Development of Irrigation Canal Simulation Models (ICSMs) and its applicability to Large Scale Irrigation Schemes in Nigeria: An appraisal

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Abstract

Irrigation Canal Simulation Model (ICSM), a computer aided model is being adopted for efficient water management in large gravity irrigation schemes in Asia, Europe and America. It is because of the model ability to understand and diagnose problems of water management in open canal irrigation schemes and present options. The basic constituents of ICSMs and their development was reviewed with aim of presenting the principles and the processes behind typical ICSMs. The key issues on how to simulate water flow in irrigation canal and the prevailing conditions that can allow such issues be studied and quantified were carefully analysed and linked with the requirements and practical uses of the ICSMs. The applicability of such a new but handy tools to the Nigerian irrigation schemes was assessed. The option of setting up an indigenous team of experts drawn from both the field agencies such as River Basin Development Authorities (RBDAs), Research Institutions and Universities to initiate the process of developing a friendly ICSM is being advocated. This is because the models can be useful in addressing the existing situation (system deterioration and state of despair) of most irrigation schemes in Nigeria. The cost effectiveness in terms of time, energy and human resources saving are among the key justifications for this advocacy.

Key words: Irrigation Canal Simulation Models, hydraulic modelling

1.0 Introduction

In this age of Information Technology (IT), Irrigation Canal Simulation Models (ICSMs) have been become useful and powerful tools for improving efficiency of irrigation water management practices especially at main and secondary systems levels. Higher efficiency often translates into higher command area and subsequently increased in crop production. Besides system maintenance and operation of irrigations, ICSMs are tools for conducting research on the hydraulic behaviours of main system level under different managerial situations (scenarios).

Research works involving water measurement of large irrigation schemes are often limited to secondary and tertiary system levels as the field experimentation at the main system level often causes inconvenience to the farmers and can adversely affect the crop performance. Complete closure of the main canal or sudden increase/decrease in canal flow over time and space make such experiment rarely applicable in real-life situation (Baume, 1993). However, inefficient management of the conveyance network at main system level requires occasional research activity as rightly observed by Chambers (1988). Functional main system of irrigation schemes is considered as the key to improve irrigation performance. ICSMs offer a viable alternative to direct experimentation on the physical system where series of tests can be run to study system behaviours under a variety of design and management scenarios. This can be achieved without modifying the physical infrastructure of the canal or disrupting its normal operations. In the system operations and maintenance, the main function of irrigation canal is to deliver water in an accurate and flexible way. To effectively do this, the scheme must have central system that allows monitoring and control of canal operations. Use of ISCMs assist to a large extent in the centralized control system, in combination with trial and error processes, most often determine efficient canal operational policies. ICSMs can also be used as a tool to modernize large irrigation schemes with the aim of improving their efficiencies. This is because when schemes have already been established, operated for some years, then, they were discovered not to be operated as design due to sudden change of crop pattern, introduction of new water demanding crop etc, leading to higher scheme water demand. The alternative is physical redesign and constructions leading to additional investment which often overweight the cost of acquiring or developing an ICSM

Thus, ICSMs are real representation of physical schemes in computer which can be calibrated to simulate the actual irrigation canal hydraulic and operational conditions. They can also be used to test design modifications (e. g. calibration of new hydraulic structures), use of different cropping pattern and diversification, and to test new (modernized) operational rules in the schemes.

In Nigeria, the numerous large scale irrigation schemes where typical open canals under gravity and upstream based operations exists, provides good opportunity for the adaptation of ICSMs and eventual adoption. The emerging problems of operation and maintenance of the over 100,000 ha already developed under such types of schemes across the country can be systematically addressed through research efforts using ICSMs. The recent achievement of promoting the concept of Participatory Irrigation Management (PIM) in some of these schemes in the country would further enhance the chances of trying the ICSMs. It would involve not only the managers and field staff of these schemes but also the users who are the key stakeholders. The paper reviewed the development approach of ICSMs based on key issues and field conditions prevalent in irrigation schemes. The paper further reviewed the requirement for ICSMs to be run and a practical uses to the managers of irrigation schemes. The paper also assessed the applicability of the ICSMs to Nigerian irrigation schemes. Finally, the paper highlighted the existing limitations that would inhibit the adoption of foreign-based ICSMs in Nigeria and argued that local expertise must be exploited to initiate such endeavour.

