Maejo Int. J. Sci. Technol. **2009**, *3*(02), 295-305

Maejo International
Journal of Science and Technology
ISSN 1905-7873
Available online at www.mijst.mju.ac.th

Full Paper

A decision support tool for basin irrigation in northern Nigeria

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Received: 19 March 2009 / Accepted: 22 June 2009 / Published:1 July 2009

Abstract : Inadequate rainfall, water resources scarcity and attendant food security-related problems have made irrigation technology a necessity. This work presents the development of a decision support system for solving surface irrigation design problems in northern Nigeria. The arid northern states affected by desert encroachment constitute a good candidate and their climatological data was obtained from the Nigerian Metrological Agency. The interactive system was defined in terms of inputs and outputs. The inputs were properties of soil, surface irrigation method and climate. The outputs were mainly the quantity of water application, scheduling pattern, possible design configuration, advance time, cut-off time, application rate, and water use efficiency. The FAO Penman-Monteith equation was used to estimate evapotranspiration values of major crops grown in Nigeria. Mathematical models outlined by Walker and Skogerboe were adapted, and heuristics applied in determining the best configuration that achieves optimum water application efficiency. We encoded the knowledge base using Matlab® software. The application was successfully used for the modification of a farm irrigation scheme in Kaduna state. This indicates that the adoption of new technologies for irrigation design issues could enhance agricultural productivity in northern Nigeria.

Keywords: decision support system, surface irrigation, basin irrigation, evapotranspiration, advance time, required opportunity time

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Introduction

Problems of inadequate rainfall, water resources scarcity and food security have made irrigation technology a necessity. Besides, the economic importance of agricultural produce and the need to be self-sufficient has brought irrigation technology to the foreground in several parts of the world, including northern Nigeria. Irrigation as defined by Garg [1] is the science of artificial application of water to land, in accordance with the 'crop requirements' through 'crop period' for full-fledged nourishment of the crops. The three broad classes of irrigation systems are pressurised distribution, gravity flow distribution, and drainage flow distribution. The term 'surface irrigation' as defined by Walker and Skogerboe [2] refers to a broad class of irrigation methods in which water is distributed over the field by overland flow. A flow is introduced at one edge of the field and covers the field gradually. The rate of coverage (advance) is dependent almost entirely on the differences between the discharge onto the field and the accumulating infiltration into the soil. Secondary factors include field slope, surface roughness, and the geometry or shape of the flow cross-section.

Irrigated agriculture faces a number of difficult problems in Nigeria. One of the major concerns is the generally poor efficiency with which water resources have been used for irrigation. A comparatively safe estimate of 40% or more of the water diverted for irrigation is wasted at the farm level through either deep percolation or surface runoff. These unfortunately cause problems of erosion and excessive loss of nutrients, which eventually leads to low productivity and sometimes failure of the entire irrigation systems. In addition, shortage of irrigation experts contributes to the failure of many irrigation projects. Having people who are conversant with the soil, water, crop, climate, etc. plays a vital role in the success of irrigation projects. These experts include agriculturists, soil scientists, and engineers. Disappointing results of irrigation development efforts in Nigeria for over 20 years have made it imperative for the incorporation of an intelligent technology such as the use of expert systems. The need to maximise land resources by encouraging all-year-round farming with the aim of boosting agricultural production in the mist of limited water supply has made this technology adaptation expedient for the Nigerian nation. This will help ensure a consistent growth of the development of quality and efficient surface irrigation systems.

Our work presents the usage of a decision support system (DSS) to solve surface irrigation design problems in Nigeria. A DSS is a computer software application designed to assist managers or operators with decision making in a particular field. It facilitates work by decomposing and tackling decision problems into smaller units that may be analysed and/or simulated. An expert system (ES) as defined by Badiru and Cheung [3] 'is an interactive computer-based decision tool that uses facts and heuristics to solve difficult decision problems based on knowledge acquired from an expert'. Agricultural decision support systems and expert systems should combine the analytical, experimental and experiential knowledge with the intuitive reasoning skills of a multitude of specialists to aid farmers in making the best decisions about their farmlands, crops and associated activities.

