.L.I) of the two crops was obtained. We fill the gap by considering the size of the irrigation land which is not considered by the Food and Agriculture Organization (F.A.O). The computational Method of solutions is carried out to get effective results. The climatic data of the study area (Bida Basin) under which our research is based includes: Rainfall, Humidity, Sunshine hours, minimum and maximum temperature, evapotranspiration were secondary data collected from Nigeria Metrological Society (NIMET). We compared the results of CROPWAT 8.0 software developed by the Food and Agriculture Organization (F.A. O) and our computational method so that we can arrive at a new finding and better results. The results for the computational method with the size of Land for irrigation shows that there is an increase in crop water need for the crops than the results of CROPWAT 8.0 software developed by the Food and Agriculture Organization (F.A. O) in which the size for the land is not considered. We therefore, recommended that the integral calculus can be used to estimate the irregular shape of the size of the land if the land shape is not in rectangular form before solutions are given for accuracy and effective results.

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1. Introduction

Bida Basin lies in the sedimentary terrain of the middle part of Nigeria. It has an area of coverage of about 27,000 km^2. The area falls under the middle climatic belt which is mainly tropical with an average rainfall of about 1250m. We are therefore considering the crop water need of Rice and Soya Bean on the aquifer of two lithological groups: unconfined and semi - confined aquifer in our selected study area.

Cropwat 8.0 software is software developed by Food and Agricultural Organisation (F.A.O), used to evaluate farmer's irrigations, irrigation practices and to estimate crop performance under both rainfall and irrigated condition. Our computational method is used as a tool to solve the models and obtain the solutions to get effective results. The weakness of the cropwat 8.0 software developed by the Food and Agriculture Organization (F.A.O) is that the irrigator farmers do not know the size of the Land the results of the software is given as the size of land for irrigation (S.L.I) is not considered by the cropwat 8.0 software

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and we fill the gap by considering the size of land for irrigation. Many irrigation farmers faced the challenges of what the crop water need of irrigation crops would be before embarking on irrigation water planning. This research aims are to develop a mathematical model for crop water need problems and determine the exact amount of water need for Rice and Soya beans crops by considering the size of the land and shape. Our objective is to use Cropwat 8.0 software developed by the Food and Agricultural Organisation (F.A.O) and our computational method to determine the crop water need of two crops and compared the two results to unravel crop water need problems.

Irrigated Agriculture in South Africa has not been profitable over the years. Even though, it is the highest user of total consumptive water [1]. Its economic returns have not been impressive. The sustainable management of irrigation water resources is therefore, a necessity. A common procedure for estimating crop water use is to first determine the daily reference crop Evapotranspiration (ET_0) and then multiply it by a specific crop coefficient(K_c), as given by the Food and Agriculture Organisation [2].

[3] determine the crop water requirements for Maize in Abshege Woreda, Gurage zone in Ethiopia, they determine crop water requirement which is the major food crop of the area, they used the climatological records of Sunshine, maximum and minimum temperature, humidity and wind speed were used as secondary data. Penman - Monteith method was used and crop water requirement was estimated using CROPWAT 8.0 the results show that a Maize variety with a growing period of 140 days to maturity would require 423 mm depth of water, while 101mm of water would be required as supplementary irrigation.

[4] came up with a quantitative analysis of hydraulic interaction process in the stream – aquifer systems. It revealed both the theoretical and laboratory tests have demonstrated that, the hydraulic connectedness of the stream aquifer system can reach a critical disconnection state.

[5] researched on the crop water requirement for Agriculture in a typical River Basin of India. The results show the crop water requirements is much below the available rainfall and even available groundwater at various location of the river basin, the crop water requirement is required to be increased by increasing the crop production with multiple crops and by using more Agriculture land for crop production. With these, there is a need to develop a Mathematical model for solving crop water need with the specific land size. [6] develop estimating aquifer hydraulic properties in Bida Basin Central Nigeria, using the Empirical method. He determined aquifer properties such as hydraulic conductivity, porosity and effective porosity, and coefficient of uniformity. [7] the understanding of crop water need becomes necessary, as it enables efficient use of water and better irrigation practices like scheduling as the supply of water through rainfall is limited in these areas.

[8] Carried out a study to determine the crop water need of few selected crops for the commanded area, the outcomes of the study are capable of planners of the water resources for future planning and helps save water in satisfying the crop water need.

[9] Cropwat 8.0 software helps irrigator planner in allocating the water resources in the future.