1.2 ICSMs Developments Approach

The flow of water in open channels of irrigation system varies spatially (steady state conditions) and sometimes both specially and temporal (unsteady sate condition). The two conditions exist every day in a real-life whenever open channels are being used to convey, distribute or drain out water. In open canal system, the two important variables under operating conditions are water level (hydraulic head “h”) and the quantity (volume) of water passing a given point per unit time (discharge “Q”). This is because to operate a canal in irrigation system, there has to be a range in the value of “h” when water can easily be diverted to the farm or another system level with a predetermined “Q”. This means that the two major issues of simulating flow of irrigation water in a canal which can deliver water in accurate and flexible way are,

1. The mathematical concept (equation) that can represent hydraulic behaviour in steady and unsteady conditions of water flow in open canals

2. The water level control function in the canal that can give the required and flexible discharge Q within the range of h value.

The first issue can be discussed under governing physical process of developing ICSMs while the second issue can be presented under water level control function

2.0 Equations Governing Water Flow in Open Channel

2.1 Unsteady Flow Condition:

This situation arise when water is released from upstream off-take at high elevation through gate opening to an open canal at lower elevation until the flow becomes steady. To date the governing equations used for simulating gradually varied one dimensional unsteady flow equation are the famous "Saint Venant equations". These equations can be derived from laws of conservation of momentum and mass. Amanda, (1999) presented a detailed method for deriving these equations. The Q and A form of the equations are given below (there are other forms in literature Amanda (1999), Othman, (2002)):

Momentum Equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} + gAS_f - gAS_O = 0 \text{---------------(1)}$$

Continuity Equation

$$\frac{\partial h}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} = q \text{---(2)}$$

$$S_f = \frac{n^2 Q^2}{A^2 R^{3/4}} \text{--(3)}$$

Where t= time, x = longitudinal distance, Q = discharge h = water depth, A = cross sectional Area, B= Top width S_o = bed slope, S_f = frictional slope and may be estimated using flow resistance equation of Manning equation n = Manning-Strickler coefficient, R = hydraulic radius and q = lateral inflow or out flow (positive indicates out flow while negative inflow)

It is pertinent to note that the equation of mass/momentum is applied only within the channel loop (reach) and different relationships are used to link the upstream and downstream flow variables at the junction (diversion), cross regulator or drop structure. The hydraulic conditions at such locations is described by the equation of mass and energy conservation (Sen, 2002). Assuming no change in storage volume the other junction, the continuity equation can be written as

$$\sum Q_i = \sum Q_o \text{---(4)}$$

Where "i" stands for the inflow branches and "o" for the outflow branches.

2.2 Steady State Flow Conditions

The steady state condition in an open canal is achieved when the effect of time variation in the water flow becomes negligible. Sen and Garg (2002) derived the steady state equation of water flow using equations 1 and 2 after neglecting the time derivatives. Misra (1996) faulted the use of gradually varied flow equation given by Chow, (1959) as equation of steady state in irrigation canal due to the assumption of no lateral flow. He opined that the flow in reality is spatially varied rather than gradually varied and the actual depth and discharge are vary significantly different from the designed ones. Therefore, he modified the spatially varied equation as:-

$$\frac{dQ}{dx} = q_s + Q_L \delta(x - x_L) \text{ --------------------------------(5)}$$

$$\frac{dh}{dx} = \frac{S_o - S_f - \frac{2\beta Q}{gA^2}(q_s + Q_L \delta(x - x_L))}{1 - \beta \frac{Q^2 B}{gA^3}} \text{ -------------(6)}$$

Where QL = turn out discharge, β = momentum correction factor which is taken as 1, $\delta(x-x_L)$ =dirac delta function, x_L = location of the turn out, q_s = rate of seepage per unit length, q_s can be obtained from Wachyan and Ruston (1987) as:

$$q_s = Kp \text{ ---(7)}$$

where K = seepage coefficient, p = wetted perimeter. Q_L is given by Tod et al (1991)

$$Q_L = \sqrt{\frac{2g}{K_L}} A_L w_L \sqrt{h - Z_L} \text{ --------------------------------(8)}$$