Related Work

In north-west China, a decision-making support system was designed to improve water management of Jingtia Chuan pumping irrigation scheme at the upper reaches of Yellow River [4].

The system is based on the application of computer network and specially developed program. Significant benefit and social benefits have been achieved by application of the system. The structure of the system is such that irrigation water management is related to water sources, climate condition, water requirement, canal feature, water distribution, etc. The system was developed with the feature of collecting and processing information dynamically.

Furrow irrigation events conducted under usual farmer management were analyzed to determine the irrigation contribution to deep drainage under surface irrigated cotton in Queensland [5]. Application efficiency was a low 48%. Losses to deep drainage were substantial, averaging 42.5 mm per irrigation. This can lead to significant environmental harm and represents an annual loss of up to 2500 m^3/ha of water that could have been beneficially used to grow more cotton. To tackle this problem, a simulation of each event was carried out using the simulation model SIRMOD; it illustrated simple recipe strategies that would lead to gain in efficiency and reductions in the deep drainage losses. Additional simulations of a selected event showed that further significant improvement in performance could be achieved by the application of more advanced irrigation management practices, involving in-field evaluation and optimisation of the flow rate and irrigation time to suit the individual soil conditions and furrow characteristics. Application efficiency in the range of 85-95% was achievable in all but the most adverse conditions. The relation between deep drainage and irrigation management was demonstrated, confirming that substantial reduction in deep drainage is possible by ensuring that irrigation application does not exceed the soil moisture deficit.

Prasad and Babu [6] surveyed the availability of various expert systems in agriculture dating back 30 years.

Methods

Surface irrigation design is a procedure for matching the most desirable frequency and depth of irrigation with the capacity and availability of water supply. For this, the basin approach was considered wherein the field is levelled in all directions, encompassed by a dyke to prevent runoff, and provided with an undirected flow of water. The design of the user interface of the DSS was accomplished in Matlab by using its graphical user interface development environment (GUIDE). The interactive system allows the user to input data about the farm, soil, crop, location, climate, and type of surface irrigation method to be employed. The resulting output will be the determination of the best configuration that achieves the highest efficiency, estimated water requirement and irrigation scheduling.

The estimation of evapotranspiration (ET) was done using climatological data of the northern region obtained from the Nigeria Meteorological Agency at Lagos. Estimation was chosen owing to difficulties in obtaining accurate direct measurement of ET under field conditions. These data initially include the following:

- Maximum temperature in ^{0}C (T_1)
- Minimum temperature in ^{0}C (T_2)
- Solar radiation in $MJm^{-2}\ d^{-1}$ (R_a)
- Air pressure in KPa (P_a)

- Wind speed in ms^{-1} (U_2)
- Saturated vapour pressure in KPa (e_s)
- Relative humidity (RH)
- Mean daily maximum sunshine hour in hr (N)
- Mean daily actual sunshine hour in hr (n)
- Monthly effective precipitation in mmd^{-1}
- Potential evapotranspiration (ETo) in mm/d

The climatological data obtained were for a period of 7-10 years back. The daily potential evapotranspiration (ETo) for each month from January to December in each year was studied and the extreme value was taken as a representation of ETo value for that particular month. The mathematical model used in estimating crop water requirement is as shown in Figure 1. It is called the FAO-Penman-Monteith evapotranspiration model [7]. The model is preferred because of its combination of energy balance and aerodynamic considerations. Methods outlined by Walker and Skogerboe [2] for calculating required opportunity time and time of advance were used to code the knowledge base.

Knowledge acquisition

The knowledge acquisition technique employed was the protocol analysis techniques, which involves the identification of basic object within a protocol. This was done by highlighting all the concepts that were relevant to the DSS. The knowledge employed was the procedural knowledge as outlined by Compton and Jansen [8]. This knowledge was coded as a set of rules and was stored in the data structure. The knowledge representation used was production rules frames. The knowledge acquisition stage was interesting because we were able to assume responsibility of modelling our own reasoning and expertise in the form of a computer program. An engineer (N.A Ajayi) from the Federal University of Technology at Akure, an expert of over 30 years, was also consulted during the knowledge acquisition process. Design manuals and reports were also used throughout the documentation process. Data related to ET and other parameters were kept in an organised and easily accessible format.