2. Mathematical Model for Crop Water requirement.

2.0.1. Metrological Data

To calculate this, the respective climatic data was collected from the Nigeria meteorological station. The data used for ET0 computation was the meteorological data obtained from the station; for instance, minimum and maximum temperatures (C), wind speed in km per day, the relative humidity (maximum and minimum, in %) and the hours of sunshine, and the physical data such as altitude, latitude and longitude. The climatic records obtained were then adjusted into the format accepted by CROPWAT 8.0. The rainfall data collection was also obtained from the meteorological station. Rainfall records from a range of years (10–15) were collected to allow for a calculation of Crop water need.

2.0.2. Soil Data

The data utilized on the soil characteristics were acquired through laboratory soil analyses done on the soil samples collected. After the collection of all these data, it was entered into the CROPWAT 8.0 program and saved. Crop and irrigation water needs were then calculated using the model for the majorly observed high - value crops including Rice and Soya Bean. The weakness of the Crop water need developing by the food and Agricultural Organisation (F.O.A) is that the results for the amount of water need for crops are given without the size of the land, thus. The size of land for irrigation have to consider.

2.1. Mathematical Derivation of Reference Crop Water Need.

Considering an energy balance at the earth surface equates all incoming and outgoing energy flux. The following governing equation is considered;

$$R_n = H + \lambda E + G \tag{1}$$

Where R_n=energy flux density net incoming radiation (w/m^2)
H= flux density of latent heat into the air(w/m^2)
λE= flux density into the water body (w/m^2)
G = heat flux density into the water body (w/m^2)
λ= the latent heat of vaporization of water
E = the vapour flux density in $kg/m^2 s$
Where

$$H = C_1 \frac{(T_s - T_a)}{r_a} \tag{2}$$

and

$$\lambda E = C_2 \frac{(e_s - e_d)}{r_a} \tag{3}$$

where,
C_1, C_2= Constant
T_s= temperature at a certain height above the surface (kpa)
e_a= Prevailing vapour pressure at the same height as T_a (kpa)
r_a= aerodynamic diffusion resistance.
Applying the similarity of transport heat and water vapour, we have a Bowen ration yield as;

$$\frac{H}{\lambda E} = \frac{C_1(T_s - T_a)}{C_2(e_s - e_d)} \tag{4}$$

Equation (4) becomes;

$$\frac{H}{\lambda E} = \gamma\left(\frac{T_s - T_a}{e_s - e_d}\right) \quad (5)$$

$$\left.\frac{C_1}{C_2} = \gamma\right\} \quad (6)$$

$$\gamma = \frac{C_p\rho_a}{\lambda\varepsilon} \quad (7)$$

making C_p the subject of the relation in (7) we have:

$$C_p = \frac{\gamma\lambda\varepsilon}{\rho_a} \quad (8)$$

where,

$$\rho_a = \frac{P_a}{T_{vk}R} \quad (9)$$

where,
T_{kv} = the virtual temperature
R = specific gas constant
ρ_a = mean air density at constant pressure kgm^{-3}
C_p = specific heat at constant pressure mj k/g/ ^0C
Equation (7) is referred to as Psychometric constant $(kpa/^oC)$
In determining the surface Temperature, we considered the Penman - Monteith equation which is given as

$$e_s - e_a = \Delta(T_s - T_a) \quad (10)$$

From equation (10)

$$T_s - T_a = \frac{e_s - e_a}{\Delta} \quad (11)$$

Substituting equation (11) into equation (5), we have:

$$\frac{H}{\lambda E} = \frac{\gamma}{\Delta}\left(\frac{e_s - e_a}{e_s - e_d}\right) \quad (12)$$

Replacing $e_s - e_a$by $e_s - e_d - e_a + e_d$

$$\frac{H}{\lambda E} = \frac{\gamma}{\Delta}\left(1 - \frac{e_a - e_d}{e_s - e_d}\right) \quad (13)$$

Considering isothermal evaporation λE_a given as:

$$\lambda E_a = C_2\frac{e_s - e_d}{r_a} \quad (14)$$

Setting $\lambda = 1$in equation (14) ,then

$$E_a = C_2\frac{e_s - e_d}{r_a} \quad (15)$$

replacing C_2 by $\frac{\varepsilon\rho_a}{p}$ in equation (15) we have:

$$E_a = \frac{\varepsilon\rho_a}{p}\left(\frac{e_s - e_d}{r_a}\right) \quad (16)$$