Where K_L = total energy loss coefficient (=2.5) given by Misra (1996) A_L= Area of turn output W_L = ratio of turn out opening to turn out area, Z_L= down stream reference level. However, Baume et al (1994) presented the equation of surface water profile of a steady state conditions in a canal as follow:

$$\frac{dh}{dx} = -S_f + k\frac{qQ}{gA^2} \text{ ---(9)}$$

Where q = lateral discharge per unit length, K= a factor ranging from 0-1

The initial stage of developing ICSMs is solving equations 1 to 9. The task of solving these equations required high mathematical skills and good knowledge of computer programming as equations 1, 2, 5, 6, and 9 respectively have no analytical solutions. There are exist only numerical solutions for these equations (Othman and Abubakar, 2003, Baume et al 1994, Misra, 1996, Sen and Garg, 2002 Kumar et al 2001 and Mishra et al 2002). The unsteady flow condition normally last for a very short duration in canal system but posses more complex and challenges to researchers in finding accurate solutions to this condition. Broadly, there exist three approaches to the solutions of unsteady flow (Saint-Venant) equations. These are; method of characteristics (Abbot, 1966, Abbot and Verwey 1970), finite difference method (Liggert and Woolhiser 1967, Mishra, 1994, Theodor et al, 1998 and Bautist et al 2003) finite volume method (Amanda, 1999) and finite–element method (Cookey and Moins 1976 and Davis (1976).

In the method of characteristics, the equations are first converted into characteristic form and then solve by finite–difference scheme. Although this method was popular in the 1960s but the method is not suitable for system having numerous geometrical changes and it fails because of the convergence of the characteristic curve whenever there is wave shock/bone (Chaudhry, 1979). As for the finite element method it may still be considered in the infancy stage for application to open channel transients since there had not been many works on this method. The finite-difference approach is the most widely used to solve Saint Venant equations. This approach consist of two methods; explicit finite–difference and implicit finite-difference methods. In the former method, the partial derivatives of the two equation are replaced by finite differences such that the two unknown conditions at a point at the end of time step are expressed in terms of the known conditions at the beginning of the time step as elaborated by Choudhry (1979). Although, this method is simple to use compared to the later method its stability depend heavily on "courant" condition given below (Chodhry, 1979, Ames,1992)

$$\Delta t \leq \frac{\Delta x}{V \pm C} \text{--} (10)$$

Where Δt = time step Δx = distance step, V= average flow velocity C= wave celerity

Strelkoff (1970) cautioned that finite-difference scheme is expected to be stable if small numerical errors, due to truncation and round-off introduced at time t_o are not amplified during applications of the difference equations and the error at subsequent time t did not grow so large as to obscure the valid part of the solution. This is because the discretizations of the x–t plane into a grid for the integration of the finite-difference equations introduces numerical errors into the computation.

The implicit finite difference also uses discretizations of the x-t plane like the explicit method, the only difference between the two methods is that while explicit uses a forward – difference scheme for the time derivative and central difference scheme for the spatial derivative, the implicit method on the other hand uses back ward difference scheme for both the temporal and spatial derivatives in terms of the dependant variable and the unknown time line. The "courant" condition does not apply to the implicit method while it is advisable to determine the minimum Δt when using explicit method. Another advantage of using implicit scheme is shorter computer time requirement as there is no restrictions in choosing the value of Δt. The advantages of using explicit method are for stimulation of sharp peaks, and wave shock due to choice of smaller size of Δt.