Algorithm for basin irrigation design system [9]

```
1   Select region
2   Select crop type
3   Select soil type
4   Determine $ET_O$ using FAO-Penman-Monteith model
5   Determine required intake opportunity time
6   Compute the maximum unit-flow associated depth near the basins
7   Select several and appropriate field layouts or configurations
8   Compute advance time
9   Compute cut-off time
10  Determine application efficiency
11  Determine irrigation scheduling
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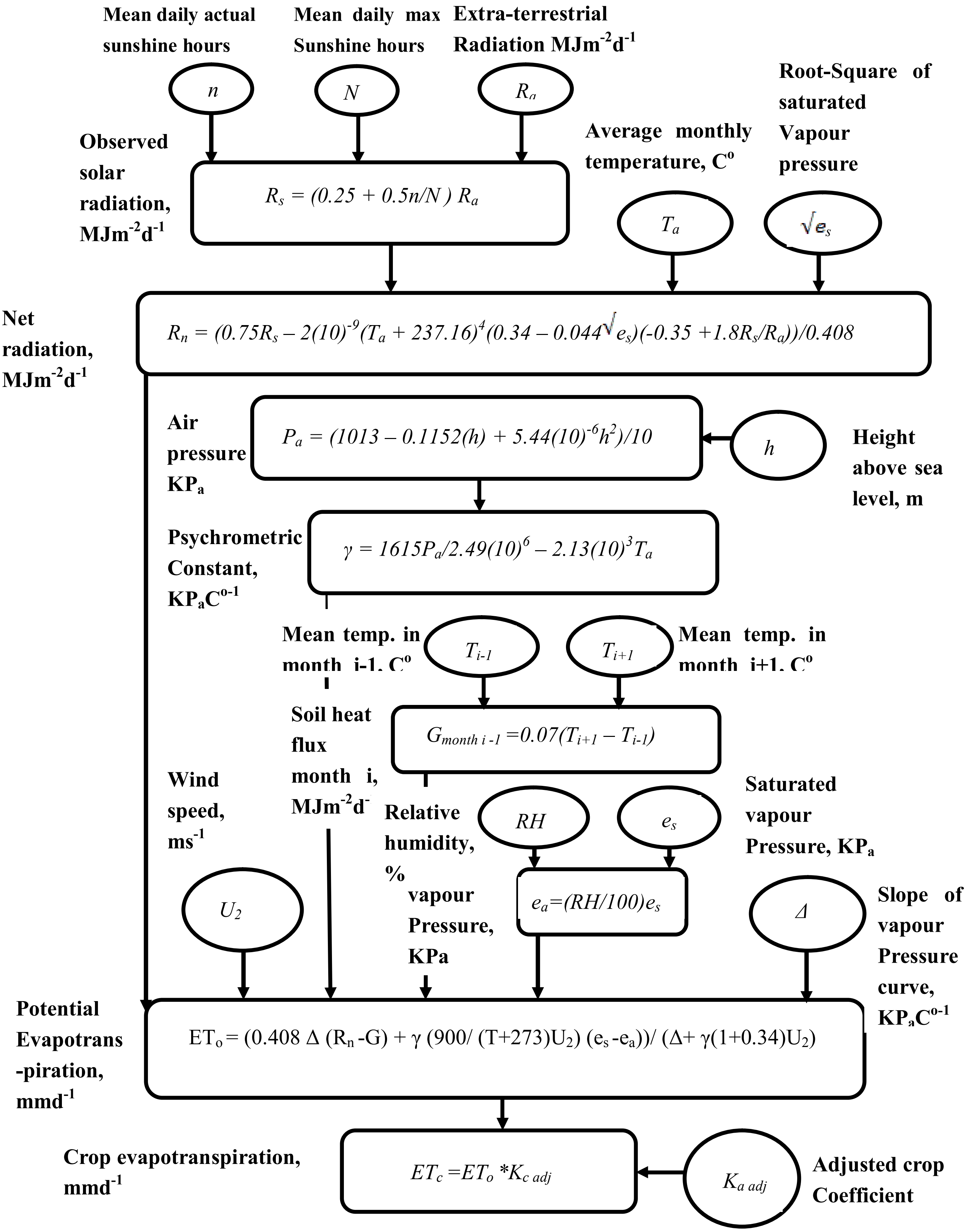


Figure 1. FAO-Penman-Monteith evapotranspiration (ET) model [7]

Key modelling equations [2]

The *required intake opportunity time* (r_{reg}) can be deduced using the following formulas after a series of numerical iterations:

$$t_2 = t_1 + \frac{(Z_{reg} - Kt_1^a - f_o t_1)}{aK/(t_1^{1-a} + f_o)} \qquad (1)$$

$$Z_{reg} = d_r(f_c - m_c)(\lambda_s/\lambda_w)100 \qquad (2)$$

$$t_1 = 5A_o L/Q_o \qquad (3)$$

where t_1 and t_2 are the initial and final estimate of r_{reg} respectively, Z_{reg} is required application depth, K is the constant coefficient, f_o is the basic intake rate, a is the constant exponent, d_r is the depth of root zone, f_c is the moisture content at field capacity, m_c is the soil moisture content, ℓ_s and ℓ_w are the density of soil and water respectively, A_o is the cross section area of flow at the inlet, L is the length of field, and Q_o is the inlet discharge. If the difference between t_1 and t_2 is within 0.5 minute, then r_{reg} is determined as the result or converged value. If they are not equal, the value of t_1 is replaced by t_2 and the iteration is performed over again.

The maximum *depth of flow* $y_O = (\frac{Q_o{}^2 \mathrm{S_n}{}^2 X}{3600})^{0.23}$ (4)

where S_n is soil roughness factor and X is advance distance from the field inlet. Allowance of up to 20% extra water volume was introduced in the design of the DSS so as to ensure adequate infiltration at the extreme ends of the basin field.