Dividing equation (16) by equation (3) we have:

$$\frac{E_a}{E} = \frac{(e_a - e_d)}{(e_s - e_d)} \quad (17)$$

Substituting equation (17) into equation (12) we have:

$$\frac{H}{\lambda E} = \frac{\gamma}{\Delta}\left(1 - \frac{E_a}{E}\right) \quad (18)$$

Replacing E by ET_0in equation (18) and make H the subject of relation, we have:

$$H = \frac{\lambda\gamma ET_0}{\Delta}\left(1 - \frac{E_a}{ET_0}\right) \quad (19)$$

Substitute equation (19) for H in equation (1) and simplify, we have:

$$ET_0 = \frac{\frac{1}{\lambda}(R_n - G)\Delta + \gamma E_a}{\Delta + \gamma} \quad (20)$$

where,
ET_0=open water evaporation rate (kg/m^2)
Δ= proportionality constant $(kpa/^oc)$
R_n= net radiation (J/kg)
γ= Psychometric constant $(kpa/^oc)$
E_a= isothermal evaporation rate (kg/m^2s)
The term $\frac{\frac{1}{\lambda}(R_n-G)\Delta}{\Delta+\gamma}$ in equation (20) is called radiation term
The term $\frac{\gamma E_a}{\Delta+\gamma}$ in equation (20) is called aerodynamic term
Substitute equation (7) and (16) into equation (20). Simplifying further to obtain

$$ET_0 = \frac{\frac{1}{\lambda}\left((R_n - G)\Delta + \frac{C_p\rho_a}{r_a}(e_s - e_d)\right)}{(\gamma + \Delta)} \quad (21)$$

where,
ε= ration of molecular masses of water vapour and dry air (-)
p_a= density of moist air (kg/m^3)
ρ_a= atmospheric pressure (kpa)
c_p=Specific heat of dry air at constant pressure $(J/Kg.k)$
Considering vapour diffusion rate then equation (16) is express as:

$$E_a = \frac{\varepsilon p_a}{p_a}.\frac{e_a - e_d}{r_a} = \frac{\varepsilon p_a}{p_a}\frac{e_a - e_d}{r_c} = \frac{\varepsilon p_a}{p_a}\frac{e_0 - e_d}{r_c + r_a} \quad (22)$$

Then,

$$\frac{\varepsilon p_a}{p_a}\frac{e_a - e_d}{r_a} = \frac{\varepsilon p_a}{p_a}\frac{e_0 - e_d}{r_c + r_a} \quad (23)$$

Simplifying equation (23) we have:

$$e_a - e_d = \left(\frac{e_0 - e_d}{1 + \frac{r_c}{r_a}}\right) \quad (24)$$

where,
E_a= Isothermal evapotranspiration rate from canopy
e_o= Internal saturated vapour pressure at (cp_a)
e_a= Saturated vapour pressure at the leaf surface
e_d= Vapour pressure in the external air
r_a= aerodynamic resistance (s/m)
r_c= Canopy diffusion resistance (s/m)
Substitute equation (24) into equation (20) we have:

$$ET_0 = \frac{\frac{1}{\lambda}\left((R_n - G)\Delta + \frac{C_p\rho_a}{r_a}e_0 - e_d\right)}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \quad (25)$$

Let

$$\gamma\left(1+\frac{r_c}{r_a}\right)=\gamma^* \tag{26}$$

then equation (25) becomes:

$$ET_0=\frac{\frac{1}{\lambda}\left((R_n-G)\Delta+\frac{C_p\rho_a}{r_a}e_0-e_d\right)}{\Delta+\gamma^*} \tag{27}$$

where,
ET_o=evaporation rate from dry surface ($kg/m^2 s$)
γ^* = Modified Psychometric constant ($kpa/^o c$)
Substitute equations (8) and (9) into equation (27) we have;

$$ET_0=\frac{\frac{1}{\lambda}\left((R_n-G)\Delta+\frac{\frac{\gamma\varepsilon\lambda}{P_a}\frac{P_a}{T_{vk}R}}{r_a}e_0-e_d\right)}{\Delta+\gamma^*} \tag{28}$$