The recent development in the use of implicit method has greatly improve the accuracy and reliability of ICSMs developmental efforts. The use of Preissmen's method for descritization of x-t plane and using double sweep or iterative Newton methods of solving the equations (Saint Venant) adopted by Mishra (1994), Kumar et al (2002), Mishra, (2001), and Fubu et al (1998) among others are available in literature. Similarly, the solution of these equations are arrived at with the use of initial and boundary conditions as indicated by Chaudhry (1979). The initial conditions are determined from solving the steady state conditions in which the solved unknowns becomes initial values

In order to quantify how well a particular numerical technique performs in generating a solution to a problem, there are four fundamental criteria that can be applied to compare and contrast the different methods or approaches. The four concepts are accuracy, consistency, stability and convergence. In theory this criteria was used in formulating the different methods but in reality, there may be some differences. The method of testing a suitable approach using above criteria was explained by Amanda, (1999)

2.3 Water Level Control Function

In general, the water level control function is part of the process of solving "Saint Venant" equations. It involves the choice of the boundary conditions at the off take or functions (gates for diversion or cross regulators). There are four common boundary conditions encountered in typical irrigation canal systems (Chaudhry, 1979)

a. constant water level at upstream gates/regulators

b. Constant water level at down stream

c. Variable discharge at up stream/down stream end

d. Conditions 1-3 at junction of two or more channels

The manipulations of these boundary conditions give rise to three types of control algorithms; feed back control, feed forward control and the combination of the two. Feed back control is a situation where the control variables are directly obtained from field measurements, details are available in Malatere et al (1998) while examples can be found in Sawadogo (1992), Rodellar et al (1993) and Burnt (1983). Feed forward control algorithm is sometimes called gate stroking where the action variables are computed from targeted variables. Example of feed forward control could be found in Roux, (1992), Liu et al (1992) and Falvey (1987). The third algorithm is the combination of the first two control algorithms, generally adopted for a scheme with multi-variable system (with several control actions and controlled variables). For instance, discharge can be feed back control while water level in feed forward control. Examples are available in Shand (1971), Burt (1983) and liu et al (1994).

The ICSMs can be developed for application in most typical open canal irrigation system through the process described in the above sections. Details can also be obtained from quoted literatures for use. There are also several soft wares available for use. Some of the available canal hydraulic models soft ware are CANALMAN, DUFLON, CARIMA, MODIS USM and SIC (www.google.com). Each of these models must be calibrated and validated before use as a tool for operational management of irrigation scheme

2.4 Requirements of ICSMs

In order to use ICMSs for a given canal it is necessary to have physical and hydraulic data (Othman 2002). The physical parameters necessary are canal geometry (sample of cross section representing the canal depth, slope, lengths or reaches, off-take from canal), description and dimensions of structures along/across the canal. The hydraulic parameters include, the discharge coefficients of the cross structures and off-takes, boundary conditions of the off-takes /tail end of the system, seepage losses and Manning –Stickler coefficients of the selected reaches. Some of these parameters are directly measured from the field , some could be obtained from design specifications while others are adjusted by running the model so that simulated values and measured field values are within acceptable range of accuracy.

2.5 Use of ICSMs

ICSMs give result of the simulation process both in graph and numerical values. Water depths and discharges in every section of the simulated canal are provided for a given control action (gate opening, position and opening duration). These results provide to the canal managers with the clear picture of the hydraulic behaviours of all the hydraulic structures and canal reach at both unsteady and steady conditions. The unsteady condition can show when the perturbation reaches (wave time arrival) each section of the canal. The time at which steady state condition is achieved at different sections of the canal can also monitored with these information, the canal managers can develop effective operation rules that minimizes water wastages, remove unnecessary operation (save energy/resource) and allow only a safe discharge to flow in the canal thereby maximizing efficient use of water along the canal and prolonging the canal life span. The managers can also create and test new scenarios using computer simulation. Such new scenarios can be change of cropping pattern, test of new irrigation schedules, introduction of more/less water demanding crops increasing crop diversity etc. The ICSMs equally assist managers to identify emergency potential operational problems for early/timely intervention to avoid disasters or great loses.

3.0 Applicability of ISCMs to Nigeria Irrigation schemes

Nigerian irrigation schemes (Mediums/large) were established by governments (state/federal) with the sole aim of achieving self sufficiency in food production. Some of these schemes were hurriedly constructed without adequate testing and necessary modifications to the design. Issues of compatibility with technical expertise and environmental conditions among others were seriously over looked. Presently, these environmental constraints ignored at the schemes establishments are militating against efficient utilization of these schemes with disappointing performance (Musa, 2002). Table 1 gives summary of practical constraints identified in eight of the existing irrigation schemes while Table 2 show overall performances of the twelve RBDAs during 2001/2002 dry season farming. The causes of these constraints and low performance indicators are many among which are shortage of qualified and experience staff, insufficient funds for scheme operation and maintenances and insufficient or lack of working materials. There is neither time nor resources to embark on elimination process of these constraints through the conventional way of redesign, award of contract, modification, testing and certification. This approach would certainly be too slow and very costly with low probability of success. The utilization of ICSMs become imperative and handy under such situation.