The *advance time* t_L can be deduced after a series of iteration using:

$$t_2 = t_1 - \frac{Q_o t_1 - .77 A_o L - S_z K t_1^a L - f_o L t_1/(1+r)}{Q_o - S_z aKL/t_1^{1-a} - f_o L t_1/(1+r)} \qquad (5)$$

where Q_o is inlet discharge in m^3/min/basin or unit width, and S_z, the subsurface shape factor, is defined as:

$$S_z = \frac{a + r(1-a) + 1}{(1+r)(1+a)} \qquad (6)$$

where a is a constant exponent (soil dependent) and r is the power of advance exponent (ranges between 0.4-0.6). If the difference between t_1 and t_2 is within 0.5 minute in eqn (5), then t_L is determined as the result or converged value.

The cross-section area of flow at the inlet in m^2 is given by

$$A_o = \left[Q_o n/(60 P_1 S_o^{.5})\right]^{1/P_2} \qquad (7)$$

The parameters P_1 and P_2 are empirical shape coefficient factors for basin and Q_o is inlet discharge in m^3/min/basin or unit width

The *cut-off time* (t_{co}) is computed using $t_{co} = r_{reg} + t_L$ (8)

The *application efficiency* (E_a) can be deduced using

$$E_a = 100 Z_{reg}(L/Q_o)60 t_{co} \qquad (9)$$

Design data (including values to be supplied at run-time) include:

a - constant exponent (soil dependent)

r - power of advance exponent (ranges between 0.4-0.6)

S_n - soil roughness factor

K - constant coefficient, m^3/min/m of length (soil dependent)
f_o - basic intake rate, m^3/min/m of length (soil dependent)
X - advance distance in metres from the field inlet
S_o - field slope
r_{reg} - required intake opportunity time, min
L - length of field, m
P_1 and P_2 - shape factors

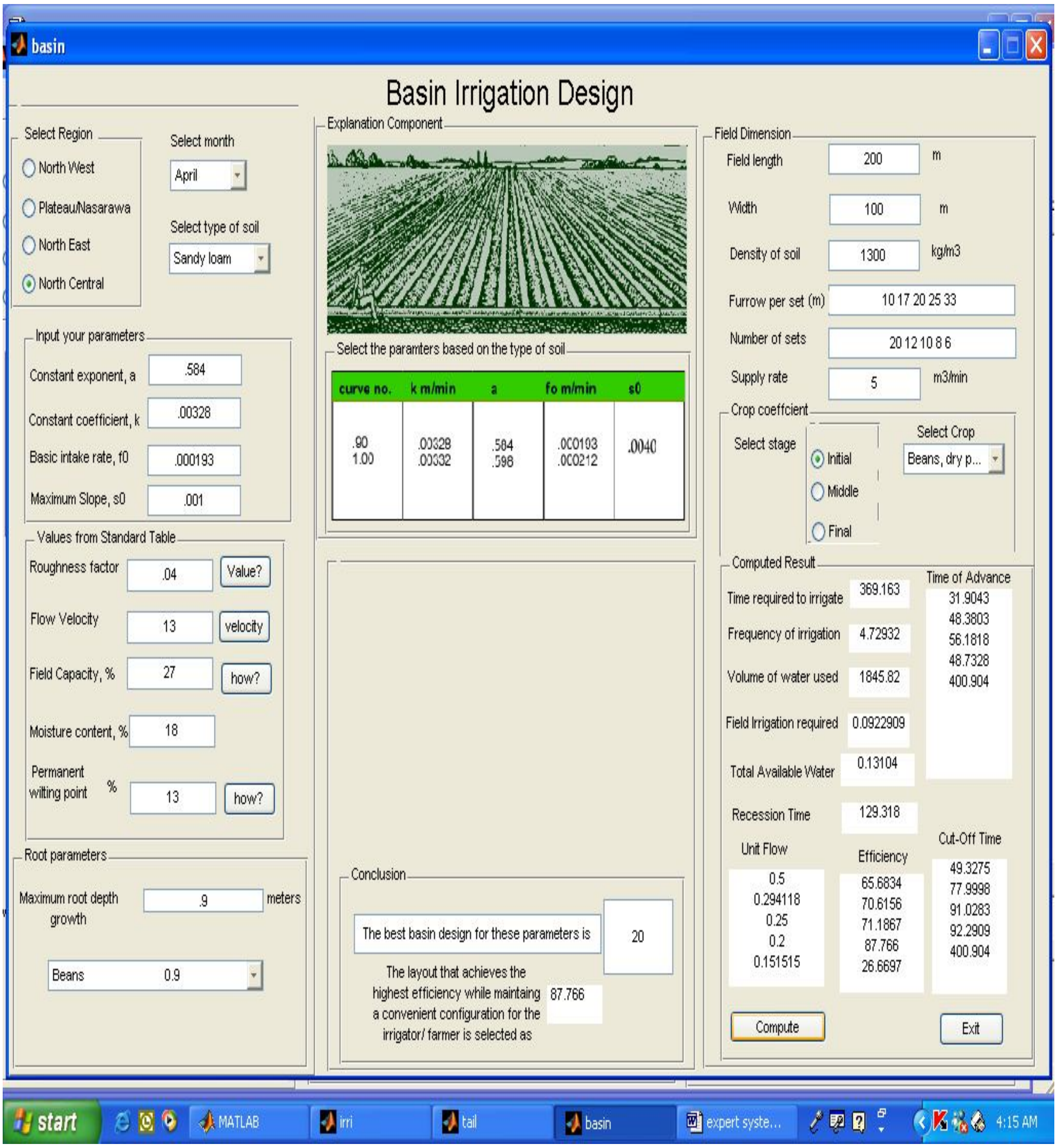
Using the above model, a DSS for solving problems associated with surface irrigation design and management in the northern region of Nigeria was designed at the University of Lagos, Nigeria [9]. The design was based on a large number of theoretical, rational and empirical relationships and heuristic experiences. The system was implemented in Matlab software which allowed the coding of the rules and equations to be easily facilitated in the background while presenting the user with a friendly dialog interface.