Simplifying equation (28) we have:

$$ET_0=\frac{\left(\frac{1}{\lambda}(R_n-G)\Delta+\frac{\gamma\varepsilon}{r_aT_{vk}R}e_0-e_d\right)}{\Delta+\gamma^*} \tag{29}$$

r_a can be expressed as:

$$\begin{aligned} r_a &= \frac{\ln\frac{(z_m-d)}{z_{om}}\ln\frac{(z_h-d)}{z_{oh}}}{k^2u_2} \\ &= \frac{\ln\left[\frac{2-0.08}{0.01476}\right]\ln\left[\frac{2-0.08}{0.001476}\right]}{(0.41)^2u_2} \\ &= \frac{208}{u_2} \end{aligned} \tag{30}$$

with the following standard values:

$$\begin{aligned} &d=0.67h, z_{om}=0.123h, \text{and} \\ &z_{ov}=0.120m, k=0.41, h=0.12. \end{aligned} \tag{31}$$

where
Z = height at which wind speed is measured (m)
d = displacement height (m)
z_{om} = roughness length for momentum (m)
z_{ov} = roughness length for water vapour (m)
K = Von Karman Constant equal 0.41
u_2= wind speed measure at height (m/s)
T_{kv} =the virtual temperature
R =specific gas constant
ρ_a = mean air density at constant pressure kgm^{-3}
C_p = specific heat at constant pressure $mj\,kg^{-1}\,{}^0C^{-1}$
From equation (30) we have:

$$\begin{aligned} \frac{C_p\rho_a}{r_a} &= \frac{\gamma\varepsilon}{r_aT_{vk}R} \\ &= \frac{(86400)(0.622)\gamma\lambda}{(T_a+273)(0.287)(208)}u_2 \\ &= \gamma\frac{900}{T_a+273}u_2 \end{aligned} \tag{32}$$

with the following standard values:

$$\begin{aligned} &r_a=(208)u_2, T_{vk}=(T_a+273), \\ &R=(0.287) \end{aligned} \tag{33}$$

From equation (30) we have:

$$\frac{1}{\lambda}=\frac{1}{2.45}=0.408 \tag{34}$$

with standard value of $\lambda = 2.45$
from equation (27)

$$\gamma^*=\gamma\left(1+\frac{r_c}{r_a}\right) \tag{35}$$

we let,

$$\begin{aligned} r_c &= \frac{r_i}{LAI_{active}} \\ &= \frac{100}{(0.5)(24)(0.12)}=70sm^{-1} \end{aligned} \tag{36}$$

Substituting equation (31) and (37) into equation (27), we have;

$$\gamma^*=\gamma(1+0.34u_2) \tag{37}$$

Substitute equation (31), (33), (37) and (38) into equation (30) we have:

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{Ta+273}u_2(e_0-e_d)}{\Delta+\gamma(1+0.34u_2)} \tag{38}$$

2.2. Mathematical Formulation of Crop Coefficient

Considering crop coefficient, we let:
$K_{cb\ tab}$= is the value for $(K_{cb})_{mid}$ or $(K_{cb})_{end}$

$$K_e=K_r(K_c-K_{cb}) \tag{39}$$

Simplifying the equation, we have

$$K_c=K_e+K_{cb} \tag{40}$$

where,

$$K_r=1 \tag{41}$$

K_e = soil evaporation coefficient
K_{cb} = Basal crop coefficient
k_c= crop coefficient value of K_c following rain or irrigation
K_r = Dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the top so

2.3. Mathematical Formulation of Irrigated Area of Land (A_i)

We consider the Area of the irrigated land as a rectangular surface;
Let L = length of the farm
B = Breadth of the farm
l = length of the spacing on the farmland
b = breadth of the spacing on the farmland
The spacing area of the farm land is considered to be;

$$lb=\left(\frac{LB}{P_n}\right)N \tag{42}$$

where,
P_n = number of plants on the farmland.
N = number of seeds per stand.

Table 1. The comparison of result Cropwat 8.0 software and the computational method for Rice Crops

Month	ET_o(F.A.O)	ET_o	K_c (FAO)	K_c	ET_{cwn} (FAO)	ET_{cwn}Mm	Ai (F.A.O)	A_i Hectares
November	4.44	4.92	4.27	3.93	1689	9571	Nill	569
December	4.45	4.32	3.3	3.12	1515	6721	Nill	569
January	4.42	4.25	4.4	3.67	1521	1826	Nill	569
February	4.73	4.21	3.24	3.84	1431	1646	Nill	569
March	5.17	4.08	5.2	1.29	7560	627	Nill	569

Table 2. The comparison of result Cropwat 8.0 software and the computational method for Soya Bean