4.0 Conclusion

Therefore, the introduction of the ICSMs to Nigerian irrigation schemes may assist in addressing several issues most especially operation and maintenance. Ready made ICSMs and their packages are available in many developed countries with complimentary expertise. Direct purchase of such packages is possible but can be expensive as it requires training of target staff by the owners of such soft wares. Moreover, the applicability of such soft wares may be difficult in most of Nigerian irrigation schemes where there is serious problem of maintenance. Thus, it may be expedient and effective to initiate the process of developing a simulation model that can accommodate the level of deterioration of the Nigerian irrigation schemes. For this to be achieve, it really calls for a team work by all experts working in this area. It requires both institutional and personal linkages between River Development

Authority and the relevant research institutions or universities and similar organizations and experts in selected learning and research centres in developed countries. This paper is a humble initiation of such effort

Table 1: Some completed Projects with Operation and Maintenance Constraints

S/N	Project name	Area developed (ha)	Year of completion	Area under operation (ha)	Remarks
1	**Lower Anambra Irrigation Project (LAIP)**	3856	1987	Nil	High imported items and scarcity of spare part for the pumps, Communal clashes, breakdown of all the intake pumps
2	**South Chad Irrigation Project Phase I and II (SCIP)**	22000	1982	820	High imported items and scarcity of spare part for the pumps
3	**Bakalori Irrigation Project (BIP)**	23000	1982	5660	Poor Institutional arrangement, inappropriate design of the sprinkler system
4	**Swashi Irrigation Project (SWIP)**	3000	1991	2000	Poor access and demography as a result of remote location
5	**Jibiya Irrigation Project (JIP)**	3400	1991	170	High cost of electro-mechanical component of the pumps, poor farmer motivation and institutional arrangement
6	**Tugan Kawo Irrigation Project (TKIP)**	880	1988	250	Faulty construction due to poor design
7	**Kano River Irrigation Project (KRIP) phase I**	15000	1982	13285	Siltation and weeds infestation in the canal, part of the conveyance system collapsed due to poor maintenance, poor scheduling leading to inadequate water delivery at the tail end
8	**Kiri Dam and Irrigation project**	12000	1981	6000	The irrigation facilities are being managed by Savannah Sugar Co. which is being rehabilitated
	Total	**83136**		**28185**	

Source: Department of Irrigation and Drainage, Federal Ministry of Water Resources, Nigeria 2003

Table 2: Performance indicators of RBDA for 2001/2002 dry season

RBDA	**Area Developed (ha)**	**Area actually Irrigatble (ha)**	**Area cropped**	**Area actually irrigable/area developed**	**Area cropped/area actually irrigable**	**Performance indicator (%)**
	A	B	C	D =(B/A)	E = (C/B)	F =(DxEx100) %
A-I	3926	3862	0	0.98	0.00	0.00
C-R	1354	502	48.6	0.37	0.10	3.59
B-O	815	600	43.5	0.74	0.07	5.34
O-O	272	222	222.5	0.82	1.00	81.80
U-N	5425	2480	1633	0.46	0.66	30.10
N-D	663	450	0	0.68	0.00	0.00
S-R	26845	7987	6680	0.30	0.84	24.88
L-N	1320	1254	762	0.95	0.61	57.73
U-B	13410	8500	6920	0.63	0.81	51.60
C-B	26480	8000	1217	0.30	0.15	4.60
L-B	1315	535	38	0.41	0.07	2.89
H-J	18475	18000	2160	0.97	0.12	11.69
TOTAL	100300	52392	19725			

Source: Department of Irrigation and Drainage, Federal Ministry of Water Resources, Nigeria 2003

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