Illustrative Example of Software Implementation

Various tests were carried out using the surface irrigation support system for northern Nigeria for different crops, soil types, etc. The following surface irrigation design problem presents a specific case for a design modification of an existing irrigation scheme. The farm under study was situated at Kujama district, Kaduna state of north-central Nigeria and had the following data:

Plantation date: 5/4/2007
Area of field: 2 ha measuring 200 m x 100 m
Drainage system: good
Soil texture: sandy loam (stable)
Field slope: 0.1%
Permanent wilting point: 13%
Field capacity: 27%
Soil moisture content: 18%
Crop to be planted: beans
Total length of crop development: 110 days
Irrigation system: basin

Results using basin irrigation design approach are as shown in the screenshot of the DSS in Figure 2. The test was further carried out for different growth stages of the crop and the results obtained are summarised in Table 1. Analysis of the results of the test showed that out of the five possible configurations for all the stages of growth, the configuration suggested by the DSS was based on the one with highest application efficiency. The design with ten 20-m basins was selected during the initial stage of growth and one with twelve 17-m basins was selected during the medium and final stages. The resulting application efficiency was found to be 82.71 %, 54.49 % and 53.83 % for the initial, medium and final growth stages respectively. Furthermore, a relationship was also established between time of advance and discharge rate for various growth stages. In Figure 3, it can be seen that as advance time increases there is a reduction in basin discharge rate. The finding from the support system was then used to prepare a scheduling table for the management of the proposed irrigation system as summarised in Table 2.



Basin Irrigation Design

○ North West
○ Plateau/Nasarawa
○ North East