MONTH	ET_0F.A,O	ET_0	K_c F.A.O	$K_c = K_{cb} + K_e$	ET_{cwn}F.A.O	ET_{cwn}	A_i F.A.O	A_i
November	4.44	4.33	0.8	0.23	19.6	12.7	Nill	569
December	4.45	4.32	2.47	0.3	114.4	128	Nill	569
January	4.42	4.25	3.18	0.82	146.5	347	Nill	569
February	4.73	4.08	1.14	1.64	36.7	666	Nill	569

Also, loss of plants on two adjacent rows is;

$$S = \left(\frac{L}{l} + \frac{B}{b} + I\right) N \quad (43)$$

The accurate plant population formula becomes:

$$P_n = \left(\frac{lb}{LB}\right) N + S \quad (44)$$

Substitute (43) into (44) which further simplified to;

$$P_n = \left(\frac{LB + Lb + lB + lbI}{lb}\right) N \quad (45)$$

Furthermore,

$$LB = lbP_n - (Lb + lB + lbI) \quad (46)$$

Replacing $LB$with A_i; then

$$A_i = lbP_n - (Lb + lB + lbI) \quad (47)$$

Where;
A_i = irrigated area of land.

$$ET_{cwn} = ET_0 \times K_c \times A_i \quad (48)$$

Where,
ET_{cwn} =crop water need
ET_0 =reference crop evapotranspiration
K_c =crop water coefficient
A_i =crop irrigated area
Combining equation (39), (41) and (48), the crop water need equation becomes;

$$ET_{cwn} = \left(\frac{0.408\Delta(R_n - G) + \gamma \frac{900}{Ta+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}\right) \times (K_{cb} + K_e) \times (lbP_n - (Lb + lB + lbI)) \quad (49)$$

3. Result and Discussion

Table 4.1 shows the comparison of the result analysis of the outcome of Cropwat 8.0 Software developed by F.A.O and the computational method for Rice irrigation crop water needs, reference evapotranspiration (ET_o) and crop coefficient (Kc) in Bida Basin Irrigation Sites. It is observed from the table that, reference evapotranspiration (ET_o) results in computational method is decreasing as the dry season is biting harder, this would enable the irrigator farmers to know the quantity of water need for crops provided the size of the land is known. while it alternates in Cropwat 8.0 Software results developed by F.A.O. the crop coefficient (K_c) results in our computational method maintains the same behaviour except in March where we have 1.29 (K_c) this is due to the harvesting period which is when crops need little or no water, comparing to Cropwat 8.0 Software developed by F.A.O which is 5.2 (K_c) in march. The crop water needs result in computing method is higher than the Cropwat 8.0 Software developed by F.A.O, this is own to the fact that the quantity of crop water need in each month of the dry season is known to the irrigator farmers within the available land size of 569 hectares

Table 4.2 shows the comparison of the result analysis of the outcome of Cropwat 8.0 Software developed by F.A.O and the computational method for Soya Bean irrigation crop water needs, reference evapotranspiration (ET_o) and crop coefficient (Kc) in Bida Basin Irrigation Sites. It is observed from the table that the crop (Soya Bean) is grown from November to February which is four months, the crop water need (ET_{cwn}) in our computational method is greater than crop water need (ET_{cwn}) in the cropwat 8.0 software, this is own to the fact that the size of the Land for irrigation is considered in the former method. The reference evapotranspiration (ET_o) results in our computational method are closer to that of cropwat 8.0 Software results developed by F.A.O. The crop coefficient (K_c) results in our computational method maintain the same behaviour which shows that the crops need little or no water during their harvesting period. The crop water needs result in our computational method is higher than the Cropwat 8.0 Software developed by F.A.O. The challenges of crop water need (ET_{cwn}) faced by the irrigator farmers can be unraveled if the size of the land for irrigation and plant population is known.

4. Conclusion

The Penman - Monteith Mathematical model for the crop water need and Mathematical model for the size of land for irrigation were solved and the results obtained are compared to CROPWAT 8.0 software results, the climatic data of the study area (Bida Basin) under which our research is based which include: Rainfall, Humidity, minimum and maximum temperature, evapotranspiration were collected from NIMET and used for the both CROPWAT 8.0 software and the computational method so that comparative analysis can be made from the two methods. Our computational method results show that crop water need for crops can better be estimated if the size of the land for irrigation is considered. The irrigator Farmers can inextricably know of the estimated crop water need for a given size of the Land before commencing irrigation exercise. We therefore, recommended that integral calculus can be used to estimate the irregular shape of the size of the land if the land shape is not in rectangular form before solutions are given for accuracy and effective results.

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