● North Central

Select month April

Select type of soil Sandy loam

Constant exponent, a .584
Constant coefficient, k .00328
Basic intake rate, f0 .000193
Maximum Slope, s0 .001

Roughness factor .04
Flow Velocity 13
Field Capacity, % 27
Moisture content, % 18
Permanent wilting point % 13

Maximum root depth growth .9 meters

Beans 0.9

curve no.	k m/min	a	fo m/min	s0
.90 1.00	.00328 .00332	.584 .598	.000103 .000212	.0040

The best basin design for these parameters is 20

The layout that achieves the highest efficiency while maintaing a convenient configuration for the irrigator/ farmer is selected as 87.766

Field length 200 m
Width 100 m
Density of soil 1300 kg/m3
Furrow per set (m) 10 17 20 25 33
Number of sets 20 12 10 8 6
Supply rate 5 m3/min

Select stage ● Initial ○ Middle ○ Final

Select Crop Beans, dry p...

Time required to irrigate 369.163
Frequency of irrigation 4.72932
Volume of water used 1845.82
Field Irrigation required 0.0922909
Total Available Water 0.13104
Recession Time 129.318

Time of Advance
31.9043
48.3803
56.1818
48.7328
400.904

Unit Flow	Efficiency	Cut-Off Time
0.5	65.6834	49.3275
0.294118	70.6156	77.9998
0.25	71.1867	91.0283
0.2	87.766	92.2909
0.151515	26.6697	400.904

Figure 2. Sample DSS consultation output screen for a basin irrigation problem

Table 1. Test results for Kujama basin design problem

Initial stage of growth								
No. of basin	Basin width (m)	Discharge (m^3min^{-1})	Advance time (min)	Cut-off time (min)	Irrigation interval (days)	Water required (m^3)	Application time (min)	Application efficiency (%)
20	10	0.5	22.78	42.82	4.7	1958.68	391.74	75.66
12	17	0.29	33.02	67.09				82.1
10	20	0.25	38.27	78.35				*82.71*
8	25	0.2	48.73	98.82				81.96
6	33	0.15	71.84	137.96				77.5
Medium stage of growth								
No. of basin	Basin width (m)	Discharge (m^3min^{-1})	Advance time (min)	Cut-off time (min)	Irrigation interval (days)	Water required (m^3)	Application time (min)	Application efficiency (%)
20	10	0.5	44.29	61.71	1.61	2973.22	594.64	52.5
12	17	0.29	71.47	101.09				*54.49*
10	20	0.25	84.53	119.38				54.28
8	25	0.2	108.75	152.3				53.18
6	33	0.15	155.78	213.37				50.13
Final stage of growth								
No. of basin	Basin width (m)	Discharge (m^3min^{-1})	Advance time (min)	Cut-off time (min)	Irrigation interval (days)	Water required (m^3)	Application time (min)	Application efficiency (%)
20	10	0.5	47.54	63.33	5.3	3009.48	601.9	51.16
12	17	0.29	75.46	102.32				*53.83*
10	20	0.25	88.82	120.42				53.81
8	25	0.2	113.53	153.02				52.93
6	33	0.15	161.32	213.45				50.09

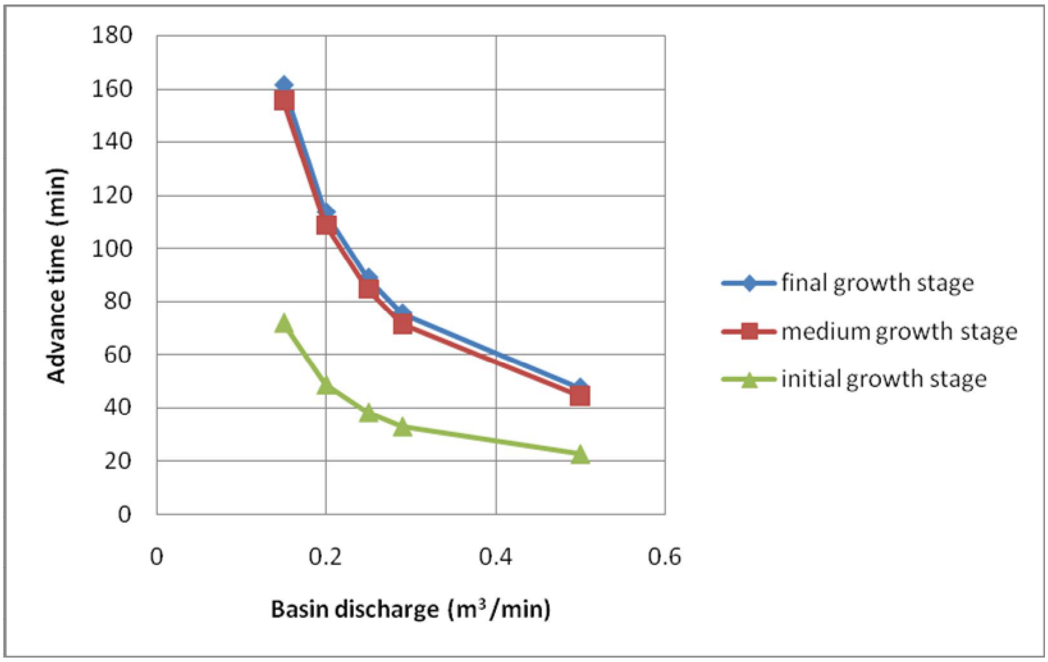


Figure 3. Relationship between inflow rate and advance time at various stages of growth for a basin problem

Table 2. Irrigation schedule for a basin problem

Month	Starting date	Water quantity	Interval	Application time (min)
		(m^3)	(days)	
April (5 times)	5/4/2007-30/4/2007	1958.68	5	394.74
May (15 times)	1/5/2007-30/5/2007	2974.22	2	594.64
June (6 times)	1/5/2007-1/6/2007	3000.48	5.3	601.9
July (3 times)	2/6/2007-16/2007	3040.93	5.4	608.19

Conclusions

Surface irrigation design is quite a difficult problem to solve optimally due to the inefficiency of water application arising mainly from deep percolation and surface runoff or tail water. This paper presents the development of a decision support system to address the issue. The decision support system (DSS) allows a much more comprehensive treatment of vital hydraulic processes occurring both on the surface and beneath it. The basin system as modelled and applied has made it possible to overcome the high costs associated with the sprinkler and trickle systems while achieving almost the same level of efficiency. Optimal design and management practices can be determined for a variety of conditions, and design historically requiring days of effort can now be made in minutes with this surface irrigation design software application. Also, the effectiveness of existing irrigation schemes or proposed ones can be predicted in a timely manner.